An International Forum For The AE Science and Technology

JOURNAL OF ACOUSTIC EMISSION


First AE Inspection Service for a Commercial Pressure Vessel (1968)

Endorsed by AEWG, AEWGI, CARP and EWGAE

Published by Acoustic Emission Group
Los Angeles, CA
1. Aims and Scope of the Journal

Journal of Acoustic Emission is an international journal designed to be of broad interest and use to both researcher and practitioner of acoustic emission. It will publish original contributions of all aspects of research and significant engineering advances in the sciences and applications of acoustic emission. The journal will also publish reviews, the abstracts of papers presented at meetings, technical notes, communications and summaries of reports. Current news of interest to the acoustic emission communities, announcements of future conferences and working group meetings and new products will also be included.

Journal of Acoustic Emission includes the following classes of subject matters:

A. Research Articles: Manuscripts should represent completed original work embodying the results of extensive investigation. These will be judged for scientific and technical merit.

B. Applications: Articles must present significant advances in the engineering applications of acoustic emission. Material will be subject to reviews for adequate description of procedures, substantial database and objective interpretation.

C. Technical Notes and Communications: These allow publications of short items of current interest, new or improved experimental techniques and procedures, discussion of published articles and relevant applications.

D. AE Literature section will collect the titles and abstracts of papers published elsewhere and those presented at meetings and conferences. Reports and programs of conferences and symposia will also be presented.

Reviews, Tutorial Articles and Special Contributions will address the subjects of general interest. Nontechnical part will cover book reviews, significant personal and technical accomplishments, current news and new products.

2. Endorsement

Acoustic Emission Working Group (AEWG), European Working Group on Acoustic Emission (EWGAE), Committee on Acoustic Emission from Reinforced Composites (CARP), and Acoustic Emission Working Group of India have endorsed the publication of Journal of Acoustic Emission.

3. Governing Body

The Editor and Associate Editors will implement the editorial policies described above. The Editorial Board will advise the editors on any major change. The Editor, Professor Kanji Ono, has the general responsibility for all the matters. Associate Editors assist the review processes as lead reviewers. Mr. T.F. Drouillard is responsible for the AE Literature section. The members of the Editorial Board are selected for their knowledge and experience on AE and will advise and assist the editors on the publication policies and other aspects. The Board presently includes the following members:

S.H. Carpenter (USA)  
D.A. Dornfeld (USA)  
P. Fleischmann (France)  
L. Golaski (Poland)  
M.A. Hamstad (USA)  
H.R. Hardy, Jr. (USA)  
R. Hill (UK)  
I.V. Ivanov (Russia)  
P. Jax (Germany)  
T. Kishi (Japan)  
O.Y. Kwon (Korea)  
J.C. Lenain (France)  
S.L. McBride (Canada)  
W. Morgner (Germany)  
C.R.L. Murthy (India)  
H. Niitsuma (Japan)  
A.A. Pollock (USA)  
T.M. Proctor, Jr. (USA)  
I. Roman (Israel)  
C. Scala (Australia)  
C. Scruby (UK)  
A. Vary (USA)  
E. Waschkies (Germany)  
M. Wevers (Belgium)  
J.W. Whittaker (USA)  
B.R.A. Wood (Australia)

4. Publication

Journal of Acoustic Emission is published quarterly in March, June, September and December by Acoustic Emission Group, 308 Westwood Blvd.- Box 364, Los Angeles, CA 90024-1647. It may also be reached at 6531 Boelter Hall, University of California, Los Angeles, California 90095-1595 (USA). tel. 310-825-5233. FAX 818-368-8309. e-mail: ono@seas.ucla.edu

5. Subscription

Subscription should be sent to Acoustic Emission Group. Annual rate for 1996 or 1997 is US $96.00. For surface delivery, add $8 in the U.S. and $11 for Canada and elsewhere. For air mail delivery to South America, add $18, Western Europe, add $25 and add $30 elsewhere. Overseas orders must be paid in US currencies with a check drawn on a US bank. Inquire for individual (with institutional order) and bookseller discounts.

6. Advertisement

No advertisement will be accepted, but announcements for books, training courses and future meetings on AE will be included without charge.
A History of Acoustic Emission

Abstract

The technology of acoustic emission (AE) traditionally had its beginning in 1950 with the work of Joseph Kaiser. During the 1950s and '60s researchers delved into the fundamentals of acoustic emission, developed instrumentation specifically for AE, and characterized the AE behavior of many materials. AE was starting to be recognized for its unique capabilities as a nondestructive test (NDT) method for monitoring dynamic processes. In the decade of the 1970s research activities became more coordinated and directed with the formation of the working groups, and its use as an NDT method continued to increase for industrial applications. In the 1980s the computer became a basic component for both instrumentation and data analysis, and today it has sparked a resurgence of opportunities for research and development. Today, waveform-based AE analysis has become commonplace and there is a shift in AE activities with more emphasis on applications than on research.

From the beginning, the developing field of acoustic emission has been nurtured by a plethora of dedicated savants with a diverse range of scientific and engineering disciplines, who have contributed in a collective way to bring AE to a mature, fully developed technology and to leave a legacy of knowledge recorded in its literature. AE literature has been a key indicator of the amount of activity, the proportion of research to application, the emphasis on what was of current interest, and the direction AE has taken. This article presents a brief survey of the history of acoustic emission, with emphasis on development of the infrastructure and some of the people involved.

1. Introduction

Acoustic emission is a naturally occurring phenomenon which man has observed from early times. Earthquakes and rockbursts in mines are the largest naturally occurring emission sources. In metals it is reasonable to assume that the first acoustic emission heard in metals was tin cry, the audible sounds produced by mechanical twinning of pure tin during plastic deformation. This occurred during the Bronze Age (about 3500 BC) after man first learned the practice of smelting and was able to produce pure tin from its naturally occurring oxide form.

1.1 Alchemy and 'Tin Cry'

The earliest recorded observation of audible acoustic emission found in the literature was in The Works of Geber (1928), originally published in London in 1678. This was an English translation of the Latin edition of Summa Perfectionis Magisterii by the 8th century Arabian alchemist Jabir ibn Hayyan (also known as Geber), published in Bern, Switzerland in 1545. Geber wrote that Jupiter [tin] gives off a "harsh sound" or "crashing noise." He also described Mars [iron] as "sounding much" during forging. This sounding of iron was most likely produced by the formation of martensite during cooling.

Since the time of the alchemists, the sound of audio-frequency acoustic emissions have become a recognized property of tin, cadmium, magnesium, zinc, and iron. During the last half of the 19th century discussions on tin cry were commonly found in textbooks and handbooks on chemistry. For example, Elroy M. Avery (1883) wrote that cadmium "...gives a crackling sound when bent, as tin does." He also described an experiment with tin: "Hold a bar of Sn near the ear and bend the bar. Notice the peculiar crackling sound. Continue the bending and notice that the bar becomes heated. The phenomena noticed seems to be caused by the friction of the crystalline particles." The following excerpt appeared in the 1894 edition of Watts' Dictionary of Chemistry (Muir and Morley, 1894): "When a bar of tin is bent, a crackling sound may be heard due to the crystals in the inner parts of the bar breaking against one another."

1.2 Metallurgists Hear Tin 'Cry'

From around the turn of the century, a great deal of work was done on the study of twinning and martensitic transformation, particularly in tin and zinc, two of the most well-characterized and documented metals for studying these phenomena. During these studies it was normal to hear the audible sounds such as tin cry which were often reported as an incidental observation. In reporting the sounds they heard, researchers often gave them some analogous description such as clicking, chatter, squeak, grinding, hissing, and snapping noises and, in one case, tinkle of Japanese glass chimes.
In 1916 in Germany, J. Czochralski (1916) published the first such article on the association between tin- and zinc-cry [Zinn- und Zinkgeschrei] and twinning. He cited Gmelin-Kraut's Handbuch der anorganischen Chemie (Friedheim and Peters, eds., 1911), which in turn referenced an article by S. Kalischer (1882). Kalischer in turn cited references to tin cry published prior to 1882 in Chemischen Handbüchern by Gmelin and Brezelius (unconfirmed date) and in Watts' Dictionary of Chemistry (Muir and Morley, 1894).

In France, Albert M. Portevin and François Le Chatelier (1923) reported that "small sharp noises [petit bruit sec]" were clearly audible at a distance of several meters during discontinuous yielding and Lüders band formation in aluminum-copper-manganese alloys.

In 1924 in Russia, Profs. Abram F. Joffé and Paul S. Ehrenfest (Classen-Nekludowa, 1929) noticed that the process of shear deformation in heated rock salt crystals and in zinc single crystals progressed by small jumps, each accompanied by a noise like the tick of a clock. This work was continued by M.V. Klassen-Neklyudova (1927, 1928).

In the United States, Robert J. Anderson (1925) reported in his doctoral dissertation that during tension testing of an aluminum alloy beyond the yield point and near the failure load, increased loading was accompanied by a series of slips which gave rise to a series of serrated lines or Lüders lines. These slips were accompanied by a series of "audible clicks or sounds" whose pitch were dependent upon the thickness of the sheet — for a thin sheet, the sounds were high pitched, "not unlike the tinkle of Japanese glass chimes;" for thick sheet, the sounds were "low in note, being on the order of a grunt."

In Germany, Erich Scheil (1929) reported that the formation of martensite in steel is accompanied by a "...clearly audible noise, whose sound was similar to the well-known tin cry [...] deutlich hörbaren Geräusch, dessen Klang dem bekannten Zinggeschrei ähnlich war."

In the United States, Prof. P.W. Bridgman (1935, 1937) observed during rotation under compressive loading that few metals and many nonmetals rotated in a noisy manner. Some "chatter," some "squeak," some make a "grinding noise," others "hiss," but the most important noise was "snapping" which was in most cases superposed on the ordinary phenomena of plastic flow.

And lastly, in the United States, Prof. Charles S. Barrett (1947) reported that "the transformation (of lithium) to the face-centered cubic form is accompanied by a series of audible clicks, as in the twinning of tin or magnesium and the formation of martensite." Further discussion on these and other observations during what might be termed The Audition Period is given in an historical review by Drouillard (1987).

1.3 Precursors of Acoustic Instrumentation

Robert Hooke (1635-1703), who was curator of experiments for the Royal Society of London from 1662 until his death in 1703, thought that mechanical inventions could be found for increasing the range of the senses, especially that of hearing. In his Posthumous Works (Hooke, 1969) originally published in 1705, Hooke delineated the precepts of nondestructive testing by enlarging the power of the senses in his discourse on "...the ways of discovering the Properties and Powers requisite to be well understood and made use of in the compiling of a Philosophical history, may be these three following. I. By the Help of the Naked Senses. II. By the Senses assisted with Instruments, and arm'd with Engines. III. By Induction, or comparing the collected Observations, by the two preceding helps, and ratiocinating from them....The Defects therefore being naturally two, we ought to provide against them with two Artificial Helps; first, for the more certain determining and defining the Sensations, and reducing them to a Standard, and next for the Discovery of those sensible Properties in Bodies, which our Senses are not able to reach, and defining them also." Alluding to the precepts of acoustic emission, Hooke stated: "There may be also a Possibility of discovering the Internal Motions and Actions of Bodies by the sound they make, who knows but that as in the Watch we may hear the beating of the Balance, and the running of the Teeth, and Multitudes of other Noises; who knows, I say, but that it may be possible to discover the Motions of the Internal Parts of Bodies, whether Animal, Vegetable, or Mineral, by the sound they make, that one may discover the Works perform'd in the several Offices and Shops of a Man's Body, and thereby discover what Instrument or Engine is out of order, what Works are going on at several Times, and Lies still at others, and the like; that in Plants and Vegetables one might discover by the Noise the Pumps for raising the Juice, the Valves for stopping it, and the rushing of it out of one Passage into another, and the like." The first two devices to enhance sounds were the acoustic horn and the stethoscope, precursors of subaudible acoustic detection instrumentation.

1.3.1 The Acoustic Horn

The first serious attempt to enhance sound by some mechanical device was the acoustic horn which was used to magnify both transmitted and received sounds. In his book Early Science in Oxford – The Life and Work of Robert Hooke, Robert T. Gunther (1930) described an ear trumpet, called an otacousticon, that Hooke made and demonstrated before the Royal Society of London in late 1667 and early 1668: "...an instrument for collecting the sounds dispersed in the air into one small pipe, to be applied to the ear, to serve for an otacousticon....Mr. Hooke produced a glass
receiver for the improvement of hearing. Being tried by holding the neck of it to the ear, it was found, that a stronger sound was conveyed by it, than would have been without it. It was ordered, that at the next meeting there should be brought a better and larger receiver for hearing....Mr. Hooke produced again the large conical tin receiver for magnifying of sounds; which being tried was found to make words softly uttered at a distance to be heard distinctly; whereas they could not so be heard without this instrument."

According to Harvard physics professor-historian Frederick V. Hunt (1978), two other men each claimed to have invented the ear trumpet during the seventeenth century – Athanasius Kircher in 1650 and Sir Samuel Morland in 1671. Athanasius Kircher (1602-1680), professor of mathematics at the Jesuit College of Rome, made a loud-speaking trumpet of iron plates – a conical horn about 16 feet long by 2 inches at one end and 2 feet aperture at the other. "He could use the tapered conduit either as a speaking-trumpet or megaphone....or as an ear-trumpet by means of which he could eavesdrop on conversations taking place in the courtyard." And in England, Sir Samuel Morland (1625-1695) described his "...first instrument was made of glass, 32 inches long and 11 inches in diameter at the mouth, and from this he progressed to a copper 21-footer with a 1-foot mouth." Upon presenting his ear horn to the Royal Society of London, Morland was given suggestions for improvement, one of which was using the horn as an aid to hearing. For a more in-depth discussion on the acoustic horn, see Hunt (1978).

1.3.2 The Stethoscope

Leonardo da Vinci (1452-1519) described in his Notebooks (da Vinci, 1939) the use of a tube to hear sounds in water and in the ground: "If you cause your ship to stop, and place the head of a long tube in the water, and place the other extremity to your ear, you will hear ships at a great distance from you. You can also do the same by placing the head of the tube upon the ground, and you will then hear anyone passing at a distance from you."

In 1705, alluding to the concept of the stethoscope, Hooke wrote (Hooke, 1699): "And somewhat more of Encouragement I have also from Experience, that I have been able to hear very plainly the beating of a Man's Heart, and his common to hear the Motion of the Wind to and fro in the Guts, and other small Vessels, the stopping of the Lungs is easily discover'd by the Wheesling, the Stopping of the Head, by the hummin' and whistling Noises, the slipping to and fro of the Joynts in many cases, by crackling, and the like;...and so to their [sound] becoming sensible they require either that their Motions be increased, or that the Organ be made more nice and powerful to sensate and distinguish them [to try the Contrivance about an Artificial Timpanum] as they are...." No further explanation could be found in any published material on Hooke on just what he meant by a "Contrivance about an Artificial Timpanum."

In 1816 in connection with the study of diseases of the chest and heart, French physician and professor at the Collège de France, René Théophile Hyacinthe Laennec (1781-1826) is credited with inventing the stethoscope, thus introducing one of the first instrumented applications of acoustics (Laennec, 1972). Recalling a simple and well-known fact in acoustics, Laennec stated: "The fact I allude to is the augmented impression of sound when conveyed through certain solid bodies, as when we hear the scratch of a pin at one end of a piece of wood, on applying our ear to the other. Immediately, on this suggestion, I rolled a quire of paper into a sort of cylinder and applied one end of it to the region of the heart and the other to my ear, and was not a little surprised and pleased, to find that I could thereby perceive the action of the heart in a manner much more clear and distinct than I had ever been able to do by the immediate application of the ear. From this moment I imagined that the circumstance might furnish means for enabling us to ascertain the character, not only of the action of the heart, but of every species of sound produced by the motion of all the thoracic viscera." Laennec described his instrument: "It consists simply of a cylinder of wood, perforated in its centre longitudinally, by a bore three lines in diameter, and formed so as to come apart in the middle, for the benefit of being more easily carried. One extremity of the cylinder is hollowed out into the form of a funnel to the depth of an inch and half, which cavity can be obliterated at pleasure by a piece of wood so constructed as to fit it exactly, with the exception of the central bore which is continued through it, so as to render the instrument in all cases, a pervious tube. The complete instrument, – is used in exploring the signs obtained through the medium of the voice and the action of the heart; the other modification, or with the stopper removed, is for examining the sounds communicated by respiration. 'This instrument I commonly designate simply the Cylinder, sometimes the Stethoscope.'"

According to Case School of Applied Science professor-historian Dayton C. Miller (1935), British physicist Sir Charles Wheatstone (1802-1875), in 1827 in Experiments on Audition, described a device similar in shape to the stethoscope. It was "...a simple instrument consisting of two metal saucer-shaped diaphragms to be placed over the ears; to each diaphragm is attached a slender brass rod, the two rods being brought together in front of the face so that they may be made to touch a sonorous body of faint sound." Because it rendered audible the weakest sounds, Wheatstone named it a microphone.

1.4 Early Instrumented AE Experiments

As a prelude to serious, on-going research into the fundamentals of acoustic emission, there were a number of
noteworthy, instrumented experiments conducted, some of which could have been the genesis of today's technology had the experimenters redirected and continued their research into the phenomenon itself. The first experiment utilized an optical technique to amplify stepwise deformations to determine coincidence with audible emissions. Common to the latter three experiments was the use of electronic instrumentation to detect and amplify the acoustic emissions generated in the materials being studied. These experiments constitute the first scientific attempt to study inaudible acoustic phenomena, i.e., sounds that could not be heard because their amplitude was below the threshold of hearing or their frequency range was beyond human detectability.

1.4.1 Klassen-Neklyudova's Experiments

Starting in 1925, M.V. Klassen-Neklyudova, or Klassen-Nekludowa (1929), at the National Physical-Technical Röntgen Institute in Leningrad, Russia, began a systematic investigation into the phenomenon of plastic deformation which was "...accompanied by very regular cracking noises reminiscent of the ticking of a clock [...eingenen knackenden Lauten begleitet, welche sehr gleichmässig sind und an das Ticken einer Uhr erinnern]." According to Klassen-Nekludowa (1929), this phenomenon had originally been observed in 1924 by Profs. Abram F. Joffé and Paul S. Ehrenfest. Klassen-Neklyudova (1927) described a magnifying recording apparatus which achieved an expansion factor of 10,000X, thus permitting her to manually plot a sharp, stepwise deformation curve as a function of time which she measured with a stopwatch. An optical technique was used to measure and record the relative displacement of the specimen holders by reflecting an image between two mirrors to produce the enlargement. Although she did not enhance the acoustic signal, by using the optical system to magnify the jerky, stepwise movements in the specimen gave her a precise correlation between the two. An additional report of this work was published in 1928 (Klassen-Neklyudova, 1928) and a summary report in 1929 (Klassen-Nekludowa, 1929) in which she cites Portevin and Le Chatelier (1923) and Anderson (1926) regarding information on the tone-producing [tonende] deformation of Duralumin. The work is also described by Joffé (1928). Unfortunately, because of the lack of source material of Soviet work and the inability to freely communicate with Soviet scientists during the Communist regime, the total contribution of the Russians to the early work in AE is only now starting to emerge.

1.4.2 Kishinouye's Experiments

The first report on a scientifically planned acoustic emission experiment was given by Prof. Fuyuhiko Kishinouye (1934) on November 21, 1933, at a meeting of the Earthquake Research Institute in Tokyo. Three years later he published a more detailed version of this work in English (Kishinouye, 1937). The original 1934 Japanese article has recently been translated into English by Prof. Kanji Ono (Kishinouye, 1990). Kishinouye designed and performed a series of Gedanken experiments to amplify and record the AE from the fracture of wood in order to study fracture of the earth's crust as the cause of earthquakes, and solve the problem of time distribution of earthquakes and, in particular, the Ito, Japan earthquake swarm that had occurred between February and June, 1930.

The apparatus Kishinouye used consisted of a phonograph pickup with a steel needle inserted into the tension side of a wooden board to which a bending stress was applied to cause fracture. In the English version of the article Kishinouye (1937) states: "When the board cracked, electric current was generated in the coil of the pick-up, the current being amplified with an amplifier, which formed a part of the Haeno radio-seismograph [see Haeno, 1930]. The current was recorded with an oscillograph on cinematographic films....As bending proceeded, cracking sounds were heard, while the oscillograms recorded many inaudible vibrations. The process of fracture varied with the velocity of bending, the kind of wood, the grain of the board, and the moisture content of the wooden board....When the materials were the same and the velocity of bending equal, the board broke with nearly equal deformation....When deformation proceeded slowly, occasionally loud creaking sounds were heard owing to rupture of the grains, and low silent vibrations were found on the oscillogram. It was found that the process of fracture is affected considerably by the condition of the experimented material and the particular way in which the force acts."

The oscillograms made by Kishinouye (1937) showing "...many rapid inaudible vibrations [acoustic emissions] and cracking sounds from fracture of wooden board" were the first acoustic emission waveforms ever recorded. A detailed discussion on Kishinouye and the early experiments can be found in Drouillard (1990).

1.4.3 Förster and Scheil's Experiments

Another series of early AE experiments were performed in Germany by Dr. Friedrich Förster and Erich Scheil (1936), and their second and last article on AE (Förster and Scheil, 1940). Förster had received his Ph.D. in physics from the Universität Göttingen in 1932. In 1935, he went to work for the then just-founded Kaiser-Wilhelm-Instutit für Metallforschung in Stuttgart, Germany, where he met and began collaborating with Erich Scheil. Scheil had already distinguished himself in metals research at the Forschungsinstitut der Vereinigte Stahlwerke A.-G. in Dortmund [see, e.g., Scheil, 1929].

Their experiments consisted of measuring extremely small voltage changes due to resistance variations produced by sudden, jerky strain movements caused by martensitic transformations in a wire-shaped nickel-steel test specimen. Förster had built an electrodynamic transmitter/receiver system to transform mechanical vibrations and acoustic emissions into electrical voltages which could be amplified and recorded.
1.4.4 Mason, McSkimin and Shockley’s Experiments

The last of the early instrumented AE experiments were performed by Drs. Warren P. Mason, Herbert J. McSkimin, and William Shockley of Bell Telephone Laboratories, Murray Hill, New Jersey. This work was published in 1948 in a short, seminal article entitled “Ultrasonic Observations of Twinning in ‘Tin’” (Mason et al., 1948). In 1950 Mason included an expanded version of the article in his book on piezoelectric crystals (Mason, 1950). Shockley had suggested they perform the experiments in order to observe moving dislocations by means of the stress waves they generate. The experiment consisted of pressing a specimen of pure tin directly against a quartz crystal transducer, then applying sufficient stress to deform the specimen and cause twinning dislocations, which, in turn, produced acoustic emission. The quartz crystal they used had a uniform sensitivity from a few kilohertz to 5 MHz.

2. Periods in AE History

The real beginning of acoustic emission technology as we know it today was inaugurated almost a half century ago. It seemed appropriate to divide this interim of time into three periods, the first of which the writer calls The Age of Enlightenment.

2.1 The Age of Enlightenment (1950-1967)

During this period major efforts were directed at probing into the fundamentals of acoustic emission phenomena and studying AE behavior during deformation and fracture of various materials.

2.1.1 Josef Kaiser – Father of Modern AE Technology

The genesis of today’s technology of acoustic emission was the research work of graduate student Joseph Kaiser (1950) at the Technische Hochschule München in Germany. Kaiser conducted the first comprehensive investigation into the phenomena of acoustic emission. He used tensile tests of conventional engineering materials to determine: what noises are generated from within the specimen; the acoustic processes involved; the frequency levels found; and the relation between the stress-strain curve and the frequencies noted for the various stresses to which the specimens were subjected. Kaiser concluded that the occurrence of acoustic emission arises from frictional rubbing of grains against each other in the polycrystalline materials he tested [which was later proven incorrect] and also from intergranular fracture. Kaiser’s most significant discovery was the irreversibility phenomenon which now bears his name – Kaiser effect. He stated in the English translation of his dissertation (Kaiser, 1950): "As is known, plastic strain, however slight, is irreversible. This suggests that the acoustic effects obtained in our experiments also involve irreversible processes [Wie bekannt, ist jede selbst noch so geringe plastische Verformung irreversibel. Das lässt vermuten, dass es sich bei den in den vorliegenden Versuchen erzielten Schalleffekten ebenfalls um irreversible Vorgänge handeln muss].” He then proceeded to clearly demonstrate irreversibility with several tensile tests.

Kaiser continued his research at the Institut für Metallurgie und Metallkunde until his death in March 1958 (Kaiser, 1952, 1953, 1957a,b; Borchers and Kaiser, 1958). It is unclear to the writer what prompted Kaiser to choose acoustic emission as a subject for research. He cited in his dissertation only three references containing some discussion on "tin cry" or noise emission – articles by Czochralski (1917) and by Classen-Nekludowa (1929) in his list of references and the book by Joffé (1928) mentioned only in the text. After Kaiser’s death, research at the Institut was continued by his colleagues, Prof. Heinz Borchers, then Director of the Institut, and Prof. Hans-Maria Tensi who later became Director. Tensi had worked with Kaiser several years while he was a graduate student. Also at the Technische Hochschule München at that time was H. Rüscher (1959) who was performing various tests on concrete specimens, one of which was to study the resumption of noise emission [Geräuschatgabe] produced during re-application of a compressive load, one of the first studies of "irreversibility," later to be called the "Kaiser effect."

2.1.2 Bradford H. Schofield – AE Technology Anglicized and Introduced

The first extensive research into acoustic emission in the English-speaking world was initiated in the United States in December 1954 by Bradford H. Schofield at Lessells and Associates in Boston, Massachusetts [Lessells and Assoc. was acquired by Teledyne Materials Research in 1971]. His involvement came about as a result of a literature survey he and co-worker A.A. Kyrala had conducted. They came across Kaiser’s article in Archiv für das Eisen­hüttenwesen (Kaiser, 1953). This prompted Prof. John M. Lessells to contact his friend in Germany, Prof. Ludwig Föppl, who was an adjudicator [Berichterstatter] of Kaiser’s dissertation, for a copy of the dissertation. Subsequently, Prof. Lessells and Schofield began a correspondence with Dr. Kaiser which continued until Kaiser’s death. In fact, according to Prof. Larry D. Mitchell (1965), Kaiser was actually hired by Lessells and Associates as a consultant. Schofield’s initial research program was directed toward the application of acoustic emission to the field of materials engineering. His first efforts were to verify the findings of Kaiser. As work progressed it became evident that there were significant differences between his results and those of Kaiser. Hence, Schofield reoriented his research efforts to establish the basic mechanisms of acoustic emission. He published this pioneering work in several seminal reports entitled “Acoustic Emission under Applied Stress”(Schofield et al., 1958; Schofield, 1961). These reports had a profound impact on launching many careers in the field of acoustic emission. Schofield was active in AE research until 1973 when he received a law degree and applied his engi-
neering and law degrees to pursue the field of product liability.

2.1.3 Clement A. Tatro - Teacher and Mentor

In the fall of 1956 at Michigan State University, East Lansing, Prof. Lawrence E. Malvern came across a one-page article entitled "Hörbare Schwingungen beim Verformen [Audible Vibrations from Deformation]" in the book Fliesen und Kriechen der Materie by Dr. Wilhelm Späth (1955). The article referenced the observations of noises [Geräuschen] by Joffé and Ehrenfest (Joffé, 1928), Classen-Nekludowa (1929), Becker and Orowan (1932), and Kaiser (1953). Interested in studying the asperity theory of friction, Malvern suggested to a new faculty member, Dr. Clement A. Tatro, that this acoustic technique would be interesting to look into. Consequently, Tatro began laboratory investigations into acoustic emission phenomena, thus initiating the second major effort in AE research. In 1957 he became aware of Schofield's work and began collaborating with him. Tatro (1960) thought that research programs in AE should follow one of two rather well-defined branches: to pursue studies concerned with the physical mechanisms that give rise to acoustic emission to completely understand the phenomenon; or using acoustic emission as a tool to study some of the vexing problems of behavior of engineering materials. He also foresaw the unique potential of AE as a nondestructive testing procedure (Tatro and Liptai, 1962). While at Michigan State University Tatro encouraged a number of his graduate students to choose acoustic emission as the subject of their research projects, viz., Paul S. Shoemaker, Robert J. Kroll, Robert G. Liptai, and Robert B. Engle.

2.1.4 Julian R. Frederick - Ultrasonics to AE

Prof. Julian R. Frederick at the University of Michigan, Ann Arbor, had been engaged in research in ultrasonics since 1939 when he was a graduate student under Prof. Floyd A. Firestone, inventor of the "Supersonic Reflectoscope." Frederick's interest in acoustic emission, particularly for studying dislocation mechanisms, was excited in 1948 after reading the article of Mason, McSkimin, and Shockley (1948), "Ultrasonic Observation of Twinning in Tin". Frederick visited both Schofield and Tatro in the late 1950s to discuss state-of-the-art in AE. In 1960 he obtained a National Science Foundation grant for two graduate students — Jal N. Kerawalla and Larry D Mitchell. A third student, Anand B.L. Agarwal, was also funded later. Some of the results are given in Frederick and Felbeck (1972).

2.1.5 Allen T. Green - Pioneer in Pressure Vessel Testing & Source Location

In the early 1960s at Aerojet-General Corp. in Sacramento, California, a special projects team of structural test engineers — Allen T. Green, Charles S. Lockman, H.K. "Spike" Haines, and team leader Richard K. Steele, and later joined by Frank J. "Paco" Climent and Carroll F. Morais — were trying to verify the structural integrity of filament-wound Polaris solid rocket motor cases fabricated for the U.S. Navy. They noticed that audible sounds, described as "popcorn-like popping noises" (Green et al., 1964), were consistently evident during hydrostatic proof-pressure testing and decided to instrument the vessel to detect, record, and then post-test analyze the acoustic signals. They conducted their first AE test in 1961, using contact microphones, magnetic tape recorder, and sound level analysis equipment. Later they improved their detection capability with accelerometers and charge amplifiers, plus employing several signal analysis techniques such as transient acceleration amplitude-frequency-time contour or missleprint analysis (Green et al., 1963). This team perfected the burst pressure prediction technique, or Stress-Wave Emission Technique (SWAT), for monitoring of rocket motor cases, a technique which is still being followed today.

As part of Aerojet's contract with the National Aeronautics and Space Administration (NASA) in 1965, Green, Lockman, and Steele instrumented the 260-inch diameter Thiokol SL-1 solid rocket motor case to monitor the vessel during hydrostatic proof-pressure testing. Analysis of the tape recorded AE data clearly showed crack initiation and propagation prior to catastrophic failure of the 250 grade maraging steel vessel at about 56 percent of proof pressure. From the recorded test data, using triangulation methods, the origin of failure was located within 12 inches (Srawley and Esgar, 1966). The fact that the SWAT instrumentation system had indeed predicted and located premature failure of the vessel immediately enabled Aerojet to obtain sponsors for the AE work of material scientists Carl E. Hartbower, Dr. Phillip P. Crimmins, Dr. William W. Gerberich, Dr. Walter G. Reuter, Dr. George S. Baker, and Dr. Douglas W. Bainbridge. The multi-channel analog computer-based SWAT system became the first commercial, real-time source location system and was built into the first mobile test vehicle used in contract field inspection service. A more comprehensive, anecdotal account of the early AE work at Aerojet is given by Green (1985) in which he credits Carroll F. Morais as being the father of AE inspection services, first at Aerojet, then briefly at Dunegan Corp., and then for many years at Acoustic Emission Technology Corp.

2.1.6 Harold L. Dunegan — Innovator, Missionary, Entrepreneur

At Lawrence Radiation Laboratory (LRL), now Lawrence Livermore National Laboratory in Livermore, California, Harold L. Dunegan began a lifelong career in AE in 1963 after hearing a paper the previous year by Tatro and Liptai (1962) at the Third Symposium on Physics and Nondestructive Testing held at Southwest Research Institute in San Antonio, Texas. Consequently, he wrote an internal report (Dunegan, 1963) which had a twofold purpose: "First, to acquaint the reader with facts concerning the acoustic emission that occurs when metals are strained; and second, to describe an approach being taken on practical applications of acoustic emission theory to pressure vessel..."
research." Assisted by co-workers Albert E. Brown and Paul L. Knauss, Dunegan developed practical AE procedures to predict failure in pressure vessels during proof testing, without taking the vessels to failure. Dunegan’s wizardry provided the growing AE community with a number of innovations such as: the S140 transducer (Dunegan et al., 1968a) – workhorse of the industry for over 25 years; the differential transducer (Dunegan et al., 1971); the passive pressure transducer based on the Kaiser effect (Dunegan and Tatro, 1967); preloading the pin area of a pin loaded tensile specimen to eliminate by the Kaiser effect acoustic emission from this area (Dunegan and Tatro, 1971); and the application of AE to study the fracture characteristics of materials and structures (Dunegan and Tatro, 1971). Over the next few years Dunegan was responsible for assembling an impressive group of researchers at the Laboratory, vis., Dr. Clement A. Tatro, Dr. David O. Harris, Dr. Robert B. Engle, and Dr. Robert G. Liptai. Dr. Marvin A. Hamstad joined the group in 1971. Dunegan’s work and counsel directly influenced the initiation of major efforts in AE research and application in the United States, particularly at a number of U.S. Atomic Energy Commission (now the U.S. Department of Energy) facilities, one of which was the writer’s work at the Rocky Flats Plant in Golden, Colorado. For further reading on some of the early work at LRL, see Dunegan and Tatro (1971), Dunegan et al. (1968b), Engle and Dunegan (1969), and Liptai et al. (1971).

2.1.7 U.S. Atomic Energy Commission Nuclear Facilities

Early in 1965, at the National Reactor Testing Station in Idaho Falls, Idaho, Dwight L. Parry of Phillips Petroleum Co., was involved in the loss of fluid test (LOFT) program where researchers were looking for a nondestructive testing technique that would be faster than the conventional methods used to detect loss of coolant in a nuclear reactor. Based on information in papers by Schofield (1961) and Kaiser (1953), Parry applied AE techniques. In May 1966, he obtained his first definitive AE data from failure of an embrittled half-scale PM-2A reactor vessel instrumented with accelerometers, charge amplifiers, and a tape recorder. Later, discontinuity location was successfully accomplished by triangulation techniques on the full size vessel (Parry, 1967).

In February 1966, the Division of Reactor Development and Technology of the U.S. Atomic Energy Commission (AEC) sponsored a dual-phase research program between Phillips Petroleum and Battelle Pacific Northwest Laboratories in Richland, Washington. Phillips Petroleum was assigned the responsibility for developing an incipient failure detection system. Parry and Dan L. Robinson developed an AE instrumentation system which would detect, locate, and characterize incipient failure conditions in the reactor pressure vessel and primary pressure system components of a nuclear power plant. Later, Parry transitioned this work into a series of commercial testing companies – Idaho Nuclear Corp., Jersey Nuclear Co., Exxon Nuclear Co., and AE International – that provided AE field testing service throughout the world.

The mission of Battelle Northwest on this program was primarily directed towards basic research of the AE phenomenon (Hutton et al., 1968). The project leader was Philip H. Hutton who had initiated AE activities at Battelle Northwest in October 1965 (Hutton and Spanner, 1965). Hutton was later joined by Jack C. Spanner, W. Don Jolly (Jolly went to Southwest Research Institute in 1970), Clifford K. Day, C.E. Fitch, Jr., Thomas E. Michaels, Norman J. Dixon, David O. Hunter, and R. Neal Ord. Their research involved studies of specimen resonance, structural evaluation of pressure vessels and piping systems, and basic instrumentation. The latter involved transducer studies, particularly in reactor environments and at elevated temperatures, plus noise level and performance of preamplifiers, cabling, and signal processing components of the instrumentation system. Hutton continues his AE work, begun under sponsorship of the U.S. AEC and then the U.S. Nuclear Regulatory Commission, as a contractor following his retirement in 1989.

At Argonne National Laboratory, Argonne, Illinois, Theodore Anderson became involved in acoustic emission in January 1967 after conducting a literature survey of acoustic boiling detection (Anderson et al., 1970). His research activities, which were directed at boiling detection in sodium-cooled reactors, were the first coordinated effort in this area. In 1969, he was joined by A.P. Gavin in developing a high temperature submersible microphone for use in the liquid sodium environment of a reactor. Also at Argonne in 1967 was Dr. Robert G. Liptai, who, in collaboration with Harold L. Dunegan and Dr. Clement A. Tatro at Lawrence Radiation Laboratory in Livermore, California, was conducting experiments on martensitic phase transformation in single crystals of a gold-cadmium alloy (Liptai et al., 1969). As a result of this collaboration, he joined Tatro’s group at LRL in 1969.

In 1967, Thomas F. Drouillard went to the Rocky Flats Plant in Golden, Colorado, which was then operated for the U.S. Atomic Energy Commission by Dow Chemical Co. and later by Rockwell International Corp. and EG&G Rocky Flats, Inc. His assignment was to investigate the possibilities of using acoustic emission as an NDT method for production applications. In February 1971, he installed several AE tests in manufacturing operations, some of the first industrial applications of acoustic emission to be used on a routine basis. The first test, originally proposed and demonstrated its feasibility to the author by Harold L. Dunegan (1963), was monitoring welded beryllium shells during proof pressure testing to evaluate structural integrity of the weld joints [see Drouillard et al., 1975 for a discussion on this type of test]; the second was monitoring braze joints between Monel tubes and beryllium shells during a stressing operation to detect fracture of em-
Faces of Acoustic Emission

Prof. Fuyuhiko Kishinouye

Dr. Friedrich Förster

Erich Scheil

Dr. Warren P. Mason

Dr. Joseph Kaiser

Bradford H. Schofield

Prof. Clement A. Tatro

Prof. Julian R. Frederick

Allen T. Green
Faces of Acoustic Emission

Harold L. Dunegan

Dwight L. Parry

Philip H. Hutton

Thomas F. Drouillard

Dr. Adrian A. Pollock

Dr. Jurgen Eisenblätter

Dr. Eiji Isono

Prof. Morio Onoe

Dr. Hiroyasu Nakasa
Faces of Acoustic Emission
Faces of Acoustic Emission

Dr. Nelson H. Hsu
Dr. Christopher B. Scruby
Prof. Wolfgang Suchse

Dr. Leonard A. Obert
Wilbur I. Duvall
Prof. H. Reginald Hardy, Jr.

Prof. Kiyoo Mogi
Jack C. Spanner
Dr. Sotirios J. Vahaviolos
brittled joints caused by overheating or too long a time at temperature during the brazing operation [see Drouillard, 1992 for a recent report describing this test]. In 1975, Dr. Clinton R. Heiple entered the AE arena at Rocky Flats where over the next 18 years he, in collaboration with Prof. Steve H. Carpenter at the University of Denver, worked on a multitude of diverse research projects, many involving the application of AE to materials research and dislocation motion [see, e.g., Heiple and Carpenter, 1983, 1987].

2.1.8 The Boeing Company, Seattle

At The Boeing Company in Seattle, Washington, two groups became involved in acoustic emission work. In 1965, Dr. Harvey L. Balderston at the Space Division initiated research on incipient failure detection in bearings, signature analysis from rotating machinery, leak detection in hydraulic systems, and cavitation and erosion from fluid flow in valves. This work is summarized in Balderston (1972).

In the summer of 1967 at Boeing Scientific Research Laboratories, Dr. Robert W. Moss engaged British graduate student Adrian A. Pollock to add acoustic emission to an existing project on the study of crack growth in titanium (Pollock, 1967). Pollock was a third-year graduate student at Imperial College, England. He had been the recipient of the first grant in AE placed in October 1964 with Prof. R.W.B. Stephens at Imperial College by Roy S. Sharpe from the NDT Centre, AERE Harwell. During his six-weeks stay at Boeing, Pollock became enamored with the practical application of acoustic emission for detecting crack growth. Consequently, upon returning to England he directed the remaining research for his Ph.D. dissertation (Pollock, 1970) towards the practical application of acoustic emission for materials testing and nondestructive testing. Upon graduation Pollock joined Cambridge Consultants, then Dunegan/Endevco, Acoustic Emission Associates, and now is with Physical Acoustics Corp.

2.1.9 Andrew W. Porter Introduces AE/Fracture Studies in Wood

Dr. Andrew W. Porter (1964a), in addressing the need for development of nondestructive strength tests for wood and the search for more efficient cutting methods, stated that "...it is essential that a clear understanding be obtained of the mechanism by which fracture proceeds in wood." Here he presented for the first time an elastic fracture theory based upon an energy balance applied to the opening mode fracture of wood which led to the establishment of a material parameter, the strain-energy release rate. In his Ph.D. dissertation from State University of New York, College of Forestry at Syracuse, Porter (1964b) described the first comprehensive study on fracture in wood using acoustic emission. He introduced the use of the Griffith-Irwin theory of fracture mechanics to determine the critical condition for unstable crack growth in the opening mode of failure of wood. A more detailed discussion on Porter's work and AE in wood is given by Drouillard (1990).

2.1.10 Other Early AE Pioneers

Other early pioneers in the United States included H.E. Romine at the U.S. Naval Research Laboratory; M.H. Jones, William F. Brown, Jr. and John E. Srawley at the NASA Lewis Research Center; Kenneth R. Notvest at Curtiss-Wright Corp. [Notvest later joined Trodyne Corp., then Physical Acoustics Corp.; he retired in 1981]; and Prof. Robert H. Chambers at the Engineering Experiment Station, University of Arizona.

In Europe the early pioneers included Hervé Bibring, François Sebilleau, and Dr. Charles Crussard in France; Dr. Don Birchon at the U.K. Admiralty Materials Laboratory; Dr. Peter G. Bentley at the U.K. Atomic Energy Authority, Risley Engineering and Materials Laboratory; Drs. Jürgen Eisenblätter and Peter Jax at Battelle-Frankfurt in West Germany; and Arved Nielsen at the Danish Welding Institute and later with the Danish Atomic Energy Commission, Research Establishment Risø [Nielsen retired in 1988 and is now a consultant].

In Japan the early pioneers included Dr. Eiji Isono at Fuji Steel [Fuji Steel merged with Yawata Steel and became Nippon Steel Corp. in 1971]; Prof. Morio Once at the Institute of Industrial Science, University of Tokyo; Dr. Hiroyasu Nakasa of Central Research Institute of Electric Power Industry; Takashi Fuji at Technical Approval Bureau of the Industrial Research Institute; and Prof. Noboru Niwa and Dr. Hajime Hatano of the Institute of Space and Aeronautical Science, University of Tokyo.

There were other pioneers throughout the world whose works — too numerous to mention in this brief history — are chronicled in their publications, most of which are cited in Acoustic Emission: A Bibliography with Abstracts (Drouillard, 1979). Several historical articles by Drouillard (1987, 1990) and Green (1985), as well as a review article by Isono (1970), elaborate further on this period.

2.1.11 Significant Accomplishments during This Period

The most significant accomplishment during this period was the pioneering work of Allen T. Green and the SWAT Team at Aerojet-General Corp. in developing inspection techniques and instrumentation for monitoring pressure vessels and performing source location by triangulation, first graphically and later by computer techniques, on solid rocket motor cases and large pressure vessels, and performing the first commercial field test service in 1968 for Humble Oil & Refining Co. in Baytown, Texas [see, e.g., Green and Hartbower, 1968; Steele et al., 1968a; Steele et al., 1968b].
Another significant accomplishment introduced by Dunegan et al. (1964), was a more effective use of instrumentation to eliminating noise by working with narrow-banded instrumentation in a frequency range well above the audio range. Engle and Dunegan (1969) give an explanation for the introduction of bandpass limitations in AE testing in the 1960s: "High-frequency limitations of [tape] recording equipment restrict the high-frequency spectrum. Background noise due to low-frequency mechanical vibration causes problems at the low-frequency end of the acoustic-emission spectrum. The use of a restricted bandwidth between 30 and 150 kHz satisfactorily eliminates mechanical background noise and allows meaningful tests in normal laboratory environments."

Another area of research which precipitated pioneering work throughout the world over the next decade or so was the relationship between AE and fracture mechanics proposed at the 67th ASTM Annual Meeting in 1964 by John E. Srawley and William F. Brown, Jr. (1965) from NASA Lewis Research Center, Cleveland, Ohio, and promulgated by Dr. David O. Harris and Harold L. Dunegan (1966) at Lawrence Radiation Laboratory, by Dr. William W. Gerberich (1966) at Aerojet-General Corp. (currently at University of Minnesota and still active in AE research), and by Prof. Alan S. Tetelman (1972) at the University of California at Los Angeles. Prof. Tetelman made significant contributions linking acoustic emission and fracture mechanics, including fatigue and hydrogen embrittlement [see, e.g., Tetelman, 1972; Dunegan and Tetelman, 1969; Dunegan et al., 1969] and was a prime promoter of AE, until his untimely and tragic death in 1978.

There were many more pioneers throughout the world whose works too numerous to mention in this brief history - are chronicled in their publications, most of which are cited in Acoustic Emission: A Bibliography with Abstracts (Drouillard, 1979). Several historical articles by Drouillard (1987, 1990) and Green (1985), as well as a review article by Isono (1970), elaborate further on this period.

2.2 The Golden Age of AE (1967-1980)

The next period, which the writer calls The Golden Age of Acoustic Emission, began in the late 1960s with the formation of three acoustic emission working groups and lasted through the decade of the 1970s. This was a period in which economic times in the United States, Western Europe, and Japan were bountiful – funding for research and equipment was plentiful; both industry and governments were supporting AE research and applications; universities were well endowed with grants to fund research as well as graduate students; and the philosophy of high quality dictated inspection of every part.

2.2.1 Study of Dislocations as a Source of AE

One of the prominent areas of research vigorously pursued during this period was the study of dislocations being the source of AE which was proposed by Mason, McSkimin, and Shockley (1948), by Tatro (1957), and by Schofield (1961). One of the most significant pieces of research work on dislocations was reported by Drs. R.M. Fisher and J.S. Lally (1967) at the Edgar C. Bain Laboratory of U.S. Steel Corp., Monroeville, Pennsylvania – the first definitive dislocation-AE study whereby, using an acoustic emission technique to observe discontinuous plastic flow in relation to the occurrence of slip avalanches, they were able to connect the amount of plastic strain accompanying each AE burst-type pulse and length of time interval over which it occurred. Another outstanding piece of research work was reported by Dr. Darrell R. James and Prof. Steve H. Carpenter (1971) at the University of Denver, Colorado – their paper on the relationship between acoustic emission and dislocation kinetics is one of the most cited research papers in AE. Several early comprehensive review articles on the subject of source mechanisms, including extensive discussions on plastic deformation and dislocations were published by Prof. Kanji Ono (1974, 1980) at the University of California at Los Angeles and by Prof. Carpenter and Dr. Clinton R. Heiple (1980).

2.2.2 EEI/TVA and HSST Programs

The landmark report on failure of the Thiokol vessel (Srawley and Esgar, 1966) triggered a wave of pioneering research and development projects such as the Edison Electric Institute and Tennessee Valley Authority joint-sponsored EEI Project RP-79 "In-Service Inspection Program for Nuclear Reactor Vessels" managed by Southwest Research Institute of San Antonio, Texas (Reinhart, comp., 1973a). A major phase of this program to demonstrate the adequacy of AE technology to detect crack growth in nuclear reactor pressure vessels is summarized in Reinhart, comp., (1973b), a compilation of individual reports from seven industrial groups who participated in an AE test program on the Experimental Beryllium Oxide Reactor (EBOR) at the National Reactor Test Site, Idaho Falls, Idaho in 1972. The principal participants and their organizations were: John S. Buck and Lloyd J. Graham representing Atomics International, Canoga Park, California; M. Nicole Chretien from Centre d’Études Nucléaires de Saclay, Commissariat a l’Energie Atomique, Paris, France; Michael P. Kelly and Robert L. Bell from Endeco, Livermore, California; H.D. Collins and R.P. Gribble from Holosonics, Inc., Richland, Washington; W. Don Jolly, Eugene R. Reinhart, and Dr. Shuh-Pan Ying from Southwest Research Institute, San Antonio, Texas; Peter G. Bentley, T.E. Burnup, and D.G. Dawson from the U.K. Atomic Energy Authority, Risley Engineering & Materials Laboratory, Risley, England; and Dr. Raj Gopal from Westinghouse Electric Corp., Nuclear Energy Systems, Pittsburgh, Pennsylvania.
Another and still on-going program was the Heavy-Section Steel Technology (HSST) Program, sponsored by the U.S. Nuclear Regulatory Commission Division of Reactor Safety Research and managed by Oak Ridge National Laboratory, Oak Ridge, Tennessee. The mission of this program was to evaluate the failure characteristics of thick-walled vessels. Both the EEI/TVA and HSST projects played heavily in the development and commercialization of source location instrumentation and software, the first commercially available systems being delivered in 1973-74. AE was on the verge of real application for the inspection of pressure vessels, particularly in the nuclear industry when the Three-Mile Island incident occurred in March 1979, resulting in curtailment of the use of nuclear energy for power generation in the United States and a number of European countries.

2.2.3 Commercial Instrumentation becomes Available

It was during this period that AE instrumentation first became commercially available, first offered in early 1968 by Nortec Corp. of Richland, Washington - Nortec manufactured a plug-in module for the Tektronix oscilloscope. Later that year, Dunegan Research Corp. of Livermore, California was formed, offering the first full line of AE sensors and modular instrumentation. Other U.S. companies to enter the market included Trodyne Corp. of Teterboro, New Jersey in 1970; Acoustic Emission Technology Corp. of Sacramento, California in 1972; and Physical Acoustics Corp. of Princeton, New Jersey in 1978. Additionally, these companies promoted AE technology by conducting seminars and short courses and providing commercial testing services all over the world.

2.3 The Transition Period (1980-Present)

The difficult financial times of the present period, the Transition Period, started about 1980. The practice of AE, as well as all technology, is governed by the economic health and current business philosophy of our respective countries. Decline of heavy industry in the 1980s, decline in the use of nuclear reactors for power generation (which was one of the most promising areas for AE application), and the end of the Cold War and break-up of the Soviet Union resulting in downsizing of defense spending in the United States and Western Europe - all had a significant, detrimental effect on NDT, and particularly on AE in the United States. Driven by economic change, the reason for inspection was challenged - it was believed that inspecting every part provided no added value, only added cost. This change in philosophy has evolved into process control and total quality management (TQM). Today, industry, government, and academia are all being managed with more emphasis on short-term profits, bottom line, and immediate gratification than on quality of product or service, quality of life, and quality of education. Nevertheless, there has been a number of success stories and areas of growing activity during the past 15 years.

2.3.1 Inspection of FRP Vessels and Piping

The AE inspection program of fiber reinforced plastic (FRP) vessels and piping initiated by Dr. Timothy J. Fowler at Monsanto Co., St. Louis, Missouri, which he first presented at the 7th International AE Symposium in Zao, Japan (Fowler, 1984), has virtually eliminated catastrophic failure of pressure vessels that have been periodically inspected in the program. This program became the primary mission of the Committee on Acoustic Emission from Reinforced Plastics (CARP), resulting in codification by the American Society for Testing and Materials (ASTM, 1992a,b) and American Society of Mechanical Engineers (ASME, 1986, 1988). The same success story can be said for the AE inspection of aerial manlifts, which has also been made an ASTM standard (1992c). Dr. Fowler (1977) recognized a breakdown in the Kaiser effect in composite structures and coined it the Felicity effect, named after his daughter Felicity.

2.3.2 Friction, Machining, and Rotating Members

AE from friction is another growing area of activity, particularly with regard to the study of tool wear and cutting processes, machine monitoring, bearings, and rotating members [see, e.g., Dornfeld, 1982; Heiple et al., 1991; Drouillard, 1993].

2.3.3 Concrete and Civil Structures

With the deterioration of many concrete bridges throughout the world, AE research and application of concrete and civil structures is an area of increasing activity [see, e.g., Ohtsu (1989a) for a review article on AE in civil engineering and concrete; Drouillard (1986) for a bibliography on concrete; and Suprenant et al., eds. (1990, 1992) for a selection of papers on NDT of civil structures]. According to the U.S. Department of Transportation one of every three bridges in the United States is either structurally deficient, meaning it can't support standard loads or functionally obsolete, meaning it was designed and built for a time when traffic conditions practically had no relevance to today's needs.

2.3.4 Acousto-Ultrasonics

What has now become known as acousto-ultrasonics (AU) was first studied at NASA Lewis Research Center in Cleveland, Ohio by Alex Vary in collaboration with Kenneth J. Bowles (Vary and Bowles, 1977) and Raymond F. Lark (Vary and Lark, 1978). Vary was looking for a practical NDT technique to characterize a selected volume of material relative to its properties and specific defect conditions. Other early researchers in AU were Prof. James H. Williams, Jr. at Massachusetts Institute of Technology, Cambridge and several of his graduate students (Williams and Lampert, 1980; Williams et al., 1980); Allen T. Green (1981) at Acoustic Emission Technology Corp., Sacramento, California; Profs. John C. Duke, Jr., Edmund G. Hennenke, II, and several co-workers (Duke et al., 1983) at Virginia Polytechnic Institute and State University.
Blacksburg; and Dr. Frank C. Beall (1987), who started his AE/AU research at Weyerhaeuser Co., Tacoma, Washington and continues it at the University of California Forest Product Laboratory, Richmond. Research using similar techniques has been conducted by Prof. Wolfgang Sachse and Kwang Yul Kim (1986) at Cornell University, Ithaca, New York and Prof. Joseph L. Rose et al. (1993) at Pennsylvania State University, University Park. Two major conferences on AU have been held to date (Duke, ed., 1988; Vary, ed., 1993). In 1993, ASTM issued the first standard on AU (ASTM, 1993). A more detailed history of AU and a comprehensive bibliography on the subject (Drouillard and Vary, 1994a,b) may be found in a special issue on acousto-ultrasonics of the Journal of Acoustic Emission.

2.3.5 Wood and Wood Products
Following the last published work of Drs. Andrew W. Porter, M.L. El-Osta, and D.J. Kusec (1972) at the Department of Forestry of Canada, Western Forest Products Laboratory in Vancouver, British Columbia, little research was done in the study of acoustic emission from wood until the 1980s. Currently there is a growing interest in the study of acoustic emission from wood and the application of acousto-ultrasonics to inspect wood and wood products. Some of the leading research in this area is being conducted by Drs. Frank C. Beall, Richard L. Lemaster, and Stephen L. Quares at the University of California Forest Products Laboratory, Richmond; by Prof. Henrique L.M. dos Reis at the University of Illinois at Urbana-Champaign; by Profs. Keiichi Sato, Hajime Takeuchi, and Masami Fushitani at Tokyo University of Agriculture and Technology, Japan; and by Profs. Masami Noguchi, Y. Kagawa, J. Katagiri, and Koichi Nishimoto at Kyoto University, Japan. A detailed history of acoustic emission from wood (Drouillard, 1990) and a comprehensive bibliography on AE from wood and wood products (Drouillard and Beall, 1990) may be found in a special issue on wood of the Journal of Acoustic Emission.

2.3.6 From Signal Analysis to Waveform-Based Analysis
Today there is a transition to waveform-based analysis which has opened up a new approach to signal analysis, source characterization, and source location. This has come about as the result of many years of research in signal analysis. Perhaps the first work in this area was begun in 1934 when Kishinouye (1937) used a galvanometer and photographic recording technique to obtain AE waveforms. In 1948, Mason et al. recorded twin-induced AE. There were a number of significant papers reporting early contributions to various aspects of signal analysis: Prof. Raymond W.B. Stephens of Imperial College, London and his former student Dr. Adrian A. Pollock of Cambridge Consultants Ltd., Cambridge, England, on waveform and frequency spectra (Stephens and Pollock, 1971); Prof. Kanji Ono, Richard Stern, and Marshall Long, Jr. (1972) at the University of California in Los Angeles, on correlation analysis; Dr. James R. Houghton of Tennessee State University, Nashville and Prof. Paul F. Packman and M.A. Townsend of Vanderbilt University, Nashville, on deconvolution of pulse shapes (Houghton et al., 1976); and Drs. John A. Simmons and Roger B. Clough (1976) at the National Bureau of Standards, Gaithersburg, Maryland, on the transfer function of a one-dimensional moving dislocation and the theoretical aspects of AE spectral measurements. Lloyd J. Graham and George A. Alers (1972) at Rockwell International Science Center, Thousand Oaks, California, used a modified Sony video tape recorder in conjunction with a broadband capacitive transducer to detect burst-type emissions and record them, then determine their frequency spectrum by playing them back in stop-action through a standard frequency spectrum analyzer. Prof. Kanji Ono and graduate students Y. Krampfner and A. Kawamoto at the University of California at Los Angeles and Allen T. Green at Acoustic Emission Technology Corp. in Sacramento utilized a similar recording system for visual waveform classification in their study of the deformation and low-cycle fatigue of copper-base alloys (Krampfner et al., 1975). The next significant work leading to source mechanism identification was reported by Drs. Franklin R. Breckenridge, Carl E. Tschiegg, and Martin Greenspan (1975) at the National Bureau of Standards, Gaithersburg, Maryland. In their seminal paper, they described the use of a capacitive transducer to capture the initial arrival of a signal produced by the fracture of a glass capillary, thus laying the foundation for standardized calibration of AE sensors and stimulating the development of quantitative theories of the propagation aspect of acoustic emission.

A number of developments followed in the evolution of signal analysis - the use of digitizers or transient recorders, and computers with elaborate software packages. Major contributors included: Drs. Nelson H. Hsu, John A. Simmons, and Stephen C. Hardy (1977) at the National Bureau of Standards, Gaithersburg; Drs. Christopher B. Scruby, Haydn N.G. Wadley, and their co-workers (Wadley et al., 1981; Scruby et al., 1985) at the National NDT Centre, AERE Harwell, England; Prof. Wolfgang Sachse and Yih-Hsing Pao (1981) at Cornell University, Ithaca, New York; Prof. Masayasu Ohtsu at Kumamoto University, Japan and Prof. Kanji Ono at the University of California at Los Angeles (Ohtsu and Ono, 1984, 1986, 1988; Ohtsu, 1989); and more recently Prof. Michael R. Gorman and Dr. Steven M. Ziola at Naval Postgraduate School, Monterey, California and Dr. William H. Prosser at NASA Langley Research Center, Hampton, Virginia (Gorman and Prosser, 1990; Ziola and Gorman, 1991). An approach with considerable promise is pattern recognition analysis in conjunction with high speed signal digitization processes [see a recent review by Ono and Huang, 1994].

AEWG Charter Fellows (1982). Prof. Kanji Ono, Dr. Robert B. Engle, Philip H. Hutton, Prof. Steve H. Carpenter, Thomas F. Drouillard (standing, l to r); Prof. Clement A. Tatro, Harold L. Dunegan, Allen T. Green (front row, l to r).
EWGAE Executive Committee members (1981): Dr. Paul F. Dumousseau, Dr. Peter G. Bentley, J. Hickman, Dr. E. Votava (front row, l to r): Dr. L. Rogers, B. Audenard, Dr. Peter Jax (back row, l to r)

Dr. J. Roget

Dr. William F. Hartman

Prof. Davis M. Egle

Prof. Kusuo Yamaguchi

Prof. Teruo Kishi

Prof. Yasuo Mori
Editors of Journal of Acoustic Emission

Prof. Kanji Ono (1982-)

Dr. Alan G. Beutie (1982-)

Thomas F. Drouillard (1982-)

Prof. Stuart L. McBride (1982-1993)

Dr. Roger Hill (1983-1993)

Prof. Morio Onue (1983-1986)

Prof. Frank Beall (1994-)

Prof. Masayasu Ohtsu (1994-)
3. Discovery of the Microseismic Method

Seismic and microseismic activity are forms of acoustic emission, differing only in frequency and amplitude, earthquakes being the most energetic. The science of seismology to study earthquake activity and the geophysical study of microseismic activity in rock are strikingly similar to the acoustic emission study of deformation and fracture in metals. Experimental techniques, instrumentation, and emission-producing events are similar. The possibility of using "supersonic vibrations" to predict earthquakes and rockbursts was suggested as early as 1923 by Dr. Ernest A. Hodgson (1923) of the Dominion Observatory, Ottawa, Canada.

Dr. Leonard A. Obert (1977) at the Eastern Experimental Station of the U.S. Bureau of Mines in College Park, Maryland, and later Denver, Colorado, described the discovery of microseismic emission in rock as purely accidental. In 1938 he was conducting seismic velocity tests in the lead-zinc mines of northeastern Oklahoma to determine if the seismic velocity in mine pillars was dependent on pillar loading. Throughout the test spurious signals kept triggering the interval time between two geophones. After eliminating possible equipment defects it was discovered that the triggering was being caused by self-generated signals in the rock. At first the significance of these microseisms was not recognized. Shortly after the completion of the Oklahoma tests, Dr. Obert and Wilbur I. Duvall, also with the Bureau of Mines, conducted similar tests in the Ahmeek Copper Mine of the Calumet & Hecla Consolidated Mining Co. on the Keweenaw Peninsula in Upper Michigan (Obert, 1941; Obert and Duvall, 1942). The same self-generated signals were encountered. However, because of the high stress condition in the deep mine (about 3800 ft. below the surface), numerous rockbursts were occurring. The source of the microseisms was attributed to these rockbursts. Obert and Duvall recognized this phenomenon provided the basis for a method of detecting and delineating areas of high stress that required no prior knowledge of the mechanical properties of the rock or the state of stress in the rock. They then carried their research into the laboratory to conduct controlled experiments to determine the origin of microseisms (Obert and Duvall, 1945).

Dr. Ernest A. Hodgson (1958), Chief of the Seismological Division of the Dominion Observatory, Ottawa, conducted a series of rockburst studies in the Lake Shore Mines at Kirkland Lake, Ontario from late 1938 through October 1945. In 1941, while studying supersonic vibrations as indicators of increasing rock pressure, he became aware of the work of Dr. Obert at the U.S. Bureau of Mines. The following year Hodgson installed "Obert recorders." Analysis of recorded data following a heavy rockburst on January 29, 1943, "...furnished the best evidence of the fact that subaudible snapping (designated 'microseisms') gives warning of a burst."

In 1970, Prof. H. Reginald Hardy, Jr. from Pennsylvania State University, University Park, joined the Acoustic Emission Working Group, bringing to the AE community a knowledge of geophysics and the beginning of a cross-fertilization between geophysical scientists and the scientists and engineers working in traditional acoustic emission. Hardy organized and conducted the series of five Conferences on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials held at Pennsylvania State University in 1975, 1978, 1981, 1985, and 1991 (Hardy and Leighton, 1977, 1980, 1984; Hardy, 1989, 1995). This collection of proceedings has become a valuable asset to the student, researcher, and applications engineer in the field of acoustic emission/microseismic activity.

Other early workers in this area included Drs. T. Persson and B. Hall (1958) and Dr. H.K. Helfrich (1966) in Sweden; A.G. Konstantinov (1959) and Prof. M.S. Antsyferov (1966) in Russia; Prof. Kiyoo Mogi (1962) in Japan; Dr. Richard E. Goodman (1963) and Dr. C.H. Scholz (1968) in the United States; and Prof. J.L. Knill, John A. Franklin, and Andrew W. Malone (1968) in England. An historical review of acoustic emission/microseismic studies, as well as an excellent review article on acoustic emission is given by Lord (1975).

4. The Acoustic Emission Working Groups

The acoustic emission working groups have, in the opinion of the author, been largely responsible for the orchestrated development of AE throughout the world. They brought together all the savants of AE technology, provided forums for the exchange of ideas and information, and helped coalesce the direction of research. They provided a peer review system and, in the case of the Acoustic Emission Working Group, a set of awards for recognizing outstanding work in the field of acoustic emission.

4.1 Acoustic Emission Working Group

The Acoustic Emission Working Group (AEWG) was conceived in the spring of 1967 by Jack C. Spanner of Battelle-Northwest in Richland, Washington and Allen T. Green of Aerojet-General Corp. in Sacramento, California. The occasion was lunch in the lounge of the Desert Inn in Richland during Green's visit to discuss AE with Spanner. They observed that research remained chiefly a decentralized and individualized activity in which researchers communicated only through their technical reports and journal articles. Few in number, these publications showed evidence that there was a lack of communication, and differences in terminology and experimental techniques used, generally reflecting each researcher's educational background and field of expertise. Spanner and Green agreed that there was enough interest in AE to consider beginning some type of informal exchange of information. A letter was dispatched by Spanner to some fifteen people working in the field of
acoustic emission, inviting them to a formative meeting to organize an informal working group that would serve, not only the AE folks from the United States and Canada, but anyone involved or interested in acoustic emission.

The Formative Meeting of the AEWG was held November 2, 1967, in the King's Room of the Esquire Inn Motel [now razed] in Alcoa, Tennessee, following the Conference on Incipient Failure Diagnosis for Assuring Safety and Availability of Nuclear Power Plants held in Gatlinburg, Tennessee. Jack Spanner presided, Allen Green served as acting secretary. Twelve persons attended the meeting: Harold L. Dunegan of Lawrence Radiation Laboratory; Prof. Julian R. Frederick of the University of Michigan; Allen T. Green of Aerojet-General Corp.; Philip H. Hutton, Jack C. Spanner, and Herb N. Pedersen of Battelle-Northwest Laboratories; Dr. Harvey L. Balderston and Dr. Robert W. Moss of The Boeing Co., Seattle; Charles W. Musser of The Boeing Co., New Orleans; Dwight L. Parry and Norman K. Sowards of Phillips Petroleum Co.; and Bradford H. Schofield of Teledyne Materials Research (formerly Lessells and Associates). During the meeting each person gave a brief discussion of his activities in AE. A constitution and bylaws were drafted using as a model the constitution and bylaws of the Western Regional Strain Gage Committee of which Green was chairman at the time. The first slate of officers was elected: Dunegan - chairman, Parry - vice-chairman, and Green - secretary-treasurer. Spanner was elected Honorary Member in light of his efforts in leading the organizational activities.

The first meeting was held February 8-9, 1968, in Idaho Falls, Idaho, with 19 people attending. In addition to the twelve founding members, eight persons were elected to membership to form the Charter membership: T. Theodore Anderson and Dr. Robert G. Liptai of Argonne National Laboratory; Thomas F. Drouillard of Dow Chemical Co., Rocky Flats Plant; Dr. Robert B. Engle of Lawrence Radiation Laboratory; D.K. Mitchell of The Boeing Co., New Orleans; R. Neal Ord of Battelle-Northwest; Ronald E. Ringsmuth of the Jet Propulsion Laboratory; and Richard K. Steele of Aerojet-General Corp. The meeting consisted of a business meeting and technical presentations, followed by a tour of the host, Phillips Petroleum Company's facility at the U.S. Atomic Energy Commission National Reactor Test Site. There was much discussion on instrumentation, test procedures, and elimination of noise.

The format of this meeting set the pace for future meetings. Informality of the technical program and presentations was, and still is, the modus operandi of the AEWG. From the beginning meetings were held every nine months; elected officers served for a three-meeting term of office. At the 27th meeting [San Antonio, 1985] the time interval between meetings was extended anywhere from nine months to a year and officers term of office was reduced to two meetings. At the 37th meeting [Sacramento, 1994], the Constitution was revised to hold regular meetings at nine to eighteen month intervals. Membership originally was by company with two voting members from each autonomous organization location. At the 7th meeting [Atlanta, 1971] the Constitution was revised to provide for individual memberships. Commercial presentations by vendors comprised part of the program between the 5th meeting [Las Vegas, 1970] and the 22nd meeting [Boulder, 1981] after which they were discontinued to provide more time for technical talks. However, they were reinstated at the 37th meeting [Sacramento, 1994]. A complete listing of AEWG meetings can be found in the Journal of Acoustic Emission (Drouillard, 1995a).

4.1.1 AEWG Committees

Some of the first activities of the AEWG were accomplished through ad hoc committees, three of which will be briefly discussed. A Terminology Committee was established at the first meeting and chaired by Philip H. Hutton; it was chartered to establish a glossary of terms common to acoustic emission. The first glossary of eight terms was published as "Recommended Acoustic Terminology" in Acoustic Emission, ASTM STP 505 (Liptai et al., eds., 1972). By the 13th meeting [Laguna Hills, 1974] this activity was totally assimilated to ASTM Task Group E07.04.01. A current glossary of AE and NDT terminology may be found in the latest revision of ASTM Standards [see, e.g., ASTM, 1992d].

Another ad hoc committee was the Bibliography Committee. At the first meeting it was unanimously agreed upon to have open and free exchange of information. Members began exchanging reports and literature. Allen T. Green distributed a bibliography consisting of 81 references (Green and Ross, 1967), which represented nearly the entire body of literature on AE up to 1967. A significant expansion was made to Green's bibliography by Jack C. Spanner (1970) and distributed at the 5th meeting [Las Vegas, 1970]. Spanner had prepared his bibliography with 295 references for his masters thesis which he published as part of a book (Spanner, 1974), a comprehensive review of the state-of-the-art of acoustic emission at that time. The committee ceased to function beyond the 10th meeting [Pasadena, 1972]. However, everyone had become familiar with the writer's penchant for collecting AE literature, so the Working Group started looking to him for any fruitful activity in this area. In 1975 he published his first bibliography (Drouillard, 1975). Over the next four years he compiled some 2000 references which were published with annotations in Acoustic Emission: A Bibliography with Abstracts (Drouillard, 1979). Since then, over 3000 additional references have been listed in the AE Literature section in the Journal of Acoustic Emission.

The Committee on Equipment and Standardization was proposed at the 8th meeting [Bal Harbour, 1971] with Dr. Robert B. Engle as chairman. Their first task was to pre-
pare a specification for calibration of transducers. At the 10th meeting [Pasadena, 1972] this became the Standardization Committee. By the 13th meeting [Laguna Hills, 1974] the activity of this committee was absorbed into ASTM Task Groups E07.04.02 on AE Sensors and E07.04.03 on AE Instrumentation.

4.1.2 AE Sessions, International Conferences, World Meetings & Primers

Organizing symposia-type technical sessions on AE has been one of the prime objectives of the AEWG. At the first meeting Secretary Green was requested to explore the mechanisms of AEWG sponsoring a session on AE at a national conference. Subsequently, arrangements were made to sponsor a half-day session at the American Society for Metals Materials Engineering Congress in Philadelphia in October 1969, in conjunction with the 4th AEWG meeting. Thomas F. Drouillard and Allen T. Green co-chaired this session. Since the ASM meeting, the Working Group has sponsored and supported numerous AE sessions given at ASNT, ASTM, and ASME conferences.

The first major symposium on AE was the Symposium on Acoustic Emission held during ASTM Committee Week in Bal Harbour, Florida, December 7-8, 1971, in conjunction with the 8th AEWG meeting. Dr. Robert G. Liptai served as general chairman with Drs. David O. Harris and Clement A. Tatro as co-chairmen. The proceedings of this symposium became the first major publication on acoustic emission (Liptai et al., eds., 1972); although in March 1971, a different version of six of the papers were published in a special issue of Materials Research and Standards, the first special issue on acoustic emission ever published (ASTM, 1971).

The first International Conference on Acoustic Emission, co-sponsored by AEWG and ASNT, was held September 10-13, 1979, in Anaheim, California, in conjunction with the 20th AEWG meeting. Harold L. Dunegan and Dr. William F. Hartman were co-chairmen and together published the proceedings (Dunegan and Hartman, eds., 1981). The Second International Conference on Acoustic Emission was held in conjunction with the 28th AEWG meeting at Lake Tahoe, Nevada, October 28-November 1, 1983. Allen T. Green was chairman. Extended abstracts of the papers presented were published in a special issue of the Journal of Acoustic Emission, Vol. 4, No. 2/3, 1985. The third international conference, called the World Meeting on Acoustic Emission, was held in conjunction with the 32nd AEWG meeting and the 1989 ASNT Spring Conference in Charlotte, North Carolina, March 20-23, 1989. Prof. W. Sachse and S. L. McBride served as co-chairmen and Dr. Alan G. Beattie was arrangements chairman. Extended summaries of the papers presented were published in a special issue of the Journal of Acoustic Emission, Vol. 8, No. 1/2, 1989. Complete papers were later published by ASTM (Sachse et al., eds., 1991) with Drs. J. Roget and K. Yamaguchi as co-editors. The most recent international conference was the 4th World Meeting on Acoustic Emission and 1st International Conference on Acoustic Emission in Manufacturing, held September 15-18, 1991, in Boston, Massachusetts, in conjunction with the 35th AEWG meeting and the 1991 ASNT Fall Conference. Dr. Sotirios J. Vahaviolos was general chairman and Prof. David A. Domfeld was chairman of the Conference on Manufacturing. Extended summaries of the papers presented at these meetings were published by ASNT (Vahaviolos, ed., 1991).

At the 25th meeting [Princeton, 1983] Prof. Davis M. Egle proposed holding a one-day workshop/tutorial/primer on the basics of acoustic emission at the next AEWG meeting. As a result, the first primer on AE was held the day preceding the 26th meeting [Reno, 1984] with Egle serving as chairman. Subsequent primers were held at the 27th meeting [San Antonio, 1985], 29th meeting [Kingston, 1986], 34th meeting [Urbana, 1990], 37th meeting [Sacramento, 1994], and 38th meeting [Hampton, 1995]; one is scheduled to be held at the 39th meeting [Dana Point, California, 1996]. At the 33rd meeting [Berkeley, 1990] Prof. David A. Domfeld held a Workshop on Acoustic Emission in Manufacturing.

4.1.3 Awards of the AEWG

In preparation for celebrating the 10th anniversary of the AEWG, it became apparent that over the past decade there was no peer recognition for outstanding accomplishments in AE. The AEWG needed to institute some form of awards, similar to what other professional societies offered. At the 20th meeting [Anaheim, 1979] four awards were proposed: the Gold Medal Award, the Achievement Award, the Publication Award, and the Fellow Award. Approved at the 21st meeting [Ithaca, 1980], the awards were inaugurated at the 24th meeting [Knoxville, 1982] with the Gold Medal Award being presented to Dr. Clement A. Tatro, the Achievement Award to Harold L. Dunegan, and Charter Fellow Awards to Clifford D. Bailey, Prof. Steve H. Carpenter, Thomas F. Drouillard, Harold L. Dunegan, Dr. Robert B. Engle, Allen T. Green, Philip H. Hutton, Prof. Kanji Ono, and Dr. Clement A. Tatro. The Inaugural Publication Award was presented to Thomas F. Drouillard at the 25th meeting [Princeton, 1983]. A complete listing of AEWG award recipients may be found in a recent issue of the Journal of Acoustic Emission (Drouillard, 1995b).

4.2 Japanese Committee on Acoustic Emission

Prior to the formation of the Japanese Committee on Acoustic Emission (JCAE) there was little indigenous AE research in Japan except for the pioneering work on rocks by Prof. Kiyoo Mogi at the Earthquake Research Institute, University of Tokyo. In the summer of 1969, at the International Institute of Welding Conference in Kyoto, several papers on AE were presented which generated considerable interest among many of the Japanese attendees. Later that
year Dr. Eiji Isono of Fuji Steel, together with Prof. Morio Onoe of the Institute of Industrial Science, University of Tokyo, organized the Japanese Committee on Acoustic Emission under sponsorship of the High Pressure Institute of Japan in cooperation with the Japanese Society for Non-Destructive Inspection (JSNDI). Some of the early history of AE activities in Japan has been summarized in articles by Onoe (1974, 1986), Isono (1970), Fuji (1972), and Nakasa (Nakasa, 1980; Nakasa et al., 1978). Dr. Hiroyasu Nakasa of the Central Research Institute of Electric Power Industry in Tokyo is a founding member of the JCAE and a savant of application engineering in acoustic emission.

The JCAE held its first meeting December 10, 1969 at Fuji Steel in Tokyo. Prof. Onoe became chairman. Meetings were held bimonthly. In 1980 the JCAE became Committee 006 on Acoustic Emission of JSNDI. At that time they began publishing the proceedings of each meeting. Upon the retirement of Prof. Onoe in 1986, Prof. Kusuo Yamaguchi of the Institute of Industrial Science, University of Tokyo, became chairman. Prof. Onoe is now professor emeritus, University of Tokyo and executive advisor for Ricoh Co. Prof. Yamaguchi remained chairman until his retirement in 1992, at which time Prof. Teruo Kishi, Research Center for Advanced Science and Technology, University of Tokyo, became chairman. In 1994, Prof. Kishi was elected president of the JSNDI, and Prof. Yasuhiko Mori of the College of Industrial Technology, Nihon University, became chairman of Committee 006 on AE.

4.2.1 International Symposia & National Conference

The biennial International Acoustic Emission Symposium were inaugurated in 1972, and have become the foremost international meeting on AE today. The first was The U.S.-Japan Joint Symposium on Acoustic Emission, held in Tokyo, July 4-6, 1972. Some of the sessions were held in English and some in Japanese. The proceedings consisted of two volumes: an English volume with six papers and a Japanese volume with 11 papers (JCAE, 1972). The Second AE Symposium was held two years later (September 2-4, 1974) in Tokyo (JCAE, 1974). Starting with this meeting all presentations and published proceedings were in English. [see JCAE, 1976, 1978 for proceedings of the 3rd and 4th symposiums, respectively]. Starting with the 5th symposium the name was changed to International Acoustic Emission Symposium [JCAE, 1980; see also Nakasa, 1980 for a review of the first five symposia]. Starting with the 6th symposium the title of the proceedings was changed to Progress in Acoustic Emission and the publication upgraded to a hard-cover, bound book (Onoe et al., eds., 1982, 1984; Yamaguchi et al., eds., 1986, 1988, 1990; Kishi et al., eds., 1992, 1994). The proceedings of these symposia have become an ongoing documentation of the progress in acoustic emission throughout the world over the past 23 years and comprise a major component of the permanent world literature on AE.

The National Conference on AE was established in order to better exchange information among Japanese researchers. Talks are presented in Japanese and cover all areas of AE research and application. Proceedings are published in Japanese for each conference. The first conference was held in 1977, followed by one every other year since then.

4.2.2 AE Short Courses & Tutorial Sessions

Starting in 1974, AE short courses, or tutorial sessions, were given every year. The first short course was given October 28-29, 1974, at the Japanese Society of Civil Engineers Hall with demonstrations at Nippon Steel Corp. The second short course was given November 25-26, 1975. The results of the third short course, given December 6-7, 1976, were reported in a special issue on AE of Pressure Engineering (Japan) (JHPI, 1977). A detailed schedule of lectures and demonstrations for the first seven short courses is given by Nakasa (1980). The JCAE also organized tutorial sessions on AE for various professional societies, e.g., the National Symposium on Atomic Energy in the spring of 1973, and the National Convention of Electrical Engineers in the fall of the same year.

4.3 European Working Group on Acoustic Emission

A series of events sparked AE interest in Europe and led to the founding of the European Working Group on Acoustic Emission (EWGAE). During the summer of 1971, Harold L. Dunegan toured England and a number of countries on the continent giving Dunegan Research Corporation's short courses and demonstrating his company's new series of AE instrumentation. On March 14, 1972, Dr. Adrian A. Pollock of Cambridge Consultants, England conducted the Institute of Physics Conference on Acoustic Emission at Imperial College in London; fifteen papers from throughout Europe and the United States were presented. This meeting brought together the key people of Europe already involved in AE research -- from England: in addition to Dr. Pollock, Dr. Don Birchon at the Admiralty Materials Laboratory, Drs. Ian L. Mogford and Ian G. Palmer at Central Electricity Research Laboratories, Dr. Peter G. Bentley at Risley Engineering and Materials Laboratory of the U.K. Atomic Energy Authority, and Dr. Brian Harris at the University of Sussex; from Germany: Drs. Jurgen Eisenblatter and Peter Jax at Battelle-Institut; from France: Dr. Paul F. Dumousseau at the Centre Technique des Industries Mecaniques and M. Nicole Chretien and Dr. E.G. Tomachevsky at the Centre d'Études Nucléaires de Saclay, Commissariat à l'Énergie Atomique; from Italy: Dr. M. Mirabile at Centro Sperimentale Metallurgico; from Denmark: Arved Nielsen at the Research Establishment Risø, Danish Atomic Energy Commission; and from the Netherlands: Dr. J.C.F. DeKanter at the Technische Hogeschool Delft. As a consequence of this meeting and Dunegan's influence, Pollock and Birchon organized the European Stress Wave Emission Working Group which held its first meeting November 29-30, 1972,
4.4 Acoustic Emission Working Group (India)

At the 28th AEWG meeting [Lake Tahoe, 1985], a delegation from India announced the formation of the Acoustic Emission Working Group (India) with a membership of 82 people from government, universities, and industry. The first slate of officers were Professor A.K. Rao - chairman, R. Visweswaran - vice-chairman, and Dr. C.R.L. Murthy - secretary. Murthy summarized the status of AE in India, i.e., there were about 100 workers in AE in India engaged in a wide range of areas of applications similar to those in North America.

4.5 South African Working Group for Acoustic Emission

At the 32nd AEWG meeting [Charlotte, 1989], Dr. Stan Botten announced the formation of the South African Working Group for Acoustic Emission.

4.6 Korean Working Group on Acoustic Emission

Twenty-two people attended an organizational meeting at Korean Advanced Institute of Science and Technology (KAIST) in Seoul, Korea on June 30, 1990 and established the Korean Working Group on Acoustic Emission (KWGAE) and approved the KWGAE constitution. Professor H.C. Kim of KAIST was elected chairman; J.S. Lee of KIMM, auditor; Dr. Oh-Yang Kwon of Korea Standards Research Institute, secretary general; Dr. H.D. Jeong of Research Institute of Science and Technology, Pohang Steel Co., treasurer; and Dr. Y.H. Kim of KSRI, archivist. The first regular meeting was held September 25, 1990 at the Korea Standards Research Institute, Taejon, Republic of Korea; over 50 members attended the meeting. Proceedings were published that included seven papers. KWGAE meetings will be held twice a year - spring and fall, and proceedings are expected to be published for each meeting.

5. Other AE Activities

5.1 ASNT Committee on Acoustic Emission

In 1968, the American Society for Nondestructive Testing (ASNT) formed a Subcommittee on Acoustic Emission with Thomas F. Drouillard appointed chairman. In 1974, Dr. Clement A. Tatro was elected chairman and the status of the group was elevated to Acoustic Emission Committee. During his tenure as chairman, Tatro arranged for at least one AE session at every spring and fall meeting of ASNT. Chairmanship was taken over by Prof. Davis M. Egle in 1980, then by Albert E. Brown in 1982, and by Dr. B. Boroco Djordjevic in 1986.

The most important function of this committee has been the production of the volume on acoustic emission testing for the second edition of the ASNT NDT Handbook series. At the 13th AEWG meeting [Laguna Hills, 1974], Harold L. Dunegan solicited input for an AE section to be included in a volume on ultrasonics. Under the technical editorship of Dr. Ronnie K. Miller and because of the bulk of material submitted, this came to fruition in 1987 as a separate volume on acoustic emission testing (Miller and McIntire, eds., 1987). Another contribution to come out of this group was a section on leak testing using acoustic techniques for Volume 1 of the Handbook series (Brown et al., 1982).

5.2 Committee on Acoustic Emission from Reinforced Plastics

The Committee on Acoustic Emission from Reinforced Plastics (CARP) was founded in 1978 by John Teti, a consultant from Wilmington, Delaware, as an activity of the Society of the Plastics Industry (SPI), a national trade association for the U.S. plastics industry. The primary objectives of CARP were to develop field AE test methods for fiber reinforced plastic vessels and piping systems and draft methods of test and recommended procedures for action by recognized standard-making organizations such as ASTM and ASME. Through the cooperative effort of representatives from chemical companies, fiberglass equipment fabricators, materials suppliers, instrument manufacturers, and academic and research institutions, the CARP developed and published its first document in 1982 (Adams, 1982). This document became the foundation for the SPI/CARP recommended practice for FRP piping systems (Droge, 1983), three ASTM standards (ASTM, 1992a,b,c), and two ASME codes (ASME, 1986, 1988). Teti was elected the first chairman of CARP and served until 1983, at which time Dr. Marvin A. Hamstad was elected chairman, a position he still holds. In 1988, CARP became a functional group within the American Society for Nondestructive Testing. To date CARP has sponsored a series of five International Symposia on Acoustic Emission from Composite Materials (SPI, 1983, 1986; ASNT, 1989, 1992, 1995).

5.3 ASTM E07.04 Subcommittee on AE

At the 9th AEWG meeting [Denver, 1972] Jack C. Spanner announced that the American Society for Testing and Materials (ASTM) had authorized the formation of Subcommittee E07.04 on Acoustic Emission under the E-7 Committee on Nondestructive Testing. Spanner called to-
together an ad hoc committee to formulate a scope and discuss practical means of implementing the newly authorized subcommittee. The ad hoc committee consisted of Robert B. Engle, Julian R. Frederick, Raymond F. Lark, Charles W. Musser, Wally W. Reinhardt, Gilbert R. Speich, and Allen E. Wehrmeister, with Spanner presiding as chairman. They defined the scope of the subcommittee to include: (1) the promotion of knowledge to advance the technology of acoustic emission and its application to engineering materials and structures; (2) the extension of this method to other engineering problems; (3) the formulation of uniform requirements relating to the performance, interpretation, and classification of acoustic emission techniques, equipment, terminology, and results, without prejudice to the jurisdiction of the product committees over their respective products; and (4) the coordination and review of AE requirements and clauses initiated by other committees. An organizational meeting of 29 people was held June 27, 1972 in Los Angeles, California. Officers appointed were Spanner—chairman, Frederick—vice-chairman, and Reinhardt—secretary. At this meeting Task Group E07.04.01 on Terminology was formed to formulate a document containing recommended standard terminology for usage in AE documentation. The activities of this subcommittee have been highly productive in the development and dissemination of consensus standards on AE. To date some thirteen Standard and Recommended Practices have been put through the ASTM consensus process and published in the Annual Book of ASTM Standards [see, e.g., ASTM, 1992e,f]. For a general overview on AE codes and standards, see Spanner (1987); for a report on the present status and future direction of AE standards, see Jolly (1992).

5.4 Journal of Acoustic Emission

By the early 1980s it became evident to Prof. Kanji Ono that acoustic emission badly needed a journal of its own to accommodate the exponentially increasing number of papers being written. As a consequence, he conceived and founded the Journal of Acoustic Emission, the first journal dedicated solely to the technology of AE. The Journal was to be an international journal with broad interest and use to both the researcher and practitioner of acoustic emission, its official language being English. Ono formed the Acoustic Emission Group to produce and publish the journal. The original editorial staff consisted of Ono as Editor, taking care of the mechanics of publication the business end of the journal, and Associate Editors: Dr. Alan G. Beattie and Prof. Stuart L. McBride responsible for the papers review process, and Thomas F. Drouillard responsible for the AE Literature section of the journal. The first issue was published in January 1982. During the second year of publication, 1983, Dr. Roger Hill and Prof. Morio Onoe joined the editorial staff as Associate Editors to coordinate the regional review processes in Europe and Japan, respectively. Upon his retirement in 1986, Onoe resigned from the editorial staff. The resulting staff, consisting of Ono, Beattie, McBride, Hill, and Drouillard, remained through 1993. Starting with Volume 11 in 1994, McBride and Hill retired from the staff and were replaced by Dr. Frank C. Beall (U.S.) and Prof. Masayasu Ohtsu (Japan). Recently published in Vol. 11, No. 2, 1993 was a Cumulative Index of volumes 1-10, 1982-1992.

6. Closing Remarks

In this short history the writer has only briefly touched on the histories of some working groups and AE activities in other societies, mentioned only a few U.S. instrument manufacturers, and been very meager in any mention of the work and contributions from outside the United States, and particularly the former Soviet Union. The history of any science is only as complete as the permanent records left through the publications of the scientists in that field. History is then written as seen and interpreted through the eyes and experiences of the author. This often introduces prejudices and biases that may offend some readers. If the author has slanted any of his recollections and interpretations incorrectly, or you the reader would like to elaborate on some portion of this article, you are invited to send your version to the author or the Editor of the Journal of Acoustic Emission.

Through the contributions of hundreds of dedicated scientists and engineers throughout the world, acoustic emission has become a mature, highly developed technology and recognized nondestructive test method. Reciprocal and synergistic gains have occurred from one-on-one interaction of people from different fields of science and engineering, and through the exchange of literature and personal correspondence. Attending international meetings and each other's working group meetings, visiting each other's laboratories, and presenting lectures, colloquia, and short courses, have indeed created a camaraderie amongst these scientists and engineers throughout the world. The fact that for a quarter of a century the North American, Japanese, and European working groups have continued to function and that a significant number of people have been continuously engaged in various areas of AE attest to the relevance of acoustic emission. In closing, there are a few observations that appear evident to the writer regarding future needs and directions in acoustic emission:

• There is a need for a textbook and training manuals on AE, both of which should be translated into a number of different languages.

• An international AE library or document center should be established to house a complete collection of the world literature on AE, which one day will be accessible for online searching.

• A concerted effort should be made to educate the layman, and particularly management, in order to take the mys-
ttery out of AE and its applications – this could be accomplished by putting together a compendium of reports on AE applications for each industry.

• The gap between researcher and application technician must be bridged with better transfer of technology – make AE more "user friendly."

• In research – the vast area of opportunity offered by the continuing advancements in electronics and computers and the spinoff technology of the telecommunication industry should be explored and utilized.

• In applications – effective techniques to inspect nuclear reactors and civil structures should be developed, particularly bridges and earthquake-prone buildings.

• Acoustically smart materials and effective ways of incorporating them into smart structures need to be developed.

• It would be prudent to consider the possibilities of coupling AE with other NDT methods and physical phenomena such as was done in combining acoustic emission and ultrasonics in developing the acousto-ultrasonic technique.

• Finally, we must broaden our horizons by looking outside of our traditional realm of research and application of AE technology and redirect our efforts as necessary to meet the ever changing needs of the future.

Acknowledgments

The writer would like to express his sincere appreciation to many colleagues who have provided input to this paper, especially Allen T. Green, Harold L. Dunegan, Prof. Kanji Ono, Prof. Masayasu Ohtsu, Prof. Steve H. Carpenter, and Prof. Gregory B. Muravin for their valuable contributions.

References


ASTM (1971), Materials Research and Standards, 11(3), March. [special issue on AE]


ASTM (1992b), "Standard Practice for Acoustic Emission Examination of Reinforced Thermosetting Resin Pipe


M. Classen-Nekludowa (1929), "Über die sprungartige Deformation [Sudden Deformation of Crystals under Strain]," Zeitschrift für Physik, 55, 555-568. (in German)


F. Förster and E. Scheil (1940), "Untersuchung des zeitlichen Ablaufes von Umklappvorgängen in Metallen [Investigation of the Progress in Time of Magnetic Reversals in Metals]," Zeitschrift für Metallkunde, 32(6), 165-173, June. (in German)


C. Friedheim and Franz Peters, Editors (1911), Gmelin-Kraut's Handbuch der anorganischen Chemie, 7th Edition, Volume IV, Part 1, Carl Winter's Universitätsbuchhandlung, Heidelberg, Germany, p 244. (in German)


JCAE (1972), Proceedings of the U.S.-Japan Joint Symposium on Acoustic Emission, English and Japanese volumes, Japan Industrial Planning Assoc., Tokyo. [proceedings of the 1st AE Symposium, held in Tokyo, Japan, July 4-6, 1972]

JCAE (1974), The Second Acoustic Emission Symposium, Japan Industrial Planning Assoc., Tokyo. [proceedings of the 2nd AE Symposium, held in Tokyo, Japan, September 2-4, 1974]

JCAE (1976), The Third Acoustic Emission Symposium, Japan Industrial Planning Assoc., Tokyo. [proceedings of the 3rd AE Symposium, held in Tokyo, Japan, September 16-18, 1976]


JCAE (1980), The Fifth International Acoustic Emission Symposium, Japanese Society for Non-Destructive Inspection, Tokyo. [proceedings of the 5th International AE Symposium, held in Tokyo, Japan, November 18-20, 1980]


J. Kaiser (1950), "Untersuchungen über das Auftreten Geräuschen beim Zugversuch [A Study of Acoustic Phenomena in Tensile Tests]," Dr.-Ing. Dissertation, Technische Hochschule München, Germany. (in German); Translation UCRL-Trans-1082(L), translated into English for Lawrence Radiation Laboratory, Livermore, California, June 1964.

J. Kaiser (1952), "Materialprüverfahren [Material Testing Procedure]," German Patent No. 852 771, October 20. (in German)


J. Kaiser (1957a), "Geräuscheffekte in kristallinem Material [Noise Effect in Crystalline Materials]." Beispiele Angewandter Forschung, pp 19-54. (in German)

J. Kaiser (1957b), "Über das Auftreten von Geräuschen beim Schmelzen und Erstarren von Metallen [Occurrence of Noises during Melting and Solidification of Metals]." Forschung auf dem Gebiete des Ingenieurwesens, 23(1-2), 38-42. (in German)

S. Kalischer (1882), "Über die Molekularstruktur der Metalle," Berichte der Deutschen Chemischen Gesellschaft, 15. 702-712. (in German)


F. Kishinouye (1937), "Frequency-Distribution of the Ito Earthquake Swarm of 1930," Bulletin of the Earthquake Research Institute, Tokyo Imperial University, 15(Part 2), 785-826 and Plate LVL (Figs. 5 and 15).


M.V. Klassen-Neklyudova (1928), "Laws of Stepwise Deformation," Zhurnal Russkogo Fiziko-Khimicheskogo Obshchestva, Chast Fizicheskaya, 60(5), 373-381. (in Russian)


M. Onoe (1986), "AE Events of Interest: The Acceptance Speech by Professor Onoe," Journal of Acoustic Emission, 5(4), i, October-December. [acceptance speech for receiving the AEWG Gold Medal Award at the 8th International AE Symposium, Tokyo, Japan, October 22, 1986]


Erich Scheil (1929), "Über die Umwandlung des Austenits in Martensit in gehärtetem Stahl [Transformation of Austenite into Martensite in Hardened Steel]," Zeitschrift für Anorganische und Allgemeine Chemie, 183, 98-120. (in German)


W. Späth (1955), Fleiss und Kreichen der Metalle, Metall-Verlag GmbH, Berlin-Grunewald, Germany, pp 37-38. (in German)


S.J. Vahaviolos, Editor (1991), 4th World Meeting on Acoustic Emission and 1st International Conference on Acoustic Emission in Manufacturing, American Society for Nondestructive Testing, Columbus, Ohio. [extended paper summaries and abstracts of papers presented at the meetings, held in Boston, Massachusetts, September 16-19, 1991]

A. Vary, Editor (1993), Second International Conference on Acousto-Ultrasonics: Acousto-Ultrasonic Materials Characterization, American Society for Nondestructive Testing, Columbus, Ohio. [conference held in Atlanta, Georgia, June 24-25, 1993]
The Fracture Dynamics in a Dissipative Glass-Fiber/Epoxy Model Composite with AE Source Simulation Analysis

Hiroaki Suzuki, Mikio Takemoto and Kanji Ono

Abstract

In order to examine the fracture modes and dynamics in a dissipative glass-fiber/epoxy composite, we employed an eight-channel AE monitoring system. Seven-channels with small sensors were used for the source location and for fracture mode analysis based on the radiation pattern of the P-wave. A displacement-sensitive sensor on the eighth channel was utilized to obtain the source waveform using a proposed computer algorithm in time domain. As the wave propagation medium in the model specimen is an epoxy polymer, both the wave attenuation and dispersion in the epoxy matrix were measured by employing a focused pulse laser transmitter and a point PZT receiver. The results were incorporated into a signal simulation algorithm for source characterization. This algorithm was developed in the time domain and can calculate the transient surface displacements of elastic waves excited by the fiber fracture and fiber/matrix disbonding in model uni-directional glass fiber/epoxy composites. It includes the source location, radiation pattern analysis, wave attenuation and the use of a relaxation function. This newly developed system was utilized in analyzing AE signals from two types of glass-fiber reinforced composite specimens. For the specimens with glass-fiber bundles parallel to the loading direction, most AE waveforms were produced by the Mode-I fiber fracture with source rise time of 0.17 to 0.5 μs. For the model composite specimens with fiber bundles perpendicular to the loading, most waveforms were produced by the matrix cracks resulting in a point of dilatation. Some signals were due to Mode-II disbonding at the fiber/matrix interface. Mode-II disbonding at the top or bottom of the fiber bundles was also detected. Detail analysis of some of the monitored waveforms also points to multi-step fiber fractures or points of dilatation with a short incubation time.

1. Introduction

Acoustic emission (AE) has been widely used to study various types of microcrack in fiber reinforced composites (FRCs) (see e.g., Awerbuch et al., 1983; Shiwa et al., 1985; Ono, 1986; Kawamoto and Ono, 1989). In principle, AE can determine the fracture dynamics of such composites with an appropriate AE source inversion processing. Orientation dependent attenuation and dispersion of elastic waves in composites are the most intractable obstacles in characterizing the fracture dynamics. Hsiao et al. (1986) may be the first to experimentally measure the out-of-plane displacements due to a step-wise point unloading (pencil lead breaking) on polyethylene and polymethyl methacrylate (PMMA), and found both the response delay and amplitude attenuation. They attempted to characterize the viscoelastic behavior of elastic waves by incorporating complex modulus. However, this method cannot accurately measure the complex modulus at the high frequency range. Weaver et al. (1989a, b) proposed a comprehensive method to calculate the displacement component of viscoelastic waves. Here, the wave relaxation was accounted for successfully by including a frequency independent relaxation function, R(t). They demonstrated a good agreement between experimental and theoretical responses to a monopole excitation. However, the computation of particle displacements due to dipole excitation appears to require further work and is not readily applicable to fracture problems in polymer and composite.

Taking the concept of Weaver et al. (1989a, b) into account, the present authors extended the approach of Ohtsu and Ono (1984a), proposing another signal processing method to calculate the displacement component of viscoelastic waves for dipole problems. They applied the new method to the source characterization of glass-fiber fracture in a model composite (Suzuki et al., 1993), in which fibers were bonded to the surface. The proposed method modified the elastodynamic response by introducing the wave attenuation term, exp[-α(x - x')], and by using the relaxation function. This concept is expressed by the following equation for displacements $U_i(x,t)$ due to a source at $(x',t')$ in the half-space as:

$$U_i(x,t) = \exp[-\alpha(x - x')] \ast T_{ij}(x,t;x',t') \ast A_{ij}(x',t') \ast R(t),$$

where the symbol $\ast$ denotes a convolution integral in time. $T_{ij}(x,t; x',t')$ represents the Green's function of the second kind for an isotropic elastic medium and $A_{ij}(x',t')$ is the source function or the time transient of crack volume, re-
Fig. 1 Specimens of model composites with three E-glass fiber bundles parallel to the loading direction (Model A) and perpendicular to the loading direction (Model B).

spectively. A and b represent the crack area and discontinuity vector (Burgers vector equivalent), respectively. \(T_b \cdot \vec{A}_b\) gives the surface displacement in a non-dissipative medium. This type of iterated simulation analysis was advocated earlier by Ohtsu and Ono (1984a; 1986) as forward signal processing. Response delay due to the velocity dispersion is incorporated by the convolution integral of the relaxation function, \(R(t)\). Suzuki et al. (1993) established its validity for fiber fracture in a model specimen. However, the model specimen in the previous study had only a small number of quartz fibers with a large diameter (200 \(\mu m\)) bonded to the surface of a PMMA beam so that the propagation medium is essentially PMMA and the source location is confined to a known area.

In this study, we examine whether the signal processing method we developed can be used to study the complicated fracture dynamics in more realistic glass-fiber reinforced plastics (GFRPs). In actual GFRPs, glass fibers of a small diameter (typ. 10 to 20 \(\mu m\) diameter) are embedded in
a polymer (epoxy being the most common), resulting in materials with the attenuation and velocity dispersion larger than PMMA or epoxy alone. In order to evaluate microfracture events in such composites, we fabricated an improved displacement-sensitive sensor, and developed a laser ultrasonic technique and a new signal processing approach that incorporates multi-channel AE monitoring. We have combined the analysis of source location and radiation pattern of the first P-wave arrivals obtained from the multi-channel monitoring system, experimental attenuation and dispersion data and the computation of source functions. This paper reports the result obtained using a model composite of 10 μm-diameter glass fibers with an epoxy matrix. However, the fibers are still concentrated in small areas and the matrix properties dictate the wave propagation.

2. Specimen and Experimental Method

Three bundles of continuous E-glass fibers, 10 μm diameter, with each bundle containing about 50 fibers, were molded in epoxy as shown in Fig. 1. The two configurations of longitudinal and transverse fiber placement were selected to examine the accuracy of AE source location and to induce different fracture mechanisms. Model A specimens contain three bundles along the loading direction. The bundle positions are at y = 0, ±8 mm and at z = 0.5 mm. Each bundle spreads over an area approximately 1 mm in diameter. Model B specimens have three bundles normal to the loading direction, spaced at 10 mm apart at z ≤ 1 mm. In this case, the fiber spread was similar, but was larger in the thickness (z) direction. E-glass fibers (supplied by Asahi Glass Fiber Co. Ltd.) were treated with silane coupling agent prior to molding. The epoxy matrix contained 6 parts Epicote 828 and 4 parts Epicote 878 (supplied by Shell Epoxy Co. Ltd.) and cured at 70°C for 48 hrs using triethyltetramine (TETA) as a catalyst. The cured matrix showed a typical viscoelastic behavior at ambient temperature. The fracture strength and strain of the epoxy matrix were 55 MPa and 5.2%, respectively.

The AE monitoring system and sensor layout are shown in Fig. 2. Each sensor output was amplified by a preamplifier (model 9913, NF Circuit Block Co., gain 40 dB, bandwidth of 0.1 kHz to 20 MHz), was digitized by an 8-channel digitizer (model APC510, Autonix, 50 ns sampling interval, 10-bit resolution, 1024-point sampling length) and was stored on a hard disk through an engineering workstation (Sun Spark IPX). AE signals monitored by the seven channels (#1 - #7) with small AE sensors (model PICO, Dunegan, 3 mm aperture size) were used for the AE source location and also for the fracture mode analysis. AE waveforms detected by a displacement-sensitive sensor (channel #8) were used for AE source characterization also with the bandwidth of 0.1 kHz to 20 MHz. The sensor for channel #8 was placed at the center of a sample. It was constructed according to the NIST design using a small conical PZT element of 1 mm tip diameter (Fig. 3). As the composite sample is electrically non-conductive, the bottom of the PZT element was grounded by a narrow copper foil (10 μm thick). Calibration of the sensor was performed according to the surface-impulse deconvolution method (Ohtsu and Ono, 1984b). Figure 4 shows a detected waveform due to a point step-wise unloading (breaking a pencil lead on a 300 mm steel cube with a rise time of 0.9 μs and released force of 3.5 N). The upper figure corresponds to the simulated elastodynamic displacement normal to the plane. Response of the sensor to the transient out-of-plane displacement is of good fidelity, giving the system calibration factor of 6.01 x 10^7 V/m for channel #8. The use of a low-noise preamplifier allowed us to measure the out-of-plane displacement of 0.5-1 pm.
3. Signal Processing

For AE source location, the wave propagation medium is assumed to be a homogeneous epoxy matrix. Three-dimensional source location is performed by using the first arrival times of the P-wave to the seven-channels (#1 to #7), according to the method given by Mogi (1968). The fracture mode was determined by the analysis of radiation pattern of the P-wave (Aki and Richard, 1980). For Mode-I cracking, the polarity of P-waves at all the sensors should be the same, while the polarity of P-wave at some sensors should be opposite for Mode-II cracking. Moment tensor analysis (Ohtsu, 1987) was not attempted here because of difficulty in the calibration of sensors after installation.

Once the location of an AE signal is determined, we can calculate the out-of-plane displacement using equation (1) for a given source function, $\mathbf{A}_b(t)$, together with experimentally determined $R(t)$ and $\alpha$. The calculated displacement was matched to the detected displacement through many iterations by varying $\mathbf{A}_b(t)$, the magnitude of which is assumed to increase with time in the form of the fourth-power sine function (Ohtsu, 1982, 1988; Ohtsu and Ono, 1984a, 1986). The variables are $\mathbf{A}$, the rise time and the relative magnitude of $\mathbf{b}_1$, $\mathbf{b}_2$ and $\mathbf{b}_3$. The present calculation of displacement only considers the P-wave segment. Although the attenuation and relaxation function for S-waves are expected to be different, these cannot be determined at present due to experimental difficulty, and are ignored.

4. Wave Attenuation and Dispersion in Epoxy Matrix

Figure 5 shows the measured 1-h off-epicentral ($h$ = thickness of plate) displacement due to a point step-wise unloading on an epoxy plate and the corresponding computed displacement assuming the epoxy as an elastic medium ($E = 2.4$ GPa, $G = 0.9$ GPa, $\rho = 1.13$ Mg/m$^3$, $v_p = 2410$ m/s, $v_s = 1160$ m/s). Severe wave attenuation and rise-time retardation of the measured P-wave (and S-wave) are apparent. To simulate this viscoelastic behavior via the use of equation (1), we need to measure the attenuation coefficient and to deduce the relaxation function from the velocity dispersion (Suzuki et al., 1993). We previously used an immersion multiple-reflection method to measure wave attenuation. However, we could not obtain a reflection due to a strong wave attenuation. Therefore, we used a system of a focused pulse-laser transmitter and a point PZT receiver, as shown in Fig. 6. The surface of an epoxy sample was coated with carbon and was irradiated with a beam from a Q-switched Nd-YAG laser with a half-value duration of 5 ns and a beam diameter of 0.45 mm. Transmitted wave due to the thermoelectrically generated short ultrasonic pulse was detected by a broad-band (20 MHz) small PZT sensor of 0.7 mm diameter (model 20C1N, Teitsu Denshi) at the epicenter. In this system, the condition of plane harmonic waves is satisfied, and the wave attenuation is obtained by following Pouet and Rasolofosaon (1993).

Let the power spectrum of the first P-wave ($P_1$) and the reflected PPP-wave ($P_3$) be $P_1(f)$ and $P_3(f)$, respectively. These are given by equations (2) and (3):
Fig. 7 Procedure for estimating the attenuation and dispersion of the P-wave for the epoxy resin used. (a) Detected waveform, (b) the signal after arrival time adjustment and filtering, (c) the extracted P₁ waveform, (d) the power spectrum of P₁ waveform, (e) the extracted P₃ waveform, (f) the power spectrum of P₃ waveform, (g) measured attenuation in the epoxy resin, (h) measured phase velocity in the epoxy resin.

\[ P₁(f) = P₀(f) h^{-1} \exp(-\alpha(f)h) \times \exp[i(\omega t - 2\pi fh/v(f) + \phi_o)] \]  
\[ P₃(f) = Pₙ(f) (3h)^{-1} \exp(-3\alpha(f)h) \times \exp[i(\omega t - 6\pi fh/v(f) + \phi_o + \Delta\phi)] \]

where \( h \) is the thickness of the specimen, \( \alpha(f) \) and \( v(f) \) are the frequency dependent attenuation coefficient and phase velocity, respectively. \( \Delta\phi \) is the difference of phase angles of the \( P₁ \) and \( P₃ \) waves, and corrected by an arrival time adjustment of the first P-wave utilizing the Q-switching signal from a laser generator. The wave attenuation is then given by equation (4), taking the ratio of power spectra of the truncated \( P₁ \) and \( P₃ \) waves;

\[ \alpha(f) = (2h)^{-1} (\ln |P₁(f)/P₃(f)| - \ln 3) \]

Figure 7(a) and (b) show the detected and processed waveforms after the noise reduction by a non-linear epsilon filtering and fourth-order Chebyshev high pass digital filtering (Arakawa et al., 1983). The \( P₁ \) and \( P₃ \) waves were then
extracted by a cosine-taper windowing (Fig. 7(c) and (e)) and subjected to the fast Fourier transform to obtain their power spectra as shown in Fig. 7(d) and (f). Wave attenuation of the P-wave given in Fig. 7(g) showed a complicated behavior at frequencies below 1 MHz. The frequency independent attenuation coefficient, \( \alpha \), was taken as 0.75 \times 10^{-2} \text{ Np/m}, which is the median value of \( \alpha \) in the frequency range of 1 to 2.5 MHz. Phase velocity dispersion is obtained by taking the ratio of imaginary parts \( P_i(f) \) and \( P_s(f) \), per equation (5):

\[
\nu_p(f) = \frac{4\pi f \eta}{\text{Im}(P_i(f)/P_s(f)) + \Delta \phi}
\]

The P-wave velocity, shown in Fig. 7(h), increases from 2410 m/s (this velocity was used for the simulation with the elastodynamic Green's function) to 2500 m/s at 5 MHz with increasing frequency. An approximate S-wave velocity of 1160 m/s was determined utilizing a shear wave transmitter and a receiver (model 2Z10, Teitsu Denshi) by the phase spectrum method of Sachse and Pao (1978). Attenuation of the S-wave is assumed to be the same as that of the P-wave. This assumption inevitably results in some discrepancies between the detected and calculated displacements beyond the initial P-wave segment.

The relaxation function \( R(t) \) is constructed by curve fitting of the experimental velocity dispersion of the P-wave to the analytical velocity dispersion for the Kelvin-Voigt viscoelastic model. According to Weaver et al. (1989a), the velocity dispersion is expressed by equations (6) and (7):

\[
\nu_p(\omega) = \left| \text{Re}\{1/C_p(\omega)\} \right|^{-1}
\]

\[
C_p(\omega) = C_p(0) \sqrt{1 - \frac{4\alpha\varepsilon C_s^2(0)}{3C_p^2(0)(1 + i\alpha\varepsilon + \varepsilon)}}
\]

where \( C_p(\omega) \) is the frequency dependent complex P-wave velocity, \( C_p(0) \) is the S-wave velocity at \( \omega = 2\pi f = 0. \varepsilon \) and \( \tau \) represent the relaxation strength and relaxation time. The relaxation function \( R(t) \) is given by equation (8) (Weaver et al., 1989a):

\[
R(t) = \begin{cases} 
\varepsilon_0 \left(1 - \exp\left(-\frac{t}{\tau}\right)\right) & \text{for } 0 \leq t \leq -\tau \ln\left(1 - \frac{1}{\varepsilon_0}\right) \\
\varepsilon_0 \exp\left[\ln\left(\frac{1}{\varepsilon_0 - 1}\right) - \frac{1}{\tau}\right] & \text{for } -\tau \ln\left(1 - \frac{1}{\varepsilon_0}\right) < t
\end{cases}
\]

where \( \varepsilon_0 = 1 / \exp(1 + \ln \varepsilon) \).

Figure 8 shows the dimensionless relaxation function obtained by curve-fitting for the epoxy used here. \( C_p(0) \) and \( C_s(0) \) are taken to be 2410 and 1160 m/s, respectively. We found the relaxation strength \( \varepsilon = 0.28 \) and relaxation time \( \tau = 0.16 \mu s \). These compare to the values of \( \varepsilon = 0.2 \) and \( \tau = 0.17 \mu s \) adapted for a model of epoxy resin (Weaver et al., 1989a). Experimentally, we obtained \( \varepsilon = 0.23 \) and \( \tau = 0.15 \mu s \) for PMMA (Suzuki et al., 1993). We note here that despite the similarity of \( \varepsilon \) and \( \tau \) values in the epoxy and PMMA, we were unable to use a more conventional ultrasonic technique used for the PMMA (Suzuki et al., 1993) in measuring the relaxation function for epoxy. The reason for these is still unknown.

Figure 9 compares the detected waveform and out-of-plane displacement waveform computed by using the above procedure at 1-h off-epicenter due to a point step-wise unloading. (transmission medium: epoxy)

PMMA, we were unable to use a more conventional ultrasonic technique used for the PMMA (Suzuki et al., 1993) in measuring the relaxation function for epoxy. The reason for these is still unknown.

Figure 9 compares the detected waveform and out-of-plane displacement waveform computed by using the above procedure at 1-h off-epicenter due to a step-wise unloading. A good agreement between the computed and detected displacement for the first P-wave demonstrates the validity of equation (1) in calculating the surface displacement of the P-wave. Since the critical angle of the incident S-wave in epoxy is 28.7°, we observe SP- and S-waves at the l-h off-epicenter position (or at the incident angle of 45°). Detected arrival time of the SP-wave coincided with the calculated arrival time. This may indicate that the velocity dispersion of the S-wave is relatively small. The detected amplitude was smaller than the simulated one, although the exact cause is unclear at present.
5. Results and Discussion

5.1 Model A Composite

The tensile stress-strain curve of a Model A composite specimen is shown in Fig. 10. This Model A composite specimen emitted the first AE signal at 21 MPa and suffered the final fracture at 32 MPa and 3.7%. Though 330 AE events were detected during the test, source location was possible only for 273 events. Triangles next to the stress-strain curve show the timing of AE signals detected by the displacement-sensitive monitoring system (channel #8). Three sizes of the triangles designate the number of detected AE signals. The small size represents one AE signal, the middle size 5 signals, and the largest size 10 signals. Filled triangles indicate the timing of AE signals due to Mode-I fiber fracture, as identified by the phases of initial P-waves. As indicated by many filled triangles, most AE signals were produced by the fiber fracture. Open triangles indicate AE signals whose source mechanisms remain unidentified.

Figure 11 shows the distribution of source locations in three different projections. Each point in the figure are the source location for the 273 events. Final fracture occurred at the position indicated by the slashed lines in the X-Y and X-Z planes. Three small rectangles in the Y-Z plane indicate approximate positions and sizes of the three fiber bundles. Most source locations are close to the fiber bundles. A relatively large scattering of source location in the Z-direction in the X-Z and Y-Z planes is due to the fact that the thickness is small and only three sensors, two sensors (#2 and #5 in Fig. 2) on the upper surface and only one (#1) on the lower surface, are used. Very weak P-waves detected at some sensors, as will be discussed later, also contribute to the observed scattering of source location.

Three representative AE waveforms (No. 1 to No. 3) are shown in Fig. 12. These three signals were detected at 25 to 27 MPa (cf. Fig. 10). The waveform No. 1 was located near the epicenter while Nos. 2 and 3 were near 1-h and 2-h off-epicenter, respectively (see Fig. 11). Source locations of these three waveforms were at the central fiber bundle. These waveforms are consistent with the fracture mode being Mode-I fiber fracture.

In Fig. 12, the waveforms for Nos. 1, 2 and 3 are compared with the simulated displacements, computed with the assumption of Mode-I fiber fracture at the observed location. Source location and propagation distance are shown at the bottom of the detected waveform (the upper row). The source parameters were determined by iteration so that both the first-peak rise time and amplitude, $\Delta T_p$ and $\Delta u_p$, of the P-wave of the computed displacement best represent corresponding values of the detected displacement. The latter values are shown with the detected displacement (the upper row) while the input parameters are given at the bottom. Computation for the Mode-I cracking set both the crack plane normal $n$ and discontinuity vector $b$ along the X-axis; i.e., $n_1 = 1$, $n_2 = n_3 = 0$ and $b_1 = 1b$, $b_2 = b_3 = 0$. The results show short source rise times $\Delta T_p$ of 0.3 to 0.5 µs and small crack volumes $Ab_1$ of 1.4 to 3.4 x 10^{-16} m$^3$. For a 10 µm diameter glass fiber, these correspond to an axial crack opening displacement of 1.8 to 4.3 µm. These values are consistent with the cleavage fracture of fine glass fibers as the source mechanism for the observed AE events.

The detected signals show P-wave as well as SP- and S-waves. The arrival times of the SP- and S-waves can be correlated well with those in the computed displacement waveforms. Amplitude differences for the SP and S-waves are probably due to the use of the attenuation coefficient for

![Fig. 10 The stress-strain curve and AE timing during the tensile test of a Model A composite specimen.](image-url)
Fig. 11 AE source location for the Model A composite test (cf. Fig. 10).

Fig. 12 Comparison of detected and simulated waves for Mode-1 fiber fracture in Model A composite.
Fig. 13 Comparison of (a) detected waveform and (b) displacements computed due to two-step fiber fractures. (c) shows the source function.

Fig. 14 Comparison of waveform and displacement for fiber fracture at a localized source location in an outer fiber bundle.
the P-wave as well as the lack of low-frequency sensitivities. The relative peak amplitudes of waveform No. 1 agree well with those of the simulated displacement. In the case of waveform No. 2, the S-wave amplitude is only about one-half of the simulated peak (marked S). The P-and SP-peaks of waveform No. 3 are in reasonable agreement. However, the observed waveform and peak amplitude beyond 8 μs hardly resemble the simulated result. In waveform No. 3 (Fig. 12), discrepancies are more than the matter of amplitude. These discrepancies appear to be due to a succession of fiber fractures. In order to examine this hypothesis, we attempted to calculate the out-of-plane displacement for 2-step fiber fractures. Figure 13(a) is the waveform No. 3 (Fig. 12). Figure 13(b) shows the displacement for the 2-step fiber fractures at the same source location while Fig. 13(c) shows the displacement at the source with the second fiber fracture occurring 3.8 μs after the first fiber fracture. Agreement between the detected and simulated displacement is significantly improved by this process. The large negative amplitude at 9 μs (marked 2P) is caused by the P-wave of the second fracture. The position of IS and 2SP peaks are shifted, but correct polarities are predicted by the simulation. We can thus explain some of the complicate waveforms by multiple-step simulation.

The discussion so far has been limited to the waveforms, whose source locations are in the central fiber bundle. However, we observed many waveforms whose source locations are in the outer fiber bundles. Three waveforms with the source locations in one of the outer fiber bundles (approximate source coordinate; x = 13.2 to 14.1 mm, y = -8.7 to -9.7 mm) are compared with the simulated displacements in Fig. 14. We observed 7 signals from this limited area within 60 seconds at stress of around 27 MPa. Three waveforms shown (A, B and C) were randomly selected and compared with the displacement computed with the Mode-I cracking model. In these instances, the source coordinates were beyond the critical angle of the S-wave as in the cases of waveforms Nos. 1 to 3 (Fig. 12). Displacements from the P-, SP- and S-waves are also evident. However, the detected waveforms contain several small peaks following the first P-wave arrival, and these disagree with the displacement computed for a single Mode-I cracking.

A possible reason for this disagreement is successive fiber fractures, i.e., two or three fibers fracture within a short time at nearly the same location. Therefore, the displacement was calculated assuming a two-step process of fiber fracture. Figure 15 compares the detected waveforms
with the displacement simulated for a 2-step process of Mode-I fiber fracture. Source waveforms assumed for this computation are shown in the bottom row. The second crack is assumed to occur after a varying period of 4.3 to 5.0 μs as shown in each figure. Agreement between the upper and middle rows is significantly improved by using this assumption. Almost all negative and positive peaks have corresponding ones in the computed displacements. For instance, the second large negative amplitude of waveform A, denoted by 2P in the figure, corresponds to the P-wave generated by the second fiber fracture 4.7 μs after the first fiber fracture. It can be seen that the various peaks correspond to the SP- and S-waves from first and second fiber fracture. In spite of the improvement, some unidentified peaks are still observed. These appear to be due to the waves reflected and distorted by another fibers in the bundle. Nevertheless, the developed system enables us to examine the dynamics of successive fiber fracture in GFRP.

5.2 Model B Composite

The tensile stress-strain curve of a Model B composite samples is shown in Fig. 16. This composite sample fractured at 35 MPa and 3.6%. We observed various types of AE waveforms from this specimen. A total of 123 events were recorded in this test. Of these, the source location of 64 events could be identified. From the polarity analysis, furthermore, three waveforms were found to be Mode-I while four waveforms Mode-II. Filled triangles are AE signals identified by the polarity analysis to be produced by the Mode-I events and half-filled triangles are by the Mode-II events. There are a number of waveforms, whose source locations are in the matrix but whose fracture mode cannot be positively identified. These waveforms are shown by open triangles, and referred to as a matrix crack. The large size triangle designates 5 events, and small one 1 event each.

As the Mode-I fiber fracture is not expected to occur in this specimen, two types of fiber/matrix interface debonding are possible; (1) Mode-I cracking along the near-vertical fiber/matrix interface (called as Mode-I debonding) and (2) Mode-II cracking along the near-horizontal fiber/matrix interface (Mode-II debonding). Figure 17 shows the distribution of source locations. Final fracture occurred along the right fiber bundle at x = 10 mm. Most AE waveforms such as Nos. 3, 4 and 5 are outside the fiber bundle, while waveforms of Nos. 1 and 2 are inside the bundle. Most of the located signals were in the matrix, while only a small fraction originated within or in the vicinity of the fiber bundles. Figure 18 shows three representative waveforms detected and corresponding displacements due to simulation. Waveform No. 1 (Fig. 18, left) has a rise time of 0.85 μs and the initial displacement step due to the P-wave of Δu_p = 1 x 10^{-12} m. This resembles the displacement computed according to the Mode-II debonding with a source rise time of 0.8 μs and a crack volume of 1.22 x 10^{-16} m^3. Here, the polarity of the P-wave is positive for Mode-II debonding. Waveform No. 2 (Fig. 18, center) exhibits a shorter rise time of 0.35 μs and the negative polarity, indicative of the Mode-I debonding. This waveform has the main features similar to the simulated waveform with a source rise time of 0.2 μs and a volume of 1.4 x 10^{-16} m^3. An interesting finding is that the source rise time for Mode-I debonding is shorter than that for Mode-I fiber fracture observed in Model A samples.

A typical signal originated in the matrix is shown in Fig. 18 (right). This is characterized by double negative peaks with a rise time of 0.55 μs and a displacement step of
3.79 x 10^{-12} \text{m}. The lower figure is the simulated waveform due to a sudden point dilatation, showing a single negative peak. Thus, it is concluded that the observed double peaks correspond to a two-step dilatation. Figure 19 shows the simulation of the two-step dilatation with the second step occurring 1.5 \mu s after the conclusion of the first step. It is interesting to note that the amplitude of the second peak (2P) is only about one-half even though the crack volumes of the two steps are close to each other. This is due to the slower source rise time (2.0 \mu s vs. 1.1 \mu s).

The source mechanism of a matrix crack waveform (No. 3 in Fig. 18) is apparently unrelated to fibers. These waveforms are probably generated by a sudden void forma-
Fig. 19 Comparison of waveform of matrix crack with displacement simulated for a two-step dilatation.

\[ \begin{align*}
\text{1st fracture} & \quad \Delta T_r = 1.10 \mu \text{s} \\
& \quad \text{Void volume} \Delta V = 8.6 \times 10^6 \text{ m} \\
\text{2nd fracture} & \quad \Delta T_r = 2.00 \mu \text{s} \\
& \quad \text{Void volume} \Delta V = 8.3 \times 10^6 \text{ m}
\end{align*} \]

Fig. 20 Comparison of the waveforms and out-of-plane displacement at channels #1 to #7 for Mode-II and Mode-I disbonding.

47
tion, giving rise to a point of dilatation. Indeed, we observed various voids on the fracture surface. Generation of voids in a polymer sample tested in tension has been demonstrated by the work of a small angle X-ray scattering method (see e.g. Takashi, 1982). When we assume that the void is produced by a point of dilation (an explosive source), we should detect only an impulse P-wave without any contribution of the S-wave as detected in the present case. Estimated diameter (5 to 6 μm) of the spherical void agrees with those observed on the fracture surface.

The fracture modes of waveform No. 1 and 2 (Fig. 18) were further examined via the analysis of radiation pattern of the P-waves detected by the 7 channels. Figure 20 compares the seven observed waveforms and corresponding simulated displacements. Since these seven channels use narrow-band sensors, these waveform pairs have no direct correspondence. However, the polarity of the first P-wave peak should be identical. For waveform No. 1 (Mode-II disbonding), the polarity of P-wave for signal #2, 6 and 7 should be positive, while others should be negative. The polarities of the signals indeed reflect this prediction with the exception of channel #2 due to the poor signal-to-noise ratio. Overall, the fracture mode can be deduced as Mode-II. In contrast, the polarity should be the same for all sensors for Mode-I disbonding, and the polarity of all the signals of waveform No. 2 is negative. This indicates that waveform No. 2 originates from Mode-I disbonding.

5.3 Source Parameters for Model A and B Specimens

Figure 21 shows a cross-plot of two source parameters for fiber fracture in a Model A composite sample. The source rise time for fiber fracture is in the range of 0.17 to 0.5 μs, and the crack volume or Ab is 0.7 to 5 x 10^{-16} m^3. Assuming the AE is produced by the fracture of a single fiber of 10 μm diameter, crack opening displacement b1 becomes 1.0 to 6.4 μm. This discontinuity corresponds to 1/8 to 1/2 of the fiber diameter, and suggests that fiber pull out does not occur in Model A composites. Indeed, we did not observe any AE signals by Mode-II fiber pull-out. Slope of b1 vs. ΔT, gives the crack velocity on the fracture surface, and it reaches the maximum of 22 m/s. As the source function is approximated by a sinusoidal ramp function, peak crack velocities reach about 2.5 times that given in Fig. 21. This figure also shows that the crack volume of 0.7 x 10^{-16} m^3 is the apparent detection limit of our experimental setup. This limit arises from the presence of background noise.

Shown in Fig. 22 is a similar plot for the source parameters for Mode-I and Mode-II disbonding in a Model B composite sample. The numbers of data points are limited, but the plot indicates generally smaller crack volumes. For Mode II signals, the source rise times ranged from 0.5 to 1 μs, which are larger than those of Mode-I cracks in either Model A or B samples. The rise time of Mode I disbonding in Model B is almost identical to those of Mode-I fiber fracture in Model A.

6. Conclusion

The fracture modes and dynamics in model glass fiber/epoxy composites were examined using a new eight-channel AE monitoring system with the signal processing algorithm that takes into account the location of AE source. The results obtained are summarized below:

1. Adoption of a focused Q-switched YAG laser source and a broadband point PZT sensor allowed us to measure wave attenuation and dispersion in the dissipative epoxy matrix.

2. Multichannel AE monitoring system with seven channels for source location and one channel for displacement.
measurement provided information to obtain the AE source wave characteristics using a new signal processing algorithm we have developed. A computer algorithm to calculate the surface displacement of elastic wave (P-wave) emitted by the microfracture in a dissipative composite is proposed. A simplified calculation algorithm including the wave attenuation and the relaxation function was demonstrated to be applicable for obtaining the AE source wave in a viscoelastic medium.

3. The developed system identified clearly the fracture mode and dynamics in a model fiber-reinforced composites. For the specimens with glass-fiber bundles parallel to the loading direction, most AE waveforms were produced by the Mode-I fiber fracture with source rise time of 0.17 to 0.5 μs. Iterated computation of the out-of-plane displacement matched the amplitude and rise time of the first P-wave arrival with the calculated displacement waveform. Results also revealed a possibility of successive fiber fractures. The second fiber fracture appears to occur 4 to 5 μs after the completion of the first fiber fracture.

4. For the model composite specimens with fiber bundles perpendicular to the loading, most waveforms were produced by the matrix cracks resulting in a point of dilatation. Some signals were due to Mode-I disbonding at the fiber/matrix interface. Mode-II disbonding at the fiber top or bottom was also detected, and found to generate signals with rise time slower than the Mode-I fiber/matrix disbonding.

Acknowledgment

We acknowledge the assistance of two undergraduate students, Messrs. K. Obara and M. Ohara. The authors are also grateful to Asahi Glass Fiber Co. Ltd. for providing glass fibers and to Teitsu Densi Co. for a special PZT sensor. This work was partially supported by a grant from the Research Institute of Aoyama Gakuin University.

References


Conferences and Symposia

22nd European Conference on Acoustic Emission Testing, incorporating EWGAE, 29-31 May 1996, Robert Gordon University, Aberdeen, UK

Keynote Speakers
Martine Wevers, Belgium
Phil Cole, UK
Emilio Fontana, Italy, Proof Testing
Len Rogers, UK, Monitoring
Peter Tscheliesnig, Austria, Leak Detection
Emilio Fontana, Italy, Standards

U. Peil, Germany; Damage Detection on structural steel ST52 in Low-Cycle fatigue with Acoustic Emission

Stuart McBride, Canada; Acoustic Emission Monitoring of Plastic Deformation and Fatigue Crack Propagation in an Aluminum which Exhibits Localized Yielding

Stuart McBride, Canada; Relation Between Acoustic Emission Amplitude and Source Energy for Crack Growth in Aluminum Alloys and Steels

Kenichi Yoshida, Japan; Acoustic Emission and Discontinuous Yield Behaviors in Al-Li-Cu-Mg-Zr Alloy

Alexander Wanner, Germany
Acoustic Emission Monitoring of Deformation Induced Microcracking in Semi-Brittle Intermetallic Alloys

Josef Sikula, Czech Republic
Electromagnetic and Acoustic Emission from Solids

Fergal Murphy, Ireland
Crack Life Prediction based on AE Measurements

Ali Siddiqui, Scotland
The study of Stress Corrosion using Acoustic Emission

Marnix Surgeon, Belgium
Damage characterisation during tensile testing of glass-ceramic matrix composites using acoustic emission

Jurgen Bohse, Germany; Acoustic Emission Characteristics of Damage Mechanism in Reinforced Thermoplastics

Hans Strauven, Belgium; Acoustic Emission for the follow-up of creep in cellular glass

Stuart McBride, Canada; Thermally Induced Acoustic Emission from Impact Damage in Graphite Epoxy Composites

Richard Nordstrom, Switzerland; Comparison of AE from Glass Fiber Breaks in Bundles and in SFFT

Werner Haselbach, Germany; Characterisation of Polymers in Materials Science Supported by Frequency Analysis

Thomas Lokajicek, Czech Republic; Influence of Rock Grain Size on Energy of Acoustic Emission

Bogdan Zogala, Poland
Acoustic Emission and Acoustic Velocity in Mudstone and Sandstone Samples Cyclicly heated to 180°C

Bernd Weiler, Germany; Acoustic Emission due to Active Under-Insulation Corrosion - A Case History

Gunther Bartholome, Germany
Application of AE to Nuclear Piping Reliability

Mohammed Cherfaoui, France
Application of AE in Pressure Vessels

Jean Charles Anifrani, France; Rupture Pressure Prediction for Composite High Pressure Tanks using Acoustic Emission

Eddie O'Brien, UK; Developments in remote crack detection and monitoring by AE for Aircraft applications

Stuart McBride, Canada
Acoustic Emission Monitoring of Full-Scale Fatigue Tests on Canadian Forces Aerospace Structures

C.W. Roland and S. Church, UK
Proof Testing of Composite Aerospace Components

Trevor Holroyd, UK
Simplifying the Routine Application of AE in Industry

Volker Hanel, Germany; Acoustic Emission Testing of Bolted Connections under Tensile Stress

Jiri Liska, Czech Republic; Acoustic Emission Leak Monitoring System for Industrial Application

C.A. Husain, UK; Quantification of Through-Valve Gas Losses using Acoustic Emission - Field Experience in Refineries and Offshore Platforms

Vaclav Svoboda, Czech Republic; Application of Acoustic Emission on High Pressure Piping Systems during Static and Cyclic Loading
Joachim Sell, Germany; AE Confirmation of Crack growth during hydrofatigue and burst test of an AS Booster model.

Phil Cole, UK; Acoustic Emission due to Active Under-Insulation Corrosion - A Case History

Gunnar Brueggemann, Germany
Analysis of Acoustic Emission data for on-line Quality Assurance in Laser Welding of Mild Steels

Claudia Caneva, Italy; Thermal Stability Assessment of AE on Ceramic Thin Film

Michael Meding, Germany
Prediction of structural composition and sawability of stone using acoustic emission signatures during scoring

Sotirios J. Vahaviolos, USA; 1st Generation AE Digital Signal Processing (DSP) Multichannel Systems

Hartmut Vallen, Germany,
Software Filters in AE Technology

Horst Kuhnicke, Germany
Inverse Methods for Determination of Orientation and Size of Cracks for multi-channel AE-Signatures

Marco Tatti, Italy
Comparison of AE Measurements during Tensile Tests carried out with Fibre Optics and Conventional PZT Sensors

Michael Gorman, USA
Modal Acoustic Emission Test Instrumentation for Composite Plates

Thomas Benziger, Germany
Laser-induced Acoustic Emission - First Results and Restrictions to the Application

Sotirios Vahaviolos, USA
Sensitivity and Noise Models for AE Sensors

Bernd Weiler, Germany
Calibration of Acoustic Emission Transducers - A Comparative Study of Different Methods

Sotirios J. Vahaviolos, USA
AE Sensor comparisons using the NIST Primary Calibration Method (ASTM E 1106)

Carlo Santulli, Italy
Analysis of Manufacturing Problems related with Metal-Metal Aerospace Structural Joints through Acoustic Emission and Differential Scanning Calorimetry

Cover Photograph

The first AE inspection service for a commercial pressure vessel was conducted at Exxon Refinery, Baytown, Texas in 1968. The service was provided by Aerojet Corp., Sacramento, CA under the direction of Dick Steele. The instrumentation was housed in a truck behind a large crane at left. The vessel developed a large crack accompanied by a strong audible sound during stress relief operation. The crack was weld-repaired and stress-relieved, but Reggie Cross of Exxon decided to call for AE testing. For the generation of reference signals, the Aerojet team placed a cracked steel beam inside the top nozzle and stressed it by a hydraulic cylinder. Allen Green, who participated in this testing, provided the photo and information.

1996 SUBSCRIPTION RATE for Volume 14

Base rate for one year (four issues, Mar. - Dec.) $ 96.00
Add Postage of U.S. - Book rate $ 8.00
All others - Book rate $ 11.00
Western Europe/S. America - Air mail rate $ 25.00
All others - Air mail rate $ 30.00
Add $5 without payment upon order. Payment must be in U.S. dollars drawn on a U.S. bank. Bank transfer accepted, but with $10 surcharge to the A.E. Group account (Account No. 080-03416470) at Sumitomo Bank of California
San Fernando Valley Office
15250 Ventura Blvd, Sherman Oaks, CA 91403-3262
Notify us of such a transfer as the bank cannot sometimes give us the name of the payer. One volume of four issues per year. Index included in the Oct.-Dec. issue. Back issues available at $50 per volume for Vols. 1-3, $90 per volume for Vols. 4-8, $96 per volume for Vols. 9-14. US surface postages $8 per volume. For Canada and overseas surface delivery, add $11 and for air mail, add $30 per volume (will be adjusted for multi-volume order).

All orders should be sent to (or Fax 1-818-368-8309)
Acoustic Emission Group
308 Westwood Blvd., Box 364
Los Angeles, CA 90024-1647 USA

For inquiry through Internet, use the following address:
ono@seas.ucla.edu

Editor-Publisher  Kanji Ono  Tel. (310) 825-5233
Cover Design  Robin Weisz (UCLA Publications)
Production  Pace Publications Arts

Publication Date of This Issue: 14 August 1996.
Notes for Contributors

1. General

The Journal will publish contributions from all parts of the world and manuscripts for publication should be submitted to the Editor. Send to:

Professor Kanji Ono, Editor - JAE
6531 Boelter Hall, MSE Dept.
University of California
Los Angeles, California 90095-1595 USA
FAX (1) 818-368-8309
e-mail: ono@seas.ucla.edu

Authors of any AE related publications are encouraged to send a copy for inclusion in the AE Literature section to:

Mr. T.F. Drouillard, Associate Editor - JAE
11791 Spruce Canyon Circle
Golden, Colorado 80403 USA

All the manuscripts will be reviewed upon submission to the Editor. Only papers not previously published will be accepted. Authors must agree to transfer the copyright to the Journal and not to publish elsewhere, the same paper submitted to and accepted by the Journal.

A paper is acceptable if it is a revision of a governmental or organizational report, or if it is based on a paper published with limited distribution.

An abstract of about 200 words is needed for Research and Applications articles, while it should be shorter than 100 words for other articles.

The language of the Journal is English. All papers should be written concisely and clearly.

2. Page Charges

No page charge is levied. Fifty copies of off-prints will be supplied to the authors free of charge.

3. Manuscript for Review

Manuscripts for review need only to be typed legibly; preferably, double-spaced on only one side of the page with wide margins and submitted in duplicate.

The title should be brief. Except for short communications, descriptive heading should be used to divide the paper into its component parts. Use the International System of Units (SI).

References to published literature should be quoted in the text citing authors and the year of publication. These are to be grouped together at the end of the paper in alphabetical and chronological order. Journal references should be arranged as below. Titles for journal or book articles are helpful for readers, but may be omitted.


Abbreviations of journal titles should follow those used in the ASM Metals Abstracts. In every case, authors' initials, appropriate volume and page numbers should be included. The title of the cited journal reference is optional.

Illustrations and tables should be planned to fit a single column width (87 mm or 3.3") or a double width (178 mm or 7"). For the reviewing processes, these need not be of high quality, but submit glossy prints or equivalent with the final manuscript. Lines and letters should be legible.

4. Review

All manuscripts will be judged by qualified reviewer(s). Each paper is reviewed by one of the editors and may be sent for review by members of the Editorial Board. The Board member may seek another independent review. In case of disputes, the author may request other reviewers.

5. Electronic Media

In order to minimize typographical error, the authors are encouraged to submit a floppy disk copy of the text. We can read Macintosh and IBM PC formats. Those who can connect to INTERNET can send the text portion to "ono@seas.ucla.edu". This will greatly shorten the time of communication.

6. Color Photograph

We can print color photographs needed to enhance the technical content of an article. Because of the cost, the author is asked to pay $350 per page.
Contents

Page 1-34
A History of Acoustic Emission  Thomas F. Drouillard

Page 35-50
The Fracture Dynamics in a Dissipative Glass-Fiber/ Epoxy Model Composite with AE Source Simulation Analysis
Hiroaki Suzuki, Mikio Takemoto and Kanji Ono

Conferences and Symposia

Page 51-52
22nd European Conference on AE

Page 52
Cover Photograph
Wavelet Transform of Acoustic Emission Signals at Aoyama Gakuin
1. Aims and Scope of the Journal

Journal of Acoustic Emission is an international journal designed to be of broad interest and use to both researcher and practitioner of acoustic emission. It will publish original contributions of all aspects of research and significant engineering advances in the sciences and applications of acoustic emission. The journal will also publish reviews, the abstracts of papers presented at meetings, technical notes, communications and summaries of reports. Current news of interest to the acoustic emission communities, announcements of future conferences and working group meetings and new products will also be included.

Journal of Acoustic Emission includes the following classes of subject matters;
A. Research Articles: Manuscripts should represent completed original work embodying the results of extensive investigation. These will be judged for scientific and technical merit.
B. Applications: Articles must present significant advances in the engineering applications of acoustic emission. Material will be subject to reviews for adequate description of procedures, substantial database and objective interpretation.
C. Technical Notes and Communications: These allow publications of short items of current interest, new or improved experimental techniques and procedures, discussion of published articles and relevant applications.
D. AE Literature section will collect the titles and abstracts of papers published elsewhere and those presented at meetings and conferences. Reports and programs of conferences and symposia will also be presented.

Reviews, Tutorial Articles and Special Contributions will address the subjects of general interest. Nontechnical part will cover book reviews, significant personal and technical accomplishments, current news and new products.

2. Endorsement

Acoustic Emission Working Group (AEWG), European Working Group on Acoustic Emission (EWGAE), Committee on Acoustic Emission from Reinforced Composites (CARP), and Acoustic Emission Working Group of India have endorsed the publication of Journal of Acoustic Emission.

3. Governing Body

The Editor and Associate Editors will implement the editorial policies described above. The Editorial Board will advise the editors on any major change. The Editor, Professor Kanji Ono, has the general responsibility for all the matters. Associate Editors assist the review processes as lead reviewers. Mr. T.F. Drouillard is responsible for the AE Literature section. The members of the Editorial Board are selected for their knowledge and experience on AE and will advise and assist the editors on the publication policies and other aspects. The Board presently includes the following members:

S.H. Carpenter (USA)
D.A. Dornfeld (USA)
P. Fleischmann (France)
L. Golaski (Poland)
M.A. Hamstad (USA)
H.R. Hardy, Jr. (USA)
R. Hill (UK)
I.V. Ivanov (Russia)
P. Jax (Germany)
T. Kishi (Japan)
O.Y. Kwon (Korea)
J.C. Lenain (France)
S.L. McBride (Canada)
W. Morgner (Germany)
C.R.L. Murthy (India)
H. Niitsuma (Japan)
A.A. Pollock (USA)
T.M. Proctor, Jr. (USA)
I. Roman (Israel)
C. Scala (Australia)
C. Scruby (UK)
A. Vary (USA)
E. Waschkies (Germany)
M. Wevers (Belgium)
J.W. Whittaker (USA)
B.R.A. Wood (Australia)

4. Publication

Journal of Acoustic Emission is published quarterly in March, June, September and December by Acoustic Emission Group, 308 Westwood Blvd.- Box 364, Los Angeles, CA 90024-1647. It may also be reached at 6531 Boelter Hall, University of California, Los Angeles, Los Angeles, California 90095-1595 (USA). tel. 310-825-5233. FAX 818-990-1686. e-mail: ono@seas.ucla.edu

5. Subscription

Subscription should be sent to Acoustic Emission Group. Annual rate for 1996 or 1997 is US $96.00. For surface delivery, add $8 in the U.S. and $11 for Canada and elsewhere. For air mail delivery to South America, add $18, Western Europe, add $25 and add $30 elsewhere. Overseas orders must be paid in US currencies with a check drawn on a US bank. Inquire for individual (with institutional order) and bookseller discounts.

6. Advertisement

No advertisement will be accepted, but announcements for books, training courses and future meetings on AE will be included without charge.
Modeling of Stress-Strain Response of Unidirectional and Cross-Ply SiC/CAS-II Ceramic Composites by Acousto-Ultrasonic Parameters

Anil Tiwari, Edmund G. Henneke II and Alex Vary

Abstract

This research effort was directed towards developing a near real-time acousto-ultrasonic (AU) nondestructive evaluation (NDE) tool to study failure mechanisms in ceramic composites. Real-time AU parameters were used to obtain the stress levels for the onset and saturation of matrix cracking in unidirectional and cross-ply SiC/CAS-II (silicon-carbide fiber and calcium-alumino-silicate matrix) ceramic composites during static tests. An acousto-ultrasonic stress-strain response (AUSSR) model was formulated based on real-time AU parameters and classical laminated plate theory (CLPT) to predict the stress-strain curve. The modified AUSSR model presented in this paper also takes into account the effect of fiber breakage along with the matrix cracking for unidirectional SiC/CAS-II ceramic composite. A similar model for cross-ply laminates is also presented.

1. Introduction

Recent work has verified the capability of the AU technique to assess the damage state in SiC/CAS-II ceramic composites (Tiwari et al., 1992; Grosskopf and Duke, Jr., 1991). Continuous monitoring of damage initiation and progression under quasi-static ramp loading in tension to failure of unidirectional SiC/CAS-II ceramic composite specimens was accomplished by monitoring near real time AU parameters (Tiwari and Henneke II, 1994a). Tiwari and Henneke II (1994b) have also shown that a decrease in real-time SWF values correlates well with the reduction of stiffness caused by damage progression in ceramic composites subjected to fatigue loading. Major portions of this article were presented elsewhere (Henneke II et al., 1993), and are presented here to lay the groundwork for predicting the stress-strain curve for a cross-ply SiC/CAS-II ceramic composite. The material presented here also summarizes the previous work done by the authors (Henneke II et al., 1993; Tiwari and Henneke II, 1993; Tiwari, 1993, 1995; Tiwari et al., 1995) for modeling the stress-strain curve of a unidirectional SiC/CAS-II ceramic composite using real-time AU data.

Real-time monitoring of damage progression in ceramic composites by a NDE technique has provided insight into failure mechanisms under loading. Monitoring damage accumulation in real-time under dynamic loads has been found to indicate the sequence of the occurrence of each damage mode and to help us understand and model the failure mechanisms of the material. Tiwari and Henneke II (1993) have used real-time AU parameters to model the effect of matrix cracking on the stress-strain curve of unidirectional SiC/CAS-II ceramic composite laminate. The AUSSR model has been further modified to incorporate the effects of a small number of fiber breaks occurring during matrix cracking.

2. Real-time AU

A block diagram of the experimental setup for AU is shown in Fig. 1. Ultrasonic pulses were introduced into the mechanically loaded specimen through a broadband transducer (Panametrics, model V133RM, 2.25 MHz, 6.35 mm diameter). The same type of transducer (Panametrics, V133-RM) was used as a receiver. The couplant used was Sonotrace-30. A Panametrics model 5052-AU pulser/receiver was used to generate and receive the ultrasonic signal continuously so as to monitor damage in real-time. The received signal was analyzed in the frequency domain to obtain various AU parameters (Tiwari, 1993, 1995). The zeroth moment of the received signal in the frequency domain, SWF(M0), is the primary AU parameter used. Here, SWF(M0) is the zeroth moment of the frequency spectra of the received AU signal represented by the area under the frequency spectra. It is a measure of the energy content of the received signal.

Details of the AU experimental setup and the rationale of selecting AU parameter SWF(M0) are given elsewhere.
(Tiwari and Henneke II, 1994b; Tiwari, 1993, 1995). The selected AU parameter SWF(M0) rates the efficiency with which stress is transferred between the sender and the receiver transducer in the material.

3. AUSSR Model

The acousto-ultrasonic stress-strain response (AUSSR) model was formulated (Henneke II et al., 1993; Tiwari et al., 1995) to study the failure mechanisms of unidirectional SiC/CAS-II ceramic composites. The AUSSR model is briefly described below.

The AUSSR model predicts strains on the top and bottom surface in the gage section of the laminate. These predictions are based on classical laminated plate theory (CLPT) and the changes in ply/constituent properties corresponding to the damage monitored by AU parameters during the test. The ply properties obtained from the rule of mixtures and ply orientation with respect to load axis are used to calculate the laminate stiffness ($A_{ij}$, $B_{ij}$ and $D_{ij}$). The laminate stiffness is a function of damage and varies corresponding to the changes in ply/constituent properties as the damage progresses during the test. The mid-plane strains and curvatures can be calculated for a given set of laminate stiffness ($A_{ij}$, $B_{ij}$ and $D_{ij}$) at a given stress level using CLPT equations (Tiwari, 1993, 1995; Tiwari et al., 1995). Subsequently, the strains at the outer-ply surface
The initial linear portion of the curve from prediction ($E = 136$ GPa) approximates closely the real experimental data ($E = 131$ GPa). The changes in the slopes in the non-linear zone follow the same trends up to 0.35% strain. The slope of the second linear zone of the predicted curve is $vE_f$ (fiber volume fraction times the elastic modulus of fiber = 77 GPa) and is steeper than the corresponding slope from the actual data.

The elastic moduli of the matrix material, $E_m$ and $G_m$, used in the CLPT FORTRAN code are now varied over the same stress range from 100% to 0% using the same Weibull parameters $\alpha = 15$ and $\beta = 235$ MPa. Here it is assumed that the matrix degrades in a similar fashion compared to the real-time AU parameter, i.e., SWF(M0). This assumption takes into account the effect of matrix cracking and its contribution to the observed global strains. Strains are then predicted for each increment of stress using classical laminated plate theory and the variation of matrix properties using Weibull parameters obtained from real-time AU data. The results of this calculation are shown in Fig. 3, together with the actual observed stress-strain curve.

The initial linear portion of the curve from prediction ($E = 136$ GPa) approximates closely the real experimental data ($E = 131$ GPa). The changes in the slopes in the non-linear zone follow the same trends up to 0.35% strain. The slope of the second linear zone of the predicted curve is $vE_f$ (fiber volume fraction times the elastic modulus of fiber = 77 GPa) and is steeper than the corresponding slope from the actual data.

4. Modified AUSSR Model

Results from AU have shown the occurrence of local fiber breaks together with matrix cracking prior to the saturation level of matrix cracks (i.e., matrix cracks fully developed). The AUSSR model was modified to account for the average number of fiber breaks occurring during matrix cracking with the help of acoustic emission events recorded along with real-time AU data. The effective fiber volume fraction was re-calculated and the AUSSR model predictions were modified accordingly as explained below.
Sample US was loaded in tension until the saturation of matrix cracks occurred as shown in Fig. 4. At this point, the majority of load is being borne by the fibers. The specimen was unloaded to zero load and reloaded to failure in constant displacement-rate control mode. Extensive AE generated by the fiber breaks was observed between 350 MPa (0.508 mm) and 425 MPa (0.762 mm) as shown in Fig. 5. The received AE signal is a combination of: i) the input signal which was modified due to damage/flaws present between the sender and receiver AU transducer and ii) the acoustic emission from the discrete damage events. At the onset of large scale matrix cracking, the additional AE events received cause a local increase in SWF(M0) initially at 180 MPa. Subsequently, there is also an increase in the formation of parallel matrix cracks (perpendicular to the fibers and the loading axis) reducing the energy content of the received signal at a rate faster than the increase due to additional AE events from further matrix cracks formation. The net effect of the two is an overall decrease in SWF(M0) till saturation of matrix cracks at 270 MPa.

The sharp peaks were generated from fiber breaks, assuming no other damage mode was present. The area under these local peaks was summed to obtain SWF(M0) or the energy content from the damage events; namely, fiber breaks, based on the above assumption. It was also assumed that each fiber breaks once and loses its load bearing capability. It was further assumed that each fiber break generated the same amount of AE and the breaks occurred in the same plane at a distance 'd' away from the AU receiver transducer.

The average number of fibers were calculated to be 87000 using the fiber volume fraction of 0.4 and fiber dimensions obtained from the manufacturer. The contribution to the AE energy from each fiber (M0) was calculated assuming each fiber breaks only one time. The local high peaks of SWF(M0) attributed to fiber breaks for a typical sample (refer to Fig. 4) were summed and compared to M0, to calculate the average number of fiber breaks (20000) that have occurred prior to the ultimate failure zone. The effective fiber volume fraction (\(\xi_{V_f} = 0.31\)) was calculated by assuming the broken fibers are not load bearing and hence could be assumed to behave as a matrix material filling up the volume without sharing any load.

The fiber volume fraction was then altered to reflect the change in laminate stiffness after saturation of matrix cracks in the AUSSR model. The Weibull parameters \(\alpha\) and \(\beta\) account for the effect of matrix cracking and the effective fiber volume fraction accounts for the fiber breaks. The modified AUSSR model predictions shown in Fig. 6 approximates the experimental stress-strain curve for a unidirectional SiC/CAS-II composite. The underlying assumption was that all fiber breaks, which occur during matrix cracking, occurred at a stress level corresponding to the
Fig. 7 SEM photo micrograph of an etched sample of SiC/CAS-II [0]_4 at saturation of matrix cracks showing fiber fracture pattern.

saturation of matrix cracks and hence a jump in strain value is seen at that stress level in the modified AUSSR model predictions. The effective fiber volume fractions could be altered, as and when the sharp peaks corresponding to fiber breaks are observed during static tests, and accordingly one could obtain a better modified AUSSR model. The slope of the second linear zone ($\xi y E_s = 61$ GPa) approximates the experimental data better than the previous model (Fig. 3). The start of the second linear zone in the stress-strain curve is experimentally higher than the predictions of the modified AUSSR model as the additional strain contribution from fiber breaks was not taken into consideration.

The AU results need to be corroborated by verifying the amount of fiber breaks at saturation of matrix cracks. Sample U7 ([0]_4, SiC/CAS-II) was loaded to 270 MPa to obtain the saturation of matrix cracks. The top layer of the sample was etched by hydrofluoric acid (HF 50% concentration, etching time = 30 s) to expose the broken fibers. Figure 7 shows a number of periodic fiber breaks with an average length of 100 $\mu$m. The composite at this stage can be analyzed as short fibers aligned with the load axis. Using Cox’s shear lag model (Cox, 1952) for a short fiber composite, an elastic modulus of 53 GPa ($E_c = 53$ GPa) for a composite laminate with aligned broken fibers with the length of 100 $\mu$m was obtained. The final stiffness value obtained from Cox's model closely approximates the experimental slope of 52 GPa. It has been speculated that fiber fracture occurs during matrix cracking in a unidirectional SiC/CAS-II ceramic composite. The predictions of the modified AUSSR model based on AU data along with SEM photo micrographs of the etched surface corroborates our assumption of approximately 25% fiber breaks occurring during matrix cracking.

5. AUSSR Model for Cross-ply Ceramic Composites

Real-time AU parameters were also used to monitor damage during quasi-static tests in cross-ply SiC/CAS-II ceramic composites. A model similar to the AUSSR model was used to predict the effect of matrix cracking on the stress-strain curve. Matrix cracking occurs in 90° plies prior to occurring in the 0° plies and occurs in both ply types over a range of stress levels, as indicated by real-time AU data for a cross-ply SiC/CAS-II ceramic composite. The ply properties used in the CLPT Fortran code for the AUSSR model were degraded accordingly by degrading the constituent properties of the matrix ($E_m^0, E_m^{90}; G_m^0, G_m^{90}$) for the respective plies from 100% to 0% over the respective stress ranges with the help of AU data. The degradation of elastic moduli for respective plies was done with the help of two sets of Weibull parameters; $\alpha^0 = 2.5$, $\beta^0 = 60$ MPa and $\alpha^0 = 7$, $\beta^0 = 118$ MPa. The $\beta_0$ value is half that of the Weibull location parameter $\beta = 235$ MPa used in the AUSSR model for unidirectional composites, as there are only eight 0° plies in comparison with 16 plies in the unidirectional SiC/CAS-II composite laminate. The stress ranges ($\Delta \sigma^0$ and $\Delta \sigma^9$) over which this matrix cracking takes place are obtained from the AU data. The Weibull shape parameters $\alpha^0 = 2.5$, $\beta^0 = 60$ MPa and $\alpha^0 = 7$, $\beta^0 = 118$ MPa are obtained by approximating the AU data curve over each stress range ($\Delta \sigma^0$ and $\Delta \sigma^9$) as shown in Fig. 8. The degradation of ply properties through degrading the elastic properties of the respective matrix constituent properties takes into account the effect of matrix cracking in each ply on the global strain response of the laminate.
predictions fracture of paper plies, the damage 0.4 (~), and 0.0 plies, for of the in the model. Damage mechanics of the cross-ply is ply degradation caused by break created trends a, and from the BHE model for thenno-structural 900 indebted by 900 from in the matrix cracking are similar to the pllr corresponds to the matrix or" each stress-strain for a cross-ply laminate using a numerical spread 00 ply cracks and to obtain the and also to incorporate caused % of the critical cracking p, curve. The of plies and denotes the degradation composites," J. Mech.

corrections to the 900 120 900 900 to the strength obtain date AUSSR MODEl defects spread and experimental stress composite. The location parameter, \( \alpha \), denotes the spread of the range, over which matrix cracking occurs. This parameter is a statistical processing parameter; the larger the value of \( \alpha \), the smaller is the range over which matrix cracking occurs and thus the better is the reliability of the processing technique. The spread in the matrix cracking range is caused by defects and flaws created in the processing stage producing crack initiation sites in the matrix material. This parameter could be used as a processing quality control tool for ceramic composites.

6. Summary and Conclusions

Results to date show that real-time AU is a useful NDE tool to assess and monitor damage growth in ceramic composites. The location parameter, \( \beta \), corresponds to the critical cracking stress levels calculated with the Budiansky, Hutchinson and Evans (BHE) model (Budiansky et al., 1986). The stress level corresponding to the onset of matrix cracking calculated from the Weibull parameters should be used as the design stress instead of the critical cracking stress obtained from the BHE model for thermo-structural applications.

The cross-ply AUSSR model shows a similar trend to the experimental data in the sense that both the model and the experimental data have two non-linear zones each corresponding to matrix cracking in the 90\(^{\circ}\) and 0\(^{\circ}\) plies, respectively. The two non-linear zones in the stress-strain curve have been modelled by two sets of Weibull parameters \( (\alpha_{90}, \beta_{90}, \alpha_0, \beta_0) \) for 90\(^{\circ}\) and 0\(^{\circ}\) plies, respectively. Further work needs to be done to obtain the correct value of \( \alpha_0 \) and also to incorporate the effect of additional fiber breaks in the model. Damage mechanics of the cross-ply is similar to that for the unidirectional ceramic composite apart from the initial 90\(^{\circ}\) ply degradation caused by the matrix cracks in those plies.

Acknowledgments

We are greatly indebted to the HITEMP Project Office and the Structural Integrity Branch at NASA Lewis Research Center for providing financial support for this project. Major portions of the results presented in this article was also presented at the sixth annual HITEMP-93 conference, held at NASA LeRC, Cleveland, Ohio.

References


A. Tiwari (1993), "The Development of an Interpretive Methodology for the Application of Real-Time Acousto-ultrasonic NDE Technique for Monitoring Damage in


Conferences and Symposia

39th Meeting of the AEWG and Primer

The 39th Meeting of the AEWG and Primer were held at Dana Point Hilton Inn, Dana Point, California, March 25-28, 1996. They were organized by Mr. Harold L. Dunegan of Dunegan Engineering Consultants Inc. Nearly forty participants attended the meeting. The 40th meeting was decided to be at Northwestern University. (See page 96.)

PRIMER
Introduction to AE, Alan Beattie, Sandia National Lab.
AE From Composites using Plate Wave Analysis, William Prosser, NASA Langley.
Metals and Alloys, Harold L. Dunegan, DECI.
Acousto/Ultrasonics and its Applications to Wood Products, Frank Beall, Univ. of California, Richland.
Practical applications of AE in Field Testing of Pressure Vessels and Piping, Claudio Allevato, Matrix Inspection.

TECHNICAL SESSION
Session 1
A. Advanced Acoustic Emission for On-stream Inspection, W. David Wang, Shell Westhollow Technology Center.
B. The Effects of Lamellar Structure in the Ti-Al Intermetallic Compound on its Acoustic Emission Behavior During Tensile Deformation, Kenichi Yoshida, University of Tokushima, Japan.
C. Analysis of Energy Release and New Industrial Technologies, Leonid I. Maslov, Globaltest Inc. Moscow, Russia.

Session 2

Session 3
B. Acoustic Emission from Carbon Structures, B.R. Tittmann, Penn State University.

Session 4
A. Effects of Pressure Profile Variation Upon Felicity Ratio Values and Their Correlations with Burst Strength. Karyn S. Downs, Lockheed Martin Astronautics.

Session 5: AEWG Business Meeting

Session 6
A. Acoustic Emission Analysis of Fatigue Crack Growth in 2024-T4 Aluminum, Kanji Ono, University of California, Los Angeles.
B. Estimates of Defect Severity Indices Based on Amplitude, Counts and Signal Area, S.L. McBride, Royal Military College of Canada.

Session 7
B. A Method for In-Plane AE Calibration of Structures in the Field. H.L. Dunegan, DECI

Session 8

Session 9: Commercial Presentations
A. Digital Wave Corporation.
B. Dunegan Engineering Consultants Inc.
C. Physical Acoustics Corporation.
D. Vallen Systeme Gmbh.

Session 10: OPEN FORUM
Conference Banquet Speaker: Steve Senne, Rockwell International Space Division
AE Development Program for the X-33/RLV

Meteorite and space debris pose a serious threat to spacecraft composite structures. Space Shuttle history indicates 0 to 12 km/s velocity impacts occur frequently. New composite spacecraft structures must have robust designs, or a modified Thermal Protection System to preclude impact damage. An alternative is to accept the risks.

If risks are accepted they must be minimized. If impacts can be “heard” and evaluated, decisions can be made to repair in orbit, or reconfigure reentry to avoid loss of the vehicle. The sensing system must be as light as possible, fully capable of determining the site and extent of damage and must not interfere with other vehicular electronic systems.

Rockwell International Space Systems Division at Downey, California has been developing an acoustic emission and acousto-ultrasonic system to be proven in-flight on the X-33 for further development and expanded use on the Return Launch Vehicles to replace the existing Space-Shuttle fleet. This presentation will focus on some of the problems, resolutions to date, and directions for the future.
Neural Network Approach to Acoustic Emission Source Location

Abstract

Accurate source location of acoustic emission (AE) is vital for the precise isolation of damage areas in engineering structures. A new method was developed utilizing arrival time differences, from a minimum of three sensors, to train a back-propagation network (BPN) for locating AE sources in 2-dimensions. AE source location accuracy using the BPN approach yielded a significant improvement over the traditional AE arrival time difference method, in both a continuous aluminum plate and across a bolted aluminum channel structure. The ability of the BPN in locating AE sources in discontinuous structures (across a mechanical joint), using a limited number of training points (<32) and iterations (<10,000) makes this approach a feasible source location tool.

1. Introduction

Acoustic emissions (AE) or stress waves are generated during irreversible damage either external or internal to a material. The stress waves can be monitored by sensors to yield information about source location and damage characteristics. Arrival times of the stress waves at multiple sensors located on a structure along with the sensor configuration (i.e., locations) and wave velocity can be measured to locate the AE source, utilizing the arrival time difference approach (Ying et al., 1974; Baron and Ying, 1987; Hamstad and Sendeckyj, 1993). The accurate location of AE sources using the arrival time difference method depends on the number of sensors and the accurate measurement of arrival times and wave velocity (Hamstad and Sendeckyj, 1993; Hamstad and Downs, 1995; Venkatesh and Houghton, 1993; Venkatesh, 1992; Yamaguchi et al., 1981).

A sensor array consisting of more than 3 sensors is required to locate sources in two dimensions without false (multiple) sources (Ying et al., 1974; Baron and Ying, 1987). However, using several 3-sensor array configurations (i.e., equilateral, isosceles and scalene), Venkatesh and Houghton (1993) reported false sources in both equilateral and isosceles configurations, but not in the scalene configuration. Further studies with scalene configurations have shown a significant improvement over equilateral arrays due to the lack of false source locations (Venkatesh, 1992). The feasibility of using a minimum number of sensors without ambiguous source locations reduces instrumentation costs associated with each additional sensor.

The classical AE method (arrival-time difference) of source location assumes a constant wave velocity which does not always hold true due to waveform attenuation, mode conversions and/or reflections at structural/material discontinuities (e.g., material surface, joints etc.) (Gorman, 1991; Hamstad and Sendeckyj, 1993; Yamaguchi et al., 1981). Therefore, information on the different wave velocities (e.g., longitudinal, shear, etc.) and their individual propagation characteristics across discontinuities, along with their corresponding arrival times is required for accurate source location.

Acoustic wave arrival times are typically determined by taking the first point of the waveform that crosses a fixed threshold level. However, this method of measurement does not take into account AE like noise spikes which are above the noise threshold level or the start of AE waveform below the threshold level due to signal reflection and/or attenuation; attenuation increasing with increasing source to sensor distance. In order to reduce these shortcomings a new mathematical method (without a fixed threshold) to measure arrival times involving the squaring and integrating of the signal will be introduced in this study.

Erroneous source location due to inaccurate arrival time and velocity measurements suggests a need for the development of better source location methods. Artificial neural networks (ANN) has recently emerged as a powerful modeling tool in several areas including non-destructive testing, signal processing and corrosion life prediction (Venkatesh, 1992; Sachse et al., 1991; Han et al., 1994; Silverman, 1994; Roy et al., 1995). The aim of this study is to evaluate a neural network approach for two-dimensional AE source location in continuous (aluminum plate) and discontinuous structures (bolted channel structures), using a three-sensor scalene configuration. More specifically, a back-propagation network (BPN) will be used to predict AE source loca-
2. Experimental Procedures

2.1 Experimental Setup

Experiments were carried out on a 1220 x 457 x 5 mm aluminum plate and two 610 mm long, 305 mm wide and 9 mm thick bolted aluminum channels (with and without damping material between channels), as shown in Fig. 1. Four Valpey-Fisher piezoelectric pinducers (VP-1093) were used, with one sensor located next to the AE source to trigger the signal analyzer and the other three sensors formed a triangular sensor array; sensors being mounted on the surface of the structure by coupling wax. Four Tektronix, model AM 502, amplifier units were used to amplify the acoustic signals, which were subsequently displayed and stored via two 2-channel Data Precision, Data 6000, waveform analyzers. A brittle fracture or pencil lead break utilizing a 0.3 mm diameter HB hardness lead provided an easily reproducible discrete AE source.

2.2 Arrival-Time Measurement

A mathematical method involving the squaring and integrating of AE signals was used to accurately measure the arrival times. Squaring the data made all the values positive and integrating the data made the arrival time more noticeable. For example, consider the arrival of a wave at 109 μs, shown in Fig. 2. The squared and squared-integrated results of the signal in Fig. 2 are shown in Figs. 3(a) and (b). An increase in the slope of the squared-integrated signal at the arrival point, called a step-jump (Demirdogen, 1988), is observed in Fig. 3(b), below which the noise portion of the signal forms a fairly straight line.

Referring to Fig. 4 the change in slope of the signal (i.e., step jump), β, is defined as the angle between lines connecting points $I_n - I_{n+1}$ and $I_m - I_n$, and can mathematically be written as (Demirdogen, 1988)

$$\beta = (\theta - \alpha)$$  (1)
2.3 Arrival-Time Difference Method

The classical arrival time difference method was used as a comparison to the BPN method for AE source location. For a three-sensor array, as shown in Fig. 5, there would be three arrival times \( t_1, t_2, t_3 \) and two time differences.

where \( \tan \theta = (I_{n+1} - I_n) / \Delta t = S_{n+1} \) and \( \tan \alpha = I_n / (n \Delta t) = \text{AVG}(S_n) \), \( S_n \) is the squared value of the \( n \)-th data point, \( \text{AVG}(S_n) \) is the average of the sum of squared values from \( n = 1 \) to \( n \), and \( I_n \) is the squared and integrated value of the \( n \)-th data point. Next by taking the tangent of both sides of equation (1) and substituting for \( \tan \theta \) and \( \tan \alpha \) the change in slope can be calculated by the following equation

\[
\tan \beta = \frac{S_{n+1} - \text{AVG}(S_n)}{1 + S_{n+1} \text{AVG}(S_n)}
\]

until the end of the step-jump (when \( \tan \beta < 10^{-4} \)) where the length of the step-jump = \( m-1 \). Step-jumps caused by noise spikes have been observed to be typically less than 0.33 \( \mu s \) (at data sampling rate of 18 Msamples/s), i.e. less than 6 data points, in length. Thus the criterion selected for the data reported in this study is that the arrival time is the first data point of the step-jump longer than 0.33 \( \mu s \).

3. Neural Network Modeling

The architecture of an ANN based on the human nervous system consists of several interconnected processing elements (PE) or neurons as shown in Fig. 6. A backpropagation network (BPN) is first presented with a set of known inputs and outputs called training points that are used by the network during the learning phase to calculate the activation level from each PE by

\[
o = \frac{1}{1 + e^{-w_x}}
\]

where \( o \) is the output from the neuron and \( w_x \) is the weighted sum of all the inputs. The squared error between the BPN output layer and the actual output from the training data is then minimized by the gradient descent method (Venkatesh, 1992; Han et al, 1994; Rich and Knight, 1991; Simpson, 1990). The strength of the connections (i.e., weights) are adjusted until a desired level of activation from each PE is attained. The weights in the \( n \)-th iteration are adjusted by...
of hidden layers and hidden neurons) and the number of training points and training iterations need to be adjusted to develop an accurate BPN model for source location. The number of hidden layers can be considered to control the indirect properties of the model that are not part of the input parameters. The BPN model used in this study uses two arrival time differences ($\Delta t_1 = t_1 - t_2$, $\Delta t_2 = t_2 - t_3$) as input data and the AE source location coordinates as the output data (see Fig. 6).

During training the neural network learning was gauged by observing the maximum error, which is defined as the summation of differences between the computed (during training) and actual outputs. The training is continued until a constant maximum error, implying that the network has learned the relationship between the input and output, is achieved (as shown in Fig. 7). After completing the training phase the network training performance was evaluated by calculating the linear correlation factor between the actual and computed training data, which for the cases reported in this study always exhibited a correlation greater than 0.9 (1.0 being a perfect linear correlation). Next the network source location performance was measured by the average error between the predicted and actual test points (i.e., points not used to train network). This was then used to compare the various architectures used in this study.

4. Results and Discussion

A number of network architectures, training sizes and iterations were used in developing a BPN model to locate AE sources on an aluminum plate and bolted channel structures. Results are discussed in the following sections.

The effect of training size on network performance was evaluated. On the aluminum plate, we defined a 7 x 11 AE source matrix schematically shown in Fig. 8(a), consisting of 11 rows, 76 mm apart, with each row having 7 source points separated by 76 mm. The training set consisted of 32, 56, 72 and 77 points respectively, shown in Fig. 8(b). In addition a 63 point training set was also evaluated by deleting rows 1 and 11 in Fig. 8(a).

Several architectures were evaluated including 8 architectures with a single hidden layer and hidden units ranging from 2 to 9 along with 25 architectures with 2 hidden layers and different combinations of hidden units ranging from 2 to 6. The architectures will henceforth be described numerically. For example, network 2-4-3-2 consists of 2 input units, 4 units in the first hidden layer, 3 units in the second hidden layer and 2 output units.

Several architectures were evaluated including 8 architectures with a single hidden layer and hidden units ranging from 2 to 9 along with 25 architectures with 2 hidden layers and different combinations of hidden units ranging from 2 to 6. The architectures will henceforth be described numerically. For example, network 2-4-3-2 consists of 2 input units, 4 units in the first hidden layer, 3 units in the second hidden layer and 2 output units.

The best architectures obtained for 40,000 training iterations based on the average error from 15 randomly chosen test points (i.e., points not in the training sets) on the aluminum plate, are compared in Fig. 9. Errors for architectures 2-2-2 and 2-3-2 oscillate with increasing...
Fig. 8 Schematic of (a) 7 x 11 training point matrix used on aluminum plate and (b) various sets of training points used to train BPN.

Fig. 9 Average error versus training size for the best three network architectures.

Fig. 10 Average error versus iterations.

training size whereas the 2-2-5-2 network reaches a maximum error for 56 training points and then decreases with increasing training size. The errors ranged between 70 mm to 101 mm, 85 mm to 116 mm and 91 mm to 114 mm for the 2-2-2, 2-3-2, and 2-2-5-2 architectures respectively. It is interesting to note that the best average error was obtained for the 2-2-2 network and 32 training point size, which clearly demonstrates that the simplest architecture can in fact perform better than the larger networks (2-3-3 and 2-2-5-2).

Up to this stage all the cases were trained for 40,000 iterations, although a constant maximum training error was achieved with under 10,000 iterations. Therefore, the number of iterations was reduced from 40,000 to 10,000 for the 2-2-2 and 2-2-5-2 networks, to observe the influence of iterations on average error. Reducing the training iterations to 10,000 improved network accuracy for the case of 2-2-5-2 network by 13 mm with 63 training points and by 2 mm with 77 points, whereas the 2-2-2 architecture’s performance remained the same as shown in Fig. 10.

Next the source location ability of the best architecture (i.e., architecture with lowest average error), i.e., 2-2-2 network with 32 and 63 training points was compared to the arrival-time difference method using 15 random points on the aluminum plate, as shown in Fig. 11. It is observed that the network locates sources to within an average error of 70 mm with a smallest error of 10 mm (location 14) and the largest error of 153 mm (location 12), while the arrival time difference method had a smallest error of 10 mm (location 12) and a largest error of 650 mm (location 11). The BPN approach also provides better location accuracy
Subsequently, the above mentioned experiments were repeated with a damping material placed between the joint. The 2-2-2 and 2-2-5-2 networks were trained for 15,000 iterations, which produced a constant (stabilized) maximum error for both cases. Subsequently, case 2-2-2 was retrained for 3000 iterations in an effort to study network performance after a limited number of iterations. The three cases provided identical average source location error of about 80 mm, as shown in Table 1. Source location for the 11 random test points using the neural network approach again showed significant improvements over the traditional AE source location method, which had no solutions for 1, 7, 9 and 10 locations, as shown in Fig. 14.

Architectures 2-2-2 and 2-2-5-2 which provided the best results with the aluminum plate were next trained using a 30 point matrix on a channel structure, with sensor C placed across the joint, as shown in Fig. 12. Both architectures were trained for 5000 iterations at which time the maximum error (associated with network training) reached a constant level resulting in an average location error of around 89 mm based on 11 randomly located sources, shown in Fig. 13. The arrival-time difference approach, on the other hand, yielded poor location accuracy, with point 6 located outside the structure (error of 365 mm) and had no solutions for locations 1, 4, 7, 8, 9 and 10.

Subsequently, the above mentioned experiments were repeated with a damping material placed between the joint. The 2-2-2 and 2-2-5-2 networks were trained for 15,000 iterations, which produced a constant (stabilized) maximum error for both cases. Subsequently, case 2-2-2 was retrained for 3000 iterations in an effort to study network performance after a limited number of iterations. The three cases provided identical average source location error of about 80 mm, as shown in Table 1. Source location for the 11 random test points using the neural network approach again showed significant improvements over the traditional AE source location method, which had no solutions for 1, 7, 9 and 10 locations, as shown in Fig. 14.
I. A numerical method involving the squaring and integrating of the AE signal was introduced to minimize ambiguous arrival time measurement due to noise spikes.

2. A back-propagation neural network was successfully trained using limited acoustic wave information (i.e., only arrival time differences) from a minimum 3-sensor scalene configuration to locate AE sources, in 2-dimensions.

3. The BPN located AE sources in the aluminum plate and bolted channel structures (with and without damping material between the joint) far more accurately than the classical time difference method.

4. A simple network architecture (2-2-2) with a limited number of training points (<32) and few training iterations (<10,000) make the implementation of a BPN AE source location system highly feasible, especially in structures with discontinuities where the wave velocity is no longer constant in all directions and traditional methods become inaccurate.

5. Conclusions

1. A numerical method involving the squaring and integrating of the AE signal was introduced to minimize ambiguous arrival time measurement due to noise spikes.

2. A back-propagation neural network was successfully trained using limited acoustic wave information (i.e., only arrival time differences) from a minimum 3-sensor scalene configuration to locate AE sources, in 2-dimensions.

3. The BPN located AE sources in the aluminum plate and bolted channel structures (with and without damping material between the joint) far more accurately than the classical time difference method.

4. A simple network architecture (2-2-2) with a limited number of training points (<32) and few training iterations (<10,000) make the implementation of a BPN AE source location system highly feasible, especially in structures with discontinuities where the wave velocity is no longer constant in all directions and traditional methods become inaccurate.

References


Table 1: Average error for network source locations on damped channel structure.

<table>
<thead>
<tr>
<th>Network Architecture</th>
<th>Average Location Error, (mm)</th>
<th>Iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-2-5-2</td>
<td>80</td>
<td>15000</td>
</tr>
<tr>
<td>2-2-2</td>
<td>79</td>
<td>15000</td>
</tr>
<tr>
<td>2-2-2</td>
<td>78</td>
<td>3000</td>
</tr>
</tbody>
</table>

Fig. 14: Comparison of source location using the classical AE method with the BPN approach on channel structures with damping material between joint.


Wavelet Transform of Acoustic Emission Signals

Hiroaki Suzuki, Tetsuo Kinjo, Yasuhisa Hayashi, Mikio Takemoto and Kanji Ono with Appendix by Yasuhisa Hayashi

Abstract

Wavelet transform (WT) allows the determination of frequency spectrum as a function of time using short waveform segments or wavelets as the basis functions. Resultant mapping of wavelet coefficients in the frequency-time coordinate plane provides more informative characterization of acoustic emission (AE) signals than the power-density spectra from usual Fourier transform. A short tutorial on WT is included. A program for performing WT procedure has been developed and is given as Appendix. As an example, wavelet transform was performed on AE signals from a longitudinal glass-fiber reinforced composite sample under tensile loading. Obtained spectrograms were classified into four types and correlated to the fracture dynamics separately determined by radiation pattern and source simulation analyses. WT is demonstrated to be a powerful new analysis method in evaluating AE signals.

1. Introduction

In the analysis of acoustic emission (AE) signals, the Fourier transform (FT) or fast Fourier transform (which is an efficiently implemented algorithm for FT) is utilized often. Beside providing the frequency spectral information of a signal, FT is the key element of many pattern recognition analysis methods as well as source characterization algorithms. However, FT cannot generate time-dependence of the frequency spectrum because the exponential basis function, exp(-i\omega t), extends over the entire signal duration. Here, i is the imaginary sign and \omega is the angular frequency, 2\pi f.

The high frequency limit of the FT in the presently practiced digitized form (commonly known as discrete Fourier transform) can be increased by increasing the rate of digitization according to the Nyquist theorem. In the FT, a signal of typically limited duration is extended in time to \pm \infty by periodically repeating the signal. This periodicity defines the resolution of the FT. Thus, the frequency resolution can be improved by extending the duration of the signal analyzed. This, in turn, reduces the time resolution, because the obtained spectrum is for the entire duration. This is due to the Uncertainty Principle in time t and frequency f; \Delta t\Delta f \geq 1/4\pi.

The short-time Fourier transform or windowed Fourier transform (WFT) overcomes the drawback of FT to some extent. It consists of multiplying a signal s(t) with a short window function w(t - \tau), centered at time, \tau, and computing the Fourier transform of the product s(t)w(t - \tau). The window, w(t - \tau), is short relative to the signal duration. Gabor (1946) used the Gaussian function as the window function and this procedure is now known as Gabor transform. By the Gabor transform, one can estimate the frequency content of the signal s(t) in the neighborhood of \tau. The window width is constant in Gabor transform and is of the order of the period of the lowest frequency being analyzed, whether s(t) around \tau has a low or high frequency content. Thus, the uncertainty in time, \Delta t, is still substantial at higher frequencies. The application of WFT to AE signal analysis has been limited. Until recently, it was confined to only one oral presentation by Carlos Salvado (of Rockwell International Science Center at the time) at one of the AEWG meetings. The voice-print or WFT's analog-equivalent was used by Green et al. (1962) in the analysis of AE signals from rocket motorcase testing.

The wavelet transform (WT) is a time-frequency transform of continuous (analog) or discrete (digitized) signals. It is described as a time-scale transform in the WT literature. The WT is a direct alternative to the windowed Fourier transform and has been applied to a number of areas, including data compression, image processing and time-frequency spectral estimation. Its theoretical foundation was developed by Morlet and Grossmann (1984). Daubechies (1988) and Mallat (1989) brought the concept of wavelets into digital signal processing. For recent monographs, see Chui (1992), Daubechies (1992) and Kaiser (1994). Within its short history, the WT has become an indispensable tool in various...
fields, but has not been used in the field of acoustic emission (AE). The WT is useful in analyzing the frequency components of an AE signal as a function of time and in separating valid signals from noise. Wavelet coefficients (or spectral intensities at a given time) in the time-frequency coordinate can be presented as a contour map (namely, a spectrogram or a voiceprint) or as a three-dimensional projection. These plots illustrate characteristic features of the signals at a glance.

Acoustic emission monitoring is useful to study the fracture modes and kinetics in various materials, especially in fiber reinforced composites. In glass fiber reinforced composites (GFRPs), many types of fractures can be distinguished by careful AE source waveform simulation studies (Suzuki et al., 1993, 1996). Some of the present authors developed a ten-channel AE monitoring system with two digitizers for conducting a wavelet transform study. We used this system to classify observed AE signals and to examine the correspondence of the classified signals with the fracture mode identified by the source simulation approach.

As a demonstration of WT, we performed the WT of AE signals obtained by using resonant-type AE sensors. Even though the waveforms of such signals are strongly affected by the sensor characteristics, we can successfully distinguish the signals due to fiber fracture, matrix crack and Mode-I or Mode-II disbonding in GFRPs by the wavelet transform. Of course, the assignment of specific fracture mechanisms still requires the source simulation analysis, but it is shown that WT is a powerful new analysis method in evaluating AE signals.

2. Wavelet Transform

Wavelets and wavelet transforms are a relatively new topic in signal processing. The theory continues to evolve and their applications are expanding to various fields as noted previously. We are interested in the application of the wavelet transform (WT) to the time-frequency analysis of AE signals and a brief introduction of WT is given below.

The Fourier transform (FT) is used widely in signal analysis. The Fourier transform and its inverse are defined as follows:

\[ S(\omega) = \int s(t) \exp(-i\omega t) \, dt \quad (1) \]
\[ s(t) = \frac{1}{2\pi} \int S(\omega) \exp(i\omega t) \, d\omega \quad (2) \]

where \( S(\omega) \) is the Fourier transform of a signal \( s(t) \). The FT of \( s(t) \), \( S(\omega) \), is a function independent of time and describes the signal in the frequency domain (in terms of \( \omega = 2\pi f \)). Here, \( \exp(i\omega t) = \cos \omega t + i \sin \omega t \) is the basis functions. This means that any given signal can be constructed by a combination of the 'basis functions' (in analogy to the description of an arbitrary vector via a weighted combination of the "basis vectors"). \( S(\omega) \) is the weight at frequency \( \omega \). We can also describe the FT as the weight in the decomposition of the signal \( s(t) \) into the basis functions \( \exp(-i\omega t) \).

In the case of the FT, these basic functions are complex sinusoids, \( \exp(i\omega t) \), that exist for \( -\infty < t < \infty \). Thus, the Fourier transform is ideal for the analysis of stationary signals (signals whose statistical properties do not change with time). When \( s(t) \) is short as in most AE signals, we assume a periodicity in the application of the FT.

For the analysis of non-stationary or transient signals, we need another method that transforms a signal into a joint time-frequency domain. The windowed or short-time Fourier transform (WFT or STFT) makes this possible. Gabor (1946) originated WFT as an extension to the classical Fourier transform. Here, \( s(t) \) is windowed by a window function \( w(t) \) around time \( \tau \) or \( w(t - \tau) \), then the FT is performed. As the window function is shifted in time by changing \( \tau \) over the whole signal and consecutive overlapped transforms are performed, we can describe the frequency spectrum of the signal as a function of time. This is commonly called the signal spectrogram. The WFT of \( s(t) \) is defined as

\[ \text{WFTs}(\omega, \tau) = \int s(t) w(t - \tau) \exp(i\omega t) \, dt \quad (3) \]

When the window function is Gaussian,

\[ w(t - \tau) = \exp[-(t - \tau)^2/\sigma^2] \quad (4) \]

with a constant \( \sigma \), the WFT is also called Gabor transform. (If we use the same type of notation as in equation (3) above, the left-side of equation (1) can be written as \( \text{FTs}(\omega) = S(\omega) \).)

It is possible to describe the WFT as the decomposition of the signal \( s(t) \) into the windowed basis functions \( w(t - \tau) \exp(i\omega t) \); i.e., these basis functions are complex sinusoids, \( \exp(i\omega t) \), windowed by the function \( w(t) \) centered around time \( \tau \). Three examples from a set of the windowed basis functions are given in Fig. 1c, which are formed by the product of cosine waves in Fig. 1a and the window functions in Fig. 1b. The length of these basis functions is constant as the shape of the Gaussian window function remains the same. The FT of the windowed basis functions are shown in Fig. 1d. These clearly indicate that the frequency resolution remains constant; this also implies that the relative resolution improves at higher frequency.

The windowing has a detrimental effect upon the frequency resolution in comparison to the infinitely extended sine or cosine basis functions. On the other hand, a short window results in a good resolution in time. This is a con-
Fig. 1 The windowed or short-time Fourier transform. (a) Continuous waves, (b) Windows, (c) The product of (a) and (b), (d) Fourier transform of (c).
Fig. 2 The wavelet transform. (a) Continuous waves, (b) Windows, (c) The product of (a) and (b), (d) Fourier transform of (c).
Due to the scaling shown in Fig. 2, wavelets at high frequencies are of short duration (good time resolution) and wavelets at low frequencies are relatively longer in duration (good frequency resolution). This varying “window” structure of the WT is reflected in the resolution on the time-frequency plane by rectangles, as shown in Fig. 4a. The corresponding partition of the time-frequency plane in the case of WFT is represented by identical squares (Fig. 4b).

Both of these factors remain constant in a WFT analysis, resulting in the WFT covering the time-frequency plane with a uniform array of resolution squares. Despite such limitations, the WFT is useful in many problems where time-frequency characteristics are required.

The wavelet transform (WT) is a further extension of WFT. Instead of the constant window shape of the basis functions of the WFT, the basis functions of the WT are scaled with respect to frequency. Figure 2c shows the fundamental basis function and two scaled basis functions. In analogy to Fig. 1, these are formed by multiplying cosine (Fig. 2a) and window (Fig. 2b) functions. Figure 2d shows the FT of the scaled wavelets. These indicate that the spectral width broadens at a higher frequency while a better frequency resolution is obtained at a lower frequency. In turn, the relative frequency resolution in WT remains constant. In WT, the amplitude is also scaled (the shorter in time, the higher in amplitude) as shown in Fig. 2c. These basis functions are short waves with limited duration; thus, the name “wavelet” is used. There are many different wavelets that can be used as the basis functions, although it is adequate for AE signal analysis to use Gabor wavelet or a Gaussian window function applied on exp(iωt). The real and imaginary parts of a Gabor wavelet are shown in Fig. 3a, whose FT is shown in Fig. 3b with the center frequency of 450 kHz in this example. The fundamental basis function is usually referred to as “mother wavelet”, while the scaled versions are daughter wavelets.

Due to the scaling shown in Fig. 2, wavelets at high frequencies are of short duration (good time resolution) and wavelets at low frequencies are relatively longer in duration (good frequency resolution). This varying “window” structure of the WT is reflected in the resolution on the time-frequency plane by rectangles, as shown in Fig. 4a. The corresponding partition of the time-frequency plane in the case of WFT is represented by identical squares (Fig. 4b).
These variable window-length characteristics of WT are obviously suited to the analysis of signals containing short high-frequency components and extended low-frequency components, which are often the case for AE signals.

As the WFT decomposes a signal into the windowed basis functions, \( w(t - \tau) \exp(i\omega t) \), the WT utilizes its basis functions, known as wavelets, and performs a decomposition of the signal \( s(t) \) into a weighted set of scaled wavelet functions \( \psi(t) \). In general, a wavelet \( \psi(t) \) is a complex valued function. A general wavelet function is defined as

\[
\psi_{a,b}(t) = a^{-1/2} \psi((t-b)/a) \tag{6}
\]

The function \( \psi(t) \) is the mother wavelet with the scale parameter \( a \) and the shift parameter \( b \) and provides a set of localized functions both in frequency and time. The scale parameter, \( a \), gives the width of window and consequently frequency as the mother wavelet is expanded or compressed in time. This can be understood from the following Fourier transform of the mother wavelet (equation (6) above);

\[
[\text{FT} \psi_{a,b}](\omega) = \hat{\psi}_{a,b}(\omega) = [a]^{1/2} \hat{\psi}(\omega) e^{-i\omega b} \tag{7}
\]

This effect of the scale parameter in the frequency domain is illustrated in Fig. 5.

The shift parameter, \( b \), determines the position of the window in time and thus defines which part of the signal \( s(t) \) is being analyzed. It is common in the WT analysis that the frequency variable \( \omega \) is replaced by the scale variable \( a \) and the time-shift variable \( \tau \) is represented by \( b \).

The wavelet transform of \( s(t) \) is then defined by:

\[
[\text{WT}s](a,b) = \int_{-\infty}^{\infty} \psi_{a,b}(t) s(t) dt \tag{8}
\]

where \( \psi^* \) is the complex conjugate of the wavelet function defined by equation (6).

In this work, we use the Gabor wavelet based on the Gaussian function, given as equation (4). The mother wavelet and its Fourier transform are given as:

\[
\psi(t) = \pi^{-1/4} \left( \frac{\omega_p}{\gamma} \right)^{1/2} \exp \left[ -\frac{t^2}{2} \left( \frac{\omega_p}{\gamma} \right)^2 + i\omega_p t \right] \\
\hat{\psi}(\omega) = (2\pi)^{1/2} \pi^{-1/4} \left( \frac{\omega_p}{\gamma} \right)^{1/2} \exp \left[ -\frac{t^2}{2} \left( \frac{\omega_p}{\gamma} \right)^2 (\omega - \omega_p)^2 \right] \tag{9}
\]

Here, \( \omega_p \) is the center frequency and \( \gamma \) is a constant taken as \( \gamma = \pi (2/\ln 2)^{1/2} = 5.336 \). From the Fourier transform, we find the half-value frequency width of the Gabor wavelet to be \( 2\omega_p/\gamma \) and the half-value time width to be \( 2\gamma/\omega_p \). The specific value of \( \gamma \) was chosen to nearly satisfy the so-called admissibility condition; i.e., the wavelet functions must satisfy the orthonormality condition.

Consider a typical digitized AE signal of the sampling interval of \( \Delta t \) and the sampling length of \( N \); the corresponding angular Nyquist frequency is \( \pi/\Delta t \). In order to obtain the wavelet transform of such a signal, we select the center frequency, \( \omega_n \), of the mother wavelet as \( (2/\ln 2)^{1/2} \pi/\Delta t \).

For the frequency range of 10 kHz to 2 MHz to be covered with adequate resolution, we need to use 20 to 40 scale parameters or \( a_n \) with \( n = 0 \) to 39. The scale parameters are selected as \( a_n = \alpha^n \), with \( \alpha = 2^{1/6} \). Other suitable values of \( \alpha \) include 2\([1/8]\) and 2\([1/6]\), which cover wider ranges of frequency with the same value of \( n \). The shift parameters, \( b_m \), are chosen as a multiple of the sampling interval of \( \Delta_t \); i.e., \( b_m = m\Delta t \). Here, \( 0 \leq m \leq N/2 \), in order to avoid the WT calculation extending beyond the sampling length. Frequency-defining parameter, \( n \), in the above wavelet transform can be converted to frequency by \( f_n = 2\omega_n/\pi \Delta t_n \), since the \( n \)-th daughter wavelet has the center frequency of \( \omega_n/\Delta t_n \).

Results of WT of a signal are a collection of wavelet coefficients; each wavelet coefficient for a given set of the scale (or frequency) and shift (or time) parameters, \( a \) and \( b \), which can also be represented by \( n \) and \( m \). The results are often represented as a contour map on a \( \log(a)-b \) plane with the gray levels (or false color levels) representing the wavelet coefficients or respective intensities of the transform at points in the \( \log(a)-b \) plane. The contour profile is basically the same as the voiceprint, and shows how the signal intensity of a particular frequency changes with time. Using a logarithmic scale-parameter axis allows a large range of frequency to be simultaneously displayed. Most discussion will be done using the contour map in the following. The original contour map is in color, showing peak height in false color, but will be presented in gray-scale diagram. Here, white represents the zeroth level wavelet coefficient, and black part the highest with different shades of gray in between. Alternate display method is the use of three-dimensional plot or bird’s-eye view with a staggered graphs.
of the intensity-time plots. This type of presentation is helpful in gaining general trends of time-frequency characteristics. The bird's-eye view of WT coefficients shows some characteristic features well, depending on the waveform type and perspective, but is difficult to present in a limited space. A suitable viewing angle may be required as certain details become hidden.

Examples of AE waveforms and their FT and WT are shown in Fig. 6. The wavelet profile is represented in the third row as a bird's-eye view and in the fourth row as a contour map. It shows in detail how different frequency components change with time in contrast to the FT shown in the second row.

Computer program for the wavelet transform is given in Appendix. This is written for the Gabor wavelet.

3. AE Signals from GFRP under Tensile Loading

In order to examine the utility of wavelet transform for AE signal classification, it was applied to AE signals from a GFRP specimen. We prepared a unidirectional GFRP

![Fig. 6 Examples of AE waveforms and their FT and WT.](image-url)
specimen with the fiber orientation shown in Fig. 7. Six thousand E-glass fibers were molded in epoxy (6 parts Epicote 828 and 4 parts Epicote 878, supplied by Shell Epoxy Co. Ltd). Glass fibers, 13 $\mu$m in diameter, were treated with silane coupling agent prior to the molding and spread uniformly on the X-Y plane at the mid-thickness. A reduced section with shallow shoulders was included at the middle part of the specimen to concentrate the fracture events. The origin of the coordinate is at the central point of the specimen. Eight sensors and a ten-channel AE monitoring system were used. Seven sensors (#1 to #7) with 3-mm aperture diameter (Dungun PICO) have mainly been used for the source location and fracture mode analysis based on the radiation pattern of the P-wave. The #8 sensor was a displacement sensor with a conical PZT element (1 mm tip-diameter). It was mounted on the opposite side of the #1 sensor. This sensor was utilized to obtain the source waveform (Suzuki et al., 1994, 1996). For the present WT study, the output of #1 sensor was utilized.

Using the calibration method of surface-impulse deconvolution (ref), we found that PICO sensors measured the velocity component of the out-of-plane displacement, while the displacement sensor detected the out-of-plane displacement with the sensitivity of $6.01 \times 10^7$ V/m. Two separate digitizers (Digitizer A and B) were used because the sampling conditions for the wavelet transform and source simulation and for the source location/radiation pattern analyses were different. The outputs of #1 and #8 sensors were recorded on both digitizers. The outputs of #1 and #8 sensors were amplified by a 40-dB preamplifier (NF Circuit Block Co. Ltd., Type 9913) and then digitized at 200-ns sampling interval and 8 bit with 4096 sampling points by the digitizer A (Tektronix, RTD 720, H310). This set of data was used for the wavelet transform and source simulation. The outputs of #1 to #8 sensors were amplified by the same amplifier and digitized at 50 ns interval and 10 bit with 1024 sampling points by the digitizer B (Autonics, APC-510). The data on 8 channels of digitizer B was used for the source location and P-wave radiation pattern analyses. This

Fig. 7 Details of a unidirectional GFRP specimen with the fiber position and sensor placements. Schematic diagram of eight sensors and a ten-channel AE monitoring system is also given.
monitoring system enables us to compare the wavelet transform results with the fracture mode deduced by the source simulation and radiation pattern analyses. Detail for the latter signal processing methods can be found elsewhere (Suzuki et al., 1996).

![Image of wavelet coefficients](image)

**Fig. 8** The stress-strain curve and the cumulative AE events vs. strain for four types of AE signals.

4. Results and Discussion

Figure 8 shows the stress-strain curve, and the cumulative AE events vs. strain. The specimen was stressed at a constant strain rate of 0.05%/min to 18 MPa (or a strain of 1.9%), and then held at this stress. After holding this stress for 42 min, the specimen fractured with the final fracture strain of 2.3%. We observed 46 AE events in all. Source location was possible for 33 events.

By examining the waveforms, their power spectra and wavelet transform of the 33 events, we classified the observed AE signals into four types; i.e., Types 1 to 4. Type 1 AE events were observed from small strains and their number increased almost linearly with stress, but little further increase was observed during the stress hold. AE events of Types 2 and 3 increased from 1% strain, but at lower emission rates than that of Type 1. Both Types 2 and 3 continued to increase after the stress hold started. Type 4 AE events increased from 0.8% strain, but its emission rate was the lowest.

Figure 9 illustrates four typical Type-1 signal waveforms from sensor #1 (the upper row), the power spectrum of the entire waveform via FFT (the second row), as well as FFT of the first 20 μs following the sharp rise of the signal (the third row). The fourth and bottom rows show the wavelet coefficients as the 3-D representation and contour map, respectively. Type 1 waveforms are short and of a typical "burst type". The FFT indicates their main power in the frequency range from 0.3 to 0.6 MHz with dips at about 0.5 MHz. The power spectra for the main part of the signals have similar features. The WT contour maps best show the characteristic features of the waveforms. Type 1 waveforms show that high frequency components of the signals last for a short time with the appearance of a vertical line at left side in the frequency range from 0.1 to 1.5 MHz. Some low frequency components are present and extend for longer periods. The bird's-eye view of wavelet coefficients shows a single sharp peak.

Four typical Type-2 signals are given in Fig. 10. As in the previous figure, waveforms from sensor #1 (the upper row), the power spectrum of the entire waveform via FFT (the second row), FFT of the first 20 μs following the sharp rise of the signal (the third row), the wavelet coefficients in the 3-D representation (the fourth row) and as the contour map (the bottom row), respectively. Characteristic features are as follows: The frequency spectra again show high intensity from 0.3 to 0.6 MHz, but with a peak at 0.5 MHz and a higher intensity below 0.1 MHz. The WT contour maps reveal that higher frequency components occur at two distinct time periods (indicated by two vertical lines) and that a weak low frequency component lasts continuously for 250 to 300 μs. The bird's-eye view of wavelet coefficients shows split sharp peaks plus an extended range of hills.

Four typical Type-3 signals are given in Fig. 11. The frequency spectra show a high intensity peak at 0.5 MHz. The short FFT spectra give a broader range of high intensity. The WT contour maps reveal that higher frequency components last longer than in Type-1. The two-vertical line feature seen in Type-2 is absent. The low frequency components appear at the same time as the high frequency components; i.e., at 30 to 120 μs. A few islands of low frequency components also appear at later times. The bird's-eye view of wavelet coefficients shows a group of sharp peaks plus a broad-top mountain. It is noted that the contour map shows a clear profile difference in the lower frequency range for Types 2 and 3, while both the waveforms and frequency spectra of these signals closely resemble each other.

Frequency spectrum of Type 4 is different from any other type as can be seen in Fig. 12. It contains higher intensity in the frequency region lower than 0.5 MHz with the highest intensity occurring below 0.02 MHz. Both WT contour maps and bird's-eye views reveal a broad peak at the low frequency region.

These examples show that the characteristic features of waveforms are best revealed by the WT contour maps and by the bird's-eye view of wavelet coefficients. Differences in these waveforms exist and can be recognized, but distinction is at times hard to discern. The WT results can separate different waveform types at a glance. The main drawback of the WT analysis is the length of computation time in comparison to nearly instantaneous calculation of FFT.
Fig. 9 Four typical Type-1 signal waveforms from sensor #1 (the upper row), the power spectrum of the entire waveform via FFT (the second row), FFT of the first 20 μs following the sharp rise of the signal (the third row). The fourth and fifth rows show the wavelet coefficients as the 3-D representation and contour map, respectively.

In order to identify the fracture mode of the four types of AE signals observed, we conducted the source location, radiation pattern and source simulation analyses. Figure 13 represents the source locations of 33 events in X-Y and Y-Z diagrams. Four symbols, filled diamonds, open circles, open squares and Xs, represent Type I, 2, 3 and 4 signals, respectively. The source locations of Type 1 signals (marked by a, b, and c) are scattered over the X-Y plane, but they all lie almost on the fiber-bundle plane. Most of Type 2 signals, (d, e, and f), and Type 3 signals, (g, h, and i), are located in the matrix and near the outer edge of the reduced section. These indicate that Type 1 signals are emitted by the fiber fracture, while Type 2 or 3 signals are by the matrix crack. The source location of Type 4 signals, (j and k), are located at the surface where a strain gauge was bonded, and appeared to be emitted by the exfoliation of the strain gauge. In this sense, Type 4 signals are noise.

These signals were also subjected to the radiation pattern and source simulation analyses in order to identify the fracture mode (Suzuki et al., 1994, 1996). From these analyses along with the above source locations, we attribute
Type 1 signals to Mode-I fiber fractures, Type 2 and 3 to multiple Mode-I matrix cracks, and Type 4 to the Mode-II exfoliation of the strain-gauge base.

5. Conclusions

Wavelet transform of AE signals provides plots of their frequency spectra as a function of time. It is useful in the recognition of AE signal features through 2-dimensional contour maps and 3-dimensional projections of wavelet coefficients. Computer programs for wavelet transform have been written and incorporated into a ten-channel AE monitoring and signal processing system. As a test of the utility of the system, it was used to examine the AE signals from a model GFRP sample. The wavelet transform and source analysis procedures for the same set of AE signals were applied and the results obtained are presented.

- We developed a set of computer programs for the wavelet transform with Gabor wavelet, as given in Appendix. These can be used for the analysis of AE signals as well as other transients.
Fig. 11 Four typical Type-3 signal waveforms from sensor #1 (the upper row), the power spectrum of the entire waveform via FFT (the second row), FFT of the first 20 μs following the sharp rise of the signal (the third row). The fourth and fifth rows show the wavelet coefficients as the 3-D representation and contour map, respectively.

- The characteristic features of waveforms are best revealed by the WT contour maps and by the bird’s-eye view of wavelet coefficients. The WT results can separate different waveform types at a glance. The main drawback of the WT analysis is the length of computation time.

- The wavelet transform was applied to AE signals emitted during tensile loading of a model unidirectional GFRP and allowed us to classify the signals into four patterns. By applying the source location, radiation pattern and source simulation analyses, the four signal types classified by the wavelet transform were correlated to the Mode-I fiber fracture, the Mode-I matrix crack and the Mode-II disbonding.

Acknowledgment

We acknowledge the assistance of undergraduate students, Messrs. N. Kugizaki, K. Ousika and M. Nemoto. The authors are also grateful to Showa Kobunsi Co. for providing us with epoxy resin and to Teitsu Densi Co. for a special PZT sensor.
Fig. 12 Two typical Type-4 signal waveforms from sensor #1 (the upper row), the power spectrum of the entire waveform via FFT (the second row), FFT of the first 20 µs following the sharp rise of the signal (the third row). The fourth and fifth rows show the wavelet coefficients as the 3-D representation and contour map, respectively.

References


Fig. 13 The source locations of 33 AE events in X-Y and Y-Z diagrams. Four symbols, filled diamonds, open circles, open squares and Xs, represent Type 1, 2, 3 and 4 signals, respectively.

Appendix

Yasuhisa Hayashi

The author is affiliated with Faculty of Engineering, Shizuoka University, Shizuoka, Japan. (hayashi@sys.eng.shizuoka.ac.jp)

The Program for Wavelet Transform

Usage: wavelet [-Nn][-Ssize] filename

n: n parameter number
size: output data size
(This size can be reduced.)
filename: output file name

#include <stdio.h>
#include <math.h>
#include "complex.h"

#define MAXDATASIZE 4096 /* Max size of data */

complex gabor(), citgO, calclwaveletO;
static char fname[50];

main(argc, argv)
int argc;
char **argv;
{
    if(argc != 1)
        usage(pname);

    ifile = *argv;
calcwavelet(ifile, N, osize);
}

 usage(pname)
char *pname;
{
    fprintf(stderr, "Usage: %s [-Nn][-Ssize] filename\n", pname);
    exit(-1);
}
The ELSE block is simple algorithm according to the definition of the wavelet transform, but takes extremely long calculations time. The IF block is new algorithm to shorten the calculating time. The concept of this algorithm consists of only one calculation of Gabor function, and reuse it by time-shifting on the memory. This calculation algorithm is much faster than conventional one.

```c
# if 1
calcwavelet(ifile, N, osiz)
char *ifile;
int N, osiz;
{
    int siz, i, j;
    double dt, A, B;
    complex c;
    static complex phi[MAXDATASIZE*2];
    static complex yfunc[MAXDATASIZE];
    static complex buf1[MAXDATASIZE];
    static complex buf2[MAXDATASIZE];

    siz = fdrsize(ifile);
    if(osiz == 0)
        osiz = siz;
    getadas(ifile, siz, yfunc, &dt);

    A = pow(2.0, N/4.0);
    wavelet(phi, siz*2, dt, A, siz*dt);

    for(i=0; i<osiz; ++i){
        for(j=0; j<siz; ++j)
            buf1[j] = cprod(yfunc[j], conjg(phi[siz-i+j]));
        c = citg(buf1, siz, dt);
        buf2[0].re = cabs(c);
        buf2[0].im = 0.0;
        printf("%d: %e\r", i, cabs(c));
    }
    toadas(buf2, osiz, dt);
}

else
calcwavelet(ifile, N, osiz)
char *ifile;
int N, osiz;
{
    int siz, i, j;
    double dt, A, B;
    complex c,
    static complex phi[MAXDATASIZE*2];
    static complex yfunc[MAXDATASIZE];
    static complex buf1[MAXDATASIZE];
    static complex buf2[MAXDATASIZE];

    siz = fdrsize(ifile);
    if(osiz == 0)
        osiz = siz;
    getadas(ifile, siz, yfunc, &dt);

    A = pow(2.0, N/4.0);
    wavelet(phi, siz*2, dt, A, siz*dt);

    for(i=0; i<osiz; ++i){
        for(j=0; j<siz; ++j)
            buf1[j] = cprod(yfunc[j], conjg(phi[siz-i+j]));
        c = citg(buf1, siz, dt);
        buf2[0].re = cabs(c);
        buf2[0].im = 0.0;
        printf("%d: %e\n", i, cabs(c));
    }
    toadas(buf2, osiz, dt);
}

complex calcwavelet(yfunc, siz, dt, A, B)
complex *yfunc;
int siz;
double dt, A, B;
{
    int n;
    complex wb;
    static complex phi[MAXDATASIZE];

    wavelet(phi, siz, dt, A, B);
    for(n=0; n<siz; ++n)
        phi[n] = cprod(yfunc[n], conjg(phi[n]));
    wb = ci tg(phi, siz, dt);
    return(wb);
}

#endif

wavelet(buf, siz, dt, a, b)
complex *buf;
int siz;
double dt, a, b;
{
    int i, n;
    double t, wp;
    complex c;

    c = cmplx(1.0/sqrt(a), 0.0);
    wp = sqrt(2.0) * M_PI / dt;

    for(n=0; n<siz; ++n){
        t = n * dt;
        buf[n] = cprod(c, gabor(t-b)/a, wp));
    }
}

complex gabor(t, wp)
double t, wp;
{
    double gam = 5.336;
    double a;
    complex b, c;

    a = pow(M_PI, -1.0/4.0) * sqrt(wp/gam);
    b = cmplx(-pow(t*wp/gam, 2.0)/2.0, wp*t);
```
c = cprod(complex(a, 0.0), cexp(b));
return(c);
}

complex citg(buf, siz, dt)
complex *buf;
int siz;
double dt;
{
    int n;
    complex sum;

    sum = CNULL;
    for(n=0; n<siz; ++n)
        sum = csum(sum, buf[n]);
    sum.re *= dt;
    sum.im *= dt;
    return(sum);
}

toadas(cbuf,siz,dt)
complex *cbuf;
int siz;
double dt;
{
    int n;
    complex sum;

    sum = CNULL;
    for(n=0; n<siz; ++n)
        sum = csum(sum, buf[n]);
    sum.re *= dt;
    sum.im *= dt;
    return(sum);
}

************ DATA OUTPUT ROUTINE

complex *cbuf: the pointer of output data arrangement
int siz: output data size
double dt: sampling interval

Prepare the data output routine for your convenience.
The simplest routine is probably as follows;

int n;
for(n=0; n<siz; ++n)
    printf("%e: %e\n", cbuf[n].re, cbuf[n].im);

************ DATA INPUT ROUTINE

char *fname: the pointer of input data filename
strings

int siz: input data size
complex *cbuf: the pointer of input data buffer
double *dt: the sampling interval of input data
(You have to set these variables.)

Prepare the data input routine for your convenience.
The simplest routine is probably as follows.

FILE *fp;
int n;
complex c;

fp = fopen(fname, "r");
for(n=0; n<siz; ++n)
    fscanf(fp, "%e%e", &c.re, &c.im);
    cbuf[n] = c;
*dt = 1e-6;
fclose(fp);

fdrsize(fname)
char *fname;
{
    FILE *fp;
    int n;
    complex c;

    fp = fopen(fname, "r");
    for(n=0; n<siz; ++n)
        fscanf(fp, "%e%e", &c.re, &c.im);
        cbuf[n] = c;
    *dt = 1e-6;
    fclose(fp);
}

getadas(fname, siz, cbuf, dt)
char *fname;
int siz;
complex *cbuf;
double *dt;
{
    FILE *fp;
    int n;
    complex c;

    fp = fopen(fname, "r");
    for(n=0; n<siz; ++n)
        fscanf(fp, "%e%e", &c.re, &c.im);
        cbuf[n] = c;
    *dt = 1e-6;
    fclose(fp);
}

fdrsize(fname)
char *fname;
{
    FILE *fp;
    int n;
    complex c;

    fp = fopen(fname, "r");
    for(n=0; n<siz; ++n)
        fscanf(fp, "%e%e", &c.re, &c.im);
        cbuf[n] = c;
    *dt = 1e-6;
    fclose(fp);
}

getadas(fname, siz, cbuf, dt)
char *fname;
int siz;
complex *cbuf;
double *dt;
{
Acoustic Emission in a Nextel 440 Fiber Reinforced 6061 Al Composite

T. Pocheco, H. Nayeb-Hashemi and H. M. Sallam

Abstract

Acoustic emission (AE) activity was monitored during tensile tests, in a 6061 Al alloy and in a Nextel-440-fiber reinforced 6061 Al alloy composite subjected to various heat treatments. The AE activity in the composites began just prior to the onset of plasticity in the matrix and quickly reached a high rate. The rate of activity then slowed down to a steady state that continued until failure. The AE activity exhibited by all of the heat-treated (aged) composites was similar. However, composites with just the solution treatment had a considerably lower activity during the onset of plasticity in the matrix. The behavior of all composites was similar in the steady state region.

Acoustic emission activity of composites during loading and reloading experiments was also monitored. It was found that during reloading the AE activity of the composite quickly rose subsequent to yielding. This was attributed to sudden unpinning of dislocations. When the specimen is loaded above its previous level the AE activity followed a constant rate.

Considering these observations, the first region of AE activity in the composite was related to dislocation motion. The AE activity in the second region is believed due to inclusion cracking in the matrix. No significant fiber failure was observed prior to composite failure.

In contrast to the composite material, the 6061 Al showed very little AE activity upon yielding. The rate of activity increased slowly until failure. This behavior was related to the inclusion cracking and void formation. The AE activity of the 6061 Al was similar to the second region of AE activity of the composites.

The fracture surface of the composite was flat with no significant fiber pullout. The composite failure is believed to be initiated from matrix damage that overloads the fibers, causing a rapid propagation of fiber failure through the composite.

Received 5 March 1996. The authors are affiliated with Dept. of Mechanical, Industrial and Manufacturing Engr., Northeastern University, Boston, MA 02115 (hamid@coe.neu.edu).

1. Introduction

Metal matrix composites (MMCs) have been under development for several decades. They have begun to show some commercial acceptance in recent years, especially particulate reinforced composites. Continuous fiber reinforced metals still require significant development for them to be accepted in the commercial market. In order to improve MMCs their failure processes needs to be fully understood. Nondestructive testing (NDT) techniques, such as acoustic emission, provide one such means for understanding the failure mechanisms and thus may provide insight into the means for the improvement of the materials mechanical properties.

Acoustic emission can be caused by any number of mechanisms that causes a redistribution of stresses in a system (Arrington, 1987; Raj and Jha, 1994). Some possible sources in MMCs are: fiber breaking, interface failure or debonding, interface cracking, fiber to fiber rubbing, cracking or sliding of damaged fibers, plastic deformation of matrix, inclusion cracking, matrix cracking and interface sliding or fretting (fiber pullout).

Detected AE signals are evaluated and their features are extracted. Some of the more common features are: AE counts or ring-down counts (RDC); event duration (ED); peak amplitude (PA); energy (ENG); rise time (RT); and slope.

A considerable number of research reports have been written, on AE in metal matrix composites. Unfortunately most of these reports have been on monofilament fiber reinforced composites. One of the most extensive studies on acoustic emission in MMCs is reported by Awerbuch and Bakuckas (1989). They studied a number of monofilament MMCs. By using an video camera to monitor the damage progression in the composites, they were able to correlate some damages with AE events. Higher amplitude events were correlated directly with fiber breaking. The majority of the lower amplitude events were below friction emission thresholds (FRET) values and believed to be generated by friction. The friction is due to rubbing of fracture surfaces, which include microcracks and macrocracks. There have been other attempts to identify damage using AE data obtained from monofilament MMCs; e.g., Madhukar and
Awerbuch (1986) used event peak amplitude distributions for the detection of various failure processes. It was inconclusively determined that the middle amplitude events were due to matrix plastic deformation. No attempts were made to distinguish the events with the various mechanisms of plastic deformation. Low amplitude events were assumed to be due to interface debonding, cracking and friction between previously fractured surfaces. Bakuckas et al. (1994) studied damage evolution in titanium matrix composites reinforced with a monofilament fiber, using AE event amplitude to correlate the different types of damage. High amplitude events were found to be related to fiber breaking. The amplitude of the events was found to increase with load with a few high amplitude events occurring just prior to failure. The AE event rate was found to increase with the load to failure. The bulk of the research reviewed on monofilament composites to date have correlated the damage occurring with peak amplitude distributions. The large fiber sizes used in these studies generate events with high amplitude when they fracture making it possible to distinguish breaking fibers.

Some work has been done on the multifilament fiber composite systems. Komai et al. (1993) studied the fracture behavior of γ-Al$_2$O$_3$-fiber reinforced Al composite. In the tensile tests the acoustic emission event rate was found to increase continuously to failure. Events with high event amplitude, short event duration and a large ratio of RDC to ED were attributed to fiber breaking. Ulman and Henneke (1982) performed some AE tests while evaluating nondestructive evaluation techniques on an FP-alumina-fiber-reinforced Al composite. AE events were found to be concentrated in two regions, one at the start of plastic deformation of the matrix and another just prior to failure. Little effort was directed toward determining the different AE sources. Esterday et al. (1991) tried to correlate strength of a graphite fiber reinforced aluminum composite to the AE response of the material. The specimens were given a series of heat treatments at various temperatures for 24 hr. in order to simulate damage. The specimens were then loaded to a small strain while the AE response was measured. The AE activity was found to increase while the strength decreased with increasing heat-treatment temperature. Attempts were made to determine the sources of AE using metallography, but no defects were distinguished as the sources of emission.

There has been extensive testing done on fiber reinforced polymers to date and some of the approaches used in this field may prove to be of use in the study of MMCs. Some attempts have been made at using pattern recognition techniques to determine failure modes. Bhat et al. (1994) used pattern recognition techniques to detect the failure modes in a graphite-fiber-reinforced polymer composite. The material was tested under tension-tension fatigue, while AE was monitored. Some basic AE parameters (PA, ENG, RT, RDC) were used for classification of the different types of damage occurring in the matrix. Three damage mechanisms were found to dominate failure: matrix cracking, interface debonding and fiber fracture. Each type of damage was classified using pattern recognition.

The purpose of the current study is to predict the strength of the Nextel-440-fiber-reinforced 6061 Al through nondestructive evaluation and understand the damage process that ultimately leads to failure. In understanding the damage process, AE monitoring is employed along with mechanical properties and microscopic analysis.

2. Experimental Investigation

2.1 Material

The material used in this research is a Nextel-440-fiber-reinforced 6061 Al (440/6061) composite. The volume fraction of the fibers was measured and found to be between 40 and 50%. Figure 1 shows a typical photomicrograph of the composite cross-section. The Nextel-440 fibers are manufactured by the 3M Corporation. Tables 1 and 2 show the chemical composition and mechanical properties of the fiber and 6061 Al. The composites were manufactured at Northeastern University using a pressure casting method. The material processing technique is similar to that reported elsewhere (Blucher, 1992; Mortenson et al., 1993).

Table 1 Nominal Properties of Nextel 440 Fiber
(Holtz and Grether, 1987)

<table>
<thead>
<tr>
<th>Composition</th>
<th>Al$_2$O$_3$</th>
<th>70%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO$_2$</td>
<td>28%</td>
</tr>
<tr>
<td></td>
<td>B$_2$O$_3$</td>
<td>2%</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>MPa</td>
<td>2110</td>
</tr>
<tr>
<td>Modulus</td>
<td>GPa</td>
<td>186</td>
</tr>
<tr>
<td>Diameter</td>
<td>µm</td>
<td>10 - 12</td>
</tr>
<tr>
<td>Grain size</td>
<td>nm</td>
<td>20 - 60</td>
</tr>
<tr>
<td>CTE</td>
<td>10$^{-4}$/C</td>
<td>4.4</td>
</tr>
<tr>
<td>Shape</td>
<td>oval</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Nominal Properties of 6061 Aluminum

<table>
<thead>
<tr>
<th>Composition: Mg 1.0%, Si 0.6%, Cu 0.27%, Cr 0.2%, Al Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength MPa T6</td>
</tr>
<tr>
<td>276</td>
</tr>
<tr>
<td>Tensile strength MPa T6</td>
</tr>
<tr>
<td>310</td>
</tr>
<tr>
<td>Modulus GPa</td>
</tr>
<tr>
<td>68.9</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion 10$^{-4}$/°C</td>
</tr>
<tr>
<td>24.3</td>
</tr>
<tr>
<td>Hardness BHN T6</td>
</tr>
<tr>
<td>95</td>
</tr>
</tbody>
</table>

Ten composite specimens were machined out of 2.16 mm thick plates, each approximately 76.2 mm by 165 mm. The composite plates were C-scanned ultrasonically prior to machining and no defects were found in the material. The specimens were fabricated using a numerically
controlled machine with a carbide bit to the dimensions shown in Fig. 2. Prior to testing the composite specimens had aluminum end-tabs applied using a Hydsol adhesive in a hot press. Four of the specimens were tested in an as-received condition, while the remaining six were given different heat treatments. These six specimens were solution-treated at 550°C for 1.5 hr, followed by water quenching. Two were tested in this condition. The remaining four specimens were aged at 203°C, two of which were aged for 30 min, and the other two for 60 min. In addition to the composite specimens, four 6061-T6 Al specimens were machined from a 3.18 mm thick plate; two along the rolling direction and the other two in the transverse direction.

The effect of heat treatment on the composite matrix and 6061 Al samples was evaluated by measuring its microhardness. All microhardness experiments were performed using a Tukon microhardness tester with a 50-g load.

2.2 Tensile Tests

All mechanical testing was performed using an Instron 1350, a servo-hydraulic system with an analog controller and a 100-kN load cell. Strain was measured using an Instron 2620-826 extensometer with 25.4 mm gage length and 2.54 mm travel. Tensile tests were performed in either stroke control at a loading rate of 2.54 μm/s or under load control for experiments involving loading and unloading at a rate of 6.67 N/s. This slow loading rate was used to increase AE sensitivity and prevent AE event pileup. Two of the as-received composite samples were tested by loading and unloading with AE recording. The remaining eight
composite and the four 6061 Al specimens were monotonically loaded in tension to failure while recording AE. The load and strain data were recorded using a chart recorder for all tests.

The AE testing was performed using an AET-5500 system. The system was equipped with 60 dB preamplifiers, with two AET AC175L transducers. The testing was performed with a total gain of 70 dB. The threshold was set at 0.12 V. The automatic threshold setting was used allowing the threshold to rise with the noise level during the test. These settings resulted in the lower amplitude cutoff of about 25 dB in reference to 0 dB at 1 µV. The system has the upper limit of 77 dB with the 60 dB preamplifier. The AE data was recorded on a computer along with load and strain data for post processing. A spring clamp system was used to attach the sensors to the specimen.

Prior to tensile testing the specimens were tested using the acousto-ultrasonic (AU) method (Kiernan and Duke, 1991). The waveform was recorded on a computer for calculation of the stress-wave factor (SWF) and relating to material strength. AU testing was performed using a Matec-515 gated-amplifier, a Tektronix CFG 11-MHz function generator. A Nicolet digital oscilloscope was used to capture the data. Waveform-BASIC software was used for recording and analyzing the waveform data on a computer. A narrow-band Panametrics transducer, with the center frequency of 2.25 MHz, was used for sending the signals. AET FC500 transducer, with a flat sensitivity between 0.1 and 2.0 MHz, was used for receiving.

Ultrasonic immersion testing was performed on all of the specimens after machining and subsequent to any heat treatments. Immersion C-scan used a Tektrnd automated scanning system equipped with transducers with a center frequency of 10 MHz and a 25 mm focus. The complete waveform was saved for later use. The scanning was done for two reasons; the first is to insure that the parts tested had no gross defects. The second was for later evaluation of its features and possible correlation of these features with tensile strength.

3. Results and Discussion

3.1 Material

The material used in this study has been partially characterized in terms of its interface and matrix microstructure. Reactions have been shown to occur between Al₂O₃ and 6061 Al (McLeod and Gabryel, 1992). The reactions that occur between magnesium present in 6061 Al and the fiber are:

\[ 3\text{Mg} + 4\text{Al}_2\text{O}_3 \rightarrow 2\text{Al} + 3\text{MgAl}_2\text{O}_4. \]

These reactions can have several effects on the composite. The amount of Mg in the matrix can be reduced through the reactions, which will affect the aging characteristics of the alloy. The reaction may help in providing better bonding between the fiber and the matrix. The reactions can damage the fiber reducing its load carrying capabilities, depending on the amount of the reaction. The matrix was dissolved from the fibers, which showed no signs of damage. Some particles appeared to be attached to the fibers have been noted during inspection, using scanning electron microscopy (SEM). These particles may be due to some type of reaction. For this reason it is believed that some random discontinuous reactions are occurring along the fiber. At this time these reactions are believed to be MgAl₂O₄, although this has not been verified at this time.

The aluminum alloy 6061 is a precipitation strengthened alloy. The precipitation process is: supersaturated solution; Si cluster formation (from vacancy loops); GP(I) zones; GP(II) zones (needles); B' (rods); B-Mg₂Si. Peak hardness comes from the combination of B' precipitate with GP zones (Smith, 1993). Dutta and Allen (1991) found that the formation of GP zones can be effected by preaging which prevents the formation of GP(I) zones. The preaging retards the formation of Si clusters favoring the formation of GP(II) zones. Dutta et al. (1991) also studied the effects of aging on the aging of Al₂O₃-particulate-reinforced 6061 Al. The reinforcement "was found to increase the volume fraction of the GP(I) zones while suppressing the formation of the B' and B phases." The aging response of the matrix is modified by the increase in the dislocation density due to residual stresses developed during manufacturing and heat treatment of the composites. The dislocations act as nucleation sites for the GP(I) zones that form in an orientation that reduces residual stresses in the composite. Although that study was of a particulate composite a similar behavior could be expected in a continuous-fiber-reinforced composite. The mechanical properties of the matrix can be affected by both interfacial reactions and modification of the aging response.

Sections of composite samples were polished and studied using an optical microscope. Inclusions were found in the matrix, and they appeared to be segregated around the fibers, as shown in Fig. 3. These inclusions also appear to form interconnected networks. At present a preliminary energy-dispersive analysis of these inclusions in SEM suggests that they are an iron impurity introduced during composite processing. It is not certain if these inclusions are reacting with the fibers. These inclusions may effect the strength of the composite through either short range stress concentrations due to the incompatibility with the matrix or if the inclusions crack they will cause stress concentrations in the fiber. Levi et al. (1978) suggested that uneven or
rough surfaces on the fibers through interactions may effect the strength of the fiber and hence the composite. McCullough et al. (1994) found interconnected networks of inclusions in a Nextel-601-reinforced 6061-Al composite. These networks lead to premature fracture of the composite.

The microhardness of as-cast specimens and solution-treated and aged specimens are shown in Fig. 4 in comparison with 6061 Al. The results show a slightly higher hardness for the composite, which is due to the additional constraint of the fibers and the presence of residual stresses. An elastic/plastic finite-element analysis showed that during cooling of composites significant tensile stresses in the matrix and compressive stresses in the fibers are developed (Yang and Nayeb-Hashemi, 1995). The composite has a peak hardness at 60-min. aging time. The composite has a faster rise in hardness with aging time than 6061 Al. This is due to an increased dislocation density, which is caused by the thermal-expansion mismatch. The higher dislocation density increases precipitation nucleation rates.

3.2 Mechanical testing

For the composite specimens tested, the stress and strain data was fit by using the least-squares-fit method. The results are plotted in Figs. 5-8 for a series of composite specimens with different heat treatments. The two artificially aged specimens behaved similarly exhibiting a bilinear stress-strain curve, Figs. 7 and 8. The stress-strain diagram was linear to about 0.3% strain where the slope of the curve began to decrease to failure. The as-received specimen (Fig. 5) also appeared to have a bilinear response, with the transition occurring at 0.05% strain. Two as-received composite specimens were loaded and unloaded several times to 227.4 MPa. Typical stress-strain curves are shown in Figs. 9-11. There was a considerable plastic strain present after the first loading (Fig. 9). This plastic strain is
due to a combination of the residual thermal stresses from the thermal-expansion mismatch and the low strength of the matrix. Figures 10 and 11 show that a small hysteresis loop remains upon subsequent loading and unloading of the specimen with little or no additional accumulation of plastic strain upon unloading. The hysteresis loop is due to micro plastic deformation of the matrix that occurs near the maximum load on loading and near the minimum load on unloading.

### 3.3 Acoustic Emission

Representative curves of cumulative AE events versus strain for the 6061-T6 Al are shown in Figs. 12 and 13. The results show a few initial AE events occurring at the yield point with a steady number of AE events emitted throughout the rest of the test. The transverse-direction specimen had a significantly higher number of events than the rolling-direction specimen.

Acoustic emission in aluminum alloys has been attributed to dislocation motion and inclusion cracking. The dislocation activity during the yielding of a material typically generates continuous-type AE (Heiple et al., 1981; Scruby et al., 1981; Kim and Kishi, 1977). This aspect of dislocation motion is not detected in our results, which have shown few events at the yield point.

Acoustic emission is not generated by the cracking of inclusions until after the material has yielded. Strain incompatibility with the surrounding material cause inclusions to fracture. Some strain is required for the stress to be high enough to fracture the inclusions. Other reports show that the AE count rate reaches a peak after yielding and slowly decreases throughout the test. The peak is due to the cracking of large inclusions, which occurs early in the test leaving only smaller ones (McK. Cousland and Scala, 1981, 1983, 1984). This is not completely consistent with the observed results that show a constant AE rate throughout the test. These results do appear to be consistent with
inclusion cracking and inclusion-matrix debonding, resulting in void formation. The random size and distribution of inclusions would cause them to fracture at various times during the test. This will result in a tendency towards a steady rate of emission. This result is consistent with that of Gangulee and Gurland (1967), who showed that the number of inclusions fractured increase linearly with the tensile strain, in Al-Si alloys, with the larger particles fracturing first followed by the smaller ones. The transverse-direction specimen has a rise in the AE event rate with the onset of necking in the specimen. This rise in event rates is attributed to an increase in the number of inclusions fracturing and void formation in the necking zone. The difference in AE activity between the specimens with rolling and transverse directions is due to the alignment of the inclusions due to rolling. This is also consistent with the AE activity observed in other reports (McK. Cousland and Scala, 1981, 1984). Some of the 6061 Al specimens were polished and examined under a microscope after testing for damage and possible identification of AE sources. Figure 14 shows an inclusion fractured during tensile tests. These fractured inclusions show that they are a viable AE source.

Curves of cumulative AE events versus strain are shown in Figs. 5-8 for the composite specimens with various heat treatments. All of the curves have an initial rapid rise in the number of AE events. The rise is followed by a decrease in the rate of AE events, which becomes steady. In the as-received specimen, the AE events initiate at an earlier strain than the other specimens. In the solution-treated and quenched specimen the rapid rise in events is much less than the other specimens. Most of these figures show that the initiation of events occurs before the matrix begins yielding. Figures 9 through 11 are of the cumulative AE events vs. strain of a specimen that was loaded and unloaded several times. These curves show that the composite produced same events vs. strain after first and second reloading with a high rise in AE events just prior to the maximum load, and the sharp rise occurs after the stress-strain curve becomes non-linear. The cumulative energy of AE events was evaluated for the composite specimens. Figure 15 shows an example of cumulative AE energy vs. strain for a specimen that was aged for 60 min. The cumulative AE energy curve has a similar appearance to that of the cumulative AE events curve, as shown in Fig. 8.

The composite has a large increase in the number of AE events just prior to the yielding of the matrix. Although the composite has many more possible sources for AE activity than an unreinforced alloy, based on the above observations it is believed that the matrix is the primary source of AE activity in the composite. These events are associated with the initiation and propagation of plastic deformation in the matrix. Analyses of peak amplitude distributions reveal that the events are low in amplitude, which is consistent with the matrix plastic deformation (Awerbuch and Bakuckas, Jr., 1989; Bakuckas, Jr. et al., 1994). The AE response of the matrix material in the composite could be affected by several factors. The residual stresses and dislocations that are present due to the coefficient of thermal expansion (CTE) mismatch, alter the aging response. Increased stress and dislocations in the matrix have been shown to increase the percentage of GP(I) zones (Dutta et al., 1991). This effect may be increased through reactions of Mg with the fibers, which may alter precipitation even further. The presence of a large amount of GP(I) zones in the 6061 matrix of the composite should lead to a large amount of AE activity. The formation of GP(I) zones has been associated with an increase in burst-type emission that occurs just prior to the yielding of the alloy (Heiple et al., 1981; Scruby et al., 1981; Wadley and Scruby, 1978). The GP(I) zones make dislocation sources less likely to become active and hence increased slip distances occur when they do become active (Thomas and Nutting, 1957). As dislocations become active the large dislocation displacements could easily produce burst type
random non-cooperative motion. This would not generate an initial burst in emission as large as that present in the other specimens.

Although a significant amount of AE activity is due to dislocation motion, other sources of AE activity become active after the matrix begins to yield. In the second region of the total events curve, the event rate becomes steady. This second region appears to be similar for all of the specimens tested. This would suggest the same mechanism is occurring in all of the specimens. As dislocations continue to move, they will interact causing increases in the dislocation density. The increasing dislocation density will reduce slip distances and lead to a reduction of AE activity from dislocations. As cross-slip occurs and dislocation pileups are freed, some AE activity will continue from dislocations. It also appears that cracking of inclusions may be occurring, due to the deformation incompatibility with the matrix. The fracturing of inclusions would be consistent with some of the activity observed by Cousland and Scala (1981, 1983) where the AE activity begins after yielding of the matrix. The linear cumulative events are also consistent with the AE activity observed in the 6061 aluminum specimens tested (see Figs. 12 and 13). The matrix material in one of the composite specimens that had been loaded and unloaded was dissolved, using HCl. The fibers were examined and few broken fibers were found. For this reason the large number of events could not be associated with fiber breaking, although fiber breaking may account for some of the activity, this contribution is not considered significant.
In the loading and unloading experiments, there is some reverse plastic deformation at the end of unloading; however, there is no AE activity. The lack of large AE activity is probably due to the smaller number of dislocations that become active in reverse deformation, compared to those that were active during loading. Upon unloading, a large number of events occur just before the maximum load, as shown in Figs. 10 and 11. This behavior could not be explained except with dislocation motion as the source of AE activity. During loading, dislocation multiplication, precipitates, inclusions, fibers, etc. produce obstacles to dislocation motion. Upon unloading, due to some reverse plastic deformation, dislocations are pushed from the obstacles in the reversed direction making them momentarily unpinned. Upon reloading, these dislocations have a short distance to move before they get pinned again. The motion of large numbers of unpinned dislocations give rise to a large number of events, as shown in Figs. 10 and 11. The specimen continues to produce AE at the constant rate after yielding due to some dislocation activity and fracturing of inclusions. Acoustic emission activity of the composite vs. strain was similar to that observed for Incoloy 901 superalloy by Fang and Berkovits (1995), with high event rates upon yielding followed by a constant event rate. This AE behavior was also attributed to dislocation motion in the first region and primarily to inclusion fracture in the second region.

Failure in the composite occurs at a significantly lower stress than expected, when calculated using the rule of mixtures. The expected tensile strength of the composite is 1.02 GPa and the maximum tensile strength measured was 480 MPa. The formation of GP zones in the matrix leads to a coarse slip. This coarse slip can impose large shear stresses on the fibers leading to their failure. Fleischmann et al. (1991) found fiber fractures to occur, in a short-carbon-fiber-reinforced aluminum composite, by the formation of shear slip bands in the matrix. The shear slip bands overloaded the fibers and caused them to fail. The fractured inclusions also act as stress concentration sources on the fibers, leading to their failure. These failed fibers could initiate composite fracture. Herring et al. (1973) showed that for a composite with little variation in fiber strength, failure may be caused by the strength of the weakest fiber. The composite fails through the failure of a few fibers. These fractured fibers cause surrounding fibers to be overloaded and fail. The surrounding fibers are overloaded due to the strong bonding between fiber and matrix, which transfers loads. This failure rapidly propagates throughout the specimen causing its fracture. This can be observed in the fracture surfaces, which have flat regions and little or no fiber pullout, as shown in Fig. 16. Besides the flat nature of the fracture surface, this figure also shows extensive plastic deformation in the matrix between the fibers. This behavior is also consistent with that observed in similar composites (McCullough et al., 1994).

3.4 Acousto-Ultrasonics

Prior to the tensile testing, all of the composite specimens were tested using the acousto-ultrasonic technique. The entire waveform was recorded and stored on computer and the stress-wave factor (SWF) was calculated. For initial evaluation and simplicity, the energy of the waveform was used and identified as SWF. The SWF is related to the sum of the square of root-mean-square voltage of the waveform (Vary, 1987).

For the initial study, the entire waveform, which contained multiple reflections, was used in the calculations of SWF. The results are plotted against fracture strength in Fig. 17. There appears to be some trend in the data, although the data is somewhat scattered. By using a smaller section of the waveform and calculating other SWFs it may be possible to obtain a better correlation between SWF and the tensile strength of the specimens.

![Normalized SWF vs. Tensile Strength](image)

**Fig. 17** Normalized SWF vs. tensile strength of composites with various heat treatments.

4. Conclusion

Acoustic emission was monitored in a 6061-T6 Al alloy loaded normal and parallel to the rolling direction. The events started after yielding and followed a linear trend with increasing strain. The events are believed to be due to inclusion cracking. The specimens loaded in the transverse direction had a significantly higher number of events. This increased number of events in the transverse specimen is due to the differences in alignment of the inclusions.

Acoustic emission was monitored in a number of composite specimens with different heat treatments. The AE activity began just prior to the yielding of the matrix and quickly rose to a high rate. The rate of the AE activity in the composite then decreased to a steady rate that continued to failure. The initial activity was attributed to a substantial number of dislocations moving in small regions of the matrix material. In contrast, this mechanism does not
produce activity in unreinforced 6061 Al due to its easy cross slip system and large grain size. The activity during the constant AE event rate is believed to be due to inclusion cracking. This activity was similar to the events occurring in the 6061 alloy. Since little fiber breaking was found to occur, it is not expected to have contributed significantly to the AE activity.

The AE activity of composites was monitored during loading and reloading experiments. During reloading of the composites the AE activity quickly rose after yielding of the matrix. This rise was attributed to a sudden increase in mobile dislocations. If the specimen was loaded above its previous level the AE event rate continued at the constant rate observed prior to unloading.

The composite failure is initiated from the failure of a few fibers. It is believed that fractured inclusions and shear slip bands may overload and cause failure of some fibers. This failure rapidly propagates and causes the composite to fail. The networks of inclusions formed during casting of the composite are also believed to contribute to the AE activity and promote early failure of the composite.

Acknowledgments

The authors would like to acknowledge Prof. J. Blucher for manufacturing the composites and Dr. Jinkui Li for the scanning electron microscopy and microhardness data. The financial support of ARPA under grant MDA 972-93-1-0023 is gratefully acknowledged.

References


K. Komai, K. Minoshima and T. Funato (1993), "Tensile and Tension-Tension Fatigue Fracture Behavior of a γ-
Al2O3/Al Metal Matrix Composite at Room and Elevated Temperature", Fractography of Modern Engineering


M. Madhukar and J. Awerbuch (1986), "Monitoring Damage Progression in Center-Notched Boron/Aluminum
Laminates Through Acoustic Emission", Composite Materials: Testing and Design (Seventh Conference),

C. McCullough, H. E. Deve and T. E. Channel (1994), "Mechanical response of continuous fiber-reinforced AI2O3-


Materials Science Letters, 3, 268-270.


A. D. McLeod and C. M. Gabryel (1992), "Kinetics of the Growth of Spinel, MgAl2O4, on Alumina Particulate in

A. Mortensen, V. T. Michaud and M. C. Flemmings (1993), "Pressure Infiltration Processing of Reinforced
Aluminum", JOM, 45, 36-43.


aluminum-magnesium alloy", Philosophical Magazine A, 44(2), 249-274.


D. A. Ulman, and E. G. Henneke II (1982), "Nondestructive Evaluation of Damage in FP/Aluminum
Composites", Composite Materials: Testing and Design (Sixth Conference), ASTM STP 787, 1982. ASTM,


H. N. G. Wadley and C. B. Scruby (1978), "Effect of ageing at 170°C on acoustic emission during deformation of
Al-4%Cu", Metal Science, 12(June), 285-289.

440 Fiber Reinforced Composites", Progress report to DARPA, (unpublished)
40th Meeting of Acoustic Emission Working Group and Primer

June 9 - 13, 1997, Northwestern University, Evanston, Illinois

The next AEWG meeting is sponsored by Infrastructure Technology Institute of Northwestern University. It will be held on June 9 to 13, 1997 at their Evanston, Illinois campus and is chaired by David W. Prine. Primer will be given on the first day, while two-day ASTM E-7 meeting will follow the AEWG.


Please submit a provisional title and brief abstract of proposed presentations by March 1, 1997 to

David W. Prine, Program Chair, 40th AEWG Meeting, Infrastructure Technology Institute, Northwestern University, 1801 Maple Avenue, Evanston, Illinois 60201-3140
Telephone: (847) 491-2873 Fax: (847) 467-2056 E-mail: dprine@nwu.edu

MEETING SCHEDULE (Tentative):
June 8, Monday 8:00 am - 4:30 pm:
Primer: Introduction to Acoustic Emission and Acousto-Ultrasoundics,
Location: Infrastructure Technology Inst., 1801 Maple Avenue, Evanston, IL
June 10, Tuesday 8:30 am - 5:00 pm:
Technical Sessions, Norris University Center, 1999 S. Campus Dr.
June 11, Wednesday 8:30 am - 5:00 pm:
Technical Sessions (Norris University Center)
5:00 - 6:30 pm: Business Meeting (Norris University Center)
7:00 - 10:00 pm: Awards Banquet, Omni Orrington Hotel, 1710 Omngton Ave.
June 12, Thursday 8:00 am - 4:30 pm:
ASTM-E7 Meeting, Infrastructure Technology Inst.
June 13, Friday 8:00 am - 12:00 pm:
ASTM-E7 Meeting (con't), Infrastructure Technology Inst.

ACCOMMODATION: A block of rooms has been reserved at the Omni Orrington Hotel located in downtown Evanston. The room rate is $94 plus tax per night for single occupancy, and $104 plus tax per night for double occupancy. The awards banquet will be held at this location. The fee for the regular technical meeting is $65. This will include a conference booklet with printed copies of the abstracts, refreshments each day of the meeting, and the Banquet Dinner on Wednesday evening.

Chicago's O'Hare International Airport is only a 35 to 40 minute drive from the Orrington Hotel in downtown Evanston. Bus service is available from O'Hare to the hotel. Public transportation is also available to Evanston from the airport.

PRIMER: A one-day course, Introduction to Acoustic Emission and Acousto-Ultrasoundics, will be held to provide a basic introduction. This is an opportunity to familiarize yourself with the most up-to-date technology by attending a series of classes conducted by experts in the field. The additional fee of $30 for the Primer will include six hours of instruction, refreshments and course notes. A list of the speakers and topics for the primer will be provided at a later time. Paid attendees of the Primer may attend the technical sessions of the regular AEWG meeting at a reduced rate of $50.

Up-to-date information for this meeting will be available at the World Wide Web site:
http://iti.acns.nwu.edu/clear/infr/aewg.html
Pattern Recognition of Acoustic Signatures Using ART2-A Neural Network

Shahla Keyvan and Jyothi Nagaraj

Abstract

Acoustic emission (AE) signals are produced from loose parts hitting a pipe wall or tube sheet of a steam generator or other surfaces of the coolant system boundary of a nuclear reactor. Present methods to detect loose parts do not provide adequate information on the size or location of a loose part. The goal of this research is to analyze AE signature of a loose object in the coolant stream of a nuclear reactor using state-of-the-art technology, namely, artificial neural networks and provide information on the size, mass, and location of the object. This feasibility study utilized the Adaptive Resonance Theory (ART) family of neural networks and examined the capability of ART2-A neural networks for pattern recognition of AE signatures created from objects of different masses. The results indicate that ART2-A neural networks can successfully classify patterns of different masses and impact energies.

1. Introduction

Acoustic emission (AE) technology has been applied for diagnostics and monitoring purpose in nuclear reactors. Currently, this technique is utilized in the following areas (Keyvan, 1990; Keyvan and King, 1991-92):
- Acoustic emission crack detection,
- Sodium boiling detection in Liquid Metal Reactors (LMRs),
- Loose parts monitoring,
- Leak detection monitoring,
- Valve position monitoring.

This research studies AE signature for loose parts monitoring purpose. The metal impact generates stress waves creating the motion on both internal and external surfaces of the reactor coolant system pressure boundary which in turn can be detected with sensors. The external measurement of acceleration is the basis for loose part detection and diagnostics. These acoustic emissions are dependent on size, mass, and shape of the loose part and material and geometry between the AE source and sensor (Mayo et al., 1988).

2. ART2-A Neural Network

ART represents a family of neural networks, which self-organize categories in response to arbitrary sequences of input patterns in real time for pattern recognition. A class of these networks called ART2 (Carpenter and Grossberg, 1987) is an unsupervised paradigm and responds to both binary and analog patterns. ART2-A ("algorithmic" ART) is a special case of ART2 which emphasizes the intermediate and fast learning rates, hence accelerating the learning process (Carpenter et al., 1991). Due to the utilization of algebraic equations and simplistic arithmetic procedures which involve less iterations, ART2-A is typically three orders of magnitude faster than ART2. Its algorithmic type nature lends itself for rapid prototyping in hardware and software.

The most challenging task in the application of ART2-A is obtaining the appropriate vigilance for proper classification. The vigilance parameter ($\rho$), a number between 0 and 1, sets the criterion for the degree of match between patterns. That is, under exact same condition, lower vigil-
lance leads to coarser categories and higher vigilance to finer categories. An appropriate vigilance parameter is usually obtained by trial and error.

Fig. 1 shows the architecture of the ART2-A paradigm. ART2-A has three fields: $F_0$, $F_1$, and $F_2$. The output of the $F_1$ field which is also the output of the $F_0$ field is the vector $I$ defined by:

$$I = \text{normal}(f(\text{normal}(I^0)))$$  \hfill (1)

where $I^0$ is an input vector of dimensionality $M$, and normal is an operator defined by

$$\text{normal}(x) = x/\|x\|$$  \hfill (2)

and $f(x)$ is a piecewise linear function:

$$f(x) = \begin{cases} 0 & \text{if } 0 \leq x \leq \theta \\ x & \text{if } x \geq \theta \end{cases}$$  \hfill (3)

with $0 < \theta \leq (M)^{1/2}$.

The weights or the Long-Term Memory (LTM) vector in ART2-A is scaled. As in ART 2, the $F_2$ node in ART2-A makes a choice if the $J$th node becomes maximally active. In addition, the $F_2$ Short-Term Memory (STM) activation represents the degree of match of the vector $I$ and the scaled LTM vector.

LTM adjustments are performed in a single iteration and are reduced to algebraic equations for fast and intermediate learning (which may need more trials to achieve stable categories) as follows:

$$z_J = \begin{cases} I & \text{if } J \text{ is uncommitted} \\ \text{normal}(\beta \text{normal}(\psi) + (1-\beta)Z_J) & \text{if } J \text{ is committed} \end{cases}$$  \hfill (4)

where

$$\psi_i = \begin{cases} I_i & \text{if } Z_J > \theta \\ 0 & \text{otherwise} \end{cases}$$  \hfill (5)

and $0 \leq \beta \leq 1$ (e.g., $\beta = 1$ for fast learning).

3. Data Acquisition

The AE signals are obtained experimentally at the Acoustics Laboratory, Mechanical Engineering Department, University of Missouri–Rolla. The experimental setup utilizes an AE signal analyzer, which consists of a Physical Acoustics Corp. LOCAN 420D Analyzer (essentially an adapted 486 PC with a transient recorder analyzer–TRA board), TRA–212 software and a PAC U1000–150 resonant piezoelectric sensor. The experiment was conducted using steel weights of 50 and 100 grams being dropped in a steel tube. AE sensor is attached to the bottom of the steel tube. The sensor feeds the signal to the AE analyzer, which digitizes the collected signals and writes them to the disk. Steel tubes of two different lengths are used to obtain AE signals having two different features of weight and distance inherent in them. The long tube is 0.984 m in length and the short tube is 0.314 m. The sampling rate is set to 50 kHz and the sample length is 1000. Four different data sets are collected; the long or short tube with the weights; 50 and 100 grams. Figures 2 through 5 show examples of the four sets of data. A feasibility study is then performed to examine the performance of the ART2-A neural network in recognizing these AE signatures apart.

4. ART2-A Performance

The four sets of AE signals: 50 g short tube (50S), 50 g long tube (50L), 100 g short tube (100S), and 100 g long tube (100L); are used for pattern recognition and classification by ART2-A neural network.

Initially, the ART2-A neural network paradigm is examined as a pattern classifier. Two sets of the 50S signals followed by two sets of the 50L signals were given as input to the ART2-A neural network. The neural network recognized the 50S and 50L signals apart, classifying them into two categories. The first category is represented by 0 and corresponds to the 50S signal. The second category is represented by 1 and corresponds to the 50L signal. Thus, the desired output of 0 0 1 1 was obtained. After experimenting with a number of vigilance values, the output was obtained at a vigilance of 0.32. Similarly, two sets of the 100S signals followed by two sets of the 100L signals were given as input to the neural network. The neural network recognized the 100S and 100L signals apart, classifying them.
into two categories represented by 0 and 1 respectively. The desired output of 0 0 1 1 was obtained. This was accomplished at a vigilance of 0.28. Results are summarized in Table 1. In both cases, the neural network identified the distance feature in the signal (short vs. long) and distinguished the signals apart. Thus, confirming the capability of ART2-A unsupervised neural networks for proper pattern recognition.
Fig. 4 Signal generated from short tube, 50 grams. Sampling rate = 50 kHz.

Fig. 5 Signal generated from long tube, 100 grams. Sampling rate = 50 kHz.

Next, the ART2-A paradigm is used as a pseudo-supervised pattern classifier network and the following experiments are conducted. In these experiments, the ART2-A network is first used as an unsupervised pattern classifier. In the classification process, long term memory (LTM) is created. Then, test signals are given as input to the neural network and tested against the LTM (weights) created earlier.
Table 1 Performance of the ART2-A network as a Pattern Classifier

<table>
<thead>
<tr>
<th>Case</th>
<th>Input Signals used</th>
<th>No. of Patterns of each signal</th>
<th>Set Size</th>
<th>Vigilance</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50S, 50L</td>
<td>2</td>
<td>1000</td>
<td>0.32</td>
<td>011</td>
</tr>
<tr>
<td>2</td>
<td>100S, 100L</td>
<td>2</td>
<td>1000</td>
<td>0.28</td>
<td>011</td>
</tr>
</tbody>
</table>

Table 2 Effect of Vigilance on Classification of AE Signals

<table>
<thead>
<tr>
<th>Case</th>
<th>Input Signals used</th>
<th>No. of Patterns of each signal</th>
<th>Set Size</th>
<th>Range of Vigilance (p)</th>
<th>Desired Output Obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50S, 50L</td>
<td>1</td>
<td>1000</td>
<td>0.36 -- 0.9</td>
<td>01</td>
</tr>
<tr>
<td>2</td>
<td>100S, 100L</td>
<td>1</td>
<td>1000</td>
<td>0.29 -- 0.9</td>
<td>01</td>
</tr>
<tr>
<td>3</td>
<td>50S, 100S</td>
<td>1</td>
<td>1000</td>
<td>0.0 -- 0.31</td>
<td>00</td>
</tr>
<tr>
<td>4</td>
<td>50L, 100L</td>
<td>1</td>
<td>1000</td>
<td>0.0 -- 0.33</td>
<td>00</td>
</tr>
<tr>
<td>5</td>
<td>50S, 100L</td>
<td>1</td>
<td>1000</td>
<td>0.35 -- 0.99</td>
<td>01</td>
</tr>
</tbody>
</table>

Experiment A:

The following experiment was conducted to study the effect of vigilance in classifying the AE signals. Different combinations of input signals were applied as input to the neural network. In each case, the range of vigilance values necessary to obtain the desired output was determined. The input signals, desired output, and the minimum and maximum vigilance values for each case are summarized in Table 2. For case 1 and case 2, it was intended to find the range of the vigilance values at which the two input signals are classified into separate categories (represented by 0 and 1) based on the distance features (short and long respectively). For case 3 and case 4, it was intended to find the range of the vigilance values at which the two input signals are classified into the same category (represented by 0) based on the distance feature (short and long).

As shown in Table 2, any common parameter (weight/distance) will be dominant and will not allow distinguishing patterns apart for up to a minimum vigilance $p$. This minimum $p$ is 0.36, 0.29, 0.31, 0.33, 0.35 for cases 1 to 5, respectively.

Experiment B:

The weights or LTM of the ART2-A network are created using one set of 50S signal as input and obtaining the expected output 0 representing the 50S signal category. Let this 50S signal which is used to create the LTM be designated as 50S(R) where R is for reference. The LTM are created at a vigilance of 0.32. Then, different input signals are tested one at a time against the original LTM created using the 50S(R) signal at a vigilance of 0.32. Results are summarized in Table 3. At vigilance of 0.32 the desired output are obtained for cases 1a, 1b, and 2. In case 3, the test result is 0 where as the desired output is 1. This is due to the fact that, 50S(R) and 50L signals are recognized apart only at vigilance of 0.36 and above (Table 2). So, at a vigilance of 0.32, 50L signal is recognized under the same category as the 50S(R) signal and hence the output of 0. Similarly in case 4, desired output of 1 is not obtained due to the fact that 50S(R) and 100L signals are recognized apart only at vigilance of 0.35 and above (Table 2).

The above experiment is repeated at a vigilance of 0.36 (maximum of all the minimum vigilance in Table 2). Case 1a - another set of 50S signal is given as input to the neural network, and an output of 1 is obtained instead of the desired output of 0. It can be observed from the results of Table 1 that, at a vigilance of 0.32, 50S(R) and 50S signals are classified under the same category (represented by 0). At any vigilance above 0.32 the two signals 50S are classified as two different categories, hence a vigilance greater than 0.32 is not appropriate. Therefore, indeed at an inappropriate high vigilance of 0.36, even the small differences in the two signals 50S(R) and 50S become dominant and they are classified as two different signals, hence, as expected the output of 1 in this case. In all other cases (1b, 2, 3, and 4), the test output is the desired output indicating that a vigilance of 0.36 is appropriate for distinguishing these patterns from the 50S(R) signal. Therefore, it is concluded that even with no pre-processing of the raw AE signal data, ART2-A can classify signals properly if the appropriate vigilance ($p$), is applied.

5. Conclusions

The performance of ART2-A neural network is examined in two ways; first as an unsupervised pattern classifier using AE signals containing 2 features, distance and weight. The signals are used in the analysis and identification proc-
Table 3 Performance of the ART2-A as a pseudo-supervised network.

<table>
<thead>
<tr>
<th>Case</th>
<th>Input Signals used</th>
<th>No. of Patterns of each signal</th>
<th>Set Size</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>To create LTM</td>
<td>50S(R)</td>
<td>1</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>Testing (1a)</td>
<td>50S</td>
<td>1</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>Testing (1b)</td>
<td>50S(R)</td>
<td>1</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>Testing (2)</td>
<td>100S</td>
<td>1</td>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>Testing (3)</td>
<td>50L</td>
<td>1</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>Testing (4)</td>
<td>100L</td>
<td>1</td>
<td>1000</td>
<td>1</td>
</tr>
</tbody>
</table>

The ART2-A paradigm is then used as a pseudo-supervised pattern classifier, where signals are tested against the LTM (weights) created earlier during the unsupervised pattern classification process. Desirable results are obtained when appropriate vigilance (p) is applied. Although ART2-A neural network can successfully classify AE signals associated with different mass and impact energy (distance) with no pre-processing, suitable pre-processing and feature extraction of the AE signals is recommended in order to avoid the noise factors inherent in the signals.

Acknowledgments

This work is supported by the National Science Foundation (Grant #ECS-9415004).

References


Far-field Acoustic Emission Waves by Three-Dimensional Finite Element Modeling of Pencil-Lead Breaks on a Thick Plate

M. A. Hamstad, J. Gary and A. O'Gallagher

Abstract

We have performed a study to validate a three-dimensional dynamic finite element code for calculating expected dynamic displacement fields in the far field from various types of acoustic emission sources. This work uses several approaches to complete the validation and to determine values for key parameters so that acoustic emission sources can be modeled. These parameters include the cell size, source diameter, and source rise time. Laboratory experiments using pencil-lead breaks on a large 25.4 mm thick steel plate were used to validate the three-dimensional code. Lead breaks were carried out both on the top surface of the plate and at various depths along one edge. Using a calibrated, wideband displacement sensor, the experimental out-of-plane displacements versus time were quantitatively compared to calculated displacements at distances of up to 366 mm from the source. In addition, certain interesting cases were examined with the code.

1. Introduction

This paper is the second publication of a research effort aimed at the use of dynamic finite element modeling (DFEM) to predict the far-field acoustic emission (AE) displacement fields generated by general AE sources buried in a plate. A previous publication (Gary and Hamstad, 1994) reported the validation of an axisymmetric two-dimensional (2-D) finite element code. That code was validated by observing the close quantitative correspondence between the DFEM results and experimental measurements using a wideband, flat-with-frequency sensor. This sensor had been calibrated for out-of-plane displacements. The source for both the modeling and experiment was an out-of-plane pencil-lead break at 254 mm from the measurement point on an aluminum alloy plate 3.1 mm thick.

As Gary and Hamstad (1994) pointed out, other approaches to the calculation of far-field displacement fields due to AE sources experience inherent difficulties in modeling real AE sources. Since a three-dimensional (3-D) DFEM approach does not experience these difficulties, we are pursuing this approach to provide modeling results for comparison to experimental AE results.

The purpose of this research is to report on the validation of a 3-D DFEM calculation of the dynamic far-field displacements. As before, the validation is accomplished by comparison with experiments with a pencil-lead break source. Other factors (such as mesh or cell size, source diameter, and source rise time), which define computational resources required for DFEM calculations consistent with actual AE testing were examined as well.

2. Experimental Conditions

Only the new experimental conditions will be fully described here. A complete description of the same elements used previously can be found in the paper by Gary and Hamstad (1994). All experimental measurements were carried out on a mild steel plate 25.4 mm thick with lateral dimensions of 1.32 m by 0.78 m. The surfaces of the plate had been ground. Lead breaks, both out-of-plane (surface breaks) and in-plane (edge breaks), were made with 0.3 mm diameter 2H lead. Measurements of out-of-plane displacement were made using a National Institute of Standards and Technology (NIST) Standard Reference Material (SRM) sensor, which has flat frequency response approximately from 20 kHz to 1.2 MHz. The calibration factor of 177.83 MV/m was used to convert the voltage response of the NIST/SRM to absolute displacement for comparison to the DFEM results.

3. Key Aspects of the Numerical Model

Again, only the new relevant aspects are fully described here. Details of the continuing aspects are found in the previous paper (Gary and Hamstad, 1994). The finite element method is based on a leapfrog approximation in time and linear elements in space. A stress-free boundary condition was used on the top and bottom surfaces as well as on the outer edges of the plate. Instead of starting with a stress in the plate, due to force applied by the pencil lead, zero stress is assumed initially. Then a uniformly distributed force is applied over the contact surface of the
lead (source diameter), starting at zero, and rising to a final constant value, with the rise time on the order of a microsecond. As pointed out in our earlier paper, this results in a time-dependent displacement at each point which is the same as that produced by the sudden release of the stress, except for sign and a constant displacement field. The temporal dependence of this applied stress is chosen to approximate the force measured by Breckenridge et al. (1990) as shown in Fig. 1. In the rise time study, a linear rise time was used. In this case, the source force has the following time dependence:

\[ S(t) = \begin{cases} S_0/t & 0 < t < \tau \\ S_0 & t > \tau \end{cases} \tag{1} \]

The force constant \( S_0 \) was typically 1 N with the rise time \( \tau \) taking on different values. In all cases, the material modeled was steel with compressional and shear-wave velocities of 5940 m/s and 3220 m/s (Kolsky, 1963) and a mass density of 7.800 Mglm\(^{-3}\).

For calculations with the 2-D axisymmetric model, the plate thickness, \( d \), was 25.4 mm and the outer boundary was at 40\( d \) (that is, a plate radius of 1.016 m). For a typical case, the displacement-time series (described here) were taken at a distance of 8\( d \) from the source at the center. At this distance, we observed no significant reflection from the outer boundary for the duration of our calculations. The 3-D model used the same plate thickness (\( d = 25.4 \) mm) with a square surface 32\( d \) on each side. A typical out-of-plane source was located on the top surface at \( x = 12d, y = 16d \), with the displacement measured at \( x = 20d, y = 16d \) (note that the coordinate origin was at a plate corner). For edge sources, the source typically was located at \( x = 0d, y = 16d \), and the displacement was computed for sources at various \( z \) positions. The cell aspect ratio was typically unity; that is, \( \Delta z = \Delta r \) for the 2-D model, and \( \Delta x = \Delta y = \Delta z \) in 3-D. The 3-D code, using a resolution of 24 cells across the plate thickness \( d \), required 21 hours of central processor unit (CPU) time on a workstation to run the model out 236 ms. This model size requires about 400 Mbyte of computer random access memory. The 2-D axisymmetric model using the same resolution (24 cells), on a circular plate of radius 40\( d \) requires only 38 s of CPU time.

4. Validation Studies

Several different aspects were examined to validate the 3-D DFEM code. Some of the validation approaches were necessary due to the limitations imposed by the currently available computing facilities, when using the 3-D code. These facilities limit the resolution (that is, the number of points through the plate thickness) that can be used to obtain results in the far field. To guide the validation studies, information derived from typical AE testing was used. First, typical far-field AE has a maximum frequency of interest of about 1 MHz. Second, it is desirable to consider frequencies high enough to be able to observe the Rayleigh surface wave. Finally, typical field use of AE operates with a high-pass filter having the cut-off frequency of 50 to 100 kHz.

4.1 Comparison of 3-D and 2-D Codes

Using the pencil-lead break source, the two codes were compared for the out-of-plane displacement at 203 mm from the out-of-plane axisymmetric source on the top surface of a steel plate 25.4 mm thick. The force-time characteristics of the source are shown in Fig. 1 (Breckenridge, et al., 1990). The key parameters for this simulation included:

(a) resolution, 24 cells through the plate; 
(b) source diameter, 2.1 mm; and
(c) rise time of pencil-lead break source, about 1 ms.

Figure 2 shows that the waveform of wideband 3-D displacement versus time (truncated at the displacement null just beyond 200 ms) is nearly identical to the 2-D waveform. The quantitative comparison extends to the relative-frequency spectrum (3-D spectrum/2-D spectrum) shown in Fig. 2c, where the waveforms used to calculate the spectra are those in Figs. 2a and b. The relative-frequency spectrum is only shown to 500 kHz since the 24 cell resolution limits the high-frequency response of the simulation, as will be shown more directly later.

4.2 Source Size and Rise Time

We had to use the 2-D axisymmetric code for the studies of source-size and rise-time requirements for the physically thick 25.4 mm plate. This limitation was required to provide for high resolution with the available computing facility. The criterion used in these studies was good definition of the Rayleigh wave at a distance of 203 mm from the out-of-plane source. Since the source rise time and source diameter interact, some iteration was necessary to achieve the final results. Figure 3 shows that a
rise time (linear, as specified in equation 1) on the order of 0.5 ms provides good time definition of the Rayleigh wave in the out-of-plane displacement, while a 1.5 ms rise time does not. We judge that a linear rise time of 1 ms or less provides sufficient definition. In this figure the resolution was 192 cells; the source diameter was 1.1 mm; and a linear rise time out-of-plane source was used. Figure 4 shows that good time resolution of the out-of-plane Rayleigh wave displacement was obtained for an out-of-plane source diameter of 0.528 mm, while a 4.23 mm source diameter results in poor resolution. In this figure the source was the pencil-lead break (Fig. 1) and the resolution was 192 cells. A four-pole Butterworth high-pass filter with 50 kHz cut-off was used to obtain the curves shown in Fig. 4. This filter provided better definition of the Rayleigh wave in the resulting waveform because it removed the large low-frequency part of the out-of-plane displacement. We judge that a source diameter of 3 mm or less provides sufficient definition.

4.3 Resolution Studies

The 2-D axisymmetric code was again required for resolution studies. To examine the effect of resolution on the accuracy of the upper range of frequencies in the DFEM simulation, a high-resolution run with 384 cells across the thickness was used (a cell size of 66 mm) as a reference curve. Relative spectra for lower resolutions were then calculated. Figure 5 shows the relative spectra for 24, 72, and 192 cells relative to the 384-cell spectrum. The parameters for this figure were:

(a) distance from source to out-of-plane displacement, 203 mm;
(b) plate thickness, 25.4 mm;
(c) pencil-lead break out-of-plane source; and
(d) source diameter varying as necessary from 0.53 to 2.1 mm.

Clearly, a resolution between 72 and 192 cells seems to be required. This question of resolution will be addressed again.

Fig. 2 Same surface out-of-plane displacement versus time at 203 mm from an out-of-plane pencil-lead break on a 25.4 mm thick steel plate: (a) 3-D code, (b) 2-D code, (c) ratio of 3-D spectrum/2-D spectrum. Parameters: resolution = 24 cells, source diameter = 2.1 mm. In (c), smoothed over 50 kHz for clarity.
4.4 Comparisons with Experiments

The first comparison between the 3-D DFEM and experiment was made for a pencil-lead break applied on the edge of a plate. This pencil-lead break was located at 1.0 mm from the bottom edge of the 25.4 mm thick plate. Figure 6 shows the wideband comparison of the top surface out-of-plane displacement versus time at a distance of 366 mm from the edge along the top surface of the plate. The resolution was 26 cells across the 25.4 mm thickness; the source diameter was 1.9 mm, and the pencil-lead break source (Fig. 1) was used. Clearly, Fig. 6 shows an excellent correspondence. To examine the correspondence more closely, both the experimental and calculated waveforms were filtered with a 50 kHz high-pass, four-pole Butterworth filter. These filtered out-of-plane waveforms are shown in Fig. 7. Except for two small regions, the two waveforms are quantitatively nearly identical. They differ in the arrival region of the "sharp" Rayleigh wave, which arrives just beyond the time of 80 ms and to a lesser degree due to another "sharp" wave arrival at approximately 115 ms. Both of these features are missing in the DFEM waveform. This result is not surprising considering that the resolution is only 26 cells across the plate and that Fig. 5 showed significant deviations above 300 kHz for a similar low-resolution calculation.

To examine the failure of the experimental Rayleigh wave to correspond with the 3-D DFEM calculation, we ran a simulation with the axisymmetric 2-D code for an out-of-plane pencil-lead break source on the top surface of the plate. This result was compared to an experimental waveform. Both the calculated and experimental waveforms were at a distance of 203 mm from the source. Figure 8
Fig. 5 Spectra of waveforms with various resolutions relative to 384 cell spectrum. Parameters: 2-D code; 25.4 mm thick plate; pencil-lead break out-of-plane source; source diameter, 0.53 to 2.1 mm as required; distance to source, 203 mm; out-of-plane displacement. Smoothed over 30 kHz for clarity.

shows the nearly identical experimental and DFEM out-of-plane waveforms after applying the 50 kHz high-pass filter to both the calculated and the experimental waveforms. In this case, the DFEM waveform still has the high-frequency Rayleigh-type features at approximately 40 ms and 60 ms. The key difference is that in this case the 2-D code allowed a resolution of 384 cells to be used. The other source parameters were a source size of 0.528 mm diameter and the pencil-lead break source with its nominal 1 ms rise time.

5. Other Source Positions in the Thick Plate

A number of other source positions of interest were examined using the DFEM code for the physically thick plate. Some of these calculations are limited in their ability to show Rayleigh wave behavior, but, as above, they provide excellent quantitative results for the rest of the wideband waveforms.

5.1 Dependence on Plate Edge Source Position (3-D code)

Figure 9 shows the substantial differences in the out-of-plane displacement of the top surface of the 25.4 mm plate at a distance of 366 mm from the edge of the plate as the pencil-lead break source is moved from near the bottom of the edge to the center of the edge and just a little below the center plane of the plate. These computed waveforms had a source diameter of 2.1 mm and a resolution of 24 cells for the pencil-lead break source with the nominal 1-ms rise time. Figure 9 clearly shows that only at the mid-plane of the plate does the low-amplitude flexural part of the observed waveform disappear. The corresponding relative
5.2 Edge Source Versus Out-of-Plane Top-Surface Source (3-D code)

Figure 11 shows the difference in the top-surface displacement (out-of-plane) at a distance of 366 mm from the source for lead-breaks near the bottom edge and on the top surface. The source diameter was 2.1 mm; the resolution was 24 cells; and the rise time of the pencil-lead break source was about 1 ms. This edge break has slightly more extensional-mode amplitude than the flexural mode, but both waveforms fit nicely on the same displacement scale.

6. Other Waveforms of Interest

Figure 12 shows the top and bottom surface spatial distributions of out-of-plane displacement from an out-of-plane top-surface lead break on the 25.4 mm thick steel plate. These waveforms were taken at 63 ms after the start of the pencil-lead break source. Two different spatial scales are displayed in the figure. We used the 2-D axisymmetric code with a source diameter of 1.1 mm and a resolution of 192 cells across the plate thickness. The large positive spike on the top surface shows the position of the high-frequency Rayleigh wave. The missing Rayleigh wave on the bottom surface displacement is the most significant difference.
Fig. 9 Series of top-surface out-of-plane displacement waveforms at 366 mm from edge pencil-lead breaks. The edge breaks were at various positions along the edge. Parameters: 3-D code; 24 cells; source size, 2.1 mm; steel plate 25.4 mm thick.

Figures 13 and 14 show that the DFEM result also provides the in-plane displacements as well as the out-of-plane displacements. Figure 13 shows these displacements at the top surface a distance of 203 mm from a pencil-lead break source on the top surface. The 2-D code was used to generate this result with a source diameter of 0.53 mm and a resolution of 192 cells. Clearly, the out-of-plane displacements are larger due to the out-of-plane source. Figure 14, which was obtained with the 3-D code, gives the two displacements on the top surface a distance of 366 mm from an edge pencil-lead break. The edge pencil-lead break was at a distance of 1.0 mm up from the bottom edge of the plate. Other source parameters were a resolution of 26 cells and a source diameter of 1.9 mm. The large in-plane displacement (relative to the out-of-plane displacement) is also shown after being filtered numerically by a 4-pole Butterworth filter set for a 50 kHz high-pass, which is representative of real AE monitoring. The filtered in-plane displacements have similar values to those of the out-of-plane signal also shown after the same filter was applied.

7. Resolution Required to Reproduce the Rayleigh Wave

In this section, we consider the spectral content of the Rayleigh pulse and the finite element resolution required to clearly represent it. First, we note that the sensor aperture of the NIST/SRM is 1.5 mm, which implies that the sensor would not provide good detection in steel for frequencies above 1.5 to 2 MHz. However, this sensor picks up the Rayleigh pulse. In addition, to estimate the frequency content of the computed time series, we truncated the Fourier transform of the time series (displacement versus time), then reconstructed the time series for the truncated transform. With a low-pass frequency between 600 kHz and 800 kHz, the reconstructed signal was in good agreement with the original. For our material, the Rayleigh wave velocity of 2980 m/s implies a wavelength of 5 mm at 600 kHz. If we assume that 10 to 30 cells per wavelength are adequate, the resolution of this wavelength would imply a mesh size of 0.16 to 0.5 mm, or 50 to 150
Rayleigh wave is displayed for different resolutions with the dashed curve on each plot obtained with a 384-cell resolution. Clearly, 48 cells are not adequate. The discrepancy between the resolution assumed for the numerical model (based upon the low-pass results) and that required to accurately represent the time series led us to suspect that the higher resolution might be needed only in the vicinity of the source. This suggested an experiment, in which the output in the vicinity of the source from a run using 192 cells was used as the boundary condition to drive a far-field computation using 48-cell resolution. This boundary was set at 75 mm from the source. Thus, the domain for the low-resolution run is the original cylindrical plate with a disk of radius 75 mm removed from the center. At each time step the displacements \((u,v)\) were specified along the vertical boundary at 75 mm using the results from the high-resolution run. The results (out-of-plane displacement at 203 mm from the source) of the restarted (48 cell) run are shown in Fig. 16. The time scale is expanded to focus on
Fig. 12 Out-of-plane displacement for source surface (top) and opposite surface (bottom) versus position at 63 ms measured from the initiation of the out-of-plane pencil-lead break source on the top surface of the 25.4-mm-thick steel plate. Note that two different spatial scales are displayed. Parameters: 2-D code; 192 cells; source diameter, 1.1 mm.

Fig. 13 In-plane and out-of-plane displacement waveforms of the top-surface of the 25.4 mm thick steel plate at a distance of 203 mm from the top-surface pencil-lead break source. Parameters: 2-D code; 192 cells; a source diameter of 0.53 mm.
the Rayleigh wave. To examine whether the restarted computation improves the far field results, Fig. 16 can be compared with Figs. 15c and 15b. A run using the pencil-lead break source with 48-cell resolution on the full domain is shown in Fig. 15c. Figure 15b shows the result for 96 cells on the full domain. The restarted calculation (Fig. 16) was clearly better than one (Fig. 15c) at the same resolution (48 cells) for the full domain. However, the representation of the Rayleigh wave in the 96-cell computation for the full domain (Fig. 15b) is far superior to that in the restarted 48-cell computation. This result implies that higher resolution is required away from the source to properly represent the Rayleigh wave.

We next turned to the spatial distribution of the Rayleigh wave. An expanded spatial plot (not shown) of Fig. 12 revealed that the full width of the Rayleigh pulse was 2.7 mm. To represent this pulse with 10 to 30 points required a cell size of 0.09 to 0.27 mm, which is equivalent to 94 to 282 cells across the thickness. This result is consistent with the original 96 to 192 cells (reference Fig. 15) required for good definition of the Rayleigh wave.

8. Discussion of Results

These results have validated in the far-field the 3-D DFEM code and have determined values of key source parameters necessary to provide AE displacement waves, which include the Rayleigh wave. These two source requirements were a rise time on the order of 1 ms or less, and a source diameter not greater than about 3 mm. The key question remaining is that of the resolution required for practical far-field AE modeling by a 3-D code. The answer to this question depends on whether good definition of the Rayleigh wave is required. If accurate modeling of the Rayleigh wave is required, then a cell size of about 0.13 to
A 3-D dynamic finite element code has been validated on a 25.4-mm-thick steel plate as a means of accurately calculating the time dependence of far-field AE displacements. This validation was accomplished by quantitative comparison with experiments using a calibrated wideband sensor. To retain accurate frequency content up to the frequencies of Rayleigh waves, a cell size of about 0.13 to 0.27 mm was required. If providing good definition of the Rayleigh wave is not required, a cell size of about 0.53 mm can be used. To model AE sources that generate frequencies up to the Rayleigh wave frequencies, the source size must be less than about 3 mm diameter and have a rise time of less than about 1 ms. The 3-D code also showed the wide variations in AE waveforms as the depth through the plate thickness was changed for a pencil-lead break source on a plate edge.

Fig. 16 Out-of-plane displacement with expanded time scale to focus on Rayleigh wave from 2-D code on 25.4-mm-thick steel plate at a distance of 203 mm from the out-of-plane pencil-lead break. The source diameter was 0.53 mm and 192 cells were used for a distance of 75 mm, and then 48 cells for the remainder. Dotted reference curve is for 192 cells over the whole distance.

Fig. 17 shows the resolution comparison on the bottom (where the Rayleigh wave is not present) of the 25.4 mm thick plate for an out-of-plane source on the top of the plate. The 2-D DFEM parameters were source diameters of 1.06, 1.06, 2.11, and 4.23 mm respectively for 192, 48, 24, and 12 cells for the pencil-lead break source at 203 mm (parallel to the plate surface) from the plotted out-of-plane displacement. Clearly, a resolution of 48 cells (cell size of 0.53 mm) compares very well with the highest resolution when a 50 kHz high-pass Butterworth filter has been applied. This resolution is within our current computing capability. Further, since our long-term objective is to use the 3-D code to make modeling calculations for buried sources, it is of interest to observe that buried near-field calculations by Pao et al. (1979) do not show a sharp Rayleigh wave. Finally, expected improvements in our computing facilities in the next few years should allow the 3-D calculations for 96 to 192 cells to be conducted.

9. Conclusions

A 3-D dynamic finite element code has been validated on a 25.4-mm-thick steel plate as a means of accurately calculating the time dependence of far-field AE displacements. This validation was accomplished by quantitative comparison with experiments using a calibrated wideband sensor. To retain accurate frequency content up to the frequencies of Rayleigh waves, a cell size of about 0.13 to 0.27 mm was required. If providing good definition of the Rayleigh wave is not required, a cell size of about 0.53 mm can be used. To model AE sources that generate frequencies up to the Rayleigh wave frequencies, the source size must be less than about 3 mm diameter and have a rise time of less than about 1 ms. The 3-D code also showed the wide variations in AE waveforms as the depth through the plate thickness was changed for a pencil-lead break source on a plate edge.

References

F. Breckenridge, T. Proctor, N. Hsu, S. Fick, and D. Eitzen (1990), "Transient sources for acoustic emission work,"

Fig. 15 Out-of-plane displacement with expanded time axis to focus on the Rayleigh wave for different resolutions. Dotted reference curve is for 384 cells. Parameters: 2-D code; source diameter, 0.53 mm; pencil-lead break with rise time, about 1 ms; distance source to displacement, 203 mm on the 25.4-mm-thick steel plate.

0.26 mm is necessary. For our current computing facilities, such a small cell size is not possible for the 3-D code because of excessive computing time. Even for the compromise of high resolution near the source and lower resolution in the far field, the computation time would be excessive. On the other hand, if good definition of the Rayleigh wave is not required, the resolution requirement does not preclude calculations with our currently available facilities. Figure 17 shows the resolution comparison on the bottom (where the Rayleigh wave is not present) of the 25.4 mm thick plate for an out-of-plane source on the top of the plate. The 2-D DFEM parameters were source diameters of 1.06, 1.06, 2.11, and 4.23 mm respectively for 192, 48, 24, and 12 cells for the pencil-lead break source at 203 mm (parallel to the plate surface) from the plotted out-
Fig. 17 Out-of-plane displacement at a horizontal distance of 203 mm from the opposite surface out-of-plane pencil-lead break source versus number of cells across the thickness. All the waveforms shown are after 50 kHz high-pass filtering. Parameters: 2-D code; the source diameter was 1.06 mm for 192 and 48 cells, 2.11 mm for 24 cells, and 4.23 mm for 12 cells. The steel was 25.4 mm thick.


Acoustic Emission Testing of Bolted Connections under Tensile Stress

V. Hänel and W. Thelen

Abstract

Tensile tests were made on bolted connections using standard bolts. In order to examine the acoustic emission (AE) behavior that depends on the applied load, AE parameters of the signals obtained, such as the AE rate and the frequency amplitude spectrum, were determined. Especially, a single frequency parameter, the weighted mean frequency, was taken into consideration. Additionally, an indirect method for the source location was applied. The results were compared with theoretical considerations with respect to the source mechanism and the frequency content of the signals obtained, and they were confirmed qualitatively. The significance of the results for in-process monitoring of bolted connections under stress is illustrated.

1. Introduction

To improve the safety of bolted connections under stress, especially under tensile stress, is an important task. It might be a progress to detect the point, where a structure is beginning to lose its reliability. A bolt has reached this point at its elastic limit, where plastic deformation is setting in. Several authors examined steel specimens during tensile tests referring to the AE behavior, especially the AE rate (Blanchette et al., 1983; Fadeev, 1988; Fuyi, 1988; James and Carpenter, 1986; Lucia and Redondi, 1975; Ono and Yamamoto, 1981; Tandon and Tangri, 1975; Ying and Grigory, 1975). They found an increase of the AE rate in the region of the elastic limit, with an amplitude strongly depending on the material and some other parameters. However, in Glass et al. (1983), a connection between the AE rate and the elastic limit was not found. Methods for source location are given in Fleischmann et al. (1982) and Rindorf (1981). A frequency analysis by one parameter was calculated in Woodward and Harris (1977). In this paper, the characteristics of some AE parameters obtained from bolted connections under tensile stress are presented. It is shown how AE signals of first and second order are produced, and how they depend on the applied load. In particular, the applicability of the results for in-process monitoring of bolted connections was taken into consideration.

2. Experimental Setup

The load necessary for the experiments was applied by a hydraulically controlled tensile testing machine (Fig. 1). A constant elongation rate was not implemented. Having reached the yield point the elongation rate of the bolts rapidly increases, until strain hardening begins. And this is the behavior of a bolt in a real situation. Special attention was given to the mounting of the bolts. The specimens (bolts M10 x 80, German standard DIN 931) were screwed into the mounting in order to realize a bolted connection. However, the experiments concentrated on signals from the bolts. The mounting cone and the washer (Fig. 2) were hardened and drawn. As a result, structural changes during the experiments, which could result in undesired AE signals, were prevented or at least minimized. During the tests the elongation and the time were measured in order to determine the elongation rate. The stress was calculated from the hydraulic pressure and the AE rate was calculated from the event counts and the elongation rate. The AE signals were detected using a commercial wideband AE sensor (Brüel & Kjær 8312) and a self-developed one. The sensor at the bottom of the bolt was spring coupled with high-viscosity oil. In order to calibrate the system a continuous ultrasonic sweep signal (between 100 kHz and 1000 kHz) was fed into the top of the specimen. The data amplified and filtered were acquired by a digital storage oscilloscope. The signal rate and the precision were limited by the 8-bit resolution of the oscilloscope and the storage duration of 0.1 ms per signal (signal length 256 points). The trigger threshold was adjusted just above the noise level. The signals exceeding this threshold (together with the elongation, the pressure and the time) were recorded for increasing load. The recorded data were used to calculate the AE rate and the frequency spectra of the AE signals as a function of the applied load and the elongation (stress-strain curve).

3. Theoretical Considerations

Two sources of AE signals can be considered. AE signals of first order occur at the beginning of the plastic range, because of internal deformation processes. They
usually have a very small amplitude. The highest AE activity is expected to come from the necking zone at the end of the thread (Fig. 3). Additionally, the necking results within the thread produce AE signals as well. These signals are called AE signals of second order, because they are induced indirectly by deformation processes within the bolt. This phenomenon is expected to generate signals with higher amplitude. It is important to note, that these signals have a source mechanism different from the mechanism producing friction signals under low stress. AE signals of second order and friction signals mostly occur in different load ranges. The stress causing a process determines the duration due to the dependence between the stress and the acceleration. The duration of a process limits the frequency range of the signal resulting from this process. As a result, AE signals are expected to possess higher frequency components than friction signals.

Fig. 1 Experimental setup.

Fig. 2 Bolt mounting.

Fig. 3 Source mechanism of AE of second order.

in another effect. Because of the decrease of the bolt diameter, nearly horizontal displacements under high pressure

Fig. 4 Stress $\sigma$ and AE rate $N_s$ versus strain $\Delta l$.

Fig. 5 Mean frequency $f_M$ and stress $\sigma$ vs. strain $\Delta l$. 
4. Acoustic Emission Rate

Figure 4 shows a typical stress-strain curve and the AE rate up to the beginning of the plastic deformation. In the elastic range, the signal level was relatively low followed by a sudden increase at the end of the elastic range. This increase has been identified as being due to the onset of AE, while the signal activity in the elastic range corresponds to friction processes, mostly in the thread.

5. Frequency Analysis

In order to distinguish the signals from the beginning of the test from those obtained at the end of the elastic range, the amplitude spectra were calculated using a fast Fourier transform algorithm. With respect to the statistical behavior of the AE phenomenon a single parameter was extracted from the spectra; i.e., the mean frequency weighted by the amplitude distribution and averaged over 15 signals. Figure 5 shows the mean frequency and the stress versus the strain. In the low stress range the mean frequency is approximately 300 kHz. A mean frequency of approximately 500 kHz was found in the plastic range. A distinct increase of the mean frequency at the end of the elastic range is remarkable. As a result, the mean frequency of 300 kHz can be correlated with friction signals, while AE signals showed a higher mean frequency of approximately 500 kHz. It should be noted that the quantitative values varied with the tests. However, a remarkable difference between friction signals and AE signals was found regularly.

6. Source Location

In order to locate the AE source, one sensor was attached to the bottom of the bolt. The construction of the tensile testing machine made it difficult to access the top of the bolt. Thus a waveguide was inserted between the second sensor and the top of the bolt (Fig. 6). As a result, the effective sound velocity could not be assumed to be uniform throughout the medium, and the AE source could not be located by the arrival time difference of the two sensors alone. Generating artificial AE by a piezoelectric sound transmitter in the region supposed to be the AE source the arrival time difference was compared with the arrival time difference obtained by real AE signals (Figs. 7 and 8). In both cases the arrival time difference was approximately 30 μs. The strongest AE was identified as being originated from the region described. With respect to the geometric proportions an averaged effective sound velocity was estimated. It was of the order of approximately 2000 m/s.
7. Conclusions

The bolted connections used in these experiments showed a remarkable AE activity starting at the end of the elastic region. AE signals could be separated from friction signals by their frequency distribution, which was demonstrated by introducing the weighted mean frequency. Source location experiments identified the signal origin as being in the region of the strongest deformations. The results could possess some evidence for a monitoring system for bolted connections under stress. The critical point where bolted connections are beginning to lose their reliability is the onset of the plastic deformation. A correlation between this region and two AE parameters was found. The AE rate and the averaged mean frequency are strongly increasing at the end of the elastic range. These two effects together could form a criterion in order to detect this loss of reliability and to stop the process in a critical situation.

References


B. Woodward and R.W. Harris (1977), "The Use of Signal Analysis to Identify Sources of Acoustic Emission," Acustica, 37, 190-197.

A Method to Determine the Sensor Transfer Function and its Deconvolution from Acoustic Emission Signals

Bernhard Allemann, Ludwig Gauckler, Wolfgang Hundt and F. Rehsteiner

Abstract

Interests in monitoring of microfracture in brittle materials or any other mechanical process by acoustic emission (AE) are steadily increasing. AE signals carry information about their source transferred in the form of elastic waves. These can be monitored by piezoelectric sensors. The characteristic of the sensor, however, distorts this information severely, particularly in the frequency range near its resonance. Hence, deconvolution of the sensor characteristic is desirable, in order to remove the sensor's effects on the measured data. Due to the high bandwidth and dynamic range of the sensor the evaluation of its characteristic requires a special approach. In this paper, a method for the determination of the transfer function of AE sensors is presented. For this purpose, an appropriate strategy with two simple sensor configurations has been developed. The advantage of the present method is that a sharp electrical impulse is used as an input function instead of an undefined mechanical excitation.

For the determination of the sensor transfer function, a linear set of equations have to be solved. Division in frequency domain yields no reasonable results. By applying optimal deconvolution in time domain, problems of instability can be avoided. This method is also used to deconvolve the transfer function of the sensor in AE signal of subcritical crack growth in alumina ceramics under load in a three point bending test.

1. Introduction

Acoustic emission (AE) can be produced by a sudden release of stress in a solid body caused by a microfracture event in the bulk of a structure. Such an event can be characterised by certain properties such as the amount of energy release, the velocity of crack propagation, the duration and the spatial orientation. Sound waves caused by the fracture event transport information about the process. The piezoelectric sensor converts the acoustic emission into a voltage signal. This signal contains characteristics of the original mechanical excitation, the transfer media (Green's function) and the piezoelectric sensor. In a first step we aim to reduce the influence of the sensor. The general idea is to improve the signals for a characterization of the original mechanical process. This can be reached by determining the transfer function of the sensor and deconvolve it from the measured signal.

The transfer function is defined as the impulse response of a filter - in our case, a piezoelectric sensor. Usually high frequency impulses are generated by short-time mechanical excitations, e.g. impacts of little spheres, electrical discharges (Breckenridge et al., 1990), fracture of a pencil lead (Higo and Inaba, 1988) and of glass capillaries (ASTM, 1993) or fracture of ceramic particles (Heipke et al., 1991). Well known also is noise AE input produced by a helium gas jet (Green and Dingwall, 1978; McBride and Hutchinson, 1978). Laser pulses, too, can be used (Matsuda, 1992). However, in all these cases the description of the input signal is based on a multitude of assumptions. All the methods work with poorly defined input signals, which are assumed to be either similar to a Dirac impulse or to white noise. Therefore, we employed a sharp electrical impulse as input function on a transceiver, whose characteristic may be well known, instead of a mechanical excitation.

Broadband piezoelectric sensors have multiple resonances. Their transfer function cannot be determined easily by an analytical approach. In general, the measured signal is utilized directly as the sensor transfer function in order to calibrate the sensor. The effects of wave propagation in the specimen is usually not taken into account as the Green's function of the specimen, which would be needed, can only be derived for very special geometries. In order to overcome this problem a symmetric sensor configuration is used in this work and the wave propagation needs not be considered.

An interesting calibration method is the reciprocity technique as described in Hatano and Mori (1978) and Hill and Adams (1979). This strategy is based on the assumption that the transfer function of the sensor does not depend on whether the sensor is used as a transceiver or a receiver of acoustic waves. We also make use of this assumption. In Higo (1994), an application of this technique is described. After deconvolution, different types of AE sources were identified.

Received 17 July 1996. B. Allemann and L. Gauckler are affiliated with Institut für Nichtmetallische Werkstoffe, ETHZ, CH-8092 Zürich, Switzerland and W. Hundt (hundt@fi.ethz.ch) and F. Rehsteiner are with Institut für Werkzeugmaschinen und Fertigung, ETHZ, CH-8092 Zürich.
2. Determination of the Transfer Function

2.1 Experimental Setup

In order to determine the transfer function two experiments with different sensor configurations were carried out. In a first experiment (see Fig. 1a) two sensors were coupled together face to face (Cavalloni and Kirchheim, 1994), one acting as the transceiver and the other one as the receiver. A short-time electrical pulse was generated by an ultrasonic pulser/receiver device (Model 5052PR, Panametrics) and applied to this setup. This and the corresponding signal after passing both sensors s1 and s2 (Kistler type 8152A) were digitized and observed on the digital oscilloscope (LeCroy 9430, 10 bits vertical resolution, 50000 points memory, 50 MHz bandwidth)

In a second experiment (see Fig. 1b) a configuration consisting of three sensors was fixed on an alumina ceramic plate (70 x 70 x 3 mm). A first sensor acted as transceiver (s3), the two others were attached as receivers symmetrically to the opposite side of the plate.

2.2 Results

All functions are defined in the frequency domain:

X(f): Electrical pulse.
Y_{s1>s2}(f): Signal after passing sensor s1 and s2.
Y_{s3>s1}(f): Signal sent by transducer s3 and received after passing the ceramic plate by sensor s1 or sensor s2, respectively.
H_{s1}(f), H_{s2}(f): Transfer functions of sensor s1 or s2.
G_{p1}(f), G_{p2}(f): Green's function for the structure between the transceiver and the corresponding sensor.

The sensor transfer function can be found using equation 1, which can be derived under consideration of Fig. 1a. The input and output signals in this first experiment with their corresponding frequency spectra are presented in Fig. 2.

For the second experiment (Fig. 1b), the input signal was also an electrical pulse, which was applied to the sensor s3. The output signals with their corresponding frequency spectra are shown in Fig. 3. The next equation can be derived by dividing Y_{s3>s2}(f) by Y_{s3}>s2(f). Writing these terms as products of each transfer media the following equation can be obtained:

\[
\frac{Y_{s1>s2}(f)}{X(f)} = H_{s1}(f) \cdot H_{s2}(f)
\]
Fig. 2 (a) Electrical impulse. (b) Frequency spectrum of electrical impulse. (c) Output of electrical impulse after passing sensor s1 and s2. (d) Spectrum of signal presented in Fig. 2c.

Fig. 3 (a) Output of sensor s1. (b) Spectrum of output of sensor s1. (c) Output of sensor s2. (d) Spectrum of output of sensor s2.
3.1 Outline of Optimal Deconvolution Method

Based on the symmetry of the experiment, it can be assumed:

$$G_{ph}(f) = G_{ph}(f).$$  (3)

As the two sensors have identical design, the coupling of both sensors is assumed to be identical, too. Thus, combining equations (1) to (3), the transfer function of the sensor $s_1$ is obtained by

$$H_{s1}(f) = \frac{Y_{s3s1}(f) \cdot Y_{s3s2}(f)}{Y_{s3s2}(f) \cdot X(f)}.$$  (4)

This equation allows the determination of the transfer function of an AE sensor.

Calculation of the transfer function in the frequency domain provides no sufficient results, especially after inverse transformation into the time domain (due to noise and amplification of artifacts due to the Fourier transformation). This can be avoided by the optimal deconvolution method.

3. Calculation of Transfer Function and its Inverse Operator

3.1 Outline of Optimal Deconvolution Method

Optimal deconvolution is a method to determine an inverse operator of a given signal. This allows the inverse problem to be solved in the time domain.

The properties of a sensor do not change with time, so the effect of a sensor in reference to the raw data set can be regarded as a stationary process. The influence of the sensor can be described by a stable time independent operator.

The calculation of the fast Fourier transform (FFT) restricts the number of data points (to power of 2). Convolution of a data set with an operator causes a loss of data points, which increases with the length of the operator. On the other hand, a long inverse operator will adapt the function to be deconvolved more precisely. However, if the data set is several times longer than the operator's length, these constraints are respected sufficiently. Our data sets had a length of 8192 points and the operator comprised 512 data points; therefore, this boundary condition is fulfilled.

The optimal deconvolution method provides minimal phase operators, i.e. stable causal operators (see Robinson, 1967). The phase characteristic between input and output function changes only in case of maximal phase at the beginning of the data set. Minimal and mixed phase signals result as output.

![Fig. 4 (a) Inverse operator of electrical impulse. (b) Frequency spectrum of inverse operator of electrical impulse. (c) Inverse operator of output of sensor s1 (2nd experiment). (d) Frequency spectrum of inverse operator](image)
3.2 Description of Algorithm

The inverse operator can be determined by minimizing the least-mean-squares deviation between the measured and the desired output (Buttkus, 1991; Dimri, 1992), in a similar way how the algorithm of a Wiener-filter can be developed.

When a signal \( b_j = (b_0, b_1, b_2, ..., b_M) \) is given, the inverse operator \( a_k \) of length \( M \) is determined by the least-mean-squares method:

\[
I = \sum_{l=0}^{N+M} e^2 = \left( \sum_{l=0}^{N+M} \sum_{j=0}^{M} a_j b_{l-j} - d_l \right)^2. \tag{5}
\]

Vector \( d \) represents the desired output and \( e \) is the derivative of the right side of the expression in equation (5). Equating the derivative, \( \partial I / \partial a_k \), for \( k = 0, 1, 2, ..., M \), to zero, the following linear set of equations can be obtained:

\[
\sum_{j=0}^{M} a_j R_{bk}(k-j) = R_{bd}(k), \quad k = 0, 1, 2, ..., M \tag{6}
\]

where \( R_{bk} \) and \( R_{bd} \) are the discrete autocorrelation functions of \( b \) and the crosscorrelation function of vectors \( d \) and \( b \), respectively.

3.3 Calculations

In order to calculate the transfer function with equation (4), the inverse operators of vectors \( Y_{s_1b_2}(f) \) and \( X(f) \) have to be determined. These inverse operators and their spectra are shown in Fig. 4. They can be applied to the vectors \( Y_{s_1b_2}(f) \) and \( Y_{s_1b_2}(f) \), respectively. The above described procedure can be carried out in the time domain. Afterwards, the terms \( Y_{s_1b_2}(f) Y_{s_1b_2}(f) \) and \( Y_{s_1b_2}(f) X(f) \) can be multiplied in the frequency domain. The square root of the result is the desired transfer function of sensor \( s_1 \), whose frequency spectrum is shown in Fig. 5a and the real part of the inverse-transformed transfer function is presented in Fig. 5b. By the optimal deconvolution method, the inverse operator of the sensor transfer function is determined (see Fig. 5c). Figure 5d reveals the correspondent spectrum of the inverse operator.
4. Application to a Microfracture Event

4.1 Experimental Setup

Subcritical crack growth was produced in a three-point bending test by applying a load smaller than the fracture load to a test specimen at a constant force rate of 50 N/min using an Instron 8562 machine. Figure 6 illustrates the setup of the experiment. The AE sensor was attached on the top of the specimen. The alumina-sample (size: 50 mm x 8 mm x 6 mm) was notched in the middle of the tensile side. The average grain diameter was 30 μm. Slow crack growth was observed before catastrophic fracture. Besides the signals of slow crack growth, signals with low frequency characteristics up to 100 kHz were observed as well at very low load levels. These signals are supposed to be emitted by the friction between the specimen and the support due to their low frequency behavior and their irregular and early occurrence. Additionally, no Kaiser effect was observed: every new loading cycle for the same specimen started with these signals.

4.2 Results

Figure 7 shows the signal of a microfracture in fine grained dense alumina and its frequency spectrum. The signal was filtered by a 4.8 MHz lowpass and a 30 kHz highpass filter to avoid noise amplification out of the sensor's resonance range.

Figure 7c reveals the signal after convoluting the original signal with the inverse operator of the sensor transfer function. Figure 7d shows the corresponding frequency spectrum. The signals in the time domain (see Figs. 7a and c) show a similar waveform. Figures 7c and 7d demonstrate the general changes of the spectrum shapes as well the reduction of noise. Due to the resonant frequency band of the sensor and the lowpass filtering of data it is possible that the highest frequency interval of the signal could be lost due to filtering of the data. The use of sensors with a higher frequency range may therefore be necessary.

5. Summary

The impulse response of a piezoelectric transducer produces a characteristic broadband signal, which contains information about the resonance properties of the sensor and possibly subsequent surface wave occurrence.

A new method was developed to determine the transfer function of the sensor. Two experiments with different sensor configurations were performed. This led to a linear equation system containing two sensor transfer functions as variables. Solving it in the frequency domain delivers no practical results and does not allow one to reconstruct the data without the influence of the sensor. Therefore, we propose to replace the division of complex vectors in the frequency domain by the convolution in the time domain with the corresponding inverse operator of the divisor. The inverse operator can be found by the optimal deconvolution method. The advantages of this method are: only stable minimum phase operators result and less artifacts introduced by Fourier transformation occur. In particular, the operating time for processing raw data with inverse operator of the sensor transfer function is reduced considerably.

![Fig. 6 Experimental setup for three point bending test.](image-url)
Fig. 7 (a) AE signal of microfracture. (b) Frequency spectrum of microfracture signal. (c) Microfracture event convolved with the inverse operator of transfer function of sensor. (d) Frequency spectrum of microfracture after deconvolution.

The method was applied to a microfracture event in an alumina ceramic specimen (mean grain size of 30 µm). This experiment demonstrated that the sensor changed the signal characteristic of the AE signal considerably.

Acknowledgment

The work was funded by the EidgenoEssische Technische Hochschule Zürich and the Swiss Commission for the Funding of Scientific Research (KTI/CTI). It was supported by Kistler Instruments AG (Winterthur, Switzerland) as supplier of high frequency AE sensors.

References


---

**1996 SUBSCRIPTION RATE for Volume 14**

Base rate for one year (four issues, Mar. - Dec.) $ 96.00  
Add Postage of  
U.S. - Book rate $ 8.00  
All others - Book rate $ 11.00  
Western Europe/S. America - Air mail rate $ 25.00  
All others - Air mail rate $ 30.00  
Add $5 without payment upon order. Payment must be in U.S. dollars drawn on a U.S. bank. Bank transfer accepted, but with $10 surcharge to the A.E. Group account (Account No. 080-03416470) at  
Sumitomo Bank of California  
San Fernando Valley Office  
15250 Ventura Blvd, Sherman Oaks, CA 91403-3262  
Notify us of such a transfer as the bank cannot sometimes give us the name of the payer. One volume of four issues per year. Index included in the Oct.-Dec. issue. Back issues available at $50 per volume for Vols. 1-3, $90 per volume for Vols. 4-8, $96 per volume for Vols. 9-14. US surface postages $8 per volume. For Canada and overseas surface delivery, add $11 and for air mail, add $30 per volume (will be adjusted for multi-volume order).

All orders should be sent to (or Fax 1-818-990-1686)  
Acoustic Emission Group  
308 Westwood Blvd., Box 364  
Los Angeles, CA 90024-1647 USA

For inquiry through Internet, use the following address: ono@seas.ucla.edu

Editor-Publisher Kanji Ono Tel. (310) 825-5233  
Cover Design Robin Weisz (UCLA Publications)  
Production Pace Publication Arts

Publication Date of This Issue: 4 March 1997.
Conferences and Symposia

13th International AE Symposium (IAES-13)

13th International AE Symposium was held on November 27-30, 1996 at Nara Prefecture Public Hall, Nara, Japan. Approximately 100 participants gathered from 16 countries. It was organized by Profs. T. Kishi, Y. Mori, Y. Higo and M. Enoki under the sponsorship of The Japanese Society for Non-Destructive Inspection (JSNDI).

Invited Lectures
Wave Propagation in Anisotropic Composite Plates, A. Mal, D. Guo, Y. Bar-Cohen and S.-S. Lih, University of California, Los Angeles, USA
Development of AE for Aircraft Applications, C.M. Scala and S.J. Bowles, DSTO Aeronautical and Maritime Research Laboratory, Australia
A Nondestructive Test for Aircraft Halon Bottles, the Development of an AE Application, A. G. Beattie, Sandia National Laboratories, USA

Composites
Characterization of Fracture Behavior during Ring Burst Test of FW-FRP Multiply Composite by AE, A. Horide, S. Wakayama and M. Kawahara, Tokyo Metropolitan University, Japan
Surface-crack Growth Mechanisms of Composite Materials, K. Noma and Y. Sakai, Tokyo Inst. of Technology, Japan
Fracture-Mode Determination of Glass-fiber Composites by Various AE Processing, H. Suzuki, T. Kinjo, M. Take-moto and K. Ono, Aoyama Gakuin University, Japan
AE Study on the Fracture Behavior in C/C Composites with Various Heat Treatment Temperature, T. Sooh, S. Wakayama, H. Hatta and Y. Kogo, Tokyo Metropolitan University Japan
AE Characteristics during Compressive Tests of 2D Carbon/Carbon Composites, N. Tohyama, B.-N. Kim, M. Enoki and T. Kishi, The University of Tokyo, Japan
AE Source / Characterization of SiC Particulate Glass Matrix Composites, M. Enoki, H. Fujita and T. Kishi, The University of Tokyo Japan
AE and Damage Evolution in Particulate Reinforced Al Matrix Composites, A. Rabieli, B.N. Kim, M. Enoki and T. Kishi, The University of Tokyo, Japan
Fiber/Matrix Interfacial Fracture Characterization by AE in Fabric Polymer Matrix Composite Laminates, T. Uenoya, Technology Research Institute of Osaka Prefecture, Japan
Source Location of AE in a Filament Wound Composite Tube through Wavelet Transform, C.-C. Yin, L.-C. Shieh and F.-T. Lin, National Chiao Tung University, Taiwan
AE Monitoring of Impact-Damaged CFRP Laminates during Flexural Tests, O.-Y.Kwon and D.-H. Hong, Inha University, Korea

Construction
Dynamic Responses of a Fluid-Filled Geothermal Reservoir Crack-Effect of the Aspect Ratio of the Reservoir Crack, K. Hayashi and S. Ito, Tohoku University, Japan
The Application of AE Technique to Estimate In Situ Stress in Virgin Coal Seam, V.S. Vutukuri, M. Seto, D.K. Nag, K. Katsayama and M. Utagawa, The University of New South Wales, Australia
AE Experience on Bridges, R.K Tyagi and H.M. Sre- vastava, Government of India-Ministry of Railways, India
AE Characterization of Failure Process of Concrete Beams Reinforced with CFRP Sheets, I. Ohsawa, I. Kimpara, K. Kageyama, T. Suzuki, S. Yuyama and Z.W. Li, The University of Tokyo, Japan
Clustering Similar AE Events Using the Filtered Waveform Envelope, A. Lesniak and H. Niituma, Tohoku University, Japan

Metals
Spectral Features of AE in Amorphous Metals, A. Y. Vinogradov and A.M. Leksovskii, Kanazawa University, Japan
AE Behavior during a Small Punch Test for Mg-Al Alloys, H. Kato, T. Tozawa and Y. Takayama, Utsunomiya University, Japan
AE Behaviors during Tensile Deformation of Ni3Al Intermetallic Compound, K. Yoshida, T. Saito, A. Zhu, H. Takagi and K. Sakamaki, University of Tokushima, Japan
AE Characteristics during Martensitic Transformation in an Fe-Pt Alloy, H. Ohtsuka, K. Takashima and G.B. Olson, National Research Institute for Metals, Japan
Non-destructive Evaluation of Weld Defects in Ring Samples by AE, M. Shiwa, A. Yamaguchi, M. Nagai and M. Sato, Japan Power Engr. & Inspection Corp., Japan

Thermal Spray/Concrete
Deformation and Fracture Analysis of Thermal Spray Coatings by AE Method, K. Akita, S. Wakayama and S. Tobe, Tokyo Metropolitan University, Japan
AE Analysis for Damage Estimation of Reinforced Concrete Structure, M. Shigeishi and M. Ohtsu, Kumamoto University, Japan
Determination of the Dynamic Elastic Constants of Concrete Using Horizontally Polarized Conical Transducers, T.-T. Wu and J.-S. Fang, National Taiwan University, Taiwan
AE Evaluation of Structural Integrity in Reinforced Concrete Beams Deteriorated due to Corrosion of Reinforcement, Y. Murakami and S. Yuyama, Hazama Corp., Japan

Fatigue / Fracture
Effect of Inclusions on AE in Fatigue, M. N. Bassim, The University of Manitoba, Canada
Relation between AE and In-situ Crack Observation by the Scanning Electron Microscope during Fracture Toughness Test of 7175 Aluminum Alloy, Y. Obata, K. Aoki, Y. Mori and A. Nozue, Nihon University, Japan
Pattern Recognition Analysis of AE from Fatigue of 2024-T4 Aluminum, K. Ono and J. Y. Wu, UCLA, USA
AE Source Location in Bending Fatigue Process of Carburizing Spur Gear, H. Sentoku and H. Yamato, Yamaguchi University, Japan

Defects/Plant Monitoring/Standards
Nondestructive Evaluation of Defects in Hot-Pressed Ceramic Nozzles by Combined Electroacoustic Technique, Y.I. Bulbik, Siberian Aerospace Academy, Russia
Evaluation of Structural Integrity Using AE for Electric Power Components for Condition Based Maintenance, H. Imaeda, Central Res. Inst. of Electric Power Industry, Japan
Experiences in Applying AE Technology to Structural Integrity Assessment, H. Nakasa, Central Research Institute of Electric Power Industry, Japan
A Proposed Standard for Evaluating Structural Integrity of Reinforced Concrete Beams by AE, S. Yuyama, T. Okamoto, T. Kamada, M. Ohtsu and T. Kishi, Nippon Physical Acoustics, Japan

Rock/Industrial Applications/Neural Network/Sensors
Fractals on AE Source Distribution and Fracture Surface Formed by Hydrofracturing of Rock Specimens K. Itakura, K. Sato and K. Nagano, Muroran Institute of Tech., Japan
AE and Electromagnetic Effects in Rocks, T. Lokajicek and J. Sikula, Geophysical Institute of Academy of Sciences, Czech Republic
Aspects of an Embedded High-Fidelity AE Transducer, C. Weiss and S.D. Glaser, Lockheed/Martin Corp., USA

Wood/Manufacture/Agriculture
Application of AE Technique for Optimization of Wood Drying Method by Use of Carbon Dioxide, T. Kono, H. Shinohara, N. Yamasaki, H. Takahashi, T. Hashida, K. Tamagawa and T. Shoji, Kochi Prefectural Industrial Technology Center, Japan
Development of Fault Detection Technique of Small Bearing by AE, S. Nishimoto, T. Imanaka and Y. Yokono, Non-Destructive Inspection Co., Japan
AE Characteristics Generated from Seedling, Adult Tree and Shoot Culture of Conifers K. Sato, K. Watanabe, N. Watanabe, M. Fushitani, Y. Motoyama, S. Ogita and M. Kaniwa, Tokyo Univ. of Agriculture & Technology, Japan

Structures
AE Sources of Field Pressure Vessel Test, C. Shen, B. Li, Q. Duan and S. Liu, National Center of Boiler and Pressure Vessel Inspection and Research, China
Application of AE Evaluation of Structural Integrity in Marine Concrete Structures, T. Kamada, M. Iwanami, S. Nagataki, S. Yuyama and N. Otsuki, Tokyo Institute of Technology, Japan
Evaluation of Hot Industrial Pipeline Condition by AE Image Recognition Method, G. Muravin, L. Lezvinsky, B. Muravin and V. Ship, Margan Physical Diagnostics, Israel

Poster Session
Investigation of Concrete Structural and Mechanical Characteristics by AE Method, G. Muravin, L. Lezvinsky and B. Muravin, Margan Physical Diagnostics, Israel
Source Characterization of AE Signals during the Molten Chloride Attack of Stressed AISI304 Steel, K. Hayashi and M. Takemoto, Aoyama Gakuin University, Japan
Structural Integrity Evaluation of Concrete Members by AE Method, M. Uchida, T. Shibata, D. Mori, T. Okamoto, M. Ohtsu and T. Kishi, Central Research Laboratory, Nihon Cement Co., Japan
The Role of Surface in AE during Plastic Deformation of Copper Single Crystals, A. Vinogradov, M. Nadtochy, D. Merson, A.P. Braginsky and S. Hashimoto, Kanazawa University, Japan
AE Characteristics during Compressive Tests of Unidirectional Carbon/Carbon Composites, B.-N. Kim, N. Tohyama, M. Enoki and T. Kishi, University of Tokyo, Japan
Inspection and Evaluation of In-Service High H2/N2 Cylinders by Acoustic Emission, L. Bang Xian, S. Cong Tian, D. Qing Ru, L. Qizhi and L. Shanfeng, Center of Boiler and Pressure Vessel Inspection and Research, China
Use of AE to Identify Defects and Evaluate Their Potential Danger in Pressurized Storage Tanks, C. Muravin, L. Lezvinsky and B. Muravin, Margan Physical Diagnostics, Israel
Development of Plywood Grader Using AE Technique, K. Sato, Y. Suzuki, H. Matsuo and S. Murase, Tokyo University of Agriculture & Technology, Japan
Notes for Contributors

1. General

The Journal will publish contributions from all parts of the world and manuscripts for publication should be submitted to the Editor. Send to:

Professor Kanji Ono, Editor - JAE
6531 Boelter Hall, MSE Dept.
University of California
Los Angeles, California 90095-1595 USA
FAX (1) 818-990-1686
e-mail: ono@seas.ucla.edu

Authors of any AE related publications are encouraged to send a copy for inclusion in the AE Literature section to:

Mr. T.F. Drouillard, Associate Editor - JAE
11791 Spruce Canyon Circle
Golden, Colorado 80403 USA

All the manuscripts will be reviewed upon submission to the Editor. Only papers not previously published will be accepted. Authors must agree to transfer the copyright to the Journal and not to publish elsewhere, the same paper submitted to and accepted by the Journal.

A paper is acceptable if it is a revision of a governmental or organizational report, or if it is based on a paper published with limited distribution.

An abstract of about 200 words is needed for Research and Applications articles, while it should be shorter than 100 words for other articles.

The language of the Journal is English. All papers should be written concisely and clearly.

2. Page Charges

No page charge is levied. Fifty copies of off-prints will be supplied to the authors free of charge.

3. Manuscript for Review

Manuscripts for review need only to be typed legibly; preferably, double-spaced on only one side of the page with wide margins and submitted in duplicate.

The title should be brief. Except for short communications, descriptive heading should be used to divide the paper into its component parts. Use the International System of Units (SI).

References to published literature should be quoted in the text citing authors and the year of publication. These are to be grouped together at the end of the paper in alphabetical and chronological order. Journal references should be arranged as below. Titles for journal or book articles are helpful for readers, but may be omitted.


Abbreviations of journal titles should follow those used in the ASM Metals Abstracts. In every case, authors' initials, appropriate volume and page numbers should be included. The title of the cited journal reference is optional.

Illustrations and tables should be planned to fit a single column width (87 mm or 3.3") or a double width (178 mm or 7"). For the reviewing processes, these need not be of high quality, but submit glossy prints or equivalent with the final manuscript. Lines and letters should be legible.

4. Review

All manuscripts will be judged by qualified reviewer(s). Each paper is reviewed by one of the editors and may be sent for review by members of the Editorial Board. The Board member may seek another independent review. In case of disputes, the author may request other reviewers.

5. Electronic Media

In order to minimize typographical error, the authors are encouraged to submit a floppy disk copy of the text. We can read Macintosh and IBM PC formats. Those who can connect to INTERNET can send the text portion to "ono@seas.ucla.edu". This will greatly shorten the time of communication.

6. Color Photograph

We can print color photographs needed to enhance the technical content of an article. Because of the cost, the author is asked to pay $350 per page.
## Contents

| Pages 53-59 | Modeling of Stress-Strain Response of Unidirectional and Cross-Ply SiC/CAS-II Ceramic Composites by Acousto-Ultrasonic Parameters | Anil Tiwari, Edmund G. Henneke II and Alex Vary |
| Pages 61-68 | Neural Network Approach to Acoustic Emission Source Location | Vasisht Venkatesh and J.R. Houghton |
| Pages 69-84 | Wavelet Transform of Acoustic Emission Signals | Hiroaki Suzuki, Tetsuo Kinjo, Yasuhisa Hayashi, Mikio Takemoto and Kanji Ono with Appendix by Yasuhisa Hayashi |
| Pages 97-102 | Pattern Recognition of Acoustic Signatures Using ART2-A Neural Network | Shahla Keyvan and Jyothish Nagaraj |
| Pages 115-118 | Acoustic Emission Testing of Bolted Connections under Tensile Stress | V. Hänel and W. Thelen |
| Pages 119-126 | A Method to Determine the Sensor Transfer Function and its Deconvolution from Acoustic Emission Signals | Bernhard Allemann, Ludwig Gauckler, Wolfgang Hundt and F. Rehsteiner |

### Conferences and Symposia

| Page 60 | 39th Meeting of the Acoustic Emission Working Group and Primer |
| Page 96 | 40th Meeting of the Acoustic Emission Working Group and Primer |
| Page 127-128 | 13th International AE Symposium (IAES-13) |
Materials Research with Advanced Acoustic Emission Techniques.....
Workshop Participants at Schloss Ringberg, Germany
JOURNAL OF ACOUSTIC EMISSION

Editor: Kanji Ono
Associate Editors: A. G. Beattie, T. F. Drouillard, F. C. Beall and M. Ohtsu

1. Aims and Scope of the Journal

Journal of Acoustic Emission is an international journal designed to be of broad interest and use to both researcher and practitioner of acoustic emission. It will publish original contributions of all aspects of research and significant engineering advances in the sciences and applications of acoustic emission. The journal will also publish reviews, the abstracts of papers presented at meetings, technical notes, communications and summaries of reports. Current news of interest to the acoustic emission communities, announcements of future conferences and working group meetings and new products will also be included.

Journal of Acoustic Emission includes the following classes of subject matters:

A. Research Articles: Manuscripts should represent completed original work embodying the results of extensive investigation. These will be judged for scientific and technical merit.

B. Applications: Articles must present significant advances in the engineering applications of acoustic emission. Material will be subject to reviews for adequate description of procedures, substantial database and objective interpretation.

C. Technical Notes and Communications: These allow publications of short items of current interest, new or improved experimental techniques and procedures, discussion of published articles and relevant applications.

D. AE Literature section will collect the titles and abstracts of papers published elsewhere and those presented at meetings and conferences. Reports and programs of conferences and symposia will also be included.

Reviews, Tutorial Articles and Special Contributions will address the subjects of general interest. Nontechnical part will cover book reviews, significant personal and technical accomplishments, current news and new products.

2. Endorsement

Acoustic Emission Working Group (AEWG), European Working Group on Acoustic Emission (EWGAE), Committee on Acoustic Emission from Reinforced Composites (CARP), and Acoustic Emission Working Group of India have endorsed the publication of Journal of Acoustic Emission.

3. Governing Body

The Editor and Associate Editors will implement the editorial policies described above. The Editorial Board will advise the editors on any major change. The Editor, Professor Kanji Ono, has the general responsibility for all the matters. Associate Editors assist the review processes as lead reviewers. Mr. T.F. Drouillard is responsible for the AE Literature section. The members of the Editorial Board are selected for their knowledge and experience on AE and will advise and assist the editors on the publication policies and other aspects. The Board presently includes the following members:

S.H. Carpenter (USA)
D.A. Dornfeld (USA)
P. Fleischmann (France)
L. Golaski (Poland)
M.A. Hamstad (USA)
H.R. Hardy, Jr. (USA)
R. Hill (UK)
I.V. Ivanov (Russia)
P. Jax (Germany)
T. Kishi (Japan)
O.Y. Kwon (Korea)
J.C. Lenain (France)
S.L. McBride (Canada)
W. Morgner (Germany)
C.R.L. Murthy (India)
H. Niitsuma (Japan)
A.A. Pollock (USA)
T.M. Proctor, Jr. (USA)
I. Roman (Israel)
C. Scala (Australia)
C. Scruby (UK)
A. Vary (USA)
E. Waschkes (Germany)
M. Wevers (Belgium)
J.W. Whittaker (USA)
B.R.A. Wood (Australia)

4. Publication

Journal of Acoustic Emission is published quarterly in March, June, September and December by Acoustic Emission Group, 308 Westwood Blvd.- Box 364, Los Angeles, CA 90024-1647. It may also be reached at 6531 Boelter Hall, University of California, Los Angeles, California 90095-1595 (USA). tel. 310-825-5233. FAX 818-990-1686. e-mail: ono@seas.ucla.edu

5. Subscription

Subscription should be sent to Acoustic Emission Group. Annual rate for 1996 or 1997 is US $96.00. For surface delivery, add $8 in the U.S. and $11 for Canada and elsewhere. For air mail delivery to South America, add $18, Western Europe, add $25 and add $30 elsewhere. Overseas orders must be paid in US currencies with a check drawn on a US bank. Inquire for individual (with institutional order) and bookseller discounts.

6. Advertisement

No advertisement will be accepted, but announcements for books, training courses and future meetings on AE will be included without charge.
Preface

An international workshop entitled "Materials Research with Advanced Acoustic Emission Techniques" was organized by Eduard Arzt, Alexander Wanner, Michael R. Gorman, and Christian Grosse. It was sponsored by the Max-Planck Society and held at Schloss Ringberg, Rottach-Egern, Germany, October 6 - 9, 1996 and attracted about 40 invited participants from several countries of Europe, the US, Japan and Israel. This issue presents articles and abstracts based on talks given at the workshop. It should be noted that it was left to the workshop participants whether they submit a manuscript and that this issue does by no means cover the whole workshop. The complete workshop program is shown on the following pages.

We thank the Max-Planck-Society for sponsoring the workshop. We also thank the editor of the Journal of Acoustic Emission, Professor Kanji Ono, for dedicating this issue to the workshop.

Introduction

More than sixty years have passed since systematic acoustic emission (AE) studies were first performed. Since then, there has been a continuous scientific interest in the phenomenon of acoustic emission with research activities having been conducted on all kinds of materials, including metals and alloys, ceramics, rocks, concrete, plastics, composites, and biological materials. From the beginning, it was obvious that AE measurements in principle offer unique opportunities to obtain information on processes that go on in materials. In many cases, even today, there is no way to acquire the desired information otherwise. However, AE data are difficult to capture and interpret and very often oversimplifying analysis techniques have been applied without consideration of sound physical principles. Unfortunately, the resulting uncertainty and conflict about the meaning and significance of AE results have led to widespread skepticism about the usefulness of AE as a tool in materials research.

In recent years, all AE-relevant techniques have undergone remarkable progress, e.g. improved high-fidelity, wideband sensors have become available and ever faster analog-to-digital converters and microcomputers allow for high-speed data acquisition, processing, and storage. Researchers are now enabled to capture and store the true waveforms of AE signals in a much wider frequency and dynamic range than before. The experimental access to such data is one prerequisite for any quantitative, wave-based approach to acoustic emission. Just as important is the development of suitable models and data analysis algorithms based on sound physical principles that allow for correct interpretation of AE results. Stimulated by related NDE techniques, as well as by seismology, there has been remarkable progress in the field of acoustic emission. There is no
doubt that AE has begun to develop into a quantitative discipline that is far removed from the previous empirical approach.

The first International Workshop on Materials Research with Advanced Acoustic Emission Techniques was held in order to assess the current status of new and promising AE techniques and to stimulate their use in materials research. The workshop took place from October 6-9, 1996, at Schloss Ringberg, the conference site of the Max-Planck-Society located on Lake Tegernsee, not far from Munich (Bavaria), Germany. The purpose of the workshop was to bring together workers in materials science and acoustical non-destructive evaluation to discuss the fundamental aspects of acoustic emissions and answer general questions such as:

- What are the capabilities and limits of advanced AE techniques?
- Are these techniques ready for use?
- How are these techniques used as tools to study materials?
- How can materials basically serve as tools for research on the phenomenon of acoustic emission?
- What is the role of traditional AE testing in light of recent advancements and results?

Stimulated by oral and poster presentations, these and related questions were discussed among 40 researchers from all over the world in the relaxed atmosphere of a beautiful conference site located in the foothills of the Bavarian Alps. The discussions turned out to be fruitful and exciting. As expected, no specific answers to the questions mentioned above were found. However, it is clear that we are at the beginning of the future where the combination of understanding and instrumentation permits the realization of standardized AE measurements. We are now all measuring waves as though with oscilloscopes. This means that no longer is event definition dependent on any manufacturer's electronics. The oscilloscopes will be specialized to be sure - like impedance analyzers or vibration testing analyzers - but the important point is we will be pursuing the same physics even as we test different materials. Industrial standards will be fundamentally based. Materials researchers can be trained to apply the technique with definite analysis methods. The role of theory will be enhanced or even paramount. AE will at last be on equal footing with other NDE techniques. It will be a reliable and indispensable tool for materials science.

**Typical Talk on AE Research in the Future**

Talks will begin with sensor calibration data for the measurement to be made. The material details will lead to different measurement numbers from the wave patterns detected. Any “claims” will be supported by theory. Speculation will be identified along with suggestions for resolving issues. Signal processing researchers will be involved and there will be research on this topic just as in ultrasonics, since modeling and wave propagation theory will contribute. We will have a lively, vibrant group of experimentalists, who are talking to the theoreticians. The experimentalists will be material scientists as AE becomes a part of the curriculum.

**Instrumentation in the Future**

Instrumentation will be based on fundamental theoretical principles. It will measure specific physical quantities and provide direct understandable analysis of materials. Perhaps instruments will be divided according to function: one type for dislocations, another for microcrack growth, and yet another for macrocrack growth. These systems will be much more complex to build and program just like a vibration analyzer.
Structural Testing in the Future

Structural evaluation will be based on fundamentals and require input from the materials data. Hopefully, various universities and institutes will become known as centers for these different aspects of AE.

A famous quote goes, "Those who do not remember the past are condemned to repeat it." Let us not merely reinvent the wheel with AE, but use this opportunity to build on a firm foundation.

WORKSHOP PROGRAM

Materials Research with Advanced Acoustic Emission Techniques

Organizers: Prof. Dr. Eduard Arzt (Stuttgart); Dr. Alexander Wanner (Stuttgart)
Dr. Michael R. Gorman (Englewood, CO., USA); Dr. Christian Grosse (Stuttgart)
Contact address: Dr. Alexander Wanner, c/o Max-Planck-Institut für Metallforschung
Seestr. 92, D-70174 Stuttgart, Germany, wanner@vaxww1.mpi-stuttgart.mpg.de

Monday, October 7

Alexander Wanner, Universität Stuttgart, Germany; Opening remarks

Morning Session: Chairman: Kanji Ono, University of California at Los Angeles, USA

William H. Prosser, NASA Langley Research Center, USA; Advanced AE techniques in composite material research
Michael R. Gorman, Digital Wave Corp., USA; Modal acoustic emission
Steve Ziola, Digital Wave Corp., USA; Signal processing for modal acoustic emission

Afternoon session: Chairman: Sergei Shapiro, Universität Karlsruhe, Germany

Ajit K Mal, University of California at Los Angeles, USA; Lamb waves from microfracture events in composite plates
Marvin A. Hamstad, University of Denver, USA; Finite element modeling of the AE displacement in the farfield of AE sources
Laurence J. Jacobs, Georgia Institute of Technology, USA; Transfer functions to remove geometry effects from acoustic emission signals
Alexander Wanner, Universität Stuttgart, Germany; Fiber fragmentation and acoustic emission

Tuesday, October 8

Morning session: Chairman: Hans-Wolf Reinhardt, Universität Stuttgart, Germany

Surendra P. Shah, Northwestern University, USA; Fracture processes in concrete and AE
Masayasu Ohtsu, Kumamoto University, Japan; Generation of acoustic emission waves and moment tensor analysis
Eric N. Landis, University of Maine, USA; Acoustic emission techniques to measure nature and extent of damage in portland cement-based materials
Christian Grosse, Universität Stuttgart, Germany; Relative moment tensor inversion applied to concrete fracture tests
Afternoon session: Chairman: Karl Schulte, Technische Universität Hamburg-Harburg, Germany
Kanji Ono, University of California at Los Angeles, USA; The fracture dynamics in a dissipative glass-fiber/epoxy model composite with AE source simulation analysis
Itzhak Roman, The Hebrew University of Jerusalem, Israel; Assessing interfacial properties in advanced composites with acoustic emission

General Discussion: Chairman: Eduard Arzt, Max-Planck-Institut für Metallforschung, Germany
Relevance of advanced acoustic emission techniques for materials research

Wednesday, October 9

Morning session: Chairman: Surendra P. Shah, Northwestern University, USA

Marnix Surgeon, Katolieke Universiteit Leuven, Belgium; The sound of composite materials in static and dynamic experiments
David Lockner, U.S. Geological Survey, USA; Brittle fracture as an analog to earthquakes: Can acoustic emission be used to develop a viable prediction strategy?
Arno Zang, GeoForschungszentrum Potsdam, Germany; Acoustic emission source analysis in laboratory stressed rock cores

Poster Presentations

Karyn Downs, Lockheed Martin Astronautics, USA and Marvin A. Hamstad, University of Denver, USA; Wave propagation effects relative to AE source distinction of wideband AE signals from composite pressure vessels
Bernd Weiler, Christian Grosse, Hans-Wolf Reinhardt, Universitat Stuttgart, Germany
Quantitative acoustic emission techniques used for the evaluation of fracture mechanisms in steel fibre-reinforced concrete
T. Cramer, H.G. Reichert, T. Bidlingmaier and A. Wanner, Max-Planck-Institut für Metallforschung und Universität Stuttgart, Germany; AE measurements during crack growth in small penny-shaped samples of a SiC ceramic

Michael R. Gorman, Digital Wave Corp., USA; Concluding remarks

Organizers of the Workshop (from l. to r.); Drs. Gorman, Wanner, Arzt and Grosse.
Friedrich Förster and Erich Scheil, Two Pioneers of Acoustic Emission

Alexander Wanner

It is well accepted in the field of acoustic emission that the genesis of today’s technology is the work of Joseph Kaiser in the early 1950’s. However, as Thomas F. Drouillard has pointed out (Drouillard, 1996), a number of the scientific experiments had already been conducted as early as the 1930’s, some of which could have been the genesis of today’s technology had the experimenters redirected and continued their research into the phenomenon itself. Among these pioneers were Friedrich “Fritz” Förster and Erich Scheil, two German researchers, who then worked at the Kaiser-Wilhelm-Institut für Metallforschung (today’s Max-Planck-Institut für Metallforschung) in Stuttgart. Erich Scheil was an outstanding expert in thermodynamics and metallurgy who studied phase equilibria in metals and alloys. Part of his work focused on “military” transformations (Umklappvorgänge) such as martensite formation in steel. Knowing that military transformations are often accompanied by audible noise he encouraged his co-worker Fritz Förster, a physicist whose main research area was nondestructive materials testing, to develop an experimental setup that allowed for monitoring the acoustic emissions from alloy specimens while varying the specimen temperature. With this setup, Förster and Scheil were able to monitor the time dependence of martensite formation in steel upon cooling below room temperature. They presented their work at the 1936 general meeting of the Deutsche Gesellschaft für Metallkunde (German Metallurgical Society) and in a short article entitled Akustische Untersuchung der Bildung von Martensitnadeln [Acoustic Investigation of Martensite Needle Formation]”, Zeitschrift für Metallkunde, 28, 245-247.


The author is affiliated with Institut für Metallkunde der Universität Stuttgart, Stuttgart, Germany

Förster continued for decades to develop new ultrasonic, magnetic, and electrical methods for materials characterization (Förster, 1983) as well as being a major proponent of nondestructive testing. Unfortunately, he has never come back to acoustic emission testing. Although Friedrich Fritz Förster can be regarded as one of the fathers of acoustic emission testing, this technique played only a minor role in his distinguished lifework.

References


Still, the 3-page article of the year 1936 remained Förster and Scheil’s only publication in the field of acoustic emission. They carried on their studies of the time dependence of martensite formation for a while but using electrical resistivity instead of acoustic emission measurements (Förster and Scheil, 1937 and 1940).
Acoustic Investigation of Martensite Needle Formation

by Fritz Förster and Erich Scheil, Stuttgart

(of the Kaiser-Wilhelm-Institut für Metallforschung in Stuttgart)

Presented by E. Scheil at the General Meeting of the Deutsche Gesellschaft für Metallkunde on 27th July, 1936 in Hamburg

Recording of the noises during martensite formation — Formation of individual needles — High formation velocity — Dependence of the number of needles on the grain size

As is well known, the formation of martensite in steel, which occurs on cooling below room temperature is accompanied with a noise 1)

By converting the noise into an electric current this process could be recorded. The experimental arrangement is shown schematically in Fig. 1. The sample was held vertical by 0.1 mm thick molybdenum wires which were tensioned by a weighted cantilever. The wires transmitted the transverse vibrations which arose in the sample from the transformation to a receiver system which converted the sounds into alternating current. The currents were amplified and, after rectification with a diode, measured on a rapid response oscillograph. As an oscillograph the electro-cardiograph from the company Siemens and Halske was used, the characteristics of which have already been described by F. Wever and N. Engel 2). The recording was made on a paper film which was fed at up to 15 mm/s. Initially increased rapidly and then fell noticeably more slowly back to zero. On the first deflection the light spot overshot the edge of the recording film strip.

For the experiments a nickel steel with 29% Ni was used. The transformation of the austenite into martensite began on cooling at -31°C. The steel sample of 1 mm diameter and 25 mm length was cooled, using a mixture of alcohol and dry ice in a cooling vessel.

The rapid increase of the deflection is primarily determined by the speed of formation of the martensite. We will return to this question when the detection speed is markedly increased. The high speed of the martensite formation has caused another effect in Fig. 2. The second curve running underneath the electrical curve indicates the temperature of a thermocouple soldered to the sample which was recorded using a second loop of the oscillograph. Simultaneous with the first large deflection of the acoustic curve the temperature rose distinctly. This was also observed at several later deflections, but not on all deflections. Obviously, only martensite formation near the thermocouple shows this phenomenon. Irregular temperature increases were already indicated in a similar fashion by F. Wever and N. Engel 3). The instantaneous temperature increase due to the almost completely adiabatic transformation is very considerable. With a specific heat of roughly 0.1 cal/g, the value of about 20 cal/g causes a temperature increase of 200°C in the transformed region.

The decay of the curve after the end of the pulse was determined by the damping of the vibrating system. In the arrangement chosen here not only the sample but also the wires of the receiver system, etc. contributed noticeably, so
that nothing can be said from the decay curve about the damping in the transformation region in the sample. In a later communication it will be shown that an abnormal damping is present in the transformation region.

Besides the high formation velocity of the martensite, above all, division of the course of the transformation into individual events is noteworthy. This has already been observed using other methods by G. Tamman and E. Scheil 3) and by H. Hanemann and H.J. Wiester 4). Above all, the photograph by Hanemann and Wiester shows very clearly that the individual events consists of the formation of single needles. Obviously each individual acoustic pulse is to be attributed to the formation of a needle.

Conversely one cannot say without qualification that every martensite needle causes an acoustic pulse. To what extent this is true should be specially examined and will be reserved for later work. For this reason initially only a few qualitative results will be communicated in the following.

In Figs. 3a to c three sections of the recording of the transformation of a coarse-grained sample are reproduced. At the start of the transformation mostly large isolated deflections were seen (Fig. 3a). With decreasing temperature, the number of needles at first increased strongly. Their size was only slightly changed. Towards the end of the cooling, both the number and size of the needles decreased (Fig. 3c).

On interrupting the cooling, the formation of martensite needles, rapid during cooling, fell quickly to zero. On further cooling, the transformation first occurred at a lower temperature corresponding with earlier examinations of carbon steels by E. Scheil 1,3). The pursuit of the individual events has shown, in contrast to the earlier examinations, that on ending the cooling, the transformation does not stop instantaneously, but simply decays rapidly.

The grain size noticeably influences the course of the transformation. In Figs. 4a and b as well as 3a the start of martensite formation is represented for a single crystal (Fig.
Fig. 4a and b. Influence of the grain size on the martensite formation. a. single crystal, b. polycrystal.

4a), for a coarse-grained polycrystal (Fig. 3a) and for a fine-grained polycrystal. The number of needles increased with the number of grains, while their size decreased. The martensite formation of the single crystal had a sort of fine structure. Following a large deflection, several smaller ones also occurred. Probably several transformation planes were activated by the large needle.

The laws determining the size of the martensite needles can be understood, as has already been shown earlier, from the photomicrographs. In Fig. 5, the two large needles, which completely cross the narrow side of the micrograph, formed first. The smaller ones then formed between them at lower temperatures. The extent of the small needles is determined by the size of the available gap. The initial size of the needles in each grain must therefore decrease with the progression of the transformation from spatial reasoning. Similarly to the needles already present, the grain boundaries also limit the needle size, so that an increase in the grain size also causes an increase in the needle size.

The authors thank the Deutsche Forschungsgemeinschaft for the loan of the electro-cardiograph.

Summary

An experimental arrangement for recording the noises arising during martensite formation is given. The noises indicate the formation of individual needles, though recording of all needles is not yet clarified. The current caused by an individual noise increases rapidly and decreases more slowly. From this, one obtains an upper bound for the formation time of martensite of 0.002 s. The number of needles which form increases initially with cooling and then decreases. On interrupting the cooling, the martensite formation stops quickly. With increasing the number of grain, the number of needles increases as their size decreases correspondingly.

Received 12th August, 1936

References

4) Z. Metallkde. Vol 24 (1932) p. 276
Advanced AE Techniques in Composite Materials Research

William H. Prosser

Abstract

Advanced, waveform-based acoustic emission (AE) techniques have been successfully used to evaluate damage mechanisms in laboratory testing of composite coupons. An example is presented in which the initiation of transverse matrix cracking was monitored. In these tests, broadband, high-fidelity AE sensors were used to detect signals, which were then digitized and stored for analysis. Analysis techniques were based on plate-mode wave-propagation characteristics. This approach, more recently referred to as Modal AE, provides an enhanced capability to discriminate and eliminate noise signals from those generated by damage mechanisms. This technique also allows much more precise source location than conventional, threshold-crossing arrival-time determination techniques. To apply Modal AE concepts to the interpretation of AE on larger composite specimens or structures, the effects of modal wave propagation over larger distances and through structural complexities must be well characterized and understood. To demonstrate these effects, measurements of the far-field, peak-amplitude attenuation of the extensional and flexural plate mode components of broadband simulated AE signals in large composite panels are discussed. These measurements demonstrated that the flexural-mode attenuation is dominated by dispersion effects. Thus, it is significantly affected by the thickness of the composite plate. Furthermore, the flexural-mode attenuation can be significantly larger than that of the extensional mode even though its peak amplitude consists of much lower frequency components.

1. Introduction

The capabilities of AE testing in composite-materials research have been significantly improved by several recent advances. These include the development of digital, waveform-based, acquisition instrumentation with sufficient memory and acquisition rates for AE testing. Another important development has been the improvements in high-fidelity, high-sensitivity, broadband sensors. However, most important has been the increased understanding of the nature of AE signal propagation as guided acoustic modes in common test-specimen geometries such as thin plates and coupons (Gorman, 1991; Gorman and Prosser, 1991; Prosser, 1991). Analysis of guided-mode AE signals has been designated Modal AE. It has led to significantly improved AE source-location accuracy (Ziola and Gorman, 1991). Modal AE has also provided the capability to better differentiate AE signals from different source mechanisms including extraneous noise (Ono and Huang, 1994; Prosser et al., 1995).

Two sets of Modal AE measurements are presented herein. The first is an example of a successful application in composite-materials research to monitor the initiation of transverse matrix cracking. The second set of measurements focused on the far-field, peak-amplitude attenuation of the extensional and flexural plate mode components of broadband simulated AE signals in large composite panels.
cracking in cross-ply graphite/epoxy coupons. In these experiments, noise signals created by
damage in the grip region were differentiated from crack signals by waveform analysis. The
signals from matrix cracks contained a higher amplitude extensional plate-mode with little or no
flexural mode. The grip damage signals contained significant flexural-mode components.

The second set of data are measurements of the peak-amplitude attenuation of the extensional
and flexural plate modes in large composite plates. The flexural mode suffered considerably more
amplitude loss even though its frequency content was much lower. Dispersion of the flexural
mode, which causes a spreading of the signal in time over increasing propagation distance, is the
dominant mechanism for this high attenuation. As shown in the transverse matrix cracking study,
simple analysis of relative plate-mode amplitudes is useful for source discrimination in coupons
where the source-to-sensor propagation distance is small. However, these results suggest that
careful consideration of attenuation effects will be required to extend this approach to larger
specimens such as panels or realistic structures.

As requested by the workshop organizers, additional comments on the generalization of these
results are included in the concluding remarks. In particular, it is noted that although Modal AE
analysis has been successfully used to discriminate source mechanisms in composite materials,
further research is required before the approach can be used in arbitrary materials, laminates,
and/or specimen geometries. Further developments in modeling AE wave propagation, which may
provide insight into the effects of different source mechanisms on AE waveforms, will likely speed
this process. It is also suggested that automated waveform-analysis approaches such as pattern
recognition and neural networks will be most successful at source discrimination when based on
knowledge of wave propagation. Furthermore, factors such as attenuation and complicated
structural geometries must be carefully considered when extending Modal AE analysis to the
testing of large specimens and real composite structures.

2. Modal AE

A number of early AE studies, including those by Pollock (1986), Stephens and Pollock
(1971), Egle and Tatro (1967), and Egle and Brown (1975), made passing mention of the
propagation of AE waves as guided acoustic modes in practical testing geometries such as
coupons, plates, shells, pipes, and rods. However, these works offered little as to the importance
of these modes on the interpretation and analysis of AE with respect to source-location accuracy
and identification of source mechanisms. In fact, Pollock (1990) raised these same questions in a
review paper on critical problems for research in AE. At about this same time, Gorman (1991) and
Gorman and Prosser (1991) published work on the effects of guided-wave AE propagation in
plates. It was pointed out that in thin plates and coupons, the two observed modes of propagation
in AE signals are the extensional and flexural plate modes. The predominant particle displacement
for the extensional mode is in the plane of the plate. The largest component of the flexural-mode
particle displacement is out of the plane of the plate. A source motion with predominantly in-plane
components and symmetric about the midplane generates AE signals with large extensional-mode
components. Examples of such a source motion include fatigue cracking in metals and matrix
cracking in the center plies of a composite laminate. Out-of-plane source motion such as
delamination or impact damage produces AE signals with large flexural-mode components. This
discovery led to a waveform-analysis method to identify sources and discriminate noise signals and
is the basis for the Modal AE technique.
The extensional mode propagates with a faster velocity and suffers little dispersion over the frequency range observed in most AE experiments (20 kHz to 1 MHz). It typically contains higher frequency components than the flexural mode. The flexural mode, however, propagates with a slower velocity and is highly dispersive with the higher frequencies traveling at higher velocities. A typical waveform detected in a composite plate with a broadband sensor identifying these two modes is shown in Fig. 1. The source of this signal was a simulated AE event caused by a pencil-lead fracture (Hsu-Neilsen source) on the surface of the composite plate.

![Fig. 1 Simulated AE signal in composite plate identifying extensional and flexural plate modes.](image)

3. Detection of Transverse Matrix Crack Initiation in Cross-Ply Laminates

The initiation and progression of transverse matrix cracking in composite materials has been, and remains, a subject of considerable interest and importance. A vast amount of literature on the experimental detection of matrix cracks is available, of which a small sampling is reviewed by Prosser et al. (1995). The improved source-location accuracy and enhanced noise-discrimination capabilities of the Modal AE technique are demonstrated in this study of the transverse matrix-crack initiation in cross-ply laminates of different stacking sequences. This work improved upon a similar study by Gorman and Ziola (1991), in which only a single cross-ply laminate was tested.

Rectangular specimens (25.4 mm wide by 279 mm long) of AS4/3502 graphite/epoxy composite material were loaded in tension under stroke control (0.127 mm/min). As grip noise was eliminated by waveform analysis, specimen end-tabs were not used in these tests. Specimens from six different cross-ply laminates were tested. The stacking sequences were \([0_n, 90_n, 0_n] \) where \(n\) ranged from one to six. Thus, the samples varied in thickness from 3 to 18 plies.

Broadband, high-fidelity sensors (B1000, Digital Wave Corp., Englewood, CO) were used to detect the waveforms. Rather than a single sensor at either end of the specimen as in many previous works, four sensors were used. At either end of the nominally 152 mm specimen gage
length, a pair of sensors were positioned. The outer edge of each 6.35 mm diameter sensor was aligned with the edge of the specimen. A diagram of a specimen showing the sensor positions and the grip regions is shown in Fig. 2. The motivation for this sensor array arrangement was the determination of the initiation site of the crack. Not only could the linear location along the length of the specimen be determined, but lateral location information was also obtained. The maximum digitization sampling frequency (25 MHz) of the digital AE acquisition and analysis system (F4000, Digital Wave Corp.) was used to provide the most accurate location results. Location was performed, post-test, using manual, cursor based phase-point matching on the extensional mode for arrival-time determination. The extensional-mode velocities used for the location analysis were measured prior to testing using simulated AE sources.

![Diagram of specimen showing grip region and position of AE sensors.](image)

After detection, the signals were amplified 20 dB by wideband preamplifiers (PA2040G, Digital Wave Corp.). It was determined during the tests that the signal amplitudes were a function of the 90°-layer thickness, so additional system gain was varied to maintain the signal within the dynamic range of the 8-bit voltage resolution of the digitizer. Thicker specimens generated signals of larger amplitude. The additional system gain ranged from as little as 6 dB for the thickest specimen to 18 dB for the nine-ply specimen (n = 3). For the three- and six-ply laminates (n = 1 and 2), the signal amplitudes were significantly smaller as will be discussed below. For these, the preamplifier gain was increased to 40 dB and the system gain was set as high as 18 dB in attempts to capture the much smaller amplitude signals.

After detection of one or more transverse matrix-crack AE signals, the specimen was removed from the test machine. One edge of the specimen, which had been polished prior to testing, was examined under an optical microscope. The specimen was mounted on an x-y translation stage to allow measurement of crack locations for comparison with the AE data. Backscatter ultrasonic scans were taken to further confirm the crack locations and to provide information about the lateral extent of the cracks. This method also confirmed that no crack existed, which was not detected at the one polished edge. In some cases, penetrant-enhanced radiography was also used as was destructive sectioning and microscopy.

Extraneous noise signals were eliminated by post-test analysis of the waveforms. Typical waveforms from both a crack source and a noise source are shown in Fig. 3. Because of the multiple reflections of the signals across the narrow width of the coupons, the signals are more complicated than those presented in Fig. 1, which were detected in a large plate. However, the high-frequency extensional mode is clear in the crack signal. A small extensional-mode component is observed in the noise signal followed by a much larger, low-frequency, dispersive flexural-
mode signal. The source of the noise signals is believed to be grip damage or specimen slippage in the grips as all of the noise signals were located outside the specimen gage length in the grip regions.

![Graph](image)

Fig. 3 Typical signals caused by a) transverse matrix crack and b) grip slippage or damage.

For the laminates with \( n = 3 \) or larger, an exact one-to-one correlation existed between AE crack signals and cracks confirmed with microscopy. Backscatter ultrasonics indicated that all of these cracks extended across the full width of the specimen and that none were present, which were not observed by microscopy of the polished edge. Destructive sectioning and microscopy of a few of these cracks also confirmed this result. The fact that only a single AE signal was detected for each crack indicates that the cracks immediately propagated across the width of the specimen.

Location analysis of the four-sensor-array data showed that all cracks initiated along one of the specimen edges. A typical four-channel set of waveforms from a matrix-crack signal is shown in Fig. 4 along with a diagram indicating the sensor positions and the crack location. The time delay between the sensor pairs associated with the crack-initiation site being located along the edge is clearly seen. Furthermore, differences in signal amplitudes between the sensors within a pair are the result of the increased attenuation from propagation across the specimen width. The differences in signal amplitudes and frequency content for signals detected at opposite ends of the specimen and thus different distances of propagation distances should also be noted. These differences, which are caused by attenuation and dispersion, can have significant effects on location accuracy in systems of threshold-based AE arrival-time measurements. Conventional amplitude-distribution analysis is also affected by this attenuation. Excellent crack-location accuracy along the length of the specimens was also obtained from the AE data as compared to microscopy measurements. The most accurate linear location was obtained by using the two sensors on the same edge as the crack initiation site. The average of the absolute value of the difference in crack locations from AE and microscopy was 3.2 mm for a nominal sensor gage length of 152 mm.

For the thin laminates \((n = 1 \text{ or } 2)\), the AE signals from cracks were not always successfully detected and the signals detected were significantly smaller in amplitude. Ultrasonic backscatter scans and destructive-sectioning microscopy analysis showed that the cracks, which were visible at the specimen edge, did not extend into the interior of the specimen. Thus, the cracks were again initiating along the edge, but not progressing immediately across the specimen. This difference in crack initiation and growth behavior explains the much smaller amplitude signals and the difficulty in detecting these cracks.
Fig. 4 a) Set of four-channel waveforms indicating crack initiation along the specimen edge and b) diagram showing sensor positions, crack-initiation site, and rays of direct propagation for the AE signal.

4. Plate Mode Attenuation

As illustrated by the measurements above, Modal AE analysis provides the capability to differentiate AE signals from damage from those caused by extraneous noise in laboratory testing of composite coupons. Other studies such as by Ono and Huang (1994) have suggested that Modal AE waveform analysis can identify and differentiate signals from other source mechanisms such as delamination and fiber breakage. However, to apply these concepts to the testing of large structures, careful consideration must be given to the attenuation behavior of the different guided modes over longer distances of propagation. This includes signal loss in both the virgin material.
and that due to structural elements such as joints, stiffeners, or coatings. As an example, Prosser (1996) presented measurements of the effects of cryogenic insulation on the attenuation of plate modes in composite laminates. In this research, measurements of far-field, peak-amplitude attenuation were made for the extensional and flexural plate modes propagating in two different thicknesses of a virgin, uncoated, composite plate.

Attenuation is the loss of amplitude of an acoustic wave with an increased propagation distance. As discussed by Pollock (1986), there are four contributing factors to attenuation. These are
1) geometric spreading of the wave,
2) internal friction,
3) dissipation of the wave into adjacent media, and
4) losses related to velocity dispersion.

As discussed and demonstrated by Pollock (1990) and Downs and Hamstad (1995), geometric spreading is the dominant source of attenuation in the near field or close to the source. For two-dimensional wave propagation in geometries such as plates, the amplitude decreases inversely as the square root of the distance of propagation. This can lead to significant attenuation of greater than 40 dB over the first few centimeters of propagation. For plate waves, the attenuation over this region will be even greater as the signal begins to separate into the distinct modes and suffer from velocity dispersion.

In the far field, attenuation is typically dominated by absorption or conversion of sound energy into heat. Absorption usually has an exponential relationship of attenuation with distance. An attenuation coefficient, $A$, with units of dB per unit distance can be measured. For plate waves, the transition distance at which exponential attenuation begins to dominate geometric spreading is given by $4.34/A$.

Another mechanism of attenuation is amplitude loss due to the dissipation into adjacent media. This can be caused by inhomogeneities in the medium which scatter the sound wave within the same material. Examples are grain structure within anisotropic metals and fiber reinforcement in composites. It can also be caused by a medium in contact with the material or structure under test. A classic example relevant to AE testing is where acoustic waves propagate out of a pipe or pressure vessel into the contained fluid. Another instance is that of amplitude losses due to structural elements such as ribs and stiffeners. Amplitude losses of this type can be considerable and must be carefully evaluated when applying AE to practical structures.

The final attenuation mechanism is that of signal loss due to velocity dispersion. Because of the different velocities for different frequency components, an initially short, broadband pulse begins to spread in time at increased distances of propagation. This causes a loss in amplitude. The magnitude of amplitude loss depends on the steepness of the dispersion curves and the bandwidth of the signal. Previously, in most AE research and testing, narrow-band resonant AE sensors have been used. Likewise, most ultrasonic measurements are made with narrow-band tone-burst input signals, and bulk wave propagation with little or no dispersion is studied. Thus, dispersion induced attenuation is seldom observed and has been little studied. However, as demonstrated by the following measurements, this mechanism of signal loss is of considerable importance for the analysis of broadband Modal AE signals. Flexural-mode attenuation, as measured by far-field peak-amplitude signal loss with propagation distance, was significantly larger than that of the extensional mode. This was true even though the extensional-mode peak
Materials Research with Advanced Acoustic Emission Techniques

contained much higher frequencies, which are typically more severely attenuated by absorption and scattering mechanisms.

Measurements were made of the loss in peak amplitude as a function of propagation distance in the far field for both the extensional and flexural plate modes in two graphite/epoxy plates. Measurements were made along the 0°, 45°, and 90° propagation directions. The two plates were quasi-isotropic laminates of IM7/977-2 graphite/epoxy with different thicknesses. Both plates had nominal lateral dimensions of 990 x 990 mm. The first plate was 1.2 mm. thick (8 plies) and the second was 3.7 mm. (24 plies). Both plates were C-scanned with conventional ultrasonics prior to testing and determined to be of good quality.

For these measurements, a simulated AE source (pencil-lead break) was used. For each propagation direction, the source was positioned 127 mm from the plate edge. A sensor (R15, Physical Acoustics Corp., Princeton, NJ) was placed next to the lead-break source to provide a trigger source for the digital waveform recording system (F4012, Digital Wave Corp.). This system digitized the signals with 12-bit voltage resolution and recorded 4096 points at a sampling frequency of 5 MHz. The preamplifier and system gain was individually adjusted for each channel to provide a measurable, unsaturated signal. A linear array of five, broadband, high-fidelity AE sensors (B1025, Digital Wave Corp.) along the propagation direction was used to detect the simulated AE signals. The sensor nearest the source was at a distance of 102 mm with the other sensors spaced at equal distances of 102 mm apart along the propagation direction.

The peak amplitudes of both the extensional and flexural mode components of the signals were measured at all sensor positions. The measured amplitude values (in dB) were corrected for differences in preamplifier and system gain and plotted as a function of propagation distance. A linear least-squares fit was then used to determine the attenuation. As expected in a quasi-isotropic laminate, the attenuation was nominally the same for the three measured propagation directions (0°, 45° and 90°). Typical plots of peak amplitude versus distance for both the 8 and 24 ply plates are shown in Fig. 5.

![Fig. 5 Peak amplitude versus propagation distance for extensional and flexural modes in a) 8 ply composite plate and b) 24 ply composite plate.](image-url)
The average attenuation of the extensional mode for the three propagation directions in the 8-ply plate was 42 dB/m. Variations in attenuation from the average along the different directions were no greater than ±3 dB/m for all measurements discussed. For the flexural mode, the average attenuation was significantly larger at 83 dB/m. This large difference in attenuation between the two modes should have a great impact on sensor placement decisions on larger structures dependent on the mode of signal desired to be detected. Furthermore, if comparisons of the relative amplitudes of the modes are to be made to differentiate source mechanisms and noise, corrections for this different attenuation will be required. This large difference in attenuation between the extensional and flexural modes was measured even though the frequency content of the flexural mode near the peak was much lower than that of the extensional mode. An estimate of the peak frequency was made from the measurement of the half period of the cycle, on which the peak amplitude was measured. The frequency of the extensional mode peak was 410 kHz while it was only 85 kHz for the flexural mode peak. Absorption and scattering losses, which are usually the dominant far field attenuation mechanisms, significantly increase with frequency in composite materials. Thus, based on the frequency content, one would expect the extensional mode attenuation to be larger. However, examination of the actual waveforms confirmed the large affect that dispersion has on reducing the amplitude of the flexural mode.

For the thicker, 24-ply plate, the average attenuation of the extensional mode was 35 dB/m. This is slightly less than that in the thin plate. This might be expected since the measured peak frequency was also lower at 230 kHz. At 51 dB/m, the flexural mode attenuation was considerably less than in the 8-ply plate, although still larger than that of the extensional mode. The estimated peak frequency was 90 kHz, which was comparable to that in the thin plate. In this thicker plate, the waveforms at different distances showed much less spreading in time due to dispersion than in the thinner plate. This observation is consistent with the smaller measured attenuation value.

5. Observations and Conclusions

The following discussion offers not only direct conclusions from the presented measurements, but also comments as to their generalization to the larger field of composite-materials research. The two sets of data presented simultaneously demonstrate the potential benefit of Modal AE, as well as some of its current limitations. The successful detection of transverse matrix cracking in cross-ply graphite/epoxy composites with thick 90° layers shows the capability to identify a particular source mechanism and differentiate noise signals. Excellent source-location results were obtained. Not only was the position of the cracks along the specimen length determined and in excellent agreement with microscopy results, but the lateral position of the crack initiation site was also determined. In these coupons, all cracks initiated along one of the specimen edges.

The difficulty in detecting matrix cracking in similar specimens with thin 90° layers illustrates a couple of points. First, the same source mechanism can produce AE signals with significantly different amplitudes. In this case, the amplitude was dependent on the thickness of 90° plies and the length of crack advance. A similar result might also be expected for other source mechanisms such as delamination. In a real structure, it is anticipated that the length of advance for a given crack or delamination might vary considerably dependent on local stress conditions. Furthermore, damage will occur in different layers which might have different thicknesses. These factors cast considerable doubts on the capabilities of conventional amplitude-distribution analyses for
differentiating source mechanisms. This is especially true in light of the considerable effects of attenuation, which are demonstrated in the second set of measurements.

The second point involves the generalization of the Modal AE technique. Other studies, for example, Ono and Huang (1994), have demonstrated success in identifying signals from different source mechanisms such as delamination or fiber breakage. However, considerable research advances are required before the technique is able to differentiate a number of source mechanisms in arbitrary materials, laminates, and/or specimen geometries. Currently, AE signals in each new type of specimen must be carefully characterized and studied. Furthermore, at least for initial specimens, other techniques such as microscopy should be used to confirm the ability to use AE to identify a particular source mechanism in a particular material/laminate/geometry. Developments in modeling AE wave propagation will aid in expanding the applicability of Modal AE by providing insight into the effects of different source mechanisms on observed AE signals.

Another important point is that the results of this study were obtained from manual, one-at-a-time waveform processing. This further restricts the generalization of the approach. Techniques such as pattern recognition and neural networks have significant potential for automating Modal AE analysis. However, it is stressed that they should be based on a sound understanding of wave propagation in order to be most successful in identifying source mechanisms. Wave-propagation effects can make initially similar AE signals from the same source mechanisms appear very different and vice versa.

The attenuation measurements demonstrate the marked difference in amplitude loss for the extensional and flexural plate modes. Dispersion is the dominant mechanism for flexural plate mode attenuation. Thus, it is affected by plate thickness and material properties. To extend Modal AE analysis beyond testing small laboratory coupons to larger specimens and practical structures, attenuation effects will need to be well characterized and corrections made for amplitude measurements.

References


Digital Signal Processing of Modal Acoustic Emission Signals

Steve Ziola

Abstract

This paper presents several digital signal processing approaches for automating the analysis of modal acoustic emission signals. Software routines for noise rejection and mode identification are presented. Frequency and 3-D analysis techniques are discussed to provide additional information about the source. The cross-correlation method is shown to be more effective over short time Fourier transform. Results of the application of these methods are shown for a typical crack signal.

1. Introduction

Modal acoustic emission (MAE) uses wideband, high fidelity instrumentation to detect and capture the surface transients associated with defect growth. By capturing the true surface displacement of the transient, AE is no longer dependent on scatter plots and empirical correlations to determine the nature of the source that created the event. Theory based on Newtonian mechanics and specimen geometry can be used for analysis of the waveforms. Prior work (Gorman, 1991; Gorman and Prosser, 1990; Prosser, 1995) has shown that MAE can positively identify crack growth signals in plates, using plate wave theory.

In work by Searle et al. (1995), MAE was extended to crack detection in lap joints. While this work illustrated several advantages of the technique, such as noise discrimination, it also revealed shortcomings of the technique when applied to more realistic structures. The most glaring of these was analysis of the data. MAE can result in the capture of thousands of waveforms during a test, of which only a few are signals from crack growth. While events can be sorted by hand, for the technique to gain wider acceptance (especially in the materials community where acoustic emission techniques have historically seen the greatest use), the analysis techniques require some level of automation. This is where the MAE approach has its greatest advantage. Analysis techniques that have been developed for voice recognition, sonar, radar, and seismology, in conjunction with wave-propagation theory, can be used to perform source discrimination based on specimen geometry and source type, orientation and location.

This paper discusses several digital signal processing approaches for automating the analysis of MAE signals. Routines for noise rejection and mode identification are presented, and the results of the application of these routines shown.

The author (stevez@digitalwavecorp.com) is affiliated with Digital Wave Corporation, Englewood, Colorado.
2. MAE Signal Analysis Requirements

MAE signals are the digitized representations of surface displacements of propagating disturbances due to transient forces acting on the structure. Typical signals contain frequencies from 20 kHz to 3 MHz, with amplitudes ranging over 60 dB. The number of samples per waveform can vary anywhere from 256 to 4096. To accurately locate events, the number of channels of acquisition may range from two to eight. Event rates can be anywhere from hundreds of events per second to only several events per hour. With these wide variations, MAE signals represent some of the most difficult to analyze. They are random and non-stationary, but at least can be considered causal.

Current analysis methods require the user to have an understanding of the effect between the source and the resulting waveform characteristics, and then analyze the signals by hand to sort the data. While this approach is viable for small test specimens since the number of signals is usually small, when the technique is applied to larger structures with more complex geometries, the amount of data can increase dramatically. Thus, methods that can automatically analyze the data and extract information about the source, e.g., crack or noise, source location, source orientation, defect size, etc., need to be implemented.

The basic approach to signal analysis for MAE is to:
1) reject obvious noise signals due to mechanical sources and electromagnetic interference (EMI), thus reducing the amount of data and subsequent analysis time,
2) determine, based on frequency content, if any of the remaining signals could have been produced by the source of interest, since the source controls the frequency content of the signal,
3) determine the wave propagation characteristics, once again these are controlled by the source, and last but not least,
4) locate the source. The source location gives the final piece of information to the user if the signal is originating from a possible damage site.

3. Digital Signal Processing Techniques

*Noise Rejection:* Most defect growth occurs at fasteners, due to the stress concentrations created by these devices. While this narrows the area of interest, the mechanical fasteners can also create acoustic emission sources due to rubbing and fretting. Thus, many of the signals acquired are due to noise events. These signals tend to be of much larger amplitude and lower frequency than defect growth signals, and normally will saturate the analog-to-digital (A/D) conversion electronics. Figure 1 shows a typical noise signal and a signal caused by a growing crack.

Because of the saturation, the frequency content and wave shape information in the signal in Fig. 1(a) have been altered, so these types of waveforms should be excluded from further analysis, and not stored. Software routines have been written that determine the number of saturated points, and if the percentage of saturated points is too high, the waveform is rejected. The routine is very fast, and based on testing in aircraft structures, reduces the amount of captured data by 50-90%. Other routines have been developed (see Searle et al., 1995) that sort noise signals based on amplitude and signal duration.

*Frequency Analysis:* The frequency content of captured signals is dependent on the force-time function of the source. Thus, simple analysis techniques such as Discrete Fourier Transforms...
Materials Research with Advanced Acoustic Emission Techniques

Fig. 1 (a) Typical noise signal; (b) typical crack signal.

Fig. 2 Frequency spectrum of noise and crack signals.

(DFT) or Power Spectral Densities (PSD) can provide additional information about the source. Figure 2 shows the frequency response of the signals in Fig. 1. Because of the much shorter time response of the crack source, it contains much higher frequency content than the noise signal. By analyzing the energy content in specific frequency bands, it is possible to further sort the captured signals.

3-D Analysis Techniques: Plate modes exhibit predictable time-amplitude-frequency characteristics (Gorman, 1991). While the DFT can show what frequencies are contained in the signal, it does not show how these frequencies are varying as a function of time. The ability to detect these characteristics is important, since the different modes provide information about source orientation (Gorman and Prosser, 1990). Also, the modes propagate with different velocities, thus it is important to identify the mode if accurate source location is to be performed. The transform to be used must be fast, yet provide high enough resolution to differentiate between the wave modes. Several transforms were tested on MAE signals from defect growth, with varying degrees of success. The short time Fourier transform (STFT) (Boashash and Black, 1987) was computationally fast, but lacked the frequency resolution required for the analysis. Wavelet (Onsay and Haddow, 1994) and Wigner-Ville transforms (Wahl and Bolton, 1993) provided better frequency resolution, but required large amounts of time to perform the computations.
To shorten computation times, Gaussian cosine signals of various frequencies were cross-correlated with the signal, and the envelopes of the resulting cross-correlations were plotted as a function of frequency. While this method is not mathematically rigorous, it does provide the necessary frequency resolution, while still being computationally fast. To show the comparison of the cross-correlation method with the STFT, an extensional mode was excited in an aluminum plate with a point source (0.3 mm Pentel 2H lead break), and is shown in Fig. 3. Figure 4(a) shows a contour plot of the STFT, while Fig. 4(b) shows the cross-correlation output. The STFT was performed by dividing the signal into 16 sections (64 samples/section), with each additional section overlapping the prior by 3/4 of the 64 samples. The 64 samples were then zero-padded to 512 samples to increase the frequency resolution. The Gaussian cross-correlation technique zero-padded the signal from 1024 samples to 2048 samples, then performed 256 cross-correlations in frequency steps of 2.74 kHz, from 100 kHz to 800 kHz. While both techniques were able to display the time-amplitude-frequency characteristics of the extensional mode (frequency increasing as time increases), the resolution of the STFT is not as high as the cross-correlation technique. Similar results as the cross-correlation output were obtained with the wavelet and Wigner-Ville transform outputs.
Fig. 5 Comparison of (a) STFT and (b) cross-correlation using the crack growth signal shown in Fig. 1(b).

When an actual crack growth signal is used in the analysis, the results are as shown in Fig. 5. The inherent limitation in frequency resolution of the STFT begins to become more apparent, as shown in Fig. 5(a), as the contour degenerates and no conclusion as to the time-frequency relationship can be made. However, the cross-correlation plot shows the frequency characteristics of the extensional mode in the waveform more clearly. As can be seen in Fig. 5(b), it provides the information required to determine the wave mode of the signal that has been captured.

Another method of determining the wave propagation mode is to compute the waveform's instantaneous frequency in the time domain. This computation is described in Ziola and Searle (1997). Figures 6 and 7 show waveforms and their instantaneous frequency for two pencil-lead breaks on a thin plate. Figure 6 is the result of breaking the pencil-lead on the plate's edge, generating a waveform that contains mostly an extensional mode. Figure 7 is the result of breaking the pencil-lead on the plate's surface, generating a flexural mode. It is interesting to note that a very small extensional wave precedes the flexural wave in Fig. 7. This feature shows up nicely in the instantaneous frequency result.

The final step of source location will not be discussed in this paper, since the methods and algorithms are discussed in detail in other sources (Tobias, 1976; Ohtsu and Ono, 1988; Ziola and Gorman, 1991). However, after the mode identification step has been performed using the 3-D transforms, the time information in these plots can then be used for the arrival times needed for source location.

4. Conclusions

Modal acoustic emission shows promise as a method for the detection of growing cracks in plate-like structures. Because the method is based on the wave propagation in the media being tested, analysis routines can be developed with the physics in mind. Several software routines for digital signal processing have been developed for the MAE waveforms, and their application to fatigue-test data have resulted in significant reductions in the data volume, while still providing information about the defect growth.
Fig. 6 Instantaneous frequency of extensional mode waveform.

Fig. 7 Instantaneous frequency of flexural mode waveform.

References


Wave Theory of Acoustic Emission in Composite Laminates

Dawei Guo, Ajit Mal and Kanji Ono

Abstract

This paper is concerned with the development of acoustic emission (AE) waveform analysis in advanced structural composites. The relationship between the surface response and microfracture modes in composite laminates is studied to establish the theoretical background for waveform analysis of AE signals. Lamb waves produced by arbitrary internal sources in unidirectional and cross-ply composite laminates are investigated. Laboratory experiments are performed to validate the theoretical models. The results of this research should be useful in developing practical nondestructive testing tools to monitor damage initiation and evolution in composite structures.

1. Introduction

Fiber-reinforced composites have desirable engineering properties, including the low weight, high stiffness and damage tolerance, and are attractive for aerospace and other modern structural applications. However, composites are sensitive to the details of their manufacturing and service conditions. Both of these can introduce hidden defects in composites significantly degrading their performance. The safety and integrity of composite structures require careful monitoring of their degradation throughout the life of the structure by nondestructive means.

Microfracture events may occur locally in composite structures before the final failure due to stress concentration in the vicinity of existing defects. Due to the strong inhomogeneity and the dependence of the strength of composites on loading direction, microfractures can occur even if the load is well below the design strength of the structure. At the initiation of damage the stored strain energy in the material radiates out in the form of elastic waves or acoustic emission (AE). By knowing the detailed relationships between the waveform signatures and source characteristics, the source mechanism can be inferred from the surface response. Since composite plates or laminates are widely used in many engineering applications, monitoring of failure evolution in these structures are extremely important. This paper will concentrate on the study of Lamb waves (guided waves) due to microfractures in composite plates.

In conventional AE analysis, parameters such as event counts, amplitude, duration, rise time and the strength (or energy) of the signals or their combinations have been used to establish empirical correlations with material damages. Another approach, waveform analysis, in AE studies has sought the physical mechanisms from the recorded signals. Such an AE analysis has the...
potential to provide a more robust information on the nature of AE sources. In the first extensive work, Ono and coworkers utilized a video-recording system for visual waveform classification of the deformation and low-cycle fatigue of copper-base alloys (Krampfner et al., 1975). In the early stage of AE-waveform studies, the limitation of data-acquisition system made it difficult to analyze the waveform of each individual AE event, especially when many events are generated in loaded composites.

The work of Breckenridge et al. (1975) laid the foundation for standardized calibration of AE sensors using a capacitive transducer to capture the initial arrival of a signal produced by the fracture of a glass capillary. This allowed the development of quantitative comparison of AE experiment with theories of the wave propagation. Here, the contributions by Hsu et al. (1977), Sachse and Pao (1981), the Harwell group (Wadley et al., 1981; Scruby et al., 1985), Kishi and coworkers (Ohira and Kishi, 1982) and Ohtsu and Ono (1984, 1986, 1988) have elucidated AE-source characteristics in metals, ceramics and composites via deconvolution techniques or source-simulation techniques along with the use of digitizers or transient recorders, and computers with elaborate softwares. These studies considered surface or body waves. For a large structures or components, Ohtsu has developed the procedures of moment tensor analysis relying on the initial p-wave segments (Ohtsu, 1989) based on the earlier work (Ohtsu and Ono, 1986, 1988). This has been successfully applied to many AE studies of concrete, as reviewed by Ohtsu in this Workshop. Takemoto and coworkers (Suzuki et al., 1993, 1996) have applied the source-simulation technique proposed by Ohtsu and Ono (1986, 1988) to the source characterization in composites.

Another approach has examined the features of plate waves (see e.g., Prosser, this issue). Considering specific modes of propagation, the plate-wave AE improved the source location accuracy and enabled the separation of in-plane and out-of-plane sources. In this area and more broadly in AE involving guided waves, theory is still inadequate. In many applications, the observation point is likely to be located away from the source. The signals received at the recording station are dominated by guided waves. Due the dispersive properties of guided waves in the plates (and other geometries), the waveforms change as they propagate away from the source. Therefore, it is necessary to understand the detailed nature of the guided waves in composite plates in order to extract source information from the recorded waveforms.

Guided wave propagation in isotropic plates have been studied intensively in the literature using a variety of techniques including: the integral transformation technique (Knopoff, 1958; Davis, 1959; Pytel and Davis, 1962; Miklowitz, 1962, 1963; Scott and Miklowitz, 1964, 1967; Scott, 1969), generalized ray theory (Pao, 1978; Pao et al., 1979; Ceranoglu and Pao 1981) and Lamb-wave modal decomposition (Weaver and Pao, 1982; Santosoa and Pao, 1989). Wave motion in composite plates is much more complicated due to their anisotropy and inhomogeneity. Only two-dimensional cases and three-dimensional case with surface loading (Green, 1993a, 1993b, 1994; Lih, 1992; Lih and Mal, 1995b, 1996) have been studied in detail. Although the solution to general three-dimensional cases can, in principle, be constructed by applying the global matrix method (Mal, 1988; Lih and Mal, 1996), the computational effort for realistic geometries and source types is enormous due to the complexity of the formulation (Lih and Mal, 1995b).

Approximate solutions have been developed for wave propagation in anisotropic plates (Sun and Tan, 1984; Reddy, 1984). Retaining only the lowest Lamb-wave modes, these solutions are valid at very low frequencies. Since AE waveform data are recorded at relatively low frequencies approximate theories may be used to analyze these data (Lih and Mal, 1995a).
A limited amount of experimental work on Lamb wave propagation in composite plates has been reported in the literature (Mal et al., 1992; Gorman and Ziola, 1991; Gorman, 1991, 1995; Ono and Huang, 1994). Comparison between theoretical calculations and experimental measurements is possible for very simple cases (Lih and Mal, 1995b). To our knowledge, no coordinated theoretical and experimental work dealing with Lamb waves from microfractures in composite plates has appeared in the literature to date.

In this paper, the theoretical background for AE-waveform analysis in composite plates is outlined first. As a relatively simple case, the solution of the wave motion produced by a general source in a unidirectional composite plate is given. The approximate solution of the same problem in a laminated composite plate is obtained using laminate theory including transverse shear correction for an internal transient source. Experiments are carried out to verify the theoretical model and to identify the distinguishing features of the wave motion produced by various microfracture events (e.g., matrix cracking, delamination, fiber break, etc.) in thin composite laminates.

2. Theoretical Modeling

2.1 Material Modeling

The behavior of elastic waves propagating through fiber-composite materials is strongly affected by their inherent anisotropy, inhomogeneity and dissipative nature. Since it is extremely difficult to include all of these features in theoretical models, we introduce simplifications in constructing tractable theoretical models. One of these simplifications arises from the fact that in structural composites, the fiber diameter is small compared to the wavelengths associated with AE signals. For example, in graphite-epoxy, the fiber diameter is about 10 μm and for frequencies up to 10 MHz the wavelength is larger than 200 μm. In most AE analysis the frequencies are below 2 MHz. Thus, the material of each lamina can be treated as homogeneous and transversely isotropic, with symmetry axis along the fibers.

2.2 Wave Motion in Transversely Isotropic Plates

Applying the above simplification, wave field in a unidirectional composite plate can be calculated by using the classical integral transform technique and the displacement in the frequency domain can be expressed in a simple closed form.

Using the coordinate system shown in Fig. 1, where the fiber direction is along \( x_1 \), the material properties are specified in terms of five elastic constants, \( C_{11}, C_{22}, C_{12}, C_{23}, \) and \( C_{55} \), and density, \( \rho \). The wave motion in the solid can be expressed in terms of the displacement potentials, \( \Phi_1, \Phi_2 \) and \( \Phi_3 \) as

\[
\begin{align*}
\frac{\partial u_1}{\partial x_1} &= \partial \Phi_1/\partial x_1 \\
\frac{\partial u_2}{\partial x_2} + \partial \Phi_2/\partial x_3 &= \partial \Phi_2/\partial x_2 \\
\frac{\partial u_3}{\partial x_3} &= \partial \Phi_3/\partial x_2
\end{align*}
\]

For a given body force \( F = (F_1, F_2, F_3) \), the equations of motion have the form
\[
\left\{ a_5 \frac{\partial^2}{\partial x_1^2} + a_4 \nabla_1^2 - \frac{\partial^2}{\partial t^2} \right\} V_1^2 F_3 + \frac{\partial F_2}{\partial x_3} - \frac{\partial F_3}{\partial x_2} = 0
\]

\[
a_1 \frac{\partial^2}{\partial x_1^2} V_1^2 F_2 + \left\{ a_5 V_1^2 + a_2 \frac{\partial^2}{\partial x_2^2} - \frac{\partial^2}{\partial t^2} \right\} \frac{\partial F_1}{\partial x_1} = 0
\]

\[
a_3 \frac{\partial^2}{\partial x_1^2} V_1^2 F_1 + \left\{ a_5 V_1^2 + a_1 V_1^2 - \frac{\partial^2}{\partial t^2} \right\} V_1^2 F_2 + \frac{\partial F_2}{\partial x_2} + \frac{\partial F_3}{\partial x_3} = 0
\]  

where \( \nabla_1^2 = \frac{\partial^2}{\partial x_1^2} + \frac{\partial^2}{\partial x_3^2} \), \( a_1 = C_{22}/\rho \), \( a_2 = C_{11}/\rho \), \( a_3 = (C_{12}+C_{55})/\rho \), \( a_4 = (C_{22}-C_{23})/(2\rho) \), \( a_5 = C_{55}/\rho \).

Fig. 1 The coordinate system for a unidirectional composite plate and an arbitrary force, \( F \). The size of fibers is exaggerated for illustration purpose.

For an arbitrary source, the wave motion in the plate with the midplane of the plate parallel to \( x_1 \) can be separated into symmetric part and antisymmetric parts. Similarly an arbitrary source can be decomposed into its symmetric and antisymmetric parts. In the case of a transversely isotropic plate, there is a one to one correspondence between the force patterns and the displacement patterns. For each part, the corresponding displacement potentials are given as the summation of the displacement potential in the infinite medium with the same elastic properties and the additional potentials included to satisfy the boundary conditions. As shown in Appendix A, the displacement components in the frequency domain for both antisymmetric part and symmetric part in the far field can be expressed in the form

\[
u_r = \frac{(2\pi)^{3/2}}{\sqrt{\mathbf{R}}} \sum_m \sum_{p=1}^{N} A_p \text{ f}(\alpha_p, \beta_p) \frac{1}{\kappa_p} \text{ exp}[i(\alpha_p x_1 + \beta_p x_2 - \omega t)]
\]  

where \((\alpha, \beta)\) is the wavenumber vector in the plane of the plate, the first summation is over all the possible modes at the given frequency, the second summation is over all the points on the corresponding slowness curve (Fig. 2), where the normal to the slowness curve, \( \mathbf{n}_p \), is parallel to the position vector, \( \mathbf{R} \), \( \nabla \mathbf{R} \) is the gradient of \( \mathbf{R}(\alpha, \beta) \), \( \kappa_p \) is the curvature of the slowness curve at \( p \), \( f(\alpha, \beta) \) is the function related to the source (Guo, 1996).

The physical meaning of the solution is as follows: if the displacement is due to a source at the origin, then the waves observed at a distant point, \( \mathbf{R} \), correspond to the point, \( p \), on the slowness
Materials Research with Advanced Acoustic Emission Techniques

curve (that corresponds to $R(\alpha, \beta) = 0$), where the normal to the curve is parallel to $R$. It can be shown that the normal to the slowness curve for a given Lamb-wave mode is the energy-flux direction, $E$, for that mode. This indicates that the total displacement field can be decomposed into Lamb-wave modes. It should be mentioned that, in the far field, only the propagating modes (corresponding to real wavenumbers) are important in the displacement-field calculation, since the displacement related to the non-propagating and decaying modes (with complex and imaginary wavenumbers) will diminish as the disturbance propagates away from the source (Vasudevan and Mal, 1985). Physically, only the propagating modes carry energy away from the source and are responsible for the radiation, while the non-propagating and decaying modes will establish local dynamic equilibrium close to the source and no energy radiation is involved. This was pointed out in Torvik (1967) for the case of an isotropic plate, but is also true for anisotropic plates.

Fig. 2 The slowness curve and its normal for a Lamb-wave mode at a given frequency. $(\alpha, \beta)$ is the wavenumber vector, $R$ is the position vector and $E$ is the energy flux direction.

2.3 Wave Motion in Thin Laminated Composite Plates

Wave motion in laminated composites is far more complicated than that in a homogeneous anisotropic plate. The exact solution can, in principle, be formulated by using the global matrix method (Lih, 1992; Lih and Mal, 1996), but the numerical effort is enormous. It has been shown that at low frequencies the surface motion due to transverse surface loads can be approximated fairly well using the laminate theory with shear correction (Lih and Mal, 1995a). Unlike transverse surface loading, microfractures in composite plates give substantial in-plane force components, and both in-plane and transverse motion could be strongly excited (Gorman and Ziola, 1991; Gorman, 1991).

Based on the observations that, at low frequencies, the laminate theory including transverse shear correction can be used to calculate the wave field associated with both flexural and extensional motion, the theory is used to predict the surface displacement in thin laminated
Fig. 3 The geometry of a laminated composite plate with an arbitrary force, \( F \).

Composite plates; the results are valid in the frequency range considered in most AE waveform analysis.

The general lay-up of a composite plate and the coordinate system used in the formulation are shown in Fig. 3. Following the procedure outlined in Appendix B, the transverse surface displacement of flexural motion due to a given force system is given as

\[
\omega = \int \sum_{-\xi_2}^{\xi_2} \frac{\Delta_3}{\Delta_{\xi}} e^{-i(\xi_2 + \xi_2\gamma)} d\xi_2
\]

where \( \xi_1, \xi_2 \) are the wavenumber components along x and y, respectively, \( \Delta \) is the dispersion function, \( \Delta_{\xi_2} = \frac{\partial \Delta}{\partial \xi_2} \), and \( \Delta_3 \) is a function related to the source. The summation in \( \xi_2 \) is over all values that satisfy \( \Delta(\xi_1, \xi_2) = 0 \) for given \( \xi_1 \). The summation is over the slowness curve after the integration is carried out. Since \( \Delta(\xi_1, \xi_2) = 0 \) gives only the slowness curve of the lowest mode, the calculated wave motion is due to the lowest Lamb-wave mode only. The method of stationary phase has been used to evaluate the approximate expression given in equation (4) in the far field.

The transverse surface displacement related to the in-plane force system is given as

\[
\omega = \frac{i}{2\pi \hbar} \int \sum_{-\xi_2}^{\xi_2} \frac{\Delta_3}{\Delta_{\xi}} e^{-i(\xi_2 + \xi_2\gamma)} d\xi_2
\]

and the far-field approximation can be calculated using the method of stationary phase. Equations (4) and (5) will be used to calculate the surface displacement for given microfracture sources in thin laminated composite plate.

2.4 Source Mechanism of Microfractures

In the above theoretical modeling, the formulation is based on given body-force distributions. However, in composite plates, microfractures give rise to displacement discontinuities across the fracture surface. The body-force-equivalence theory can be applied to change the source into its equivalent force distribution (Burridge and Knopoff, 1964). The body-force distribution and the displacement discontinuity are equivalent in the sense that both give the same radiation field. As
long as the largest dimension of the microfracture surface is much smaller than the dominant wave length, the creation and the existence of the microfracture surface can be ignored in the formulation of the wave-propagation problem and the medium can be considered as continuous if the equivalent force system is included. Wave scattering by distributed microfracture surfaces can also be ignored for low crack densities. At high microfracture densities, the material properties of the composite would have to be changed to their overall values, but this is not done here. Therefore, the properties and the geometry of the bulk material are assumed to be the same before and after the creation of a microfracture surface, except that additional body-force terms are introduced in the configuration to represent the effect of the displacement discontinuity. The fracture surface for a microfracture event is assumed to be a flat element with a given normal, and the microfracture can be described as the displacement discontinuity across the flat surface element. Furthermore, the temporal and spatial dependence of microfracture process can be separated for the response calculation at low frequencies, although the temporal and spatial dependencies are coupled together in real physical processes. Based on the above assumptions, the equivalent body force is given in the form (Burridge and Knopoff, 1964)

\[
e_t = - \int_{\Sigma} \{[u_i](\xi, \omega)\nu_j c_{ijkl}(\xi)\delta_k(x, \xi)\} d\Sigma_{\xi}
\]

where \(e_t\) is the body force component along \(l\)-th direction, \(\Sigma\) is the fracture surface, \([u_i]\) is the displacement discontinuity across the fracture surface, \(\nu_j\) is the normal to surface elements on the fracture surface, \(c_{ijkl}\) are the elastic constants, and \(\delta\) is the Dirac delta function. Since both the displacement discontinuity and the normal to the microfracture surface are vector quantities, the equivalent force system can be given in terms of a moment tensor, \(M_{ij}\) (Ohitsu and Ono, 1988). The basic force systems, which form the moment tensor, are illustrated in Fig. 4.

Fig. 4 Moment tensor components and the corresponding force systems.
3. Experimental Studies

Laboratory experiments were conducted to validate the theoretical model presented earlier. In all the experiments, the data acquisition system used is a Fracture Wave Detector, manufactured by Digital Wave Corp. (DWC), Englewood, CO. The receivers are broad-band transducers (DWC B-1025) with the diameter of the sensor element of 10 mm.

First the surface responses of a unidirectional graphite/epoxy composite due to a pencil-lead-break source on the surface were measured at different locations. The experimental setup and the receiver locations with respect to the source are shown in Fig. 5. The source-receiver distances are 50 mm. Edge reflection effects were minimized by choosing optimum position for the pencil-lead breaks. The experimental measurements and the theoretical calculations were compared. Next, laminated composite samples were prepared with pre-embedded defects and inclusions. All the samples were subjected to tensile loadings. The applied loads were increased to the level, at which a significant amount of AE signals were obtained. The signals were processed and those associated with microfractures in the central region of the samples were extracted and analyzed. Five types of signals were identified corresponding to different microfracture mechanisms or displacement discontinuities. Body-force equivalence theorem was used to obtain the equivalent force system for each mechanism. These body force systems were then used to calculate the theoretical response of composite plates. The experimental measurements and the theoretical calculations were compared.

Fig. 5 Experimental setup for recording the surface response of the unidirectional composite plate to a pencil-lead-break source.
3.1 Surface Response of a Unidirectional Composite Plate due to Surface Loading

In order to calculate the surface response of an applied source, the source time history and the response function of the recording system has to be known a priori. The combined effect of the source time history and the response of the recording system was recovered from the Raleigh wave pulse due to the same source on the free surface of a large aluminum block used to simulate a halfspace.

The unidirectional composite plate was prepared with eight plies of Hercules AS4/5032 prepreg with the total thickness of 1 mm. The size of the plate was 240 x 200 mm. The material properties of the plate are listed in Table 1. For reference, the dispersion curves for the first symmetric and antisymmetric modes are given in Fig. 6 for the propagation angle \( \theta = 0^\circ \). An out-of-plane pencil break as shown in Fig. 5 can be modeled as a vertical force on the surface. The major contribution to the displacement comes from the first antisymmetric (flexural) mode with a very small contribution from the first symmetric (extensional) mode. Using the combined source time history and receiver response given in Fig. 7a, the calculated surface responses at the receiver locations of 50 mm distance and along 0°, 45° and 90° are shown in Fig. 7b, c and d by solid curves. These figures also show corresponding experimental measurements (dashed curves). Agreement between experimental measurements and theoretical calculations is excellent.

Table 1 Elastic constants (in GPa) and density (in Mg/m³) of the unidirectional graphite/epoxy composite.

<table>
<thead>
<tr>
<th>( C_{11} )</th>
<th>( C_{22} )</th>
<th>( C_{12} )</th>
<th>( C_{23} )</th>
<th>( C_{55} )</th>
<th>( \rho )</th>
</tr>
</thead>
<tbody>
<tr>
<td>160.7</td>
<td>13.9</td>
<td>6.44</td>
<td>6.9</td>
<td>7.1</td>
<td>1.58</td>
</tr>
</tbody>
</table>

Fig. 6 The dispersion curves (phase and group velocities) for the first antisymmetric (left) and symmetric (right) modes. Solid line: phase velocity; dashed line: group velocity.

3.2 Lamb Waves due to Microfractures in a Composite Laminate

Four laminated composite specimens (referred to as specimen A, B, C, D) were prepared from Hercules AS4/3502 prepreg. Specimens A and C were unidirectional, while B and D were cross-ply. Each specimen consisted of three plies of unidirectional graphite/epoxy laminae. Each lamina had the thickness of 0.125mm. The lay-up and the position of the cuts are illustrated in Fig. 8 and 9. The dimensions of all the specimens were 100 mm x 185 mm. End-tabs were glued at the end of each specimen to reduce stress concentration. The accessible area for surface response measure-
Fig. 7 (a) Combined source time history and receiver response, (b), (c) and (d) are calculated displacement responses at 50 mm in the directions 0°, 45° and 90°, respectively. The dashed curves show the corresponding experimental measurements.

All specimens were subjected to tensile loading and Lamb waves due to microfractures in the central region were extracted from the recorded AE events. After analysis of the recorded surface response, five types of signals were identified, each of which was tentatively attributed to different microfracture mechanisms. Typical signals are shown in Figs. 10-14.
These five types of signals are referred to as type I, II, III, IV and V. Type I signals are assumed to be due to fiber breakage; type II signals from matrix cracking along the fiber direction in the 90° ply; type III signals from fiber splitting in 0° plies due to displacement discontinuities normal to the fiber direction; type IV signals by fiber splitting in 0° plies due to displacement discontinuities along the fiber direction; type V signals the delamination between the first and the central plies. The sources related to signal types I, II, III, IV and V are referred to as source I, II, III, IV and V, respectively (see Fig. 15).

As indicated earlier, the microfracture sources were modeled by displacement discontinuities. Non-zero components of the moment tensor are calculated by using the body-force equivalence theorem (Table 2). For signal type III, the dominant force system shown is used in the theoretical model.

The transverse surface displacements of composite plates are calculated from the laminate theory with each laminae modeled as a transversely isotropic layer. The properties for each lamina are list in Table 1 (with $x_i$ as the fiber orientation).

The source time history is assumed to have the following form for the force function, $s$, with the rise time, $\tau$, as the shape parameter:
Fig. 10 Waveform and spectra of signal (I). The top figure illustrates the direction of displacement discontinuity expected (arrows) and the receiver positions used in the measurable area of the specimen.

Fig. 11 Waveform and spectra of signal (II). The top figure illustrates the direction of displacement discontinuity expected (arrows) and the receiver positions used in the measurable area of the specimen.
Fig. 12 Waveform and spectra of signal (III). The top figure illustrates the direction of displacement discontinuity expected (arrows) and the receiver positions used in the measurable area of the specimen.

Fig. 13 Waveform and spectra of signal (IV). The top figure illustrates the direction of displacement discontinuity expected (arrows) and the receiver positions used in the measurable area of the specimen.
Fig. 14 Waveform and spectra of signal (III). The top figure illustrates the direction of displacement discontinuity expected (arrows) and the receiver positions used in the measurable area of the specimen.

Table 2 The ratios of non-zero moment tensor components used in modeling microfractures in the composite plate.

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Non-zero Components of Moment Tensor</th>
<th>Ratio</th>
<th>Rise Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. fiber breakage</td>
<td>$M_{xx}$, $M_{yy}$, $M_{zz}$</td>
<td>1 : 0.1 : 0.1</td>
<td>0.5 µs</td>
</tr>
<tr>
<td>II. matrix cracking</td>
<td>$M_{xx}$, $M_{yy}$, $M_{zz}$</td>
<td>1 : 0.3 : 0.3</td>
<td>1.0 µs</td>
</tr>
<tr>
<td>III. fiber splitting</td>
<td>$M_{yy}$</td>
<td>1</td>
<td>1.0 µs</td>
</tr>
<tr>
<td>IV. fiber splitting</td>
<td>$M_{xy}$, $M_{yx}$</td>
<td>1 : 1</td>
<td>1.0 µs</td>
</tr>
<tr>
<td>V. delamination</td>
<td>$M_{zz}$, $M_{xx}$</td>
<td>1 : 1</td>
<td>2.0 µs</td>
</tr>
</tbody>
</table>

$$s(t, \tau) = \begin{cases} 
0 & \text{for } t < 0 \\
\sin^2(\pi t/2\tau) & \text{for } 0 < t < \tau \\
1 & \text{for } \tau < t
\end{cases} \quad (7)$$

A sample response of the recording system, including a transducer, to this input function for $\tau = 0.125$ µs is given in Fig. 16. This response was obtained by exciting one sensor (DWC B1025) by square waves and receiving it face-to-face by the other sensor (also B1025).

After further study of the influence of the rise time on the response spectrum of the recording system, and the frequency content of the measurements, the rise time for local microfractures in the composite plates was chosen to be 0.5, 1.0, and 2 µs for fiber breakage, matrix cracking or splitting and delamination source, respectively. The calculated results and the experimental measurements at given transducer positions are shown in Figs. 17 - 23 for different sources. It can be seen that good agreement between experimental measurements and the theoretical calculations at the beginning of the waveform has been achieved in Figs. 17 - 20. For type V
source, two groups of pulses arrive because of the shear character of the source. For clearly showing the results for type V, the experimental measurement and the theoretical calculation are represented separately in Figs. 22 and 23, respectively. Again, the beginning parts of both pulse groups are predicted well. Because of these observed agreements, the assumed source mechanisms appear to be the operating source for the five different types.

The experimental waveforms after the first few pulses are primarily due to reflections from the edges of the sample which are not included in the theoretical model. It is possible that multiple microfractures in very short time windows have occurred.

4. Conclusion

The theoretical solution of the wave motion in a transversely isotropic plate is used to model the surface response of a unidirectional composite plate. For a composite plate with general lay-up, laminate theory including shear correction was used to predict the surface response due to a localized internal source. The solution is valid only at frequencies of interest in AE waveform analysis (<2MHz). Experiments were conducted to validate theoretical model. The surface response of a unidirectional composite plate due to an pencil break source was calculated and compared with the experimental measurements. Special specimens were prepared to produce acoustic emission signals due to microfracture in composite laminates. Five types of signals were
Fig. 17 Comparison between the theoretical calculation and the experimental measurement for a fiber breakage (type I) source. Dashed line: calculated; solid line: experimental.

Fig. 18 Comparison between the theoretical calculation and the experimental measurement for a matrix cracking in 90° ply (type II) source. Dashed line: calculated; solid line: experimental.

observed in the experiments; these are attributed to different microfracture sources modeled by displacement discontinuities across the microfracture surfaces. The experimental measurements and theoretical calculations are compared and are found to agree well in the time domain of interest.

Acknowledgments

The research was supported by the Air Force Office of Scientific Research under grant F49620-93-1-0320.
Fig. 19 Comparison between the theoretical calculation and the experimental measurement for a fiber splitting normal to the fiber direction in 0° ply (type III) source. Dashed line: calculated; solid line: experimental.

Fig. 20 Comparison between the theoretical calculation and the experimental measurement for a fiber splitting along the fiber direction in 0° ply (type IV) source. Dashed line: calculated; solid line: experimental.

References


Fig. 21 Comparison between the theoretical calculation and the experimental measurement for a delamination due to shear (type V) source. Dashed line: calculated; solid line: experimental.

Fig. 22 The experimental measurement for a delamination due to shear (type V) source. Solid line: experimental.


Fig. 23 The theoretical calculation for a delamination due to shear (type V) source. Solid line: calculated.


Appendixes

A. Lamb Waves in a Transversely Anisotropic Plate

The displacement field in a transversely anisotropic solid with the axis of symmetry parallel to the $x_1$-axis can be expressed as

$$
\begin{align*}
&u_1 = \partial \Phi_1 / \partial x_1 \\
&u_2 = \partial \Phi_2 / \partial x_2 + \partial \Phi_3 / \partial x_3 \\
&u_3 = \partial \Phi_2 / \partial x_3 - \partial \Phi_3 / \partial x_2
\end{align*}
$$

(A.1)

where $\Phi_1$, $\Phi_2$ and $\Phi_3$ are the displacement potentials. The corresponding constitutive relations are

$$
\begin{pmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{23} \\
\sigma_{31}
\end{pmatrix} =
\begin{bmatrix}
C_{11} & C_{12} & C_{12} & 0 & 0 \\
C_{12} & C_{22} & C_{23} & 0 & 0 \\
C_{12} & C_{23} & C_{22} & 0 & 0 \\
0 & 0 & 0 & C_{44} & 0 \\
0 & 0 & 0 & 0 & C_{55}
\end{bmatrix}
\begin{pmatrix}
u_{1,1} \\
u_{2,2} \\
u_{3,3} \\
u_{2,3} + u_{3,2} \\
u_{1,3} + u_{3,1} \\
u_{1,2} + u_{2,1}
\end{pmatrix}
$$

(A.2)

where $C_{44} = (C_{22} - C_{23})/2$, and $u_{i,j} = \partial u_i / \partial x_j$.

In terms of the displacement potentials the equations of motion have the form

$$
\begin{align*}
\left\{a_5 \frac{\partial^2}{\partial x_1^2} + a_4 \nabla_1^2 - \frac{\partial^2}{\partial t^2}\right\} \nabla_1^2 \Phi_3 + \frac{\partial F_2}{\partial x_3} - \frac{\partial F_3}{\partial x_2} &= 0 \\
a_3 \frac{\partial^2}{\partial x_1^2} \nabla_1^2 \Phi_2 + \left\{a_5 \nabla_1^2 + a_2 \frac{\partial^2}{\partial x_1^2} - \frac{\partial^2}{\partial t^2}\right\} \frac{\partial^2 \Phi_1}{\partial x_1^2} + \frac{\partial F_1}{\partial x_1} &= 0 \\
a_3 \frac{\partial^2}{\partial x_1^2} \nabla_1^2 \Phi_1 + \left\{a_5 \frac{\partial^2}{\partial x_1^2} + a_1 \nabla_1^2 - \frac{\partial^2}{\partial t^2}\right\} \nabla_1^2 \Phi_2 + \frac{\partial F_2}{\partial x_2} + \frac{\partial F_3}{\partial x_3} &= 0
\end{align*}
$$

(A.3)

where

$$
\Delta_1 = \frac{\partial^2}{\partial x_1^2} + \frac{\partial^2}{\partial x_3^2}, \quad a_1 = C_{22}/\rho, \quad a_2 = C_{11}/\rho \\
a_3 = (C_{12} + C_{55})/\rho, \quad a_4 = (C_{22} - C_{23})/(2\rho), \quad a_5 = C_{55}/\rho
$$

(A.4)

$\rho$ is the density and $F_i = (F_1, F_2, F_3)$ is the body force per unit volume.

Considering $F_i$ as a function of position, representing a spatially distributed source with time dependence $e^{i\omega t}$, its components in the double transformed domain $\tilde{F}_i$ are of the form

$$
\tilde{F}_i = \frac{1}{8\pi^3} \int \int \int_{-\infty}^{\infty} F_i e^{-ik\cdot r} dx dy dz
$$

(A.5)

with the inverse transform determined through

$$
F_i = \int \int \int_{-\infty}^{\infty} \tilde{F}_i e^{ik\cdot r} d\alpha d\beta d\gamma
$$

(A.6)
where \( r = (x, y, z) \) is the position vector in Cartesian coordinates and \( k = (\alpha, \beta, \gamma) \) is the wavenumber vector. Generally, \( \tilde{F} \) is a function of \((\alpha, \beta, \gamma)\).

Based on the source representation in Equation (A.5), the displacement potentials \( \Phi_i \) are expressed in the form

\[
\Phi_i = \int \int \int_{-\infty}^{\infty} \bar{\Phi}_i e^{ik \cdot r} d\alpha d\beta d\gamma
\]  

(A.7)

Substituting the form of the solution (A.7) in the equations of motion (A.3) we have

\[
\begin{align*}
[a_5 \alpha^2 + a_4 (\beta^2 + \gamma^2) - \omega^2] & (\beta^2 + \gamma^2) \Phi_3 + (i \gamma \tilde{F}_2 - i \beta \tilde{F}_3) = 0 \\
a_3 \alpha^2 (\beta^2 + \gamma^2) \Phi_2 + [a_5 (\beta^2 + \gamma^2) + a_2 \alpha^2 - \omega^2] \alpha^2 \Phi_1 + i \alpha \tilde{F}_1 = 0 \\
a_3 \alpha^2 (\beta^2 + \gamma^2) \Phi_1 + [a_5 \alpha^2 + a_1 (\beta^2 + \gamma^2) - \omega^2] (\beta^2 + \gamma^2) \Phi_2 + i \beta \tilde{F}_2 + i \gamma \tilde{F}_3 = 0
\end{align*}
\]

(A.8)

where \((\tilde{F}_1, \tilde{F}_2, \tilde{F}_3) = \tilde{F} \) are the body force components in the transformed domain. Then the displacement potentials in the transformed domain \( \bar{\Phi}_i \) are given by

\[
\begin{align*}
\bar{\Phi}_1 &= \frac{f_1}{G(\alpha, \beta, \gamma)} \\
\bar{\Phi}_2 &= \frac{f_2}{G(\alpha, \beta, \gamma)} \\
\bar{\Phi}_3 &= \frac{f_3}{F(\alpha, \beta, \gamma)}
\end{align*}
\]

(A.9)

where

\[
\begin{align*}
G(\alpha, \beta, \gamma) &= [a_5 (\beta^2 + \gamma^2) + a_2 \alpha^2 - \omega^2][a_1 (\beta^2 + \gamma^2) + a_5 \alpha^2 - \omega^2] - a_3 \alpha^2 (\beta^2 + \gamma^2) \\
\alpha^2 f_1 &= i a_3 \alpha^2 (\beta \tilde{F}_2 + \gamma \tilde{F}_3) - i \alpha [a_1 (\beta^2 + \gamma^2) + a_5 \alpha^2 - \omega^2] \tilde{F}_1 \\
(\beta^2 + \gamma^2) f_2 &= i a_3 \alpha (\beta^2 + \gamma^2) \tilde{F}_1 - i [a_5 (\beta^2 + \gamma^2) + a_2 \alpha^2 - \omega^2] (\beta \tilde{F}_2 + \gamma \tilde{F}_3) \\
F(\alpha, \beta, \gamma) &= \omega^2 - [a_4 (\beta^2 + \gamma^2) + a_5 \alpha^2] \\
(\beta^2 + \gamma^2) f_3 &= i (\gamma \tilde{F}_2 - \beta \tilde{F}_3)
\end{align*}
\]

(A.10)

Transforming back to the frequency domain, the displacement potentials for the given source in a transversely anisotropic solid are

\[
\Phi_i = \int \int \int_{-\infty}^{\infty} \frac{f_i}{G(\alpha, \beta, \gamma)} e^{ik \cdot r} d\alpha d\beta d\gamma
\]

(A.11)

where \( i = 1, 2 \). The corresponding displacement and the stress components are given by Equations (A.1) and (A.2), The triple integrals in Equation(A.11) can be reduced to double integrals by means of contour integration in the complex \( \gamma \) plane. Subsequently it is assumed that the \( z \)-coordinate of the receiver is positive, i.e., \( z_r \geq 0 \). Choosing a contour in the complex \( \gamma \) plane which consists of the real axis together with a large semi-circle in the upper half-plane, the integration with respect to \( \gamma \) can be replaced by the appropriate contributions from the singularities of the integrand. Then the displacement potentials have the form

\[
\begin{align*}
\Phi_1 &= 2i \pi \sum_k \int \int_{-\infty}^{\infty} \left\{ \frac{f_1}{G_k(\gamma)} \right\}_{\gamma = \eta_k} e^{iK \cdot R} d\alpha d\beta d\gamma \\
\Phi_2 &= 2i \pi \sum_k \int \int_{-\infty}^{\infty} \left\{ \frac{f_2}{G_k(\gamma)} \right\}_{\gamma = \eta_k} e^{iK \cdot R} d\alpha d\beta d\gamma \\
\Phi_3 &= 2i \pi \sum_l \int \int_{-\infty}^{\infty} \left\{ \frac{f_3}{F_k(\gamma)} \right\}_{\gamma = \eta_l} e^{iK \cdot R} d\alpha d\beta d\gamma
\end{align*}
\]

(A.12)
Here \( F, G = \partial F/\partial \gamma, G, \gamma = \partial G/\partial \gamma \) and \( \gamma_k, \gamma_l \) are the roots of
\[
G(\alpha, \beta, \gamma) = 0, \quad F(\alpha, \beta, \gamma) = 0
\]
respectively, for a given pair of \((\alpha, \beta)\) with \( k = 1, 2 \) and \( l = 1 \).

In the subsequent discussions the potentials (A.12) will be referred to as primary potentials in constructing the wave propagation solution in a plate. For a plate of uniform thickness without surface loading the wave field in the plate must satisfy the stress-free boundary conditions
\[
\sigma_{iz} = 0, \quad z = \pm H, \quad i = x, y, z
\]
where \( H \) is the half thickness of the plate. The primary potentials (A.12) for a given source do not satisfy the boundary conditions and the additional potentials must be included. Considering the form of the primary potentials, the additional potentials are chosen to have the forms
\[
\begin{align*}
\phi_1 &= [(q_{11} B_1^+ e^{i\eta_1 z} + q_{12} B_2^+ e^{i\eta_2 z}) + (q_{11} B_1^- e^{-i\eta_1 z} + q_{12} B_2^- e^{-i\eta_2 z})] e^{iK \cdot R} \\
\phi_2 &= [(q_{21} B_1^+ e^{i\eta_1 z} + q_{22} B_2^+ e^{i\eta_2 z}) + (q_{21} B_1^- e^{-i\eta_1 z} + q_{22} B_2^- e^{-i\eta_2 z})] e^{iK \cdot R} \\
\phi_3 &= (A_1^+ e^{i\eta_3 z} + A_1^- e^{-i\eta_3 z}) e^{iKR}
\end{align*}
\]
where \( \eta_j \) is replaced by \( \eta_j \) in order to make it clear that \( \eta_j \) are the poles in the upper half plane of the complex \( \gamma \) plane, \( K = (\alpha, \beta) \) is the wavenumber in the middle plane of the plate, and \( R = (x, y) \) is the position vector of a point on the same plane, \( r = 1, s = 1, 2 \). The summation convention for repeated indices is implied. The coefficients \( A_j, B_j \) and \( C_j \) are determined by the requirement that the total field \( \Phi_1 + \phi_1, \Phi_2 + \phi_2 \) and \( \Phi_3 + \phi_3 \) must satisfy stress-free boundary conditions on the plate surfaces. The time factor \( e^{-i\omega t} \) and the double integral \( \int_{-\infty}^{\infty} d\alpha d\beta \) are suppressed, and
\[
\begin{align*}
B_1^\pm &= a_3 (\beta^2 + \gamma_1^2) \equiv a_3 b_3 \equiv q_{1s} \\
C_1^\pm &= \omega^2 - a_2 \alpha^2 - a_3 (\beta^2 + \gamma_1^2) \equiv \omega^2 - a_2 \alpha^2 - a_3 b_3 \equiv q_{2s}
\end{align*}
\]
where \( b_s = \beta^2 + \gamma_1^2 \). In Equation (A.15) there are six unknown constants which can be determined from six boundary conditions, Equation (A.14). Since the stress components on the surfaces from the primary potentials are known, the stress-free boundary conditions give
\[
\begin{pmatrix}
\sigma_{zz} \\
\sigma_{zy} \\
\sigma_{zx}
\end{pmatrix}
= -
\begin{pmatrix}
\sigma_{zz} \\
\sigma_{zy} \\
\sigma_{zx}
\end{pmatrix}
\begin{pmatrix}
\phi_1 \\
\phi_2 \\
\phi_3
\end{pmatrix}
\]
Equation (A.17) results in a system of linear algebraic equations for the unknowns \( A_i \) and \( B_i \).

We first consider a point source located at \( z = h \) with components \((F_x, F_y, F_z)\). This source can be decomposed into a symmetric part, \((F_x/2, F_y/2, F_z/2)\) at \( z = h \) and \((F_x/2, F_y/2, -F_z/2)\) at \( z = -h \) and an antisymmetric part, \((F_x/2, F_y/2, F_z/2)\) at \( z = h \) and \((-F_x/2, -F_y/2, F_z/2)\) at \( z = -h \). For the symmetric motions the additional displacement potentials in the double transformed domain can be written as
\[
\begin{align*}
\phi_1 &= [q_{11} D_1 \cos(\eta_1 z) + q_{12} D_3 \cos(\eta_2 z)] \\
\phi_2 &= [q_{21} D_1 \cos(\eta_1 z) + q_{22} D_3 \cos(\eta_2 z)] \\
\phi_3 &= D_6 \sin(\eta_3 z)
\end{align*}
\]
where $D_i$ are functions of $(\alpha, \beta)$, and the phase factor related to the propagation of the wave, e.g., $e^{iK\cdot R}$, has been suppressed.

Applying the stress-free boundary conditions on the surface $z = H$, the left side of Equation (A.17) becomes

$$
\begin{bmatrix}
S_{11} & S_{12} \\
-2i\beta \eta_1 q_{21} \sin(\eta_1 H) & -2i\beta \eta_2 q_{22} \sin(\eta_2 H) \\
-(q_{11} + q_{21}) \eta_1 \sin(\eta_1 H) & -(q_{12} + q_{22}) \eta_2 \sin(\eta_2 H)
\end{bmatrix}
\begin{bmatrix}
D_1 \\
D_3 \\
D_6
\end{bmatrix}
$$

(A.19)

where

$$
S_{11} = -(a_3 - a_5)\alpha^2 q_{11} - (a_1 - 2a_4)\beta^2 q_{21} - a_1 q_{21} \eta_1^2 \cos(\eta_1 H)
$$

$$
S_{12} = -(a_3 - a_5)\alpha^2 q_{12} - (a_1 - 2a_4)\beta^2 q_{22} - a_1 q_{22} \eta_1^2 \cos(\eta_2 H)
$$

(A.20)

By setting the determinant of the coefficient matrix to zero we have the dispersion equation for the symmetric motion

$$
\Delta_1^x \cos(\eta_1 h) \sin(\eta_2 h) \sin(\eta_3 h) + \Delta_1^y \sin(\eta_1 h) \cos(\eta_2 h) \sin(\eta_3 h) + \Delta_1^z \sin(\eta_1 h) \sin(\eta_2 h) \cos(\eta_3 h) = 0
$$

(A.21)

where

$$
\Delta_1^x = \eta_2 [(\beta^2 + \eta_5^2) q_{22} - (\beta^2 - \eta_5^2) q_{12}] [(a_5 - a_3)\alpha^2 q_{11} - (a_1 - 2a_4)\beta^2 q_{21} - a_1 \eta_1^2 q_{21}]
$$

$$
\Delta_1^y = -\eta_2 [(\beta^2 + \eta_5^2) q_{21} - (\beta^2 - \eta_5^2) q_{11}] [(a_5 - a_3)\alpha^2 q_{12} - (a_1 - 2a_4)\beta^2 q_{22} - a_1 \eta_1^2 q_{22}]
$$

$$
\Delta_1^z = 4a_4 \beta^2 \eta_1 \eta_2 \eta_3 (q_{11} q_{22} - q_{12} q_{21})
$$

(A.22)

The corresponding quantities for the antisymmetric motion can be obtained in a similar manner.

Including time dependence, the general form of the displacement component can be written as

$$
u_r = e^{-i\omega t} \int_{-\infty}^{+\infty} \int \mathcal{H}(\alpha, \beta) \frac{R_D(\alpha, \beta)}{R(\alpha, \beta)} e^{i(\alpha x + \beta y)} d\alpha d\beta
$$

(A.23)

where $r = 1, 2, 3$. The solution for any given location $(x, y)$ requires numerical integration; but this is impractical due to the fact that the domain of $(\alpha, \beta)$ is infinite, unless the behavior of the integrand is known at infinity.

A contour integral can be used to simplify the integral and the displacement can be written in the form

$$
u_r = e^{-i\omega t} \int_{-\infty}^{+\infty} \sum_{\beta(\alpha)} f(\alpha, \beta) e^{i(\alpha x + \beta y)} d\alpha
$$

(A.24)

where the summation on $\beta(\alpha)$ is over all the points which satisfy $R(\alpha, \beta) = 0$ for a given $\alpha$.

In the far field the integral can be evaluated by using the method of stationary phase and which gives

$$
u_r \simeq \frac{(2\pi)^{3/2}}{\sqrt{R}} \sum_{m} \sum_{p=1}^{N} A_p \frac{f(\alpha_p, \beta_p)}{(\sqrt{R} \cdot n_p)_p |k_p|^{1/2}} \exp [i(\alpha_p x + \beta_p y - \omega t)]
$$

(A.25)
where $\nabla R$ is the gradient of $R(\alpha, \beta)$ and $n_p$ is the normal to the slowness curve at point $p$. The curvature $k_p$ can be expressed in terms of the partial derivatives of $R$ as follows

$$k_p = \frac{R^2_{\alpha\beta} - 2R_{\alpha}R_{\beta}R_{\alpha\beta} + R^2_{\beta}R_{\alpha\alpha}}{(R^2_{\alpha} + R^2_{\beta})^{3/2}}$$

(A.26)

B. Wave Motion in Thin Laminated Composite Plates

In thin composite plates transverse shear and transverse normal stress components are much smaller than the in-plane stress components; thus, the stress state in the plate can be approximated as plane stress. In the following derivation we assume that each lamina of the composite laminate can be modeled as an orthotropic plate with one of its symmetry planes parallel to the plate surface.

The stress-strain relationship for the lamina is

$$\{\sigma_i\} = [C_{ij}]\{\varepsilon_j\}$$  
(B.1)

By assuming $\sigma_{zz} = 0$, corresponding to the assumption of plane stress condition, the transverse normal strain $\varepsilon_z$ is given as

$$\varepsilon_z = -\frac{C_{13}}{C_{33}}\varepsilon_x - \frac{C_{23}}{C_{33}}\varepsilon_y - \frac{C_{36}}{C_{33}}\varepsilon_{xy}$$  
(B.2)

Then the constitutive relations reduce to

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & Q_{16} \\ Q_{12} & Q_{22} & Q_{26} \\ Q_{16} & Q_{26} & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix}$$
(B.3)

where $Q_{ij}$ are the reduced stiffness constants

$$Q_{ij} = C_{ij} - \frac{C_{i3}C_{j3}}{C_{33}}$$  
(B.4)

Starting from the equation of motion in the 3D case without body forces

$$\frac{\partial \sigma_{ij}}{\partial x_j} = \rho \frac{\partial^2 u_i}{\partial t^2}$$
(B.5)

the equations of motion for laminae under plane stress assumptions can be derived by an integral operation.

Applying the operator $\int_{-h}^{h} dz$ for $i = z$, the equation of motion become

$$\frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} + p = \int_{-h}^{h} \rho_0 \frac{\partial^2 u_z}{\partial t^2} dz$$
(B.6)
where $Q_x$ and $Q_y$ are the transverse shears per unit length

$$
(Q_x, Q_y) = \int_{-h}^{h} (\sigma_{xz}, \sigma_{yz}) \, dz
$$

and $p = \sigma_z(h) - \sigma_z(-h)$ is the transverse load on the surface of the plate. Applying the same operator $\int_{-h}^{h} \, dz$ to Equation (B.5) for $i = x, y$, we obtain the equations of motion in terms of the normal and shear force resultants

$$
\frac{\partial N_x}{\partial x} + \frac{\partial N_{xy}}{\partial y} + T_{zx} = \int_{-h}^{h} \rho \frac{\partial^2 u_x}{\partial t^2} \, dz
$$
$$
\frac{\partial N_{xy}}{\partial x} + \frac{\partial N_y}{\partial y} + T_{xy} = \int_{-h}^{h} \rho \frac{\partial^2 u_y}{\partial t^2} \, dz
$$

where $(T_{zx}, T_{xy}) = (\sigma_{zx}, \sigma_{zy})|_{-h}^{h}$ are the shear stress components on the surface of the plate, and $N_x, N_y$ and $N_{xy}$ are the force resultants

$$
(N_x, N_y, N_{xy}) = \int_{-h}^{h} (\sigma_x, \sigma_y, \sigma_{xy}) \, dz
$$

In a similar manner, applying the operator $\int_{-h}^{h} \, dz$ for $i = x, y$, we find

$$
\frac{\partial M_x}{\partial x} + \frac{\partial M_{xy}}{\partial y} - Q_z = \int_{-h}^{h} z \rho \frac{\partial^2 u}{\partial t^2} \, dz
$$
$$
\frac{\partial M_{xy}}{\partial x} + \frac{\partial M_y}{\partial y} - Q_y = \int_{-h}^{h} z \rho \frac{\partial^2 v}{\partial t^2} \, dz
$$

where $M_x, M_y, M_{xy}$ are moment resultants with respect to the middle plane of the plate

$$
(M_x, M_y, M_{xy}) = \int_{-h}^{h} (\sigma_x, \sigma_y, \sigma_{xy}) \, dz
$$

Considering the kinematics of the flexural motion, the displacement can be approximated as

$$
u = u_0(x, y, t) + z\phi_z(x, y, t) \quad v = v_0(x, y, t) + z\phi_y(x, y, t) \quad w = w(x, y, t)
$$

It should be noted that the transverse displacement is independent of $z$, and the second terms in $u$ and $v$ are due to in-plane motion in bending. The in-plane strain components are

$$
\epsilon_x = \epsilon_x^0 + z\kappa_x, \quad \epsilon_y = \epsilon_y^0 + z\kappa_y, \quad \epsilon_{xy} = \epsilon_{xy}^0 + z\kappa_{xy}
$$

and the inter-laminar shear strain components are

$$
\epsilon_{xz} = \phi_x + \frac{\partial w}{\partial x}, \quad \epsilon_{yz} = \phi_y + \frac{\partial w}{\partial y}
$$

where $(\epsilon_x^0, \epsilon_y^0, \epsilon_{xy}^0)$ are the mid-plane strains due to the displacement field $(u_0, v_0, w)$, and $(\kappa_x, \kappa_y, \kappa_{xy})$ are the curvatures of the mid-plane given as

$$
\kappa_x = \frac{\partial \phi_x}{\partial x}, \quad \kappa_y = \frac{\partial \phi_y}{\partial y}, \quad \kappa_{xy} = \frac{\partial \phi_x}{\partial y} + \frac{\partial \phi_y}{\partial x}
$$
In order to take the shear correction into account, the transverse shear stress components are written as
\[
\begin{bmatrix}
\sigma_{yz} \\
\sigma_{xz}
\end{bmatrix} =
\begin{bmatrix}
k_4A_{44} & k_{45}A_{45} \\
k_{45}A_{45} & k_5A_{55}
\end{bmatrix}
\begin{bmatrix}
\epsilon_{yz} \\
\epsilon_{xz}
\end{bmatrix}
\]
(B.16)
where \(k_4, k_5\), and \(k_{45}\) are constants to be adjusted to achieve a good match in the dispersion curves between the exact solution and the approximation.

In the case of a distributed force inside the plate,
\[
f_i = f_i(z)\delta(x)\delta(y)e^{i\omega t}
\]
(B.17)
where \(f_i(z)\) is the distribution along the thickness direction, the displacement components can be obtained in the form
\[
(u, v, w) = \int_0^\infty \int_{-\infty}^{\infty} \left( \frac{z\Delta_1}{\Delta}, \frac{z\Delta_2}{\Delta}, \frac{\Delta_3}{\Delta} \right) e^{-i(\xi_1z+\xi_2y)} d\xi_1 d\xi_2
\]
(B.18)
where \(\Delta\) is the dispersion function, and \(\Delta_i, i = 1, 2, 3\) are functions containing source information.

The calculation of the vertical displacement, therefore, reduces to the evaluation of the integral
\[
w = \int_0^\infty \frac{\Delta_3}{\Delta} e^{-i(\xi_1z+\xi_2y)} d\xi_1 d\xi_2
\]
(B.19)
Since the only poles of the integrand are those that satisfy \(\Delta(\xi_1, \xi_2) = 0\), a contour integral can be used to simplify the integral.

After applying the residue theorem the transverse displacement can be written in the form
\[
w = \int_0^\infty \sum_{\xi_2(\xi_1)} \frac{\Delta_3}{\Delta_{\xi_2}} e^{-i(\xi_1z+\xi_2y)} d\xi_1
\]
(B.20)
where the summation in \(\xi_2\) is over all values that satisfy \(\Delta(\xi_1, \xi_2) = 0\) for a given \(\xi_1\). The summation is over the slowness curve after the last integration is carried out. Since \(\Delta(\xi_1, \xi_2) = 0\) gives only the slowness curve for the lowest mode, the calculated wave motion is due to the lowest Lamb wave mode only. In the far field, the method of stationary phase can be used to evaluate the approximation of Equation (B.20).

The case of extension motion can be formulated following a similar procedure.
Fiber Fragmentation and Acoustic Emission

Alexander Wanner, Thomas Bidlingmaier and Steffen Ritter

Abstract

In this paper the use of acoustic emission (AE) measurements in association with the single-fiber-composite (SFC) test is investigated and critically assessed. The SFC test is an experimental procedure used for assessing interfacial as well as fiber strength. Upon straining, the single fiber in this test fragments repeatedly. The basic concept of the SFC test is to draw conclusions with respect to the desired strength parameters from the course of the fragmentation process and from the resulting fiber-fragment-length distribution. It is well known that AE measurements are useful to monitor the general course of the fragmentation process and to determine the mean fragment length. It has also been shown that, in principle, the fragment length distribution can be obtained via AE source location. This study shows, however, that the resulting distributions may be distinctly distorted due to the uncertainty, with which the fiber-break positions can be located under typical test conditions. Results of a series of Monte Carlo simulations show that meaningful and reliable distribution data are obtained only if the location error is smaller than about 10% of the mean fragment length. The capability of AE source location for measuring fragment-length distributions is therefore restricted to composites with relatively thick and strong fibers or low interfacial strength.

The second part of the paper focuses on the qualitative and quantitative understanding of typical wave patterns and on the use of waveform-based AE analysis to characterize the individual fragmentation-fracture events. Experiments on flat, dog-bone-shaped E-glass/polycarbonate SFC specimens using a four-channel AE monitoring system show that the AE stress waves that are detected by the sensors are plate waves of the first symmetrical mode. The recorded AE waveforms are strongly affected by complex reflections of the stress waves within the specimen. Only the leading parts of the signals can be evaluated in a straightforward manner. Results of this study show that the amplitude of the very first peak, which is the most simple parameter that characterizes the leading part of the signal, is correlated to the fiber diameter and the fiber-fracture stress. The amplitude of the first peak therefore appears to be a useful parameter to characterize the fiber breaks. Micromechanical studies of individual fiber-fracture events are required to clarify the parameters that govern the first peak amplitude in more detail.

1. Introduction

It is well known that the mechanical performance of fiber-reinforced polymer and metal-matrix composites is, among other factors, closely related to the fiber/matrix interfacial shear strength as
well as to the in situ tensile-strength distribution of the fibers. The so-called single-fiber-composite (SFC) test is an experimental procedure used for assessing interfacial as well as fiber strength (see e.g. Drzal et al., 1983a and 1983b; Netravali et al., 1989a; Henstenburg and Phoenix, 1989). In this test, a single fiber is embedded along the center line of a dog-bone shaped specimen of matrix material. Upon straining the specimen in a uniaxial tensile test, the fiber fragments repeatedly. If the strain to failure of the matrix material is sufficiently high, the fragmentation process comes to an apparent standstill (saturation) before the fracture of the entire dog bone specimen. The basic concept of the SFC test is to draw conclusions with respect to the desired strength parameters of fiber and fiber/matrix interface from the course of this fragmentation process and from the resulting fiber-fragment lengths. Although the SFC test appears to be simple, various inherent mechanical and statistical difficulties exist which have been investigated by a number of authors (see e.g. Henstenburg and Phoenix, 1989).

The SFC test has almost ideal preconditions for acoustic emission (AE) measurements, since the sources of AE as well as their locations are predetermined to a large degree. AE measurements along with SFC tests have been undertaken by a number of authors. The first part of this paper reviews and assesses the use of AE measurements with respect to traditional tasks such as counting the fragmentation-fracture events and locating the fracture sites in the SFC samples. The second part of the paper will focus on the qualitative and quantitative understanding of typical wave patterns and on the use of waveform-based AE analysis to characterize the individual fragmentation-fracture events.

2. Counting and Location of Fragmentation Fractures

In its simplest form, the primary goal of the SFC test is to obtain the mean fiber-fragment length at saturation. Once the mean fragment length is, \( \langle L \rangle \), known, the interfacial shear strength, \( \tau \), can be estimated roughly under the simplifying assumptions that the matrix/fiber stress transfer can be described by the Kelly-Tyson linear shear-lag model (Kelly and Tyson, 1965) and that the fiber strength \( \sigma_f \) is a constant:

\[
\tau = d \sigma_f K/2\langle L \rangle
\]

where \( d \) is the fiber diameter and \( K \) is a dimensionless constant of about 0.75.

Although simple in principle, the procedure to determine the mean fragment length optically is cumbersome and subject to errors, especially if the specimen is opaque or if the fibers exhibit fibrillar fracture (such as Kevlar®). It has been shown that AE measurements can be very helpful in solving this problem (Netravali et al., 1989b; Ma et al., 1990) and for many different fiber/matrix combinations it has been possible to establish a one-to-one correlation between microscopically observed fiber fractures and AE signals in SFC tests.

An additional and most important advantage of AE over other techniques is the ability to capture not only the total number of fiber fractures but also the moments in time and the corresponding test parameters (such as global stress and strain), at which these fractures occur. Knowing the initial total fiber length, the mean fragment length can readily be deduced at every stage of the experiment and the general course of the fragmentation process can be followed from the start through saturation (see e.g. Ma et al., 1990).

Henstenburg and Phoenix (1989) showed that the fragment-length distribution in the strained specimen is correlated to the strength distribution of the fiber along its length and on the mechanics
of stress transfer from matrix to fiber. In order to allow for a detailed evaluation of the SFC test it is therefore desirable to know the distribution of fragment lengths and not just the mean fragment length. It is a general statistical problem that in order to get reliable information about the distribution of a quantity, a relatively large sample (here: a high number of individual fragment lengths) must be surveyed. Because of the problems associated with optical measurements described above, a number of authors have tried to establish AE source location as a more convenient method to obtain fragment-length data sets. The most extensive work so far on fragment-length distribution measurements via AE source location has been performed by Netravali et al. (1989b). In their work on E-glass/epoxy single-fiber composites (fiber diameter = 22 μm), they used a sophisticated AE locating technique that included small sensors with 1 mm contact area diameters positioned along the length of the specimen, instrumentation with outstanding time resolution, and a linear source-location algorithm calibrated to ultrasonic wave-speed measurements. Unfortunately, Netravali and coworkers did not compare their acoustical length measurements of individual fragments to corresponding optical measurements, so that no direct information on the AE location error statistics can be obtained from their publication. In their article they mention only a certain “discrepancy in the measurement of lengths below 0.5 mm”, which they did not take much notice of because, in their opinion, it did not affect the “middle portion” of the length distribution significantly.

However, in order to assess the capability of AE source location for fragment-length distribution measurements, it is essential to have an idea of how location uncertainty may affect the length-distribution measurement and it is very instructive to closely examine at Netravali’s results in this respect. Netravali et al. (1989b) showed that their optically determined fragment-length distributions could be described quite well with the two-parameter Weibull function (Weibull, 1951),

\[ F(L) = 1 - \exp\left[-\left(L/\beta\right)^\alpha\right] \]  

in which \( L \) is the fragment length, \( \alpha \) is the Weibull shape parameter, and \( \beta \) is the Weibull scale parameter. As an example, the Weibull parameters and the mean fragment-length of one of Netravali’s composites are listed in Table 1. The probability-density function corresponding to these parameters is shown in Fig. 1. Also shown in Fig. 1 and Table 1 is the distribution obtained via AE source location. With respect to the mean fragment length, there is perfect agreement between optical and AE results.

It should be noted, however, that the faulty location of a fragmentation-fracture site always affects the length measurements of two fragments in opposite directions. As a result, there is generally no effect of faulty source location on the mean fragment length. Attempts to show that the fragment-length distributions obtained from optical and AE measurements are the same based on the fact that the mean fragment lengths obtained by these methods are identical (Netravali and Sachse, 1991; Netravali, 1995) are misleading. Faulty source location, however, will always affect the resulting length distribution and it can be assumed that the considerable deviation of the AE result from the optical result in Fig. 1 is a direct result of the uncertainty of AE source location. In order to clarify the distorting effect of location uncertainty on the length distribution we have performed a series of Monte Carlo simulations. Our simulation algorithm included the following steps:

1. 200 fragments are generated with the length distribution according to the two-parameter Weibull function with parameters \( \alpha \) and \( \beta \).
2. The fragments are arranged randomly in a straight line as in an SFC specimen.
(3) The length distribution is distorted by moving the fracture sites by random displacements in the range \([-\delta, \delta]\) (\(\delta\) is the maximum location error).

(4) The Weibull parameters \(a\) and \(b\) of the distorted length distribution are determined.

![Graph](image)

**Fig. 1** Probability-density functions illustrating the fragment-length distributions in E-glass/epoxy SFC specimens as determined by Netravali et al. (1989b) via optical (——) and AE (---) fracture-site location (see Table 1 for Weibull parameters).

**Table 1** Results of fragment-length measurements by Netravali et al. (1989b).

<table>
<thead>
<tr>
<th>Measurement method</th>
<th>Optical</th>
<th>Acoustic Emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean fragment length (&lt;L&gt;)</td>
<td>965 (\mu)m</td>
<td>965 (\mu)m</td>
</tr>
<tr>
<td>Weibull scale parameter (\beta) of fragment-length distribution</td>
<td>1066 (\mu)m</td>
<td>1090 (\mu)m</td>
</tr>
<tr>
<td>Weibull shape parameter (\alpha) of fragment-length distribution</td>
<td>3.92</td>
<td>2.08</td>
</tr>
</tbody>
</table>

This kind of simulation was performed 20 times for each considered combination of \(\alpha_o\) and \(\delta\). In Fig. 2 the averages and standard deviations of the distorted Weibull parameters obtained in this manner are plotted as a function of the normalized location error \(\delta/\beta_o\) for \(\alpha_o = 3, 4, 5,\) and 10. These results show that the Weibull shape parameter decreases systematically with increasing location error indicating that the distorted distributions are always broader than the corresponding undistorted distributions. It is important to note that the location uncertainty has an equalizing effect and for location errors greater than \(0.4\beta_o\), completely non distinguishable results around \(\alpha = 2\) are obtained for all \(\alpha_o\). The Weibull scale parameter, \(\beta\), however, is only weakly affected (Fig. 2b). This is due to the fact that the scale parameter depends predominantly on the mean fragment length which, as mentioned above, is not affected at all by faulty location of fracture sites.
Fig. 2 Effect of the maximum location error $d$ on (a) the shape parameter $\alpha$ and (b) the scale parameter $\beta$ of the two-parameter Weibull fragment-length distribution. The plot shows results of Monte Carlo simulations for true shape parameters $\alpha_0 = 3, 4, 5,$ and $10$. Each data point represents the mean result of 20 simulations, the error bars indicate the standard deviation.

In light of these insights, it is interesting to reconsider the experimental data of Netravali et al. (1989b) (see Table 1 and Fig. 1). The difference between the "true" shape parameter $\alpha_0 = 3.92$ and the distorted shape parameter $\alpha = 2.08$ indicates that the AE source location error in these experiments was $0.35\beta_0$ ($\sim 350 \mu m$) or larger. On the other hand, the curves in Fig. 2a imply that, in order to obtain realistic shape parameters, an accuracy of about $\pm 0.1\beta_0$ (in this case about $\pm 100 \mu m$) is required.

From the experimental point of view, the work of Netravali and coworkers (1989b) still represents the state-of-the-art today. The capability of AE source location for measuring fragment-length distributions is therefore restricted to composites with considerably larger mean fragment lengths. Taking equation 1 as a rough guideline, these are composites with weaker interfaces or with thicker or stronger fibers as compared with the glass/epoxy material investigated by Netravali et al. (1989b).

Henstenburg and Phoenix (1989) showed in a theoretical study that the distribution of fragment lengths does not strictly obey Weibull statistics. Our simulations, therefore, do not cover all the relevant cases. However, the result that reliable information about the fragment-length distribution is only obtained if the mean fragment length exceeds the maximum location error by at least a factor of ten can still be regarded as a general rule of thumb.

3. Waveforms of Fragmentation-Fracture Events

The previous section has shown that AE measurements are useful to monitor the general course of the fragmentation process and, under certain conditions, to obtain statistical information about
the fragments. This section focuses on the individual fragmentation events. The general understanding of the AE wave patterns is a prerequisite for developing evaluation algorithms that allow for a quantitative characterization of the micromechanical processes in the sample. Recently, Suzuki et al. (1996) have investigated the waveforms generated from fiber fractures in relatively large glass/epoxy tensile samples (volume of gauge section 10 x 26 x 100 mm$^3$) in great detail. However, as SFC samples are typically much thinner in one direction, these results do not apply directly. In the present study model experiments on thin SFC specimens were performed in order to quantitatively study the wave-patterns in this kind of sample.

3.1 Experimental

Polycarbonate (PC3200, Bayer AG) was chosen as the matrix material because of its photomechanical behavior which is suitable for birefringence studies. As reinforcements E glass fibers of variable thickness and lengths were used (see Table 2). From these components single fiber composites were produced via hot pressing using the foil-fiber-foil technique. Dog bone-shaped tensile specimens as shown in Fig. 3 and Fig. 7a were cut out of the hot pressed 400 μm thick material. This specimen fabrication route allowed for good control of the position and alignment of the single fiber in the center of the specimen. Specimens were tensile tested at a crosshead velocity of 1 mm/min using a screw-driven miniature testing machine that fits on the object table of a confocal laser scanning microscope (LSM 410, Zeiss). The microscope was set up as a circular polarscope for high resolution photoelastic experiments. During straining, isochromatic fringe patterns of the matrix material in the vicinity of the fiber were taken at regular time intervals.

Table 2 Fiber dimensions in E-glass/polycarbonate SFC specimens with shape and dimensions as shown in Figs. 3 and 7a.

<table>
<thead>
<tr>
<th>SFC specimen</th>
<th>Fiber diameter (μm)</th>
<th>Fiber length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>77</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 3 Sketch of experimental set-up for tensile tests on E-glass/polycarbonate SFC specimens.
Acoustic emission measurements were performed using four broadband sensors of the same kind (Model BI025, Digital Wave Corp., Englewood, CO) having a reasonably flat response in the frequency range of 100 kHz to 2 MHz. These sensors have casing diameters of 9 mm and aperture diameters of 6.3 mm and are sensitive to the out-of-plane specimen-surface displacements. The sensors and were attached in pairs on opposite sides of the specimen as shown in Fig. 3. A multipurpose grease (Molykote®, Dow Corning GmbH) was used as couplant.

The waveforms of AE signals were captured using an AE recording unit (Model F4000, Digital Wave Corp.) that includes preamplifiers, filters, amplifiers and a 4-channel, 8-bit transient recorder with a sampling rate of up to 25 MHz per channel. While the filter settings (20 kHz-1.5 MHz) were identical throughout all experiments, the total gain of the amplifiers was adjusted in the range of 26 to 67 dB to the strongly varying amplitude levels of the experiments with different fiber diameters.

3.2 Results and Discussion

Figure 4 shows a typical tensile stress-strain diagram of an SFC specimen with a 100-μm-thick glass fiber. The stresses and strains, at which fragmentation fractures were observed, are indicated. Due to the negligible fraction of the fiber in the strained volume of the sample, the fractures do not visibly influence the global stress-strain curve. In the particular specimen of Fig. 4, four fragmentation cracks were observed and this corresponds to a mean saturation fragment length of the order of 1 mm. Figure 5 shows a typical series of isochromatic fringe patterns obtained by *in situ* microscopy observation of the fiber and its vicinity during the fragmentation process.

![Stress vs. Strain Diagram](image)

**Fig. 4** Typical stress vs. strain diagram of a uniaxial tensile test on a dog bone shaped SFC specimen with shape and dimensions as depicted in Fig. 3 and Fig. 7a.
In all the experiments, the AE events recorded during the tensile tests could be unambiguously correlated with the results of optical observations. In Fig. 6, typical AE waveforms of fiber fracture are shown. The figure shows a set of AE signals recorded simultaneously with the four sensors attached to the specimen in the way shown in Fig. 3. It is remarkable that the signals recorded on opposite surfaces of the specimen at the same length position coincide almost perfectly. This means that the recorded stress waves are symmetrical with respect to the specimen mid-plane. According to the theory of Mindlin and Medick (1959), the first symmetrical mode of plate-wave propagation shows hardly any dispersion as long as the wavelength is considerably larger than the plate thickness. Calculations based on that theory as well as ultrasonic experiments performed previously have shown that in 400-μm-thick polycarbonate foils, the of wave-propagation velocity of the first symmetrical mode is about 1600 m/s at zero frequency and remains essentially constant up to 600 kHz (Bidlingmaier et al., 1997). Using this propagation velocity to
Fig. 6 Typical waveforms of a fiber-fracture event as recorded simultaneously with the four AE sensors arranged as shown in Fig. 3. Signals recorded at the same position on the specimen length but on opposite sides of the specimen coincide almost perfectly, which means that a symmetrical mode of plate-wave propagation is dominant.

Fig. 7 SFC specimens (all sizes in mm).
Schematic illustration of wave propagation with reflections in specimens with (a) standard geometry and (b) modified geometry.

locate the AE sources with a linear location algorithm based on the first peaks, positions within 0.5 mm of the optically determined fracture locations are obtained. It can be concluded that the AE waveforms detected by the sensors are plate waves of the first symmetrical mode, which propagate considerably slower than P waves in the same material (v_p = 2160 m/s).

As illustrated schematically in Fig. 7a, the stress waves emitted from a fiber-fracture event are expected to propagate directly to the sensors as well as indirectly via reflections at the specimen edges. The higher the number of reflections involved, the longer is the path length and the corresponding time of flight. It can be assumed that the leading part of a recorded AE signal is dominated by the direct AE wave, while the trailing part is a result of superimposed direct and reflected waves. To confirm this assumption experiments on samples with a modified shape as depicted in Fig. 7b were performed. This kind of sample has the same total length as the standard specimen shown in Fig. 7a. However, the single fiber has been moved from the specimen center to
Fig. 8 Waveforms (a: sensor 1, b: sensor 3) and corresponding frequency spectra (c: sensor 1, d: sensor 3) from a fiber fracture in an SFC specimen with modified geometry as shown in Fig. 7b.

A position close to one of the shoulders, and the width of the specimen in the central section is increased from 18 to 50 mm. These changes were intended to alter the reflection paths such that the waveforms recorded by the first sensor pair (sensors 1 and 2 in Fig. 7b) are to be dominated by the direct stress wave while the signals of the second sensor pair (sensors 3 and 4 in Fig. 7b) are affected by reflections. With this sample geometry, this works only if the radiation pattern of the AE source is of the kind described by Kim and Sachse (1986) for thermal surface cracks in glass, which includes very low amplitudes in directions that are inclined by more than 60° to the direction to the crack plane normal (assumed to be the fiber direction here). The experimentally determined AE waveforms of a fiber fracture in this sample as well as the corresponding frequency spectra are shown in Fig. 8. The AE signal detected by sensor 1 (Fig. 8a) is a relatively short, broadband pulse and it can be concluded that indeed only the direct stress wave reached this sensor. The frequency spectrum (Fig. 8b) shows a bell shaped magnitude distribution with a maximum at ~300 kHz. The upper frequency limit is ~700 kHz which corresponds to a wavelength of ~2 mm. Keeping in mind that the sensor aperture was 6.3 mm and that the sensors were oriented perpendicular to the direction of wave propagation, it is clear that aperture effects contribute to this frequency cut-off. As expected, the AE signal detected by sensor 3 (Fig. 8c) is much longer due to the reflections. The corresponding frequency spectrum (Fig. 8d) is shifted to considerably lower frequencies.

These results show clearly that a quantitative correlation between parameters that characterize the AE source and parameters that describe the waveforms would require the removal of the reflections from the AE signal. Only the leading parts of the signals can be evaluated in a straightforward manner. The most simple parameter that characterizes the leading part of the signal is the amplitude of a very first peak. The following paragraphs will concentrate on the empirical correlation between the first-peak amplitude, $A_1$, and two parameters that are assumed to have a
key influence on the AE source characteristics: the fiber diameter $d$ and the fiber fracture stress $\sigma_f$. The empirical analysis is based on AE recordings during tensile tests on four dog-bone SFC samples containing fibers with different diameters (see Table 2). The signal waveforms detected by the four sensors were evaluated with respect to their first-peak amplitude $A_l$. Due to the symmetric experimental arrangement of the four sensors with respect to the position of the short fiber, the path lengths differ only slightly and it is assumed that the effects of attenuation are similar for all signals. In order to minimize the influence of differences in attenuation and of non-reproducible sensor coupling quality, only the mean $A_l$ values of the four-sensor signals were considered further. For each fiber fracture the failure stress $\sigma_f$ was estimated from the strain of the SFC specimen at the moment of fracture using a simple iso-strain approach, i.e. the tensile stress in the fiber (or fiber fragment) at the fracture site was, for a first approximation, assumed to be equal to the strain of the composite times the Young’s modulus of the fiber.

In Fig. 9 the results of the four SFC tests are summarized in a log-log plot of $A_l$ versus $\sigma_f$. This plot shows that the effects of fiber diameter and fiber-fracture stress can be separated easily as all data points are scattered around parallel lines with similar slope. This slope is about unity, which means that, for a first approximation, the first-peak amplitude $A_l$ can be assumed to be directly proportional to the fiber-fracture stress. In Fig. 10, the ratio $A_l/\sigma_f$ is plotted against the fiber diameter $d$ in a log-log diagram. This diagram shows that a power-law correlation exists with a diameter exponent of 2.7. The dependence of the first-peak amplitude $A_l$ on the fiber diameter $d$ and the fiber-fracture stress $\sigma_f$ can therefore be expressed by the following empirical equation:

$$A_l(d, \sigma_f) = C \ d^{2.7} \ \sigma_f$$  \hspace{1cm} (3)
Fig. 10 First-peak amplitude/fracture stress vs. fiber diameter.

with \( C = 6.61 \times 10^{-5} \mu \text{V}(\text{MPa})^{-1}(\mu \text{m})^{-2.7} = 1.05 \text{ MPa}^{-1}\text{m}^{2.7} \).

With respect to the influence of fiber-fracture stress, this equation only describes a general trend. The scatter of the data points in the plots of Figs. 9 and 10 indicates that it is not possible to directly calculate the fracture stress of a particular fragmentation event from the corresponding first-peak amplitude with acceptable precision. Part of the scatter can be attributed to the uncertainty, with which the fiber-fracture stresses have been determined up to this point. Further studies will, therefore, concentrate on quantitative analysis of isochromatic fringe patterns in order to obtain the stress distributions in the vicinity of a fracture site before and after the fracture. With a more detailed characterization of the micromechanical processes, it will be possible to assess the meaning of waveform parameters in a more quantitative manner.

4. Summary and Conclusions

The single-fiber-composite (SFC) test is a well established experimental procedure used for assessing interfacial strength as well as fiber strength. In this study, the use of AE measurements along with the SFC test has been investigated and critically assessed. The results obtained are summarized below:

- AE measurements are useful in controlling the general course of the fragmentation process and in obtaining the mean fragment length. In order to avoid erroneous and misleading results, however, it is essential to independently verify the number of fragmentations for selected specimens.

- In principle, AE source location offers the possibility of obtaining information about the fragment-length distribution. However, under typical test conditions the resulting distribution may be distorted distinctly by the location error. Results of Monte Carlo simulations show that only if
the location error is smaller than about 10% of the mean fragment length are reliable distribution
data obtained.

• Experiments on flat, dog-bone-shaped SFC samples using a four-channel AE monitoring system
showed that the AE detected by the sensors are plate waves of the first symmetrical mode. The
recorded AE waveforms are strongly affected by complex reflections of the stress waves within the
specimen. Therefore, only the leading parts of the signals can be evaluated in a straightforward
manner. Results of this study show that the amplitude of the first peak, which is the most simple
parameter that characterizes the leading part of the signal, is correlated to the fiber diameter and the
fiber-fracture stress. The first-peak amplitude therefore appears to be a useful parameter for
characterizing the fiber breaks. Micromechanical studies of the individual fiber-fracture events are
required to clarify the parameters that govern the first-peak amplitude in more detail.

Acknowledgment

This work has been sponsored by the Deutsche Forschungsgemeinschaft (DFG), projects
SFB381/A1 and SFB381/B1. The authors wish to thank Dr. M.R. Gorman for helpful discussions
and Mr. U. Malter for preparation of specimens.

References

Schädigungsprozessen in Faserverbundwerkstoffen mit duktiler Matrix”, DGZfP-Berichtsband
58, 47-56 (in German).


Epoxy Matrices. II. The Effect of Fiber Finish”, J. Adhesion, 16, 133-152.

R.B. Henstenburg and S.L. Phoenix (1989), “Interfacial Shear Strength Studies Using the Single-
Filament-Composite Test. Part II: A Probability Model and Monte Carlo Simulation”, Polym.
Compos., 10, 389-408.


26, 6741-6752.


Filament Carbon/Polycarbonate and Kevlar®/Polycarbonate Composites Under Tensile
Deformation”, Polym. Compos., 11, 211-216.

Materials Research with Advanced Acoustic Emission Techniques


Wave Propagation Effects Relative to AE Source Distinction of Wideband AE Signals from a Composite Pressure Vessel

Karyn S. Downs and Marvin A. Hamstad

Abstract

Numerous acoustic emission waveforms were recorded using wideband, non-resonant sensors during the initial proof-pressurization ramp of a graphite/epoxy pressure vessel following a single controlled impact. The waveforms exhibited a variety of characters and frequency spectra. Some of the observed differences are presented, and potential source distinctions are discussed.

1. Experimental

A cylindrical filament-wound graphite/epoxy aerospace-type pressure vessel was used in the testing. Approximate dimensions of the vessel are as follows: 457 mm overall length, including domes; 125 mm outside diameter; 3 mm thick composite overwrap over 1.3 mm aluminum alloy (non-load-sharing) liner. The composite overwrap was applied using an anisotropic lay-up, i.e., axial and hoop wraps interspersed by layers, with some of the hoop wraps on the outer most cylindrical surface layer.

The virgin vessel was hydraulically proof pressurized to 58.6 MPa (8.5 ksi). Afterward, a single controlled impact of 14.9 J was applied (perpendicularly) to the cylinder portion of the unpressurized vessel using a 13 mm diameter hemispherical tup. The vessel was monitored using acoustic emission (AE) during the next pressurization ramp after the impact. Subsequently, the vessel was pressurized to burst. The burst strength was 75 MPa (10.9 ksi), approximately 85% of the nominal burst strength for similar non-impacted vessels. Figure 1(a) is a photograph of the test vessel type used, showing the premarked location for the impact and the eight AE sensor positions. Figure 1(b) shows the vessel fully installed in the test fixture with the sensors attached.

Eight wideband non-resonant AE sensors (Digital Wave model B 1025T) were spring-loaded against the cylindrical surface of the vessel, and were acoustically coupled with Apiezon M (a viscous grease). Sensor installation and performance were verified by manual lead breaks on the vessel surface before and after the AE-monitored pressure ramp. Figure 2 (showing an “unwrapped and flattened” view of the cylindrical portion of the vessel surface) indicates the impact location and the positions of the AE sensors.

Eight channels of waveform-based 12-bit AE data were simultaneously recorded for each event triggering the system during the post-impact hydraulic pressurization ramp from 0 to 58.6 MPa.

Karyn S. Downs (karyn.s.downs@lmco.com) is affiliate with Lockheed Martin Astronautics, Denver, Colorado and Marvin A. Hamstad (mhamstad@du.edu) is with University of Denver, Denver, Colorado, USA. This paper is based on poster presentation at the Workshop.
(8.5 ksi) at 2.1 MPa/min (300 psi/min). Data were digitized at 5 megasamples/second with 2048 points recorded per wave.

2. Results and Discussion

Numerous different signal types (i.e., characters) were observed for the AE waveforms recorded. Some examples are as follows:

a) "lead-break-like" events with a smaller extensional amplitude and a much larger flexural amplitude;

b) events with a similar waveform character (with regard to time domain and frequency spectra) on all eight channels for the same event, including channels at a smaller distance (e.g., less than 50 mm) and a larger distance (e.g., more than 250 mm) from the AE source; and,

c) events hitting only one of the eight sensors with significant amplitude (i.e., showing a significantly large difference in peak amplitude between the 1st and 2nd sensors hit in the event). Some examples of these various waveform types are shown in Figs. 3 through 6.

Fig. 1 Photograph of test vessel type used: (a) premarked impact location and sensor positions; (b) fully installed in proof test fixture and with sensors attached.
Fig. 2 “Unwrapped and flattened” view of cylindrical surface of test vessel.

Fig. 3 (a) Waveform from manual lead break on vessel surface; (b) Waveform from real AE with “lead-break-like” character.

Figures 3(a) and 3(b) show the similarities in waveforms recorded from a manual lead break (i.e., pseudo-AE recorded before the pressure ramp) and from one of the “lead-break-like” real AE events (#113) recorded during the pressurization ramp. Note that both events in Fig. 3 exhibit a lower amplitude initial extensional mode followed by a much larger flexural mode.

Figures 4(a) and 4(b) show two different real AE events (#980 and #677, respectively) wherein a distinct frequency character is apparent and consistent across all sensors hit during the
Fig. 4 Two real AE events showing consistent frequency character across all eight hits in each event: (a) event #980; (b) event #677.

Fig. 5 FFT spectra for two events showing consistent frequency character across all eight hits in each event: (a) event #980; (b) event #677.
event (even those sensors more than 285 mm away from the 1st hit sensor). It is apparent, even when judging by naked eye, that each of these two events in Fig. 4 has a very different frequency content. This observation is confirmed by the fast Fourier transforms (FFTs) shown in Figs. 5(a) and 5(b), which give the spectra for the waveforms in Figs. 4(a) and 4(b), respectively. One explanation for the difference in frequency content between the two events is that they potentially arose from different source mechanisms. For each event, some signal loss (especially of higher frequencies) is expected as the AE wave propagates from the earliest hit sensors to the later hit sensors; a loss of higher frequencies can, in fact, be observed from the FFTs shown in Figs. 5(a) and 5(b).

As mentioned earlier, several AE events hit only one of the eight sensors with a significant peak amplitude, thus creating a significant difference in peak amplitude between the 1st and 2nd sensors hit (e.g., up to 33.1 dB difference or Δ-dB). Figure 6 shows all eight hits for four such events. Figure 6(a) for event #916 has 21.3 Δ-dB between the 1st and 2nd hits; similarly, Figure 6(b) for event #987 has 33.1 Δ-dB, Figure 6(c) for event #1004 has 27.6 Δ-dB, and Figure 6(d) for event #1068 has 21.9 Δ-dB. [Note: There is a low frequency (approx. 3 kHz) signal that was continuously and uniformly recorded on all channels for all recorded events which is an artifact of the particular AE measurement and recording unit used; this low frequency signal is especially apparent in many of the waveforms in Fig. 6.] Because of the uniqueness of the type of events shown in Fig. 6, a number of aspects were explored for these events.

First, the dramatic difference in the peak amplitudes of the 1st and 2nd hits for the four events shown in Fig. 6 raises the specter of whether all eight hits truly belong to the same event or perhaps to different events. Thus, wave velocities were considered to explore this issue. It was observed (from lead breaks performed on the test vessel itself) that the AE group velocities were greater when traveling parallel to the hoop wraps (i.e., along the fiber direction on the outer surface) vs. velocities at approximately a 45° angle to the hoop wraps. Next, the AE data from lead breaks on the vessel surface were examined to determine typical AE group velocities for signals traveling in graphite/epoxy. Typical average measured group velocities for lead breaks were about 5.2 mm/μs for the front of the extensional mode, and about 1.4 mm/μs for the front of the flexural mode.

Next, the velocities of the signals traveling between the 1st to 2nd, and 1st to 3rd hit sensors were measured from recorded waveforms for the four real AE events shown in Fig. 6. The first discernible signal arrival was used to determine the arrival time. Table 1 summarizes the measured velocities for the four AE events examined. The measured velocities between hits in these events (i.e., from 1.7 to 6.5 mm/μs) do correspond well with the empirical velocities from lead breaks. Thus, we concluded (for the four events examined) that all eight hits simultaneously recorded in each “event” did in fact have velocities consistent with all the hits belonging to the same event.

We then considered the attenuation behavior observed in the four events of Fig. 6, in which the signals showed dramatic reductions in peak amplitude between the 1st and 2nd hits. Figure 7 shows empirical data for AE-signal attenuation (both parallel to the hoop wraps and perpendicular to the hoop wraps) for lead breaks performed on the exterior surface of a graphite/epoxy vessel similar in materials and construction to the test vessel described earlier. Also shown in Fig. 7 is a theoretical curve for signal attenuation solely due to geometric spreading, which accounts for the greatest reduction in peak amplitude in the immediate vicinity of an AE source (Downs and Hamstad, 1995).
Fig. 6 Four events with a significant difference in peak amplitude between the 1st and 2nd hits:
(a) event #916, Δ-dB = XX dB; (b) event #987, Δ-dB = 33.1 dB; (c) event #1004, Δ-dB = 27.6 dB; (d) event #1068, Δ-dB = 21.9 dB.
Table 1 Measured velocities for four real AE events with a dramatic difference in the peak amplitudes of the 1st and 2nd hits.

<table>
<thead>
<tr>
<th>Event #</th>
<th>1st Hit to 2nd Hit</th>
<th>1st Hit to 3rd Hit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Direction</td>
<td>ΔTime</td>
</tr>
<tr>
<td>#916</td>
<td>45 degrees to</td>
<td>30.3 μs</td>
</tr>
<tr>
<td></td>
<td>hoop wrap</td>
<td></td>
</tr>
<tr>
<td>#987</td>
<td>parallel to</td>
<td>76.7 μs</td>
</tr>
<tr>
<td></td>
<td>hoop wrap</td>
<td></td>
</tr>
<tr>
<td>#1004</td>
<td>parallel to</td>
<td>75.2 μs</td>
</tr>
<tr>
<td></td>
<td>hoop wrap</td>
<td></td>
</tr>
<tr>
<td>#1068</td>
<td>parallel to</td>
<td>76.0 μs</td>
</tr>
<tr>
<td></td>
<td>hoop wrap</td>
<td></td>
</tr>
</tbody>
</table>

Note:
The peak amplitude value at a distance of 0 mm shown by Δ (i.e., at the center of the sensor) was provided from a lead break performed on the center of the epoxy wear-plate of the sensor.

Fig. 7 Change in peak amplitude as a function of propagation distance on a cylindrical graphite/epoxy pressure vessel. Experimental and theoretical amplitudes were normalized to 0 dB at a distance of 6 mm away from the center of the sensor face.

From Fig. 7, it is apparent that one could expect signal losses of 20 dB or more between when a sensor is located approximately 100 to 200 mm away from the AE source. Thus, for those events experiencing approximately 20 dB or more loss between the 1st and 2nd hits (which are either 133 or 197 mm apart on this test article), we concluded that the first hit sensor likely was located very near or directly above the AE source.

Finally, the character of the waveform type shown in Fig. 6 was explored to see if this aspect was also consistent with the hypothesis that the AE source was located directly below the 1st hit sensor. Figure 8(a) shows a waveform for a lead break (0.3 mm 2H Pentel lead) performed directly on the face of a wideband AE sensor (Staveley HLI G-0504). Note the fast rise time (about 2.2 μs, measured from first deviation from the noise to the first and greatest peak amplitude) and the short duration (about 15-20 μs) of Fig. 8(a). Figure 8(b) shows the 1st hit (for event #687) of the same waveform type of interest; this event has a peak amplitude difference of 26.8 Δ-dB between the 1st and 2nd hits. Note that Fig. 8(b) also has a fast rise time (about 2.2 μs
if measured from the first deviation to the initial significant peak, or about 4.5 μs if measured from the first deviation to the greatest peak amplitude), a short duration (about 15-20 μs), and the same general wave shape as that of Fig. 8(a). Figures 8(c) (showing the 2nd hit of event #687, and located far from the AE source) and 8(d) (showing the 1st hit of a “lead-break-like” real AE event), however, do not exhibit significant similarity with either Fig. 8(a) or 8(b).

Thus, several facts point to the conclusion that those events with a large Δ-dB between the peak amplitudes of the 1st and 2nd hits must be located directly beneath the 1st hit sensor:

- All such waveforms have reasonably consistent differential arrival times between the 1st hit sensor and the next physically nearest sensor parallel to the hoop wraps.
- All such waveforms have reasonably consistent differential arrival times between 1st hit sensor and the next physically nearest sensor at a 45° path to the hoop wraps.
- Geometric spreading can account for the observed substantial attenuation between such 1st and 2nd hits.
- The general character for such waveforms is the same as for lead breaks performed on a wideband sensor face.

Additional observations regarding propagation effects and source distinction can be made using those events having a large Δ-dB between the peak amplitudes of the 1st and 2nd hits as convenient examples for study.

![Fig. 8](image-url)  
**Fig. 8** Comparison of waveform characters: (a) manual lead break on wideband sensor face; (b) 1st hit of real AE (event #687) having large peak amplitude difference (Δ-dB = 26.8 dB) between 1st and 2nd hits; (c) 2nd hit of same event (#687) far from AE source; (d) 1st hit (far from AE source) of real AE (event #133) with “lead-break-like” character.
The spectra of AE signals can be affected by their propagation direction, as is evident in Fig. 9. Figure 9(a) shows the AE waveforms for the 1st through 4th hits of an event, in which the AE source is presumed to be directly underneath the 1st hit sensor. Figure 9(b) gives the FFT spectra for the waveforms in Fig. 9(a). Note the dramatic change in spectral content for the 1st hit vs. subsequent hits, as well as the fact that the spectrum for propagation parallel to the hoop wraps is different than the two spectra for propagation at approximately 45° to the hoop wraps.

Different types of AE source mechanisms potentially exist for several of the recorded waveforms in which the AE sources were presumed to be directly underneath the 1st hit sensor. Figures 10(a) and 10(b) show actual waveforms and FFT spectra, respectively, for eight such events (#345, #687, #760, #916, #1004, #1068, and #1078). All the events display a sharp rise time and a short duration for the 1st hit (as described earlier). However, the 1st hits (which all were recorded very near the AE source) display very different characters in their time domain and spectral content.

Interestingly, some of the events shown in Fig. 10 display much less distinct differences in their spectra when viewed at somewhat greater distances from the AE source. Waveforms of the 1st and 2nd hits for event #1004 are shown in Fig. 11(a), and the 1st and 2nd hits for event #1068 are shown in Fig. 11(b). When one examines the spectral content of the two 1st hits, as seen in Fig. 12(a), significant spectral differences are quite apparent between the two events. However, a similar spectral comparison of the two 2nd hits (whose sensors were each about 197 mm away from the 1st hit sensors and in a direction parallel to the hoop wraps compared to their corresponding 1st hit sensors) shows only slight differences, as seen in Fig. 12(b). Thus, even small lengths
Fig. 10 First hits of several events with AE source directly underneath 1st hit sensor: (a) waveforms; (b) corresponding FFT spectra.

Fig. 11 1st and 2nd hits of two events with AE source directly underneath 1st hit sensor: (a) event #1004; (b) event #1068.
Materials Research with Advanced Acoustic Emission Techniques

Fig. 12 Comparison of FFT spectra for events #1004 and #1068: (a) 1st hits of events, showing significant spectral differences; (b) 2nd hits of events, showing minor spectral differences.

of propagation can substantially change the ability to detect differences in AE signal spectra of different events.

For further comparison with the graphite/epoxy result, AE data from isotropic composite panels of chopped fiberglass/epoxy were considered. AE events were recorded from a flat panel (approx. 370 mm x 370 mm x 6 mm) of chopped fiberglass/epoxy during a four-point bend test (Hamstad, 1996). All events considered were generated from the uniform stress region (i.e., the region between the two inner loading supports). The AE data were recorded using wideband, high sensitivity NIST-Boulder (National Institute of Standards and Technology) sensors (approx. 19.0 mm outer diameter x 31.5 mm long) with internal electronics and a 20 kHz highpass filter (Hamstad and Fortunko, 1995). Eight channels of AE data were simultaneously recorded by 12-bit Nicolet digital waveform recorders; 8000 points were recorded per wave at 10 megasamples/second.

Figures 13(a) and 13(b) each show a set of waveforms (eight separate hits) from two different events in the chopped fiberglass/epoxy panel. Wide variations in waveform character are apparent within each event due to propagation effects. However, when only those waveforms recorded at a fixed distance from the AE source were examined, then all recorded AE events had a similar character in their time domain and spectra content. Figure 14(a) shows waveforms of six such events (recorded at a distance of approx. 16 times the plate thickness from the AE source); Figure 14(b) shows their corresponding FFT spectra.
Fig. 13 Two typical events recorded during four-point bend testing of isotropic chopped fiberglass/epoxy panel, showing variations in waveforms due to propagation effects.

Fig. 14 Several events recorded (at a fixed distance from AE source) during four-point bend testing of isotropic chopped fiberglass/epoxy panel, showing remarkable similarity in waveform character and spectral content: (a) waveforms; (b) corresponding FFT spectra for portion of waveforms from approximately -50 μs to +60 μs.
3. Conclusions

1. Recorded waveforms for various AE events from proof testing of a graphite/epoxy pressure vessel exhibited a wide variety of waveform characters and frequency spectra.

2. In contrast, waveforms for various AE events (recorded at a fixed distance from the AE source) from four-point bend testing of an isotropic chopped fiberglass/epoxy composite exhibited remarkably uniform waveform character and frequency spectra for all waveforms recorded.

3. Signal-propagation distance (from the AE source to the sensor) significantly affects waveform character and frequency spectra for any single event recorded from the graphite/epoxy pressure vessel.
   a) The most dramatic changes occur within the immediate vicinity of the AE source.
   b) At larger distances from the AE source, differences are typically much less dramatic, especially for the frequency spectra. More specifically, those events that have significantly different characters when observed very near their AE sources may appear to have quite similar characters when examined farther away from their AE sources.

4. Some potential reasons for the differences in graphite/epoxy vs. glass/epoxy, respectively, are as follows:
   a) Layered vs. uniform construction.
   b) Biaxial vs. unidirectional normal stresses.
   c) Anisotropic vs. isotropic material.

Acknowledgments

This work was sponsored by Lockheed Martin Manned Space Systems in New Orleans, Louisiana, USA. The authors wish to give special thanks to the following people for their contributions: Dr. W. H. Prosser (NASA Langley Research Center) - provision and operation of waveform-based AE equipment; Mr. Ron Reightler (Lockheed Martin Manned Space Systems) - assistance in test performance; Mr. Kevin S. Payne (NASA JSC White Sands Test Facility) - coordination and application of impact damage; Mr. David R. Sheahan (Lockheed Martin Astronautics) - design of proof test fixturing.

References


Relative Moment Tensor Inversion Applied to Concrete Fracture Tests

C. U. Grosse, B. Weiler and H. W. Reinhardt

Abstract

An advanced acoustic emission (AE) technique requires the recording of the AE activity and its whole waveforms during the loading of a specimen. Together with the calculation of the AE source coordinates, this enables numerous analysis techniques in the time and frequency domain including waveform comparisons and fault-plane solutions. The radiation pattern of AE sources and the seismic moment (as an equivalent for the emitted energy) as well as the type and orientation of the cracks can be determined using moment tensor inversion methods. This leads to a better understanding of the fracture process in the matrix and the debonding of the reinforcement. The methods have been applied to pullout tests to study the steel-concrete interaction in reinforced concrete cubes as well as in steel-fiber-reinforced concrete.

1. Introduction

There are several different approaches to the evaluation of acoustic emission (AE) data for material characterization, depending on the way of recording, the equipment used, and the analysis technique applied. In general, it has to be distinguished between the classical statistical analysis technique and a more quantitative approach to the problem including waveform recording and interpretation (Scruby, 1985; Sachse and Kim, 1987). Both methods offer the advantage to investigate a specimen or a structural part under loading conditions in an integral way. Very often the acoustic emissions are directly correlated with the failure of structural integrity. The difference between these two methods are the extent of data acquisition and data analysis as well as the degree of reliability of the interpretation. Obviously, concrete is a very suitable material for the application of quantitative AE technique, what was reported by several authors (Berthelot and Robert, 1987; Ohtsu et al., 1991; Landis and Shah, 1993; Maji and Sahu, 1994; Suaris and van Mier, 1995). A modern quantitative AE technique is capable of giving detailed information on the defect formation and the failure process in materials. It provides a deep insight into material behavior under load and can largely influence the optimization of material design. The recording of acoustic emissions with a reasonable amount of sensors and the 3D localization of the sources are the fundamentals of these techniques.

This paper deals with the application of AE analysis techniques including localization, and more sophisticated procedures such as moment tensor inversion methods to characterize the fracture mechanisms in concrete and fiber-reinforced concrete. After a short description of the analysis techniques, applications to pullout tests with a single steel bar, single steel fibers and three-point bending tests will be reported.
2. Equipment and Localization Technique

The measuring device used for the experiments described in this article is based on a multi-channel transient recorder. Between eight and twelve channels with sampling frequencies of 1 or 10 MHz at 12-bit resolution have been used for the experiments described in this paper. A broadband equipment was employed including sensors with significant sensitivity over a wide frequency range up to 10 MHz, as described earlier in more detail (Grosse, 1996).

A software called Hypo\textsuperscript{AE} to localize the sources of acoustic emissions was developed in cooperation with the Institute of Geophysics at the University of Karlsruhe in Germany (Oncescu and Grosse, 1996). The program is a derivative of the Hypo71 program for the localization of earthquake hypocenters and is based on an idea developed by Ludwig Geiger (1910). For the determination of the hypocenter by extraction of the arrival times, at least 4 stations are necessary; having more than 4 stations, the problem is over determined and the calculation is done using an iteration algorithm (Buland, 1976). By now, the arrival times of the compression waves of all channels have to be read off by hand. Assuming a time resolution of at least 1 \textmu s, a localization accuracy of 8 to 10 mm has to be accepted. To reduce the time-consuming P-wave-onset picking, we are actually working on an automatic picker (Mikhailov and Grosse, 1995).

The broadband recording of acoustic emissions during the loading of a specimen together with the three-dimensional localization of the sources facilitates different analysis tools. One is the waveform comparison in terms of pattern recognition. This assumes that similar fracture mechanisms cause similar waveforms and allow the classification of signals. As a first step, a method to determine the coherence function of two signals was employed. This technique was adapted from the field of telecommunications. Similar events can be separated from less similar in the frequency domain by extracting one parameter called the coherence sum (Grosse, 1996). The mathematical background together with some applications was presented in Grosse et al. (1997). Although a classification of the signals can be done using the coherence method, this does not lead to the determination of crack type and orientation. To meet these requirements, usually an inversion of the moment tensor is performed.

3. Moment Tensor Inversion

To determine the fracture type and orientation of a fault as well as the seismic moment - which describes the released energy - the waveforms of the recorded AE events have to be interpreted by the inversion of the moment tensor. As illustrated by Fig. 1, the failure of a brittle specimen is accompanied by a sudden release of energy in form of acoustic waves. Using a moment tensor inversion in combination with the three-dimensional localization, a fault-plane solution can be applied which enables the analysis of the fracture process in the material.

There are several ways to determine the crack type and orientation of AE sources. One concept is the determination of the polarity of the initial P-wave pulses. The distribution of the two senses of the wave polarity around the focus is determined by the radiation pattern of the source. This way, it is possible to estimate the orientation of the nodal planes and thus the mechanism of the source. Unfortunately, it is not possible to quantify the deviation from a pure shear dislocation source (Double Couple or DC) with this method.
The analysis of the moment tensor is a different approach to the problem. The symmetric moment tensor with six independent components mathematically defines the strength and the 3D radiation pattern of a general seismic point source. The diagonal and the off-diagonal elements of the moment tensor represent force dipoles without or with moment, respectively. It was shown by several authors (Shigeishi and Ohtsu, 1992; Landis and Shah, 1993) that a determination of the crack orientation in concrete can be performed by the eigenvalue analysis of the moment tensor, picking the P-wave amplitudes of AE signals. With this method, deviations of DC mechanisms can be extracted as well as the radiation pattern of the whole damage process. A determination of the DC, compensated linear vector dipole (CLVD) (Knopoff and Randall, 1970), and the isotropic tensile components are the basis for the fracture mechanics analysis. To estimate the six moment tensor components, the amplitude information of at least six AE recordings has to be used - a reasonable number in AE experiments.

Solving the problem with this method, the Green's functions of the specimen, describing the wave propagation in a medium, and the transfer function of the recording system have to be known. Considering the wave propagation in concrete, a unique Green's function is hardly to be found for a specimen because of the heterogeneity of the medium. Consequently, a moment tensor inversion based on P-wave amplitudes was employed in a relative way to eliminate the influences of inhomogeneity and anisotropy. The method was developed for the determination of the radiation pattern using cluster analysis (Dahm, 1993 and 1996).

This relative approach is suitable for the requirements in AE experiments, as will be demonstrated in the next chapter. Up to hundreds of acoustic emissions are recorded which occur commonly in certain regions. This is called clustering. The travel path from different events of a cluster to a certain sensor is approximately the same, and thus the dynamic part of the Green's functions can be eliminated. A description of the mathematical procedure can be found in Grosse et al. (1997). For the application of this method to AE experiments, the following assumptions are made:

1. The events of a cluster can be examined as point sources with respect to space and time.
2. The high frequency approximation is valid for the body-waves under study.
3. The derivation of this method is valid for far field terms only. A biasing effect of near field terms on the results may be present in the case of hypocentral distances less than a few wavelengths, and has not yet been investigated. Due to uncertainties regarding the last item, deviations of pure shear mechanisms have not been investigated during the experiments described below.

4. Applications to Steel-reinforced Concrete (pullout tests)

To apply the quantitative AE technique to concrete and to test the developed algorithms, data have been used, which were obtained during pullout tests on reinforced concrete. Investigating the steel-concrete interaction, a series of AE tests have been carried out. The specimens were concrete cubes of 100-mm-side length and centrally reinforced with a single deformed bar of 16-mm diameter. The bond length was limited to twice the rib spacing (20 mm) in order to minimize the number of sources producing local damage. In this experiment, eight sensors were coupled to the sides of the cube. During the pullout tests, the actual tensile force together with the relative displacements and the AE signals were recorded simultaneously. The results of the force and slip measurements for tests with different load histories (monotonically increasing displacements, cyclic loads and long term loads) are summarized in Balazs et al. (1996). These results show also the automatically extracted peak amplitudes of the burst signals versus time in form of histograms, representing a statistical evaluation of acoustic emissions. Unfortunately, this procedure does not consider the relative location of the sensors and the sources. It will neither allow a discrimination between signals and noise, nor the classification of the signals according to fracture mechanisms.

4.1 Localization

With a 3D localization some first statements about the failure process can be made. As reported (Grosse et al., 1994), the spatial distribution of the events give some indications about the stress accumulation in the specimen. A more detailed analysis of travel time residuals can even be used to locate significant inhomogeneities in terms of a passive tomography.

Another interesting result is concerning the spatial and time dependent distribution of the events. During the experiment, the specimen had cracked into two parts due to the load prior to the failure due to debonding. In Fig. 2, the AE sources are represented in the x/z plane by numbers according to their appearance. The reinforcement bar was located in the middle of the figure and was pulled out upwards. At first glance, this representation seems somehow bewildering, but it becomes obvious that the numbers do not show an assorted pattern. As expected, most of the sound sources are located near the bar or in the area slightly above, which is the area of highest load amplitude in the cube. Assuming a failure process extending from the middle to the edges of the cube upwards, parallel to the trajectories of the stress, the AE accumulation should follow this direction. Obviously this is not the case for the time dependent appearance of the events. Examining for instance the signals along the two dashed lines, a discontinuous AE pattern (mixed numbers) can be observed. Destructive tests of the specimen indicated that not only the cement-based matrix but also the aggregates have been fractured. This effect and the failure of the specimen depend apparently on the quality of the bond between cement and aggregates as well as between the concrete and the steel bar. Zones with a higher porosity show earlier AE activities than homogeneous regions with a better bond. In case of a good bond between concrete and reinforcement, the specimen is splitting before a debonding of the bar occurs.
Fig. 2 Localization of AE events. Projection to the x/z plane with events numbered according to their appearance.

Fig. 3 Example of a Mode-II-fracture - moment tensor inversion and interpretation.
4.2 Results of the moment tensor inversion

The steel-bar reinforcement of a concrete cube (100 mm side length) was pulled out of the specimen as described. Because of the load history, cracks with fault planes parallel to the pullout direction are expected as the dominant failure mechanisms. On the basis of the 3D localization, the AE signals were separated into clusters of up to ten events. A moment tensor inversion of every single event of the clusters resulted in numerous P/T diagrams as reported earlier (Grosse, 1996).

In conclusion, considering the polarity constraints, it seems that shear faults in downward direction are predominant. The P-axes, pointing to the principal stress axes, are generally vertical with a shift between 10 and 25°. Regarding the T-axes, east-west directions are dominant but are not as well-fixed as the P-axes. Obviously, fractures of the Mode-II-type (normal shear faults) are the sources of these acoustic emissions. This is illustrated by Fig. 3, showing the results of a moment tensor inversion for a single event of a cluster with nine signals. The best solution for the P and T axis is indicated with a cross and a star, respectively. The estimated P and T axis are the eigenvectors corresponding to the minimal and maximal eigenvalue of the moment tensor. For pure shear dislocation sources, the fault plane normal is at 45° between the P and T axis, which are also the principal stress axes if the fault plane is a plane of maximum shear. The errors of the decomposed source components are estimated with a bootstrap analysis (Efron and Tibshirani, 1986) and are shown as small circles. This representation differs from the commonly used graphs of the nodal planes but, since errors are visualized, it helps to estimate the quality of the results. Additionally, from simulation studies Dahm (1996) concluded that P and T axes are the best resolved source parameters in the case of statistical noise in the data. The values below the graphs indicate the relative values (expressed as a percentage) for the shear component (DC), the extensional component (ISO) and the relative strength (MR). In addition, the relative seismic moment (SM) was calculated, which is proportional to the energy emitted by the source. The data quality and hence the scattering of the error points is closely related to the seismic moment (SM). The scattering of the error points is smaller with higher SM-values. In the middle of Fig. 3, the fault-plane solution resulting from the inversion of the moment tensor is shown, indicating the regions of pressure and dilatation. On the right, the fracture mechanical interpretation is represented summarizing the results of the fault-plane solution and taking into account the polarity information of the AE recordings. In this example, the normal fault is inclined by 20°.

Some events of the examined clusters show variations of normal faulting. As represented in Fig. 4, very few events had to be interpreted as Double-Couple mechanisms with a strong strike slip component. This could be explained as a turn around of a matrix crack formation caused by the aggregates in concrete.

Even though these interpretations seem plausible, it is important to know that this conclusions are based on an insufficient and inherent data base (non-favorable hypocenter distance to wavelength relation). A summary of the results of the relative moment tensor inversion for the events and clusters of this experiment is reported in Grosse et al. (1997). Experiments investigating the fracture mechanisms in more detail as well as enhancing and improving the data basis are conducted nowadays.

5. Steel-fiber Reinforced Concrete

The characterization of the damage process in steel-fiber reinforced concrete is rather difficult due to the random distribution of the fibers and the inhomogeneity of the concrete matrix. To set
Materials Research with Advanced Acoustic Emission Techniques

Fig. 4 Example of strike slip faulting - moment tensor inversion and interpretation.

about solving this problem, initial tests on simple structured materials were carried out in order to understand the single damage mechanisms before moving to research on the real material. The two basic damage mechanisms, fiber pullout and matrix microcracking, could be investigated by means of pullout tests on reinforced concrete and three-point bending tests on plain concrete, respectively. A next step was to transfer these results to steel fiber reinforced concrete. Starting with fiber pullout tests and three-point bending tests with few, aligned fibers, finally concrete with randomly distributed fibers can be tested.

The main stress of works by other authors lay on research concerning the applicability of different types of fibers, the mechanical properties of the material, as well as on different applications of this material. Examples for this research can be found in Falkner and Henke (1996), Balaguru and Shah (1992), Rossi (1994) as well as in the monograph by Maidl (1991). Our previous research involved the fracture of the material (Reinhardt and Hordijk, 1989), debonding aspects between steel and concrete (Reinhardt and Balazs, 1995), and the application of fibers as reinforcement for cement based construction materials (Naaman and Reinhardt, 1996).

5.1 Fiber Pullout

Based on the experiences made previously on reinforced concrete, nondestructive testing methods were applied to fiber-reinforced concrete. The focus was set on steel fibers. Initially, fiber-pullout tests on cubes of 15 x 15 x 15 cm were carried out. In these cubes, steel fibers of type DRAMIX® ZC 60/80 were embedded at half-length. This cold-drawn wire fiber of 0.8 mm diameter and 60 mm length is provided with hooks at both ends and is frequently used in construction industry. At a constant cross-head speed of 0.4 mm/min, the fibers were pulled out by an electro-mechanical 10 kN testing machine. In addition to the load-slip curve, acoustic emissions were recorded.

Figure 5 is an example of a load-slip curve showing the typical behavior of load and sum of AE events. Considering observations made during pullout test on fibers embedded in epoxy resin (Weiler and Grosse, 1996), this plot can be divided into three stages. A video recording made during one of the above mentioned tests elucidates the following behavior.
Fig. 5 Typical load-slip curve and sum of AE events.

After an initial linear-elastic phase, and the following nonlinear phase, the load maximum of 400 N is achieved at approximately 2 mm of pullout. This first stage corresponds to the fiber-tip’s sliding through its channel around the first edge. Afterwards, the load decreases slightly until it reaches a second maximum at about 5 mm of pullout, denoting the end of stage 2. That is the point of the fiber’s movement around the second edge. Stage 3 starts with an extreme descent of the load followed by a cyclical increase and release of the load at a level of about 250 N. The fiber is straight then and is pulled through the straight channel.

The results of the AE localization justify these assumptions. As shown in Fig. 6, all AE events are located in an area in the middle of the cube, at a height of between 2 and 3 cm. This area corresponds very well to the position of the fiber edges within the concrete cube. During the third stage, only very few acoustic emissions were recorded. They are located in a height below 2 cm and are due to the friction between the straight steel fiber and the concrete matrix of the pullout channel. This mechanism is also indicated by the frequency spectra that exhibit a single dominating frequency, whereas events of the early stages, governed by microcracks, have a wide spectrum of different frequencies.

A cluster of events recorded during stage 2 was investigated further by means of the relative moment-tensor analysis. The polar plots of the P-T-distributions and the locations of the according events (zoom of xz-plot in Fig. 6) are displayed in Fig. 7. The calculations revealed cracks with a high shear component (DC-component always > 65 %), although they are not of pure shear type. Nevertheless, the orientations of the P- and T-axes do not point to shear movement along the fiber axis. The reason for that is the generation of microcracks in the angled area of the fiber due to its geometry.
Fig. 6 The xy- and xz-projections of AE localizations of a typical fiber-pullout test.

Fig. 7 The xz-projection of clustered events with three analyzed events of stage 2.

Further details of these tests have been presented and discussed in detail in other papers (Weiler et al., 1996a, b). In addition, other tests on Dramix fibers without hooks as well as tests on fibers with other geometries (e.g., Twincone) have been carried out. They revealed the importance of the geometry of the fibers, as straight fibers are only capable of a minimal bond-stress absorption. On the other hand, fibers with end cones have a very strong bond, leading to a spontaneous failure of the fibers or wide-ranging stress redistributions in the concrete matrix.
5.2 Three-point Bending Tests

In most applications, concrete structures are subjected to bending loads. Hence, three- and four-point bending tests play a major role in laboratory experiments. During the different stages of failure, pure matrix cracks as well as cracks caused by fiber debonding are expected. With regard to the separation of the two cracking types by means of AE, concrete beams with dimensions 150 x 150 x 700 mm were cast, containing between one and four fibers aligned parallel to the long axis in the center of the beam. In this area, the beams were notched at a depth of 50 mm in order to concentrate the stress and create a well-defined failure zone. Twelve AE transducers were mounted spherically on the concrete surface around this zone to enable a detailed examination of the microcracks being created upwards from the notch and along the fibers.

As shown in Fig. 8, the first AE events are generated at the end of the sawcut. With increasing load, more and more acoustic emissions can be localized in an area vertically above the sawcut. Obviously, the detected events come from microcracks of the concrete matrix, leading gradually to the progress of a macrocrack that causes the final failure of the beam. This can be justified by the fact that the statistical center of the event locations move upwards as the experiment proceeds and is in contrast with the observations during steel-bar pullouts described in the previous section. A rough estimation of the crack-tip position could be given. Nevertheless, due to microcracks in slightly damaged areas and crack-surface friction, acoustic emissions are generated also far below and beyond this horizon. Moment-tensor inversions for some of these events have not yet been carried out.

![Fig. 8 The yz-projection and cross-section of the central part of a concrete beam with two embedded steel fibers subjected to three-point loading. Chronological sequence of the localized acoustic emissions events: ○ - ■ - △.](image)

After complete failure of the matrix by the formation of a continuous macrocrack, the fibers have to absorb the applied load and connect the two parts of the broken beam that touch each other only in the line below the loading arrangement. In this area, high stresses are applied, leading to a degradation of the matrix. Consequently, at this time of the test, a high AE activity is recorded from this area. Unfortunately, there were no acoustic emissions that could be unequivocally identified as coming from fiber pullout. Some events that could not be localized, however, give evidence to fiber pullout. Figure 9 shows four tracks of an example event in the time as well as in the frequency domain. Channels 2 and 3 show transient signals with significant energy in a rather
broad frequency range. The corresponding transducers were located at the part of the beam that the fibers were pulled out from. The signals generated during the pullout of the fibers in that part are transmitted to the other part as low frequent vibrations (see Channels 1 and 4). This also explains why such events could not be localized.

During these tests ultrasonic transmission was also carried out to extract changes in parameters such as wave velocity and transmitted energy. These could be compared to the results of the AE analysis and to mechanical data like load, displacement, and crack-mouth-opening distance, which will be published elsewhere.

6. Summary and Conclusions

The AE technique was used to study the fracture processes within steel-reinforced concrete and steel-fiber-reinforced concrete. A more quantitative analysis of the signals including a 3D localization based on the recordings of a sensor network is particularly valuable for making inferences on microscopic damage. The moment-tensor method can be used to investigate the fracture process in detail, extracting the fracture type (Mode I, Mode II or Mixed Mode), the crack orientation and the released energy. It is equivalent to the seismic moment. The present method, called relative moment-tensor inversion, has some advantages compared to others. Procedures of cluster analysis can be used to avoid uncertainties in Greens functions associated with the inhomogeneities of the material and in the sensor characteristics. In common with an efficient localization technique, the relative moment-tensor method is a valuable tool for materials research. With this knowledge of basic fracture properties using a variety of AE parameters, a comprehensive characterization of the fracture propagation in fiber-reinforced, cement-based materials can be developed.
First, the interaction between concrete and a reinforcement bar under load was studied including the dynamic aspects of concrete failure. A significant AE activity around the steel bar has been caused by normal faults with slip parallel to the load direction or within 20° shift.

Secondly, as a first approach to understand the debonding in steel-fiber-reinforced concrete, some pullout tests have been conducted with a single steel-fiber embedded in a concrete cube. Together with experiments on transparent materials the failure process during the pullout of a fiber was understood. The acoustic emissions related to the debonding were discriminated from those of the matrix-fracture process.

Still in progress is work done on beams of steel-fiber-reinforced concrete, starting with a few, aligned fibers and ending up with an industrial volume fraction of randomly distributed fibers. First tests indicate good results with respect to the localization of matrix cracks and difficulties in the identification of fiber pullouts within the beams.

Acoustic emission analysis as represented in this paper can be used to understand the failure process in concrete and to optimize the bond between matrix and reinforcement. In the near future the present analysis methods will be supplemented by ultrasound techniques using B- and C-Scan as well as certain imaging algorithms. In addition, finite-difference methods will be used to understand the wave propagation in the material.

Acknowledgments

The experiments investigating the steel concrete interaction were conducted with the help of Assoc. Prof. Dr. G. Balázs from the Technical University of Budapest and Dr. R. Koch from the Forschungs- und Materialprüfungsanstalt FMPA Baden-Württemberg (Otto-Graf-Institute). The steel fiber reinforced concrete tests were intensively supported by Mr. G. Schmidt from the Forschungs- und Materialprüfungsanstalt FMPA Baden-Württemberg and Mrs. Dipl.-Ing. L. Krüger from the Institute of construction materials, University of Stuttgart. The help of Dr. T. Dahm from the Institute of Meteorology and Geophysics of the University of Frankfurt and Dr. L. Oncescu from the Geophysical Institute, University of Karlsruhe, is gratefully acknowledged. The presented work was partly funded by the Deutsche Forschungsgemeinschaft (DFG) within the framework of the collaborative research center SFB 381 at the University of Stuttgart.

References


Materials Research with Advanced Acoustic Emission Techniques


Brittle Fracture as an Analog to Earthquakes: Can Acoustic Emission Be Used to Develop a Viable Prediction Strategy?

David A. Lockner

Abstract

One of the main strategies for developing useful medium- and short-term earthquake prediction schemes relies on identification of spatial and temporal patterns in regional seismicity. Even with improved earthquake catalogues, there is limited availability of useful data sets for developing and testing new methods. As a result, laboratory acoustic emission studies may be used as scale models of earthquakes and mining rock bursts.

1. Characteristics of Earthquakes and Acoustic Emissions

The purpose of this article is to assess the role that acoustic emission (AE) techniques might play in the development of a viable earthquake-prediction strategy. Other papers in this volume have shown how full waveform recordings in laboratory AE experiments are being used to infer source characteristics such as focal mechanisms, moment release and fiber breakage or delamination. However, in the context of earthquake prediction, parameters to be considered include event location, timing and amplitude. (Changes in near-source attenuation may also be important as a possible precursory phenomenon, but we will not consider it here.) In this case, we will be primarily interested in the statistics of event clustering and microcrack interaction. The success of this approach will depend on the appropriateness of treating sub-meter-scale laboratory samples as suitable analogs for earthquake-nucleation regions that may have linear dimensions that are three to six orders of magnitude greater (Johnston, 1990; Johnston et al., 1990). In this regard, mining applications and the problem of rock-burst prediction serve as an intermediate scale between laboratory studies and earthquakes. Indeed laboratory brittle-fracture studies, rock bursts and earthquakes are all members of a continuum and have many similar attributes.

It is worth mentioning some of the characteristics of large, damaging earthquakes that provide an incentive for studying laboratory analogs. One important constraint is the time scale involved. The recurrence time for large, damaging earthquakes (magnitude M>7) is generally measures in hundreds of years. While instrumentation and spatial coverage of seismic networks has improved greatly in recent years, seismic catalogues that are complete down to approximately M3 earthquakes are generally less than 20 years old. Parkfield, California, on the San Andreas fault, has experienced repeated earthquakes of about M6 since at least the mid-1800’s. It was identified as a high-probability region for another moderate earthquake and was heavily instrumented in anticipation of the next event. The fact that we are still waiting for the next Parkfield earthquake shows just how uncooperative earthquakes can be in occurring at a predictable time and place. This

The author (dlockner@isdml.wr.usgs.gov) is affiliated with U.S. Geological Survey, Menlo Park, California, USA.
lack of predictability under the best characterized circumstances makes it very difficult to obtain high-quality field measurements of the rupture-nucleation process of large earthquakes.

Another problem with studying earthquakes directly is that they occur in a highly complex and heterogeneous medium. The Earth's crust is fractured on all scales from $10^{-6}$ to $10^3$ meters. Large-scale fault systems have complexity on a broad range of scales with individual fault strands separated by stepovers or meeting at geometrically complex junctions. Added to this are spatial variations in rock types and associated rheological properties as well as ground water systems and pore fluid pressures. In addition to this spatial complexity, geophysicists are faced with the problem that fracture nucleation processes for large crustal earthquakes generally occur at depths of ten to 25 km and may be restricted to relatively small volumes. Thus earthquake systems must be studied remotely from the Earth's surface with all the difficulties of signal loss and non-uniqueness associated with remote sensing.

**Advantages of AE:** The difficulties encountered when making direct observations of earthquake nucleation are what provide the appeal of laboratory analogs. For example, if the main interest is to obtain accurate 3D locations of microcrack events, then automated P-wave-picker systems are quite satisfactory. In this case, we routinely obtain 10,000 to 20,000 reliably located microcrack events in a single fracture experiment (Lockner et al., 1992; Lockner and Byerlee, 1995). These large data bases provide the opportunity to carry out meaningful statistical analyses of event distributions. In addition, laboratory experiments offer all the usual advantages of controlled test conditions including stress, strain, temperature, rock type, and pore fluid. The investigator has direct or nearly direct access to the test sample and can conduct post mortem studies of crack geometries in thin section or with other petrographic techniques (Moore and Lockner, 1995).

**Disadvantages of AE:** While there is ample evidence that earthquake rupture size and amplitude are self-similar, microcracking that leads to AE in laboratory rock samples is generally related to grain size. When loaded in compression, the primarily tensile microcrack damage that accumulates in rock samples (Peng and Johnson, 1972; Tapponnier and Brace, 1976; Kranz, 1983; Moore and Lockner, 1995) is the result of stress concentrators or flaws in the rock matrix. Many of these stress concentrators are related to pores or grain boundaries and therefore have an upper limit associated with grain size. Larger scale features such as bedding planes or vugs are often avoided when selecting samples to eliminate this source of variability. The other obvious scale introduced in laboratory samples is the sample size itself. Thus, the fracture process in rock samples often involves a jump in scale from grain size or sub-grain size microcracking to the rapid development of a single through-going fault. There is a counterpart to this scale dependence in seismology where the vertical dimension of large strike-slip earthquakes is limited by the thickness of the brittle crust. However, the nucleation zone, even for large earthquakes, may never be large enough to 'feel' these spatial constraints.

A second potential problem in using AE experiments to model earthquakes involves source mechanisms. Earthquakes are well-characterized as double-couple shear events that propagate (usually along a pre-existing fault) from a nucleation zone. AE events, resulting from microcrack growth, are generally more complex and contain a significant proportion of opening or tensile crack growth (Lockner, 1993; Ohtsu, 1995). The fact that rocks have porosity indicates that microcracks and free surfaces exist on the grain scale. However, unless near-lithostatic fluid
pressures exist in fault zones at hypocentral depths, the ambient compressive stress field precludes the existence of large scale open fractures.

In addition, damaging earthquakes generally initiate at depth, along pre-existing faults and in the presence of pore fluids while laboratory AE experiments have often been carried out on unconfined, dry, intact rock cylinders. There is, however, a trend towards conducting experiments that are more consistent with natural conditions. For example, many confined tests are reported in the literature (Lockner and Byerlee, 1980; Hirata et al., 1987; Satoh et al., 1990; Lockner et al., 1992) as well as experiments on pre-existing fractures (Weeks et al., 1978; Lockner et al., 1982) and water-saturated samples (Lockner and Byerlee, 1977; Masuda et al., 1990; Masuda et al., 1993).

**Some common features:** In spite of the differences between AE and earthquake sources, there are a number of important similarities that support the use of AE studies as earthquake analogs. These similarities stem largely from the fact that both acoustic emission and earthquakes are the result of brittle-failure processes. Recent studies (Harris and Simpson, 1992; Reasenberg and Simpson, 1992; Stein et al., 1992; King et al., 1994; Harris et al., 1995; Stein et al., 1997) show that stress-field perturbations can be computed by treating large earthquakes as crack-like dislocations in an elastic medium. Also, there exist strong parallels between statistics of earthquake and AE occurrences (Lockner, 1993). The well-known Gutenberg-Richter frequency-magnitude relation for earthquakes is expressed as

\[ N(M) = a - bM \]  

where \( N \) is the number of earthquakes of magnitude greater than or equal to \( M \) and \( a \) and \( b \) are constants (\( b \) is approximately unity). The power-law relation expressed by equation (1) has a direct and well-documented counterpart in AE-deformation studies (Lockner, 1993). In addition, aftershock decay characteristics can be explained in terms of their relation to primary creep relaxation and the associated decay in AE (Lockner and Byerlee, 1977; Lockner, 1993). The modified Omori's law for earthquake aftershock sequences is

\[ v(t) = \frac{K}{(t + c)^p} \]  

where \( v \) is the rate of earthquake occurrence, \( t \) is time and \( K, c \) and \( p \) are constants (\( p \) is approximately unity). For \( p = 1 \), this is identical to acoustic emission decay measured during primary creep in rock (Lockner and Byerlee, 1977; Lockner, 1993).

2. **Examples of AE Applied to Earthquake Prediction**

Numerous studies have identified systematic changes leading to fracture in laboratory AE studies and suggested that similar phenomena should be observed for earthquakes (Lockner, 1993). The most commonly studied are b-value and spatial clustering. Many studies, for example, report systematic decrease in b-value (i.e., an increase in the relative number of larger events) prior to large earthquakes (Von Seggern, 1980; Imoto and Ishiguro, 1986; Jin and Aki, 1986) as well as prior to failure in laboratory samples (Scholz, 1968; Weeks et al., 1978; Cai et al., 1988; Meredith et al., 1990; Lockner et al., 1991). The primary correlation appears to be between increasing applied stress and decreasing b. Thus, at higher stress levels, there is more stored elastic energy available to propagate larger and more energetic cracks. From our own experience (Lockner and Byerlee, 1995), we find that b-value changes do not always provide a consistent measure of impending sample failure. Apparently, this is also the case for earthquakes. Otherwise, this
phenomenon, which has been discussed for many years, would now be used to reliably predict earthquake occurrence. We are currently using laboratory data to test a refinement of the varying b-value phenomenon (Kuksenko et al., 1996). In this case, we propose that enhanced seismicity prior to a large earthquake will occur in a narrow energy band rather than being distributed across all energy bands as is generally assumed in b-value studies. For example, prior to a magnitude 7 earthquake, we would expect an enhanced occurrence ratio of magnitude 4's and 5's.

Event clustering is the other phenomenon that has been studied extensively in laboratory simulations of faulting. This is not surprising since of all the earthquake-precursory phenomena that have been studied, foreshocks remain the most readily accepted. If we define foreshocks as precursory earthquakes occurring near the hypocentral region of an impending quake at a rate above the normal background seismicity rate, then it is often the case that few or no foreshocks will be detected. Even when foreshocks occur, it is often difficult to recognize them as such or to assign them statistical significance. This, then, is an area where laboratory studies should be of use. By controlling stress, strain rate and sample geometry, predictable precursory patterns should be observable. Since Mogi's (Mogi, 1962) early studies of AE localization in bending, event-location techniques have improved to where accurate 3D locations (with resolution of approximately 3 mm) can be acquired for tens of thousands of acoustic emission events in a single fracture experiment (Lockner et al., 1992). Many studies have involved unconfined uniaxial tests (Sondergeld and Estey, 1981; Nishizawa et al., 1984; Yanagidani et al., 1985; Zang et al., 1996). Because of spalling and other properties associated with uniaxial failure, these tests may be difficult to compare to earthquake-nucleation processes that occur at ten to 20 km depths.

Preexisting flaws or bedding planes included in test samples tend to act as weak zones or stress concentrators that lead to localized AE early in the loading cycle (Lockner et al., 1992; Sobolev et al., 1996). By contrast, homogeneous, low porosity crystalline rocks deformed under jacketed triaxial conditions seem to show much more uniform microcrack accumulation until just before peak stress is reached, or in some cases, after peak stress (Lockner and Byerlee, 1980; Hirata et al., 1987; Lockner et al., 1992). Few tests have been reported on confined samples containing preexisting fractures (Weeks et al., 1978) or on re-mobilized fractures created during early stages of the experiment (Ponomarev et al., 1997). This last sample geometry may be the most appropriate analog for crustal earthquakes, which generally occur repeatedly on preexisting faults.

**Correlation coefficient:** The spatial distribution of AE events can be evaluated using the correlation integral $C(r)$ described by Hirata et al. (Hirata et al., 1987) as

$$C(r) = \frac{2}{N(N-1)} N_{(R<r)}$$

for a set of $N$ hypocenters $(p_1, p_2, ..., p_N)$. In this case, $N_{(R<r)}$ is the number of pairs $(p_i, p_j)$ separated by a distance smaller than $r$. If the distribution has a fractal structure, $C(r)$ is expressed by

$$C(r) \propto r^D$$

were $D$ is a kind of fractal dimension called the correlation exponent (Grassberger, 1983). $D$ can be estimated from the slope of a log-log plot of $C(r)$ versus $r$ (Fig. 1). One property of the correlation integral is that for events randomly filling a volume, the resulting exponent becomes $D = 3$. Similarly, for random events restricted to a plane, we obtain $D = 2$. For distances below 20 mm in Fig. 1, there is a decrease in $D$ from 2.7 to 2.0 as the macroscopic fracture develops in the sample. This systematic decrease reflects the transition from AE events occurring randomly throughout the sample to events being restricted to the fracture plane. The correlation integral, therefore, is useful...
Fig. 1 Correlation integral $C(r)$ is shown for pre- and post-nucleation stages of Westerly granite deformation at 50 MPa confining pressure. $C(r)$ provides a measure of the distribution of interevent distances. AE events occurring randomly within a fault plane (post-nucleation) will have a slope $D = 2$. Events occurring randomly within a volume (pre-nucleation) would have a slope $D = 3$. The observed value of $D = 2.7$ indicates a tendency for events to cluster spatially somewhat more than would be expected for a purely uncorrelated population.

in identifying large-scale features in the spatial distribution of events. However, if the early stages of fault nucleation involve only a small cluster of events, it may be difficult using the correlation exponent to identify this local change in event distribution when masked by a high level of background activity.

When fracturing intact rock cylinders, we have had mixed results in observing precursory changes in both $b$ and $D$. Plotted in Figs. 2 and 3 are time histories of granite and sandstone deformation experiments. In both examples, $D$ steadily decreased between peak stress and fault nucleation. The values of $b$ showed a marginal decline during this time interval in the sandstone experiment but not in the granite experiment. Other similar experiments (Weeks et al., 1978; Meredith et al., 1990; Lockner and Byerlee, 1995) have shown variations in $b$ but in some cases not in $D$ (Lockner and Byerlee, 1995). Until we can identify the processes that lead to this inconsistency in precursory response, it seems risky to extrapolate these results to earthquakes, which occur at such different scales in size and energy.

**Fault nucleation:** Acoustic emission has proven of great benefit in important aspects of the fault-nucleation process. Other techniques require loading samples to varying stages of failure and then undertaking the laborious process of preparing thin sections and counting microcrack densities (Hallbauer et al., 1973; Hadley, 1976; Madden, 1983). Besides being labor intensive, this approach has the disadvantage of requiring comparison of different samples so that natural variations from sample to sample would add variability to the results. By contrast, the non-destructive nature of AE recording makes this an excellent technique for monitoring damage accumulation during deformation experiments. In this way we have demonstrated that fault nucleation in granite is associated with the onset of tertiary creep in creep tests (Lockner and Byerlee, 1980), is restricted to a small region of the sample (Lockner et al., 1992) and generally occurs at or after peak stress in constant strain rate or constant AE rate experiments (Fig. 4). In the latter case,
Fig. 2. Time variations of differential stress, b and D-values for an intact Westerly granite experiment at 50 MPa confining pressure and nominally constant acoustic emission rate. Zero seconds represents the time when fault nucleation occurred as indicated by abrupt localization of AE locations and reversal of axial displacement rate (see Figure 4). b-value shows no significant variation prior to fault nucleation. By contrast, spatial clustering, as measured by decrease in D shows a subtle but steady change from a time (-600 s) prior to peak stress.

we have also shown that the large stress drop accompanying fault formation is the result of propagation of the shear fracture across the sample after the nucleation phase has ended (Fig. 4).

Inversion of AE arrival times provides 3D locations as well as event times of the source events. When amplitude information is also stored, we have the ability to compile space/time/magnitude catalogues of AE events much like earthquake catalogues are compiled. Because of the large number of events recorded in a single experiment, we have the opportunity to carry out statistical analyses of spatial and temporal clustering that are difficult to do on what are generally smaller numbers of recorded earthquakes. As an example, we next look at clustering statistics for a set of 4811 consecutive AE events recorded during a 2000-second interval spanning the peak stress period in a granite deformation experiment (50 MPa confining pressure). In this case, we begin
Fig. 3 Time variations of differential stress, b and D-values for intact Berea sandstone experiment at 50 MPa confining pressure and nominally constant AE rate. In this case, \( t = 0 \) is chosen by reversal of the axial displacement rate and an accompanying rapid drop in differential stress. However, unlike the previous granite example, nucleation developed gradually as a 'focusing' of diffuse AE which began in the early loading stages (Lockner et al., 1992). In this experiment, b shows a modest, steady decline from peak stress to 'nucleation' while the decline in D is much more apparent.

with the first event \( p_1 \) and record the distance \( r_{ij} \) and time \( t_{ij} \) between this event and all other events in the catalogue. We then take the second target event \( p_2 \) and compute the same \( (t_{ij}, t_{ij}) \) pairs. Once this procedure is carried out for all events, the spatio-temporal densities are computed. Densities are then normalized by \( 1/r^3 \) to compute the number of events occurring per unit volume and unit time. The results are shown in Fig. 5a. If events occurred randomly in space and time, the event density would be constant with a value of unity everywhere. While to first order the AE events are occurring randomly in this prenucleation period, two additional features can be seen. First, there is a gradual drop off in event density with increasing distance but which is independent of time (time-stationary). This reflects the D-value of 2.7 observed during this time interval and indicates that there is a subtle fractal structure to the AE activity that is apparently distributed throughout the
Fig. 4 Plots of AE locations occurring during deformation of intact cylindrical granite sample at 50 MPa confining pressure. Lower views show time progression of AE in sample as viewed along strike of the eventual fracture plane (seen as diagonal line in e and f). Upper plots show same AE events viewed perpendicular to strike. Stress-displacement plot is shown at bottom. Note that fault nucleation (d) occurs at reversal in stress-displacement plot. Once fault nucleates, it moves across sample as a propagating damage front (upper views d, e and f).

sample volume. Events have a tendency to occur closer to each other than would be expected by a purely random filling of the sample volume. The second feature to notice in Fig. 5a is the increase in density of events near the origin. This increased activity is localized both in distance and time and indicates that it is approximately 2.5 times as likely for an event to be accompanied by a second event as would be expected by random chance. This correlation of events has a range of approximately 5 mm and 20 seconds. The enhanced probability is rather weak when compared to
Fig. 5 Plots of spatial and temporal distributions of AE event occurrences during pre-nucleation stage of deformation in intact Westerly granite at 50 MPa confining pressure. Normalized event density is plotted as a function of interevent time and distance. Events randomly filling the sample volume would plot as a uniform surface with density of 1. (a) Interevent distances are computed for all detected events (4811 events) occurring in a 2000-s-interval which includes peak stress (see text). Increased event density near the origin indicates that a small population of events are correlated in space and time. (b) In this case, the largest events (206 events in a 5000-s-window having amplitudes greater than 30 mV) are chosen as 'main shocks' and the distribution of smaller events before and after these main events is computed. For these master events, the increased probability of a second event near the origin is more than seven times the background level.
the total event population, but it shows that event doublets do occur during the peak-stress phase of
the experiment (Lockner and Byerlee, 1995; Lockner et al., 1995) in a manner similar to event
clusters reported for earthquakes (Reasenberg, 1985).

In the preceding example, we examined at the correlation of all AE events located in the sample
within a given time interval. We now repeat this exercise while targeting only the largest or 'master' events to occur within the prenucleation stage. In this case, we will look for miniature
foreshock and aftershock sequences associated with the largest AE events. The results for 206
large prenucleation events occurring within a 5000-second interval are shown in Fig. 5b. Once
again, the event densities have been normalized by \(1/r^3\) so that purely random activity would plot
with a uniform value of unity. Once again, we can see the main features observed in the previous
example. First, there is an overall decrease in event probability with distance from the master
events which seems uncorrelated with time. This inverse correlation with distance reflects the
fractal nature of the spatial distribution of AE activity. It does not appear any stronger for the large
events shown in Fig. 5b than for the general AE population shown in Fig. 5a.

The second prominent feature in Fig. 5b is the increased probability of events centered at the
origin. This increased event correlation was also seen in the previous example. However, now
there is more than a seven-fold increase in probability, relative to the background AE level, that a
large amplitude event will be accompanied by a second event. Enhanced activity occurs both before
(foreshocks) and after (aftershocks) the main events. The increased probabilities observed in Fig.
5b as compared to Fig. 5a indicate a positive correlation between main shock magnitude and the
intensity of foreshock and aftershock activity. However, we have not yet demonstrated the cause
of the correlation between the master AE events and their foreshock and aftershock sequences.
While there may be a causal relationship, it is also possible that the entire foreshock-main shock-
aftershock sequence is the result of a local stress buildup due to the continuous redistribution of
stress and strain within the deforming sample.

4. Conclusions

This paper has shown the close correspondence between the statistics of earthquakes and
laboratory AE studies. These include basic properties such as the Gutenberg-Richter frequency-
magnitude relation and the correspondence of Omori's law for aftershocks and primary creep decay
sequences. AE foreshock-main shock-aftershock sequences have also been shown here as well as
in earlier work (Weeks et al., 1978). As a result, it seems appropriate to treat laboratory AE studies
as valid analogs to earthquake sequences. The advantages of this approach come from our ability to
control test materials and experimental conditions, from the large event catalogues that can be
acquired for statistical analysis and from the accelerated time frame of laboratory tests when
compared to earthquake repeat times measured in hundreds of years. As long as earthquake
prediction is pursued by seismologists, there should be a place for conducting model AE
experiments in the laboratory.

Acknowledgments

I thank J. Byerlee, D. Moore (USGS), A. Ponomarev (IPE, Moscow), and V. Kuksenko and
S. Stanchits (Ioffe Institute, St. Petersburg), who have all contributed to various aspects of this
research.
References


S98


Modal AE: A New Understanding of Acoustic Emission

Michael R. Gorman

Modal AE provides increased understanding of acoustic emission through analysis of guided waves in plates, rods and shells. Modal AE technology means wideband detection of the elastic displacements, theoretical calculations of velocities and wave shapes, and signal processing of wave mode details in order to establish a definite and physical correspondence with AE source mechanisms. The fundamental assumptions upon which Modal AE technology is based are stated and discussed in this paper. Some relationships between sources and waves in various materials and geometries are presented. In this paper the basic assumptions behind AE parameter analysis are reviewed, and it is shown that these assumptions are in direct opposition to the true nature of wave modes in finite media. Further, it is explained why the AE parameters are highly correlated - they are in effect dependent variables. It is concluded that future research should be focused on wave detection and analysis in conjunction with materials science and mechanics.

Mike Gorman (mikey@digitalwavecorp.com) is affiliated with Digital Wave Corp., Englewood, CO.

Finite Element Modeling of Acoustic Emission Displacement in the Far-field of AE Sources

M.A. Hamstad, J. Gary and A. O’Gallagher

We have performed a study to validate a three-dimensional dynamic finite element code for calculating expected dynamic displacement fields in the far field from various types of acoustic emission sources. This work uses several approaches to complete the validation and to determine values for key parameters so that acoustic emission sources can be modeled. These parameters include the cell size, source diameter, and source rise time. Laboratory experiments using pencil-lead breaks on a large 25.4 mm thick steel plate were used to validate the three-dimensional code. Lead breaks were carried out both on the top surface of the plate and at various depths along one edge. Using a calibrated, wideband displacement sensor, the experimental out-of-plane displacements versus time were quantitatively compared to calculated displacements at distances of up to 366 mm from the source. In addition, certain interesting cases were examined with the code.

M.A. Hamstad (mhamstad@du.edu) is affiliated with University of Denver, Denver, CO 80208.


Transfer Functions to Remove Geometry Effects from Acoustic Emission Signals

Laurence J. Jacobs

To be effective, quantitative acoustic emission (AE) techniques must be able to identify the nature of an arbitrary emission source and determine its location. A measured AE signal depends upon three factors: its source; the component geometry and material properties; and the receiving sensor and instrumentation. The finite geometry of a laboratory specimen changes a measured AE signal because of reflections, transmissions and mode conversions at the interfaces and boundaries of the specimen, thus making it difficult to interpret the measured signal. This research quantifies and removes the effect of specimen geometry on measured AE waveforms. An experimental transfer function is developed using laser interferometer for the sensor and a pulsed laser for the generation of a broadband, repeatable point source. Optical detection is critical because of its high fidelity, broadband and non-contact nature. The technique treats the specimen geometry as a corruptive channel and develops a filter that models this bias on a measured AE signal. This filter is based on comparisons between signals measured in a finite specimen and those made in a half space. The accuracy of this filter is verified and used to remove geometry related features from AE signals.

The author (laurence.jacobs@ce.gatech.edu) is affiliated with School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0355.

The Sound of Composite Materials during Static and Dynamic Experiments

M. Surgeon and M. Wevers

Composite materials are very attractive for use as lightweight construction materials due to their high strength over weight ratio. During the past decades the three types of composite materials (polymer, metal and ceramic matrix composites) have received increasing research attention.
A property that distinguishes composites from monolithic materials is their more complex damage evolution scheme under loading: a variety of damage mechanisms can occur and can interact so that in the end lead to failure of the composite material. A number of NDT techniques are available to monitor this gradual damage evolution. However, of these techniques, only acoustic emission (AE) has the potential to detect all of the main damage mechanisms in composite materials: matrix cracking, delamination, debonding and fibre fracture. Moreover, AE offers some additional advantages: it monitors damage continuously and in situ during testing or service. However, an interpretation of AE signals is not generally straightforward and often other techniques have to be used to 'calibrate' the AE data. This was illustrated with some examples of research carried out at Leuven.

A first example discussed the tensile testing of a carbon/epoxy composite, having a quasi-isotropic lay-up. Based on the amplitude of the AE signals a distinction was possible between stable matrix cracking, unstable matrix cracking, delamination growth and fibre failure.

A second example considered the fatigue loading of a cross-plied carbon/epoxy composite with different levels of fibre surface treatment. During these tests a perfect correlation was obtained between high amplitude signals and the number of cracks that spanned the width of the specimen. During testing of the specimen with the highest fibre surface treatment an overlap was seen between the signals coming from matrix cracking and signals from another damage mode. These signals were attributed to fibre fracture. The third example considered a ceramic matrix composite consisting of Tyranno SiC fibres incorporated in a BMAS glass ceramic matrix. Four different lay-ups were considered. Based on the duration of the AE signals a differentiation was possible between matrix microcracking, matrix macrocracking, matrix debonding and delamination initiation and growth which demonstrates the feasibility of the AE technique to monitor damage evolution in this type of composites.

The final example discussed fatigue testing of a metal matrix composite consisting of different contents of SiC particles embedded in an aluminium matrix. Damage was monitored by AE and in situ light optical microscopy. A good correlation was obtained between the number of AE events and the crack length measured with optical microscopy. The AE signals were attributed to particle fracture.

As a general conclusion it can be stated that AE provides useful and additional information during the testing of composite materials: damage initiation can be detected and a discrimination between different damage mechanisms is possible if the data are carefully calibrated with other techniques.

The authors (Mamix, Surgeon@mtm.kuleuven.ac.be) are affiliated with Department of Metallurgy and Materials Engineering, Katholieke Universiteit Leuven, De Croylaan 2, 3001 Heverlee, Belgium.

Generation of Acoustic Emission Waves and Moment Tensor Analysis

Masayasu Ohtsu

The theory of acoustic emission (AE) waveforms in the three-dimensional elastic body is summarized. AE sources are modelled as crack nucleation, which mathematically corresponds to dynamic displacement discontinuity. The waveform is represented by an integral formulation, containing the spatial derivatives of Green's functions, a moment tensor, and a source-time function. Kinetics on crack motion is governed by the source-time function, while kinematics on crack type and crack orientation are derived from the moment tensor. AE waveforms can be synthesized by the integral formulation when the crack location, crack kinetics, and crack kinematics are known.

The source-time function is recovered from the deconvolution analysis. By combining the flaw location, a procedure to determine moment tensor components is developed as a simplified Green's function for moment tensor analysis (SIGMA) code. From AE waveforms recorded at more than six sensor locations due to one crack nucleation, the arrival time differences lead to crack location and moment tensor components are determined from the amplitudes of the first motions of AE waveforms. On the basis of the eigenvalue analysis of the moment tensor, AE source is classified into a tensile crack and a shear crack. Crack orientation is determined from the eigenvectors. Applications of the moment tensor analysis to the fracture mechanics are presented.

The author (ohtsu@kumamoto-u.ac.jp) is affiliated with Institute of Mechanics, Technical University of Vienna, Wiedner Hauptstrasse 8-10/32, A-1040 Vienna, Austria; on leave from Department of Civil Engineering and Architecture, Kumamoto University, Kumamoto 860, Japan.


Eric N. Landis

Advanced acoustic emission techniques were applied to basic problems of microfracture in cement-based materials. Acoustic emissions in cement-based materials result from microcracks, particle sliding, and other dynamic phenomena in the fracture process zone (an area that surrounds the main crack tip and accounts for the nonlinear fracture properties of concrete). The goals of this research program were to characterize microcracking in cement-based materials of varying composition, track the evolution of damage in those materials, and to examine the relationships to overall mechanical behavior.
Toward this end, microcracks were modeled using a seismic moment tensor such that their individual fracture characteristics could be analyzed through an inversion of the measured acoustic emission waveforms. The measurement system consisted of an eight channel transient recorder and controlling computer, which was able to record waveforms at a rate of about 3 events per second. Analysis consisted of deconvolution of measured waveforms to produce surface displacement transients, followed by source location determination. Finally, the moment tensor for the AE event was evaluated using a six channel nonlinear least-squares algorithm.

Characterizations of the microcracks showed a dependence on the degree of inhomogeneity in the material. Fine-grained materials showed different microfracture characteristics than coarse-grained materials. The fine-grained materials tested showed different mixed mode microfracture, whereas the coarse-grained materials showed primarily mode II (shear) microfracture. It was found that a relationship between the microcrack characteristics established through quantitative acoustic emission analysis and the fracture toughness of the material may be established. Nonlinearities in the load-displacement relationships are also traced to AE-generating phenomena.

The author (landis@maine.edu) is affiliated with Department of Civil and Environmental Engineering, University of Maine, Orono, Maine, 04469 USA.

The Fracture Dynamics in a Dissipative Glass-Fiber/ Epoxy Model Composite with AE Source Simulation Analysis

Kanji Ono, Hiroaki Suzuki and Mikio Takemoto

In order to examine the fracture modes and dynamics in a dissipative glass-fiber/epoxy composite, we employed an eight-channel AE monitoring system. Seven-channels with small sensors were used for the source location and for fracture mode analysis based on the radiation pattern of the P-wave. A displacement-sensitive sensor on the eighth channel was utilized to obtain the source waveform using a proposed computer algorithm in time domain. As the wave propagation medium in the model specimen is an epoxy polymer, both the wave attenuation, and dispersion in the epoxy matrix were measured by employing a focused pulse laser transmitter and a point PZT receiver. The results were incorporated into a signal simulation algorithm for source characterization. This algorithm was developed in the time domain and can calculate the transient surface displacements of elastic waves excited by the fiber fracture and fiber/matrix disbonding in model uni-directional glass fiber/epoxy composites. It includes the source location, radiation pattern analysis, wave attenuation and the use of a relaxation function.

This newly developed system was utilized in analyzing AE signals from two types of glass-fiber reinforced composite specimens. For the specimens with glass-fiber bundles parallel to the loading direction, most AE waveforms were produced by the Mode-I fiber fracture with source rise time of 0.17 to 0.5 μs. For the model composite specimens with fiber bundles perpendicular to the loading, most waveforms were produced by the matrix cracks resulting in a point of dilatation. Some signals were due to Mode-I disbonding at the fiber/matrix interface. Mode-II disbonding at the top or bottom of the fiber bundles was also detected. Detail analysis of some of the monitored waveforms also points to multi-step fiber fractures or points of dilatation with a short incubation time.

Kanji Ono (ono@ucla.edu) is affiliated with Dept. of Materials Science and Engineering, University of California, Los Angeles, CA 90095-1595, and H. Suzuki and M. Takemoto (takemoto@me.aoyama.ac.jp) are with Department of Mechanical Engineering, Aoyama Gakuin University, 6-16-1 Chitosedai, Setagaya, Tokyo 157, Japan.


Experience with Conventional Acoustic Emission Monitoring to Resolve and Characterize Interfacial and Mechanical Issues in Advanced MMC Composites

Itzhak Roman

Conventional acoustic emission (AE) activity was monitored during a variety of tests by employing resonant transducer with a center frequency of 250 kHz. Some of the waveform parameters (peak amplitude, duration, etc.) as well as appropriate strain, stress, and temperature values were recorded during the tests.

Program began with single fiber fragmentation testing of SCS-6 SiC-fiber-reinforced MMC (Al and Ti) composites at RT and elevated temperatures. Along with mechanical test results, it was established that in these materials, AE events generally fall into three separate populations that vary in signal intensity and duration. Those events corresponding to fiber fracture could be easily distinguished from other events based on their high intensities (>90 dB) and long duration (>8 ms). The origin of the lower intensity events is related to matrix plasticity and interfacial failure, but a definite correlation was not established. This means of determining, non-destructively, fiber fracture in real time, was utilized during high temperature testing of titanium-matrix composites. These include the fatigue and thermomechanical fatigue (TMF) tests of SCS-6 SiC-fiber/ TIMETAL121S-matrix composite, and the creep behavior
(427-760°C) characterization of SCS-6/Ti-6Al-4V. TMF tests were stress-controlled with stress ratio of 0.1, and temperature was cycled from 150° to 650°C.

The AE monitoring provided information unavailable by other means. For example, in-phase and out-of-phase TMF cycling were characterized by distinct AE behaviors. The rate of fiber fractures as indicated by AE during in-phase cycling was much higher than out-of-phase cycling, correlating with metallography and micromechanics analyses which indicate that the fiber stress is higher under in-phase than under out-of-phase. The fiber-fracture rate was proportional to the maximum fiber stress. Many AE events occurred on the initial loading, but very few on unloading and subsequent loadings, indicating that most of the transient damage in metal-matrix composites occurs during the initial loading. It can be concluded that conventional AE monitoring is an effective technique providing useful information about damage progression and accumulation in advanced materials under stress, when combined with microstructural studies.

The author is affiliated with (romana@vms.huji.ac.il) Graduate School of Applied Science, The Hebrew University, Jerusalem, Israel 91904.

Acoustic Emission Source Analysis in Granite Cores under Symmetric and Asymmetric Compressive Load.

Arno Zang, F.C. Wagner, S. Stanchits and G. Dresen

Twenty-five uniaxial compression tests were performed on dry and wet granite from the Erzgebirge, Germany. Beside standard symmetric loading, asymmetric loading is applied to three cores, where a part (20%) of the rock-cylinder top surface remains unloaded. Acoustic emissions (AE) are detected in twenty-one cores using eleven conventional piezoceramic transducers and one calibrated broadband sensor. Calculated AE positions during symmetric loading document the development of two opposite fracture cones as expected from uniaxial testing with end-cap friction. During asymmetric loading AE hypocenter focus on a single fracture plane. The correlation coefficient of AE hypocenters before rock failure drastically increases; this behavior is independent of the strain rates used (10^{-4} to 10^{-3} s^{-1}). The correlation coefficient doubles going from symmetric to asymmetric loading conditions. A single stress drop occurs during symmetric loading whereas multiple stress drops are evident in asymmetric rock failure. The positions of AE signals with high amplitude correspond to the trace of the future asymmetric fracture plane.

Conventional X-ray analysis and X-ray computer tomography reveal cone fractures in symmetrical shape and a single pre-fracture with multiple main fractures in asymmetrically loaded cores. First pulse statistics of AE wavelets lead to the conclusion that shear microfractures dominate the failure of granite in both loading scenarios. Cumulative event polarity shows anomalies before significant stress drops. Lower hemisphere projections of cumulative polarities indicate the dominant type of microfractures as well as the orientation of the developing macrofracture plane. Emission based b-values drop before the main fracture and recover afterwards for both dry and wet granite cores. First-pulse-amplitude and peak-amplitude analysis lead to similar b-values. The statistics of focal amplitude taking into account the travel path of the elastic waves is the most reliable indicator for detecting anomalies in b-values.

The authors (zang@gfz-potsdam.de) are affiliated with GeoForschungsZentrum, Dept. 3.2, Telegrafenberg A17, 14473 Potsdam, Germany.
Sixth International Symposium on Acoustic Emission from Reinforced Composites will be held June 1 - 5 or June 8 - 12, 1998 at San Antonio, Texas, USA. This meeting is sponsored by American Society For Nondestructive Testing (ASNT) Committee on Acoustic Emission from Reinforced Plastics (CARP).

General
It is proposed to follow the successful format of previous symposia in this series. An educational seminar will be held on Monday. Formal papers will be presented Tuesday through Friday morning.

Applications
Papers describing applications of acoustic emission will be emphasized and field test companies and industrial companies will be asked to submit papers describing their work.

Work-in-Progress
Time will be made available for short "Summaries of Work-in-Progress". These presentations will require an abstract but not a formal written paper.

Prospective authors should submit the following information with their 200-300 word abstract: title, author names and organizations, mailing addresses for all authors including phone, fax, and email (indicate which author is primary contact point), and indicate whether for formal presentation or Work-in-Progress Summaries.

Organizing Committee is chaired by Dr. Timothy J. Fowler, The University of Texas, 417 Beardsley Lane, Austin, TX 78746-4927 USA ph.: 512-329-0653; Fax: 512-329-9054
and co-chaired by Dr. Sotirios J. Vahaviolos, Physical Acoustics Corporation, Princeton, New Jersey.

San Antonio is located in south central Texas, 200 miles west of Houston, 300 miles south of Dallas. The population is approximately 1-1/2 million. San Antonio has a strong Mexican flavor and specializes in tourism. There are numerous historic sights including the Alamo, La Villita (the original settlement) and El Mercado (market square). The River Walk winds through downtown 20 feet below street level. Shops, restaurants, cafes, galleries, and hotels line the River Walk on the banks of the San Antonio River. Several miles of tree shaded walks run along each bank, and water buses run at frequent intervals.
The 14th International Acoustic Emission Symposium and 5th Acoustic Emission World Meeting
August 9-14, 1998, Hawaii, USA

The 14th International Acoustic Emission Symposium and 5th Acoustic Emission World Meeting will be held August 9-14, 1998 at The Royal Waikoloa Hotel on the Kohala Coast of the Big Island of Hawaii, USA. “Transitions in AE for the 21st Century” is the theme of this united meeting, jointly sponsored by the Committee 006 of the Japanese Society of Non-Destructive Inspection (JSNDI) and the Acoustic Emission Working Group (AEWG).

The program will consist of formal papers (published in preprinted hardbound proceedings) and informal oral briefs (which will not require a written submission, except for abstract). Technical program starts with a keynote speaker and/or a lively debate on acoustic emission technology on the first afternoon, Sunday Aug. 9th. Presentations of formal papers will take place over the next 3 to 4 full days, depending upon response. If response is especially great, papers of a more specialized nature may be displayed as poster papers rather than delivered as formal presentations; these poster papers will also be included in the preprinted proceedings. An additional half-day may also be allotted for presentation of short, informal oral briefs of work in progress; these oral briefs will not require a formal manuscript.

Abstracts are solicited on waveform acquisition, wideband sensing, high rate digitization, new methods of acoustic emission signal processing, and other relevant acoustic emission topics as well as acoustic emission applications. Abstracts must include the objective and approach of the work discussed, point out work that is new, and present results. Prospective authors should submit the following information with their 200-300 word abstract: title, author names and organizations, mailing addresses for all authors including phone, fax, and email (indicate which author is primary contact point), and indicate whether for formal presentation or informal brief. Send abstracts to:

Dr. Kanji Ono (e-mail: ono@ucla.edu), Dept. of Materials Science Engineering/6531 BH
Box 951595, 405 Hilgard Avenue, Los Angeles, CA 90095-1595 USA

For formal papers, deadline for receipt of abstracts is Sept. 30, 1997 (although email abstract submissions may receive consideration after this date). Abstracts will be reviewed by Dr. Kanji Ono and Dr. Teruo Kishi. Authors will be notified on a rolling basis, and not later than Jan. 15, 1998. Instructions for the preparation of camera ready formal papers will be supplied with the acceptance. The official language of the Conference will be English. Formal manuscripts (in English) must be received by May 15, 1998. Presentations of formal papers will not be allowed without a formal manuscript appearing in the preprinted proceedings.

For informal oral briefs, a notice of intent to submit an abstract is due by Feb. 1, 1998. The actual abstract submission is due May 1, 1998. Authors will be notified by May 15, 1998.

Please direct any questions or requests for further information about the meeting to:

Karyn S. Downs, Lockheed Martin Astronautics, PO Box 179; M/S DC3005, Denver, CO 80201 USA
email karyn.s.downs@lmco.com; ph. 303-977-1769; fax 303-971-7698
Program of the 40th AEWG Meeting

June 9-11, 1997 at Infrastructure Technology Institute, Northwestern University, Evanston, Illinois; David W. Prine, Program Chair.

MONDAY, JUNE 9, 1997

AE PRIMER
Introduction to AE, Alan G. Beattie, Sandia National Laboratories
Metals and Alloys, Harold L. Dunegan, Dunegan Engineering Consultants, Inc. (DECI)
AE from Composites, Yolanda L. Hinton, NASA Langley Research Center
AU and Its Application to Wood Products, Frank C. Beall, University of California, Forest Products Lab.
Geotechnical Applications of AE, H. Reginald Hardy, Jr., Penn State University
AE Testing of Pressure Vessels and Piping, Allen T. Green, Acoustic Technology Group

TUESDAY, JUNE 10, 1997

APPLICATIONS #1; SESSION CHAIR: David W. Prine, Infrastructure Technology Institute, Northwestern Univ.

1a. AE Detection of Cracking in Pipe Socket Welds, Bryan Morgan, Pacific Gas & Electric Co.

1b. Field Data on Testing of NGV Containers Using Proposed ASTM Standard E070403-95/1, Roy D. Fultineer, Jr., Spencer Testing Services

1c. The Use of Portable Wireless Acoustic Emissions Systems for Bridge Monitoring, Lozev, M.G., Virginia Transportation Research Council; Washer, G., Federal Highway Association; Carlos, M. and Miller, R., Physical Acoustics Corporation

1d. Underground Pipeline Leak Detection Using Acoustic Techniques, Carlyle, J.M., New Jersey Institute of Technology; Tafuri, A.N., U.S. Environmental Protection Agency; Watts, D.J., New Jersey Institute of Technology; and Yezzi, J.J., Jr., U.S. Environmental Protection Agency

1e. Waveform-Based AE for Damage Evaluation of FRP-Reinforced Glued-Laminated Wood Beams, Marsh, K., and Landis, E., Department of Civil and Environmental Engineering, University of Maine

1f. Acoustic Emission During Rotary Cutting of Coal, Hardy, H.R., Jr., Pennsylvania Mining and Mineral Resources Research Institute; Shen, H.W., Department of Mineral Engineering, Pennsylvania State University; and Khair, A.W., Mining Engineering Department, West Virginia University

1g. An Evaluation of the Performance of Acoustic Emission Systems, Surgeon, M., Wevers M., and De Meester, P., Katholieke Universiteit Leuven; and Ono, K., University of California - Los Angeles

APPLICATIONS #2; SESSION CHAIR: Kanji Ono, University of California, Los Angeles

2a. Analysis of AE Data from a Rocket Motor Case: Key Questions in AE Source Location, Maochen Ge, Natural Resources Canada, Mineral and Energy Technology

2b. Evaluation of Prototype Retrofit of a Steel Bridge Using AE and Strain Gages, David W. Prine, Infrastructure Technology Institute, Northwestern University

2c. The Role of the Shear Wave in AE Testing of Plate-Like Structures, Harold L. Dunegan, Dunegan Engineering Consultants, Inc. (DECI)

2e. Considerations for Time-of-Arrival Measurements Based on Lamb Wave Theory, Miller, R.K., Pollock, A.A, and Almeida, A.F., Physical Acoustics Institute

2f. AE Analysis and Applications Using Moment Tensor, Yuyama, S., Nippon Physical Acoustics; and Carlos, M., Physical Acoustics Corporation


WEDNESDAY, JUNE 11, 1997

SIGNAL PROCESSING; SESSION CHAIR: Harold L. Dunegan, Dunegan Engineering Consultants, Inc. (DECI)

3a. The Use of Neural Networks to Discriminate Defect Signals from Noise, Pollock, A.A, Almeida, A.F., and Miller, R.K., Physical Acoustics Institute

3b. Collecting AE Activity Graphs into an Atlas - A Proposed Format, Nordstrom, R. and Brunner, A.J., EMPA Dubendorf, Switzerland; and Bohse, J., BAM, Germany

3c. Wideband and Narrowband Acoustic Emission Waveforms from Extraneous Noise During Fatigue of Steel Samples, Hamstad, M.A. and McColskey, J.D., National Institute of Standards and Technology

3d. Wavelet Transform of AE Signals, Suzuki, H. and Hayashi, Y., Aoyama Gakuin University; Takemoto, M., Shizuoka University; and Ono, K., University of California - Los Angeles

3e. Wave Propagation Effects Relative to AE Source Distinction of Wideband AE Signals from a Composite Pressure Vessel, Downs, K.S., Lockheed Martin Astronautics; and Hamstad, M.A. University of Denver

3f. PolyMODAL® AE Waveform Analysis Application, Yan, W., and Carlos, M., Physical Acoustics Corporation


SENSORS/CERTIFICATION; SESSION CHAIR: Maochen Ge, Natural Resources Canada, Mineral and Energy Technology


4b. Improved Signal-to-Noise Wideband Acoustic/Ultrasonic Contract Displacement Sensors for Wood and Polymers, Marvin A. Hamstad, University of Denver - Department of Engineering and National Institute of Standards and Technology


COMMERCIAL PRESENTATIONS

BUSINESS MEETING

AWARDS BANQUET, Omni Orrington Heritage Ballroom

THURSDAY, JUNE 12, 1997; ASTM-E07.04 MEETING

FRIDAY, JUNE 13, 1997; ASTM-E07.04 MEETING
AVAILABLE BOOKS ON ACOUSTIC EMISSION

Journal of Acoustic Emission, Vol. 4 - 8 (1985 - 89) $ 90 per volume (plus shipping)

Above are available from Acoustic Emission Group, 308 Westwood Blvd, Box 364
Los Angeles, CA 90024-1647, FAX 1-818-990-1685

Eds. R.K. Miller and P. McIntire. 650 pages. $110.25

Available from Book Dept., ASNT, P.O.Box 28518, Columbus, OH 43228. Also call (800) 222-2768.

First International Symposium on AE from Reinforced Plastics (1983); $ 50 + shipping.
Second International Symposium on AE from Reinforced Plastics (1986); $ 65 + shipping.
Available from Publication Sales, SPI, 355 Lexington Ave., New York, NY.


22nd European Conf. on AE Testing, Aberdeen, Scotland, May 1996; Available from Univation, Robert Gordon University, Kepplestone, Queen’s Road, Aberdeen, AB9 2PG, UK; fax (44) 1224 263323

1996 SUBSCRIPTION RATE for Volume 14

Base rate for one year (four issues, Mar. - Dec.) $ 96.00
Add Postage of U.S. - Book rate $ 8.00
All others - Book rate $ 11.00
Western Europe/S. America - Air mail rate $ 25.00
All others - Air mail rate $ 30.00
Add $5 without payment upon order. Payment must be in U.S. dollars drawn on a U.S. bank. Bank transfer accepted, but with $10 surcharge to the A.E. Group account (Account No. 080-03416470) at
Sumitomo Bank of California
San Fernando Valley Office
15250 Ventura Blvd, Sherman Oaks, CA 91403-3262
Notify us of such a transfer as the bank cannot sometimes give us the name of the payer. One volume of four issues per year. Index included in the Oct.-Dec. issue. Back issues available at $50 per volume for Vols. 1-3, $90 per volume for Vols. 4-8,

$96 per volume for Vols. 9-14. US surface postages $8 per volume. For Canada and overseas surface delivery, add $11 and for air mail, add $30 per volume (will be adjusted for multi-volume order).

All orders should be sent to (or Fax 1-818-990-1686)
Acoustic Emission Group
308 Westwood Blvd., Box 364
Los Angeles, CA 90024-1647 USA

For inquiry through Internet, use the following address:
ono@seas.ucla.edu
Editor-Publisher Kanji Ono Tel. (310) 825-5233
Cover Design Robin Weisz (UCLA Publications)
Production Pace Publication Arts
Publication Date of This Issue: 18 August 1997.
INDEX

Contents of Vol. 14, 1996

Number 1

Pages 1-34  A History of Acoustic Emission  Thomas F. Drouillard

Pages 35-50  The Fracture Dynamics in a Dissipative Glass-Fiber/Epoxy Model Composite with AE Source Simulation Analysis  Hiroaki Suzuki, Mikio Takemoto and Kanji Ono

Conferences and Symposia

Pages 51-52  22nd European Conference on AE
Page 52  Cover Photograph

Number 2

Pages 53-59  Modeling of Stress-Strain Response of Unidirectional and Cross-Ply SiC/CAS-II Ceramic Composites by Acousto-Ultrasonic Parameters  Anil Tiwari, Edmund G. Henneke II and Alex Vary

Pages 61-68  Neural Network Approach to Acoustic Emission Source Location  Vasisht Venkatesh and J.R. Houghton

Pages 69-84  Wavelet Transform of Acoustic Emission Signals  Hiroaki Suzuki, Tetsuo Kinjo, Yasuhisa Hayashi, Mikio Takemoto and Kanji Ono with Appendix by Yasuhisa Hayashi


Pages 97-102  Pattern Recognition of Acoustic Signatures Using ART2-A Neural Network  Shahla Keyvan and Jyothi Nagaraj

Pages 103-114  Far-field Acoustic Emission Waves by Three-Dimensional Finite Element Modeling of Pencil-Lead Breaks on a Thick Plate  M. A. Hamstad, J. Gary and A. O'Gallagher

Pages 115-118  Acoustic Emission Testing of Bolted Connections under Tensile Stress  V. Hänel and W. Thelen

Pages 119-126  A Method to Determine the Sensor Transfer Function and its Deconvolution from Acoustic Emission Signals  Bernhard Allemann, Ludwig Gauckler, Wolfgang Hundt and F. Rehsteiner

Conferences and Symposia

Page 60  39th Meeting of the Acoustic Emission Working Group and Primer
Page 96  40th Meeting of the Acoustic Emission Working Group and Primer
Page 127-128  13th International AE Symposium (IAES-13)

Number 3/4

Proceedings of International Workshop at Schloss Ringberg

Pages i-iv  Materials Research with Advanced Acoustic Emission Techniques  Alexander Wanner and Michael R. Gorman, Topical Co-Editors
Page v  Friedrich Förster and Erich Scheil, Two Pioneers of Acoustic Emission  Alexander Wanner
Pages vi-viii  Acoustic Investigation of Martensite Needle Formation by Fritz Förster and Erich Scheil, Translated by Peter G. Thwaite and Alexander Wanner
Advanced AE Techniques in Composite Materials Research
William H. Prosser

Digital Signal Processing of Modal Acoustic Emission Signals
Steve Ziola

Wave Theory of Acoustic Emission in Composite Laminates
Dawei Guo, Ajit Mal and Kanji Ono

Fiber Fragmentation and Acoustic Emission
Alexander Wanner, Thomas Bidlingmaier and Steffen Ritter

Wave Propagation Effects Relative to AE Source Distinction of Wideband AE Signals from a Composite Pressure Vessel
Karyn S. Downs and Marvin A. Hamstad

Relative Moment Tensor Inversion Applied to Concrete Fracture Tests
C. U. Grosse, B. Weiler and H. W. Reinhardt

Brittle Fracture as an Analog to Earthquakes: Can Acoustic Emission Be Used to Develop a Viable Prediction Strategy?
David A. Lockner

Abstracts of Talks Presented

Conferences and Symposia

6th International Symp. on Acoustic Emission from Reinforced Composites

14th International Acoustic Emission Symposium and 5th Acoustic Emission World Meeting

40th Meeting of the Acoustic Emission Working Group and Primer

Available Books on AE

Index to Vol. 14

AUTHORS INDEX

Bernhard Allemann
Thomas Bidlingmaier
Karyn S. Downs
Thomas F. Drouillard
J. Gary
Ludwig Gauckler
Michael R. Gorman
C. U. Grosse
Dawei Guo
V. Hänel
M. A. Hamstad
Yasuhiro Hayashi
Edmund G. Henneke II
J.R. Houghton
Wolfgang Hundt
Shahla Keyvan
Tetsuo Kinjo
David A. Lockner
Ajit Mal
Jyothi Nagaraj

119
S47
S61
1
103
119
i (3/4)
S74
S19
115
103, S61
69
53
61
119
97
69
S88
S19
97

H. Nayeb-Hashemi
A. O’Gallagher
Kanji Ono
T. Pocheco
William H. Prosser
F. Rehsteiner
H. W. Reinhardt
Steffen Ritter
H. M. Sallam
Hiroaki Suzuki
Mikio Takemoto
W. Thelen
Peter G. Thwaite
Anil Tiwari
Alex Vary
Vasishth Venkatesh
Alexander Wanner
B. Weiler
Steve Ziola

85
103
35, 69, S19
85
S1
119
S74
S47
35, 69
35, 69
115
vi (3/4)
53
53
61
i, v, vi (3/4), S47
S74
S12
Notes for Contributors

1. General

The Journal will publish contributions from all parts of the world and manuscripts for publication should be submitted to the Editor. Send to:

Professor Kanji Ono, Editor - JAE
6531 Boelter Hall, MSE Dept.
University of California
Los Angeles, California 90095-1595 USA
FAX (1) 818-990-1686
e-mail: ono@seas.ucla.edu

Authors of any AE related publications are encouraged to send a copy for inclusion in the AE Literature section to:

Mr. T.F. Drouillard, Associate Editor - JAE
11791 Spruce Canyon Circle
Golden, Colorado 80403 USA

All the manuscripts will be reviewed upon submission to the Editor. Only papers not previously published will be accepted. Authors must agree to transfer the copyright to the Journal and not to publish elsewhere, the same paper submitted to and accepted by the Journal.

A paper is acceptable if it is a revision of a governmental or organizational report, or if it is based on a paper published with limited distribution.

An abstract of about 200 words is needed for Research and Applications articles, while it should be shorter than 100 words for other articles.

The language of the Journal is English. All papers should be written concisely and clearly.

2. Page Charges

No page charge is levied. Fifty copies of off-prints will be supplied to the authors free of charge.

3. Manuscript for Review

Manuscripts for review need only to be typed legibly; preferably, double-spaced on only one side of the page with wide margins and submitted in duplicate.

The title should be brief. Except for short communications, descriptive heading should be used to divide the paper into its component parts. Use the International System of Units (SI).

References to published literature should be quoted in the text citing authors and the year of publication. These are to be grouped together at the end of the paper in alphabetical and chronological order. Journal references should be arranged as below. Titles for journal or book articles are helpful for readers, but may be omitted.


Abbreviations of journal titles should follow those used in the ASM Metals Abstracts. In every case, authors' initials, appropriate volume and page numbers should be included. The title of the cited journal reference is optional.

Illustrations and tables should be planned to fit a single column width (87 mm or 3.3”) or a double width (178 mm or 7”). For the reviewing processes, these need not be of high quality, but submit glossy prints or equivalent with the final manuscript. Lines and letters should be legible.

4. Review

All manuscripts will be judged by qualified reviewer(s). Each paper is reviewed by one of the editors and may be sent for review by members of the Editorial Board. The Board member may seek another independent review. In case of disputes, the author may request other reviewers.

5. Electronic Media

In order to minimize typographical error, the authors are encouraged to submit a floppy disk copy of the text. We can read Macintosh and IBM PC formats. Those who can connect to INTERNET can send the text portion to "ono@seas.ucla.edu". This will greatly shorten the time of communication.

6. Color Photograph

We can print color photographs needed to enhance the technical content of an article. Because of the cost, the author is asked to pay $350 per page.
# Contents

Proceedings of International Workshop at Schloss Ringberg

<table>
<thead>
<tr>
<th>Pages</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>i-iv</td>
<td>Materials Research with Advanced Acoustic Emission Techniques</td>
</tr>
<tr>
<td>v</td>
<td>Alexander Wanner and Michael R. Gorman, Topical Co-Editors</td>
</tr>
<tr>
<td></td>
<td>Friedrich Förster and Erich Scheil, Two Pioneers of Acoustic Emission</td>
</tr>
<tr>
<td></td>
<td>Alexander Wanner</td>
</tr>
<tr>
<td>vi-viii</td>
<td>Acoustic Investigation of Martensite Needle Formation by Fritz Förster and Erich Scheil, Translated by Peter G. Thwaite and Alexander Wanner</td>
</tr>
<tr>
<td>S1-S11</td>
<td>Advanced AE Techniques in Composite Materials Research</td>
</tr>
<tr>
<td>S12-S18</td>
<td>Digital Signal Processing of Modal Acoustic Emission Signals</td>
</tr>
<tr>
<td>S19-S46</td>
<td>Wave Theory of Acoustic Emission in Composite Laminates</td>
</tr>
<tr>
<td>S47-S60</td>
<td>Fiber Fragmentation and Acoustic Emission</td>
</tr>
<tr>
<td>S61-S73</td>
<td>Wave Propagation Effects Relative to AE Source Distinction of Wideband AE Signals from a Composite Pressure Vessel</td>
</tr>
<tr>
<td>S74-S87</td>
<td>Relative Moment Tensor Inversion Applied to Concrete Fracture Tests</td>
</tr>
<tr>
<td>S88-S101</td>
<td>Brittle Fracture as an Analog to Earthquakes: Can Acoustic Emission Be Used to Develop a Viable Prediction Strategy?</td>
</tr>
<tr>
<td>S102-S105</td>
<td>Abstracts of Talks Presented</td>
</tr>
</tbody>
</table>

## Conferences and Symposia

- 6th International Symp. on Acoustic Emission from Reinforced Composites
- 14th International Acoustic Emission Symposium and 5th Acoustic Emission World Meeting
- 40th Meeting of Acoustic Emission Working Group

## Available Books on AE

- Index to Vol. 14