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**Assessment of Impact Damage in
Kevlar®-Epoxy, Filament-Wound, Spherical Test Specimens
by Acoustic Emission Techniques**

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ABSTRACT

The results of a study of the acoustic emission (AE) behavior of impact-damaged, spherical, composite test specimens subjected to thermal cycling and biaxial mechanical loading are presented. Seven Kevlar®-epoxy, filament-wound, spherical composite test specimens were subjected to different levels of impact damage. The seven specimens were a subset of a group of 77 specimens made with simulated fabrication-induced flaws. The specimens were subjected to two or three cycles of elevated temperature and then hydraulically pressurized to failure. The pressurization regime consisted of two cycles to different intermediate levels with a hold at each peak pressure level; a final pressurization to failure followed. The thermal and pressurization cycles were carefully designed to stimulate AE production under defined conditions.

Both impacted and nonimpacted specimens produced thermo-AE (the term given to emission stimulated by thermal loading), but impacted specimens produced significantly more. Thermo-AE was produced primarily by damaged composite material. Damaged material produced emission as a function of both rising and falling temperature, but the effect was not repeatable. More seriously damaged specimens produced very large quantities of emission.

Use of multiple AE sensors enabled monitoring of different portions of the specimens during pressure loading. Emission sources were active at all monitored locations, but material damaged by impact produced significantly more emission. Specimen strength and AE Felicity Ratio (FR) decreased approximately linearly with impact damage level. Several alternative methods for determining FRs were examined; one method based on event rate provided the best correlations with specimen strength.

Emission recorded during the static portion of the hydraulic loading cycles varied with load, time, and degree of damage. Static load AE behavior was quantified using a newly developed concept, the event-rate moment, and various correlations with residual strength were attempted. Correlations between residual strength, long-duration events, and even-rate moments were developed with varying degrees of success.

1. INTRODUCTION

Composite structures and structural elements are being used increasingly in engineering applications because of their superior strength-to-weight characteristics. Because of the heterogeneous nature of composite materials in general and filament-based composites in particular, the mechanical behavior of a structure or component is more difficult to characterize than its metallic counterparts. One complicating factor is that unplanned perturbations in the manufacturing process can produce composite material with properties significantly different than planned. Even though a design remains constant, each individual unit that is produced should be considered unique because of the potential for anomalies. Nondestructive evaluation (NDE) technologies provide the most effective means of assessing the fitness for use of composite structures and components.

A study sponsored by the Oak Ridge Y-12 Plant¹ and jointly performed with Virginia Polytechnic Institute and State University and the University of Delaware evaluated the effect of manufacturing-type defects on the strength of filament-wound, spherical composite structures [1,2]. NDE technologies were evaluated for their effectiveness in defect detection and prediction of structure strength. Filament-wound, spherical specimens were used because they were representative of a broad class of true engineering structures and were relatively economical to make. By their design, they also provided nearly uniform biaxial loading during pressure testing. Defect types introduced were (1) simulated delamination, (2) simulated voids or inclusions, (3) low-fiber content, (4) variable fiber tension, (5) low-modulus fiber, and (6) dry (low-matrix content) fiber. The main study incorporated ten standard specimens (i.e., nominal design and construction) and ten specimens of each defect type. A small number of additional specimens of the same construction and flaw types were made at the same time and set aside for future use.

Impact damage played a minor, unintentional role in the study when several of the specimens were dropped during handling.

Acoustic emission (AE) was one of the NDE technologies evaluated in the study; other techniques were ultrasonics, acousto-ultrasonics, X-ray computed tomography, radiography, thermography, and optical stress coating. AE is produced in a composite by several mechanisms when the material is loaded. Factors affecting AE production include stress state, stress history, absence or presence of damage, time at load, time between loadings, friction between damage surfaces, etc. The initial goals of the AE portion of the work were to find some AE-based method for predicting specimen strength from a proof test [i.e., Felicity Ratio (FR) or other] and to evaluate the effects of manufacturing defects on AE response.

The initial portion of the study (10 standard specimens and 10 defective specimens, each containing one of the six defects; 70 specimens total) yielded the following conclusions [3,4]:

1. AE detection sensitivity was greater when specimens were hydraulically pressurized rather than pneumatically pressurized,
2. FR values decrease as time between pressurization cycles increases;
3. the simulated fabrication defects did not alter the specimens' failure strengths or affect the FRs calculated;
4. no correlations were found between FRs and specimen strength;

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5. FR values were dependent, to a minor degree, on the spool of fiber used; and
6. minor impact damage determined the physical location of failure but did not statistically degrade a specimen's strength.

When the effects of impact damage on specimen performance were discovered, a follow-on study was initiated with the goal of evaluating the AE and strength behavior of impact-damaged specimens under increasing and static load. The study used eight specimens, one of which was part of the original study. The other seven specimens (one standard specimen and one specimen each with the aforementioned defects) were made at the same time as the 70 specimens in the initial study but were not part of that study. The follow-on study also provided an opportunity to evaluate the use of AE monitoring during thermal cycling.

2. LITERATURE

Sato and his coworkers introduced the concept of thermo-AE as part of their studies of emission produced during thermal cycling of carbon-based composite materials [5,6]. They used mechanical loading (uniaxial tension, tension-tension fatigue, and bending) to induce damage. AE monitoring of samples cut from parent pieces was performed while the specimens were thermally cycled. Sato's studies revealed that undamaged composite (i.e., as fabricated) produced little emission and that damaged material produced much more emission. Thermo-AE was thought to be produced by friction between damage surfaces. The amount of AE produced was observed to be directly related to the stress level achieved or the number of fatigue cycles performed during the preceding mechanical loading.

Fowler and Gray [7] introduced the concept of the Felicity effect in 1979, and it has since found wide application in the composites/AE community. In essence, the effect describes the tendency of a composite structure or specimen to produce emission on the second and following load cycles at a lower (generally) load than the previously attained peak load. FR is the quantity (usually, but not always, <1) that "results when the load at which *significant* AE begins on a subsequent cycle is divided by the maximum load during the previous cycle" [8]. Hamstad identified a list of factors that influence AE behavior and, hence, FR calculation [9]; Table 1 contains a partial listing of these factors. No standard definition of *significant* AE exists. A working definition that is essentially dependent on the rate of emission upon re-initiation was developed as part of the initial study and will be used here [3].

Table 1. Factors that affect Felicity ratio behavior

1. Specimen or structure geometry
 2. Time at load
 3. Peak load as a proportion of failure strength
 4. Loading rate
 5. Construction materials
 6. Time between successive loading
 7. Number of load cycles
 8. Friction between damage surfaces
-

The literature contains many references to AE produced during static loading of composite coupons and structures. Jinen [10] studied creep-related damage progression in notched, carbon fiber-reinforced nylon specimens. He observed that the AE rate was directly related to crack growth rate. His specimens exhibited a generalized behavior in which emission rate was initially at a maximum when static loading began. The rate decreased with time until a generally constant, but low, rate occurred. Acceleration of the emission rate began immediately before failure.

McNally [11] described the AE response of composite rocket motor cases under static loading. When damage was distributed through the structure, additional damage tended to progress on a distributed, incremental basis, which enabled localized stress concentrations to be redistributed. Each damage increment produced bursts of emission. However, when motor case damage was concentrated, additional damage tended to occur at the concentration and to weaken the structure, ultimately leading to failure. The rate of emission produced by such damage progression increased until failure occurred.

Gorman and Rytting [12] studied AE produced by rocket motor cases in which delamination was the primary failure mode. Emission bursts produced by delamination exhibited durations that were generally an order of magnitude longer than other emission.

In a study of other composite rocket motor cases [13], Gorman introduced impact damage into cases after they were pressurized to ~80% of their expected failure strength. When the cases were repressurized and held at pressure, the damaged areas always produced more AE than did undamaged material.

3. EXPERIMENTAL

3.1 Test Design Philosophy

Evaluation of the thermo-AE response was performed after the specimens received impact damage but before pressure testing. AE monitoring of the specimens was performed during both heating and cooling to gather a more complete picture of their response to temperature gradients. All specimens received two cycles to the same temperature, and one specimen received a third cycle for a better assessment of repeatability. The maximum test temperature was selected to be below the epoxy glass transition temperature of 85°C.

The primary goals for the design of the pressure testing regime were as follows:

1. to enable determination of FRs,
2. to evaluate AE response during static loading,
3. to determine specimen failure strength, and
4. test all specimens consistently.

By definition, determination of FRs requires a minimum of two pressurization cycles. It was also desirable to evaluate specimen response at different static loads. Thus, in its simplest form, the pressure test regime required two pressurizations to different levels with holds at each peak pressure followed by depressurization. Pressurization to failure followed the intermediate pressurization cycles. Intermediate pressure levels of 62.0 and 78.6 MPa (47% and 60%, respectively, of the specimen design strength of 130.9 MPa) with 10-min holds at each level were selected. (See Fig. 1). A constant loading rate of 3.45 MPa/min was selected to avoid any loading-rate effects on AE production. Time between pressurization cycles was minimized to avoid the time-dependency of FRs discovered during the initial study [3]. Hydraulic pressurization was selected over pneumatic pressurization to minimize structural damage during failure and to maximize AE detection sensitivity [3].

Fig. 1 Pressure test sequence. AE monitoring periods denoted by 1, 2, 3, and 4.

3.2 Specimens

The specimens (Fig. 2) were composed of a spherical aluminum shell (114-mm OD, 2-mm wall thickness) fitted with a fill tube and then wrapped with epoxy-wetted Kevlar®-49 fiber. Specimen outer diameter was approximately 123 mm after winding. The nominal fiber content was 72.5% by volume. Seven of the specimens contained the various anomaly types used in the original study [1,2]. The effects of the anomalies will be ignored (except for the low-matrix-content specimen) for the reasons presented in Ref. 3. Seven specimens were dropped from different heights onto a hard surface to induce different degrees of impact damage. It was desirable for the impact-damaged area to be at the equators of the specimens; thus, the specimens were released so as to minimize specimen rotation. In all cases, impact occurred within 30° of the equator, but it was generally within 5°. The specimens, anomaly types, and absorbed impact damage (based upon specimen rebound heights as measured from a videotape recorded during impact) are summarized in Table 2.

Fig. 2 Specimen cross-section.

Table 2. Specimen summary

Specimen No.	3234	0779	0780	0781	0782	0783	0784	0785
Impact location (mm) ^a	0.0	-3.2	+6.4	+2.1	0.0	-26.8	-16.0	-4.3
Absorbed energy (J)	0.0	2.24	5.00	8.02	10.02	13.06	16.21	16.24
Residual strength (MPa)	138.5	128.2	124.0	87.0	115.8	97.1	103.4	83.4
Anomaly type ^b	L	A	K	D	S	M	DL	L

^a(+) = above equator (-) = below equator

^bL=low fiber winding tension A=alternate pattern K=Kevlar® 29

D=dry windings S=Standard M=macrospheres DL=delaminations

3.3 Apparatus

3.3.1 Thermo-AE Tests

The apparatus assembled for thermo-AE monitoring is shown in Fig. 3. Resonant AE sensors (PAC/Dunegan S-140A) were modified after the manner of Hamstad and Patterson [14] to increase their sensitivity. Three sensors were used to enable monitoring of different locations on a specimen. Sensor output was amplified 40 dB and bandpass-filtered (100 to 300 kHz) by preamplifiers (PAC 1220A). The analog section of a standard computer-based AE monitoring system (PAC 3000/3104)

provided additional amplification and filtering (~ 30 dB and 100 to 300kHz, respectively.) A hardware threshold of 0.2 V was selected for each channel of the 3104, giving an overall signal-detection threshold of ~ 34 dB (referenced to 80 dB = 1V). System deadtime was selected to be 100 μ s. A Hewlett-Packard 3400A Root-Mean-Squared (RMS) voltmeter was used to measure the RMS-voltage level of one channel of AE output. Its output was recorded by a Gould 2400 strip chart recorder.

Fig. 3 Experimental apparatus for thermo-AE tests.

Temperature was measured at three locations on the specimen (two externally on the equator and one internally) by chromel-alumel thermocouples. The externally mounted thermocouples were taped on, and the internally mounted thermocouple was inserted down the specimen fill tube and pressed in contact with the aluminum liner. The strip chart recorded the signal from one external thermocouple and the internally mounted thermocouple. The output of the remaining surface-mounted thermocouple was supplied to a digital temperature read-out device for visual observation. A manually adjusted voltage supply was used to input a signal proportional to specimen external temperature to the parametric input of the AE monitor. A computer-controlled oven was used to heat the specimen.

3.3.2 Pressure Testing

Pressure tests were performed with the specimen mounted in a holding fixture. It was supported only by a Teflon[®] clamp around the fill tube to ensure minimal contact with materials that might alter the AE response. Four S-140A sensors (modified in the same way as those used in the thermo-AE experiments) are spring-loaded in contact with the specimen surface. One sensor was located at the specimen equator within the damaged area; the remaining three sensors were located 90° from the first sensor on a great circle passing through the poles. This configuration was chosen to enable

broad coverage of the specimen and location of AE source events. Source location was discussed in a previous work [15] and will not be covered here. A lead break device was mounted on the fixture during system check and then removed. Pressurization was performed by a servo-controlled hydraulic pressurization system.

The pressurization and AE monitoring systems are shown schematically in Fig. 4. The same preamplifiers and computer-based AE monitor used in the thermo-AE experiments were used during the pressure tests. As in those experiments, preamplifier gain and filtering were set to 40 dB and 100 to 300 kHz. The analog section of the AE monitor provided an additional 20 dB gain and another stage of 100 to 300 kHz filtering. The monitor triggering threshold was set at 0.1 V. The combination of monitor gain and triggering threshold yielded an AE signal detection threshold of 40 dB (referenced to 80 dB = 1V). Monitor deadtime was set at 500 μ s. A signal proportional to pressure was recorded by the monitor's parametric sampling circuitry with a minimum resolution of 0.2 MPa.

Fig. 4 Experimental apparatus for AE monitoring of pressure tests.

3.4 Procedures

3.4.1 Thermo-AE Tests

A measured amount of acoustic couplant (Apiezon-M[®] vacuum grease) was applied to the face of each AE sensor using a syringe. The sensor was then mounted at the appropriate location on the specimen using tape. The Channel 1 sensor was mounted near the fill tube; the Channel 2 sensor was mounted on the equator 180° from the damage site; and the Channel 3 sensor was mounted on the

equator within the damaged region. The specimen was then placed in the computer-controlled oven supported by a Teflon® ring which provided thermal isolation from the oven floor. After all electrical connections were made, an AE system check was performed. Using a hand-held mechanical pencil, leads 0.3 mm diameter, 4 mm length, 2H lead, leads were broken on the specimen equator approximately equidistant from the three sensors. The system check was complete if all signal amplitudes which resulted were above an arbitrarily set level of 70 dB. The oven door was closed after the system check was completed. The oven heating rate was set at 7°C/min and the oven controller and AE monitor activated. The system check was heated until its surface temperature reached ~68°C at which time the oven controller was deactivated. The oven door was opened and the specimen allowed to cool until its internal temperature reached ~30°C. Maximum cooling rates achieved were ~86°/min externally and ~0.86°/min internally. The same thermal cycle was performed a second time for all specimens and a third time for one specimen to evaluate the repeatability of AE production. AE monitoring was performed on all cycles until it ceased (or nearly so).

3.4.2 Pressure Testing

The specimen was mounted in the fixture and positioned so that the damaged area was centered under the equatorial sensor (Channel 3). Apiezon-M® couplant was applied to all sensors using a syringe. The sensors were then spring-loaded into contact with the specimen surface and electrical connections were made. After connection to the hydraulic pressurization system, the specimen was backfilled with hydraulic fluid. Following preloading to 4.1 to 6.9 MPa, an AE system check was made using a lead break technique. The specimen was pressurized through the regime pictured in Fig. 1. Constant pressurization and depressurization rates of 3.45 MPa/min and 13.8 MPa/min, respectively, were used. Peak intermediate pressures of 62.0 and 78.5 MPa were achieved and each held for ten min. Time between pressure cycles was limited to five min. AE was monitored during periods 1 through 4 as indicated in the figure. The AE data were recorded into separate data files for each period to promote ease of analysis.

4. RESULTS AND DISCUSSION

4.1 Nondestructive Inspection

Surface photography and tangential radiography techniques were used to record damage indications; results are shown in Figs. 5 and 6. Visible surface indications (Fig. 5) include matrix cracks between fibers, a crack transverse to the fibers, and microbuckling (wavy, light-colored areas). Radiography (Fig. 6) revealed additional, subsurface damage modes: composite/liner disbonding, liner deformation, and delaminations. The following is proposed as a scenario for damage introduction. The composite shell is pushed inward during initial impact, loading the composite in biaxial compression, and producing fiber buckling. As loading continues, inner surface fibers are probably loaded in tension. As the specimen rebounds, the inner fibers are placed in compression until the composite buckles outward. Microbuckling is expected to result from compressive loading due to Kevlar®'s known poor resistance to compression [16]. Additional fiber weakening is expected to occur when the buckled fibers are loaded in tension. The delaminations were not expected to affect specimen strength because of the specimens' symmetric construction. They could, however, be a source of AE if they grow.

Fig. 5 Example of surface damage indications.

Fig. 6 Radiograph showing internal damage including delaminations, liner-composite disbonding, and liner plastic deformation.

4.2 Mechanical Behavior

The strength behavior of the impacted specimens is summarized in Fig. 7 where strength is plotted versus impact damage (i.e., absorbed energy, E). Lines representing the mean and lower 2-standard-deviation (2σ) bounds on strength of the original specimens [3] are shown for perspective. The failure strengths of 95% of the original specimens lie within the $\pm 2\sigma$ bounds. The results demonstrate that impact truly degraded specimen strength. The dry bands specimen [denoted by (D)] exhibited a much lower than expected strength. The lower epoxy content of that specimen provided less lateral support for the fibers during the compressive loading of impact which may have led to more extensive buckling and, thus, increased fiber damage.

All specimens failed in the impacted regions which were centered within 25° of the equator. Failure in unimpacted specimens was generally in the northern or southern polar regions [1]. The exception to this was the alternate pattern specimens which generally failed in the equatorial region due to liner ripping promoted by lower fiber thickness.

Fig. 7 Increased damage leads to decreased specimen strength. (See text for mean and 2σ values)

4.3 Acoustic Emission

4.3.1 Background

In composite materials, physical processes such as cracking, delamination growth, and friction produce the vibrational phenomenon known as AE. An "event" is the discrete physical occurrence which launches a packet of waves which propagate through the composite. Depending upon the strength of the source event and the media through which the waves travel, an individual wave packet may encounter none, one, some, or all the AE sensors in contact with the structure. When a wave packet encounters a sensor and produces an electrical output high enough in amplitude to trigger the AE instrumentation, a "hit" is said to have occurred. The hit(s) produced by a single physical event are ideally grouped together by the AE monitor and are collectively known as an AE event. Thus, there is a correspondence between a physical event and the response it induces in the AE instrumentation.

4.3.2 Thermo-AE

The overall AE behavior observed during the first heating cycles of three specimens (damaged and undamaged) is shown in Fig. 8. Included are all AE events with amplitudes ≥ 38 dB detected by all three channels. From this, we conclude that all specimens produce thermo-AE. Potential sources are matrix microcracking and/or rubbing of existing damage surfaces caused by differential thermal expansion.

Fig. 8 First heating cycle thermo-AE for 3 specimens. Higher AE rates were produced by the moderately damaged specimen. (Damage levels: a. 0; b. 2.24J; c. 13.06J)

The wave velocity in these structures is constant and independent of propagation direction [15]. Thus, the sensor, which is first hit by a wave packet from a source event, is closest to the physical location of the event. If the recorded AE events are sorted on the basis of which sensor was first hit, a crude determination of the location of the source events can be made (first hit analysis). When this was done with the event data shown in Fig. 8, the results in Fig. 9 occur. First hit AE was detected by all channels which implies that AE sources occurred throughout the specimens. Looking only at the results from impacted specimens (Fig. 9 b,c), the number of events produced by impacted material (Channel 3) is ~50% greater than that produced by unimpacted material (Channels 1 and 2).

Undamaged and damaged specimens produce AE. Within an individual specimen, undamaged and damaged material produces AE, but the damaged material produces more. Specimens with greater impact damage produce significantly more emission, sometimes so much that the event detection hardware in the AE monitor was unable to accurately measure the event rate. However, a reasonable measure of the threshold crossings [i.e., individual voltage excursions (+ or -) known as counts] could be made for each channel. An example of count rate data from damaged composite (Channel 3) for three thermal cycles of a moderately damaged specimen is shown in Fig. 10. Emission is produced during all heating and cooling portions of the cycles. A comparison between count rate data from undamaged and damaged material for the three cycles was made. It revealed that emission from undamaged material was produced during all heating cycles, but at decreasing

rates on succeeding cycles. Little to no emission was produced by undamaged material during cooling. In contrast, damaged material produced vast quantities of AE in the heating and cooling portions of the cycles, but the rates were not repeatable.

Fig. 9 A comparison of the origin of first cycle thermo-AE shows that most originates in damaged material (i.e. near sensor 3). (Damage levels same as in Fig. 8)

Taken together, the data imply that AE monitoring during thermal cycling of composite structures, such as these, can provide valuable insight into whether the structure has been damaged by impact and, if damaged, where the damage is located.

Fig. 10 The nonrepeatability of damage-related thermo-AE activity is revealed by its count rate behavior over multiple thermal cycles. (a. Cycle 1; b. Cycle 2; c. Cycle 3)

4.3.3 Rising Load AE

First hit analysis was a valuable tool for evaluating the emission produced during the rising load portions of the hydraulic pressurization cycles (Fig. 1) also. When the data were sorted on a first-hit-channel basis, more emission was always detected by Channel 3 (sensor located within the damaged area) than by any other channel. This is comparable to Gorman's results in Ref. 13. During the second pressurization cycle of Specimen No. 0784, for example, 54% of the first hits were detected by Channel 3 and 23, 17, and 6% of first hits were detected by Channels 1, 2, and 4, respectively. The conclusion is damaged material produced more AE during loading than did undamaged material and, thus, more damage *growth* occurred in the impacted area than in undamaged material.

Event rate format is used in Fig. 11 to summarize typical rising load AE behavior. Emission was not recorded during loading on the first cycle because experience has shown that such emission is primarily from benign sources. Emission from damaged regions is present, but it generally cannot be sorted from the rest. The lightly-shaded bars represent emission from the second loading and the black bars from the third loading. In each case, the AE rate is observed to accelerate as the previous peak pressure ($P_1 = 62.0$ MPa and $P_2 = 78.5$ MPa for the first and second cycles, respectively) approaches. The Felicity effect is in evidence because AE reinitiates before the previous peak pressure is achieved. Using the Sustained Emission definition of *significant emission* introduced in Ref. 3 (continuing occurrence of emission with maximum intervals between events of 0.83 MPa, noted by P_{AE} in Fig. 11), FRs were calculated for the second and third loading cycles. This method utilized all first hits from all channels.

Fig. 11 Typical pressure test event rate data used for FR calculation. Previous peak pressures, P_1 and P_2 and P_{ae} for FR calculation are shown. (Specimen 0783)

FR values from the second loading cycle (FR_2) are plotted against impact damage level in Fig. 12. The linear decrease in FR with damage level demonstrates that the FR is a good indicator of the damage level in this type structure.

Fig. 12 As damage increases, FR values decrease. (Second cycle data)

FRs resulting from pressurization cycles 2 and 3 are plotted against failure strength in Fig. 13. In each case, there is an approximately linear relationship between FR and strength. Using this type relationship, periodic proof tests could be used to predict residual strength trends of similar vessels. The slope of the $FR_3 - P_f$ line is lower than that of the $FR_2 - P_f$ line; thus, on the third cycle, the FR is a less sensitive predictor of strength. This is evidence of the FR's sensitivity to prior load history.

The data point representing the dry-bands specimen (S/N 0784) is an outlier in Figs. 7 and 13. The specimen failed at a lower strength than would have been predicted by the relationship in Fig. 7. The low matrix content increased the effect of impact damage on specimen strength. A potential reason for this is the lower epoxy content provided less lateral support to the fibers during impact loading allowing more buckling to occur and, consequently, more fiber weakening. The higher than predicted FR (Fig. 13) can be explained as follows. Any AE produced in the damaged area will be attenuated to a greater degree as it propagates through the dry bands. This results in detection of only the higher amplitude (and, thus, fewer) AE events which causes sustained emission to be achieved at a higher pressure. A higher FR then results.

In this experiment, the site of the damage is known *a priori* and detection of AE originating there was optimized by positioning a sensor in the damaged region. How effective would the FR technique be if it was not known whether damage existed or where the damaged location was, if it existed? The rising load AE data can be manipulated to give answers to those questions. We can ensure that we are examining AE which originates in the damaged material by limiting the data to events which hit Channel 3 first. By further filtering the events to select only the ones which *also* hit at least one of Channels 1, 2, and 4, we ensure that the emission is detected at a distance from the damage site. This filtering scheme was performed on the rising load AE data and FRs determined from the resulting data.

Fig. 13 Decreasing strength leads to lower FRs on the second and third pressurization cycles.

FRs determined from all events which hit Channel 3 first are plotted against failure strength in Fig. 14a; as in Fig. 13, approximately linear relationships result for cycles 2 and 3. (The dry bands specimen is omitted from the cycle 3 relationship.) The sensitivity of the FR technique increased for the cycle 3 data as evidenced by the increased slope of the FR_3 - P_f relationship. In the circumstance where the location of damage is not known, FR analysis may be beneficial when based on data from the most active channel since it most likely is nearest the damage site(s). FRs determined from events originating in the damage site, but detected remotely from it, are plotted against failure strength in Fig. 14b. Linear relationships are again in evidence, but, in this case, are essentially the same for both cycles. (Again, the dry bands specimen is omitted from the cycle 3 relationship.) Sensitivity demonstrated by the cycle 2 results is lower than in Fig. 13; but, taken as a whole, the data demonstrate that meaningful FR results can be had when the damage site (if one exists) is not known before testing.

Additional analysis was performed on the data using alternative definitions of significant emission based on cumulative events, event energy, and cumulative event durations. Results were mixed and the reader is referred to Ref. 4 for a further review of them.

4.3.4 Static Load AE

The static load AE behavior described is limited to that recorded during the second static load period (78.6 MPa, or 59% of the mean failure strength of unimpacted specimens) of the tests. The first hit and remote hit techniques described in sections 4.3.2 and 4.3.3 were utilized during static load AE analysis. In the following discussion and associated figures, "residual strength" should be considered as identical to "strength" used in the preceding discussion. Typical AE behavior from undamaged, slightly damaged, and heavily damaged material can be observed in Fig. 15. The figure

Fig. 15 Static pressure loading AE behavior is affected by presence and level of pre-existing damage.

includes event rates detected by Sensors 1 (undamaged material) and 3 (damaged material) on a lightly damaged specimen (2.24 J) and a heavily damaged specimen (16.24J) one. Undamaged material, in both cases, produced an initial relatively high event rate which progressively decreased until the end of the hold when only random events occurred. This behavior is typical of loaded material progressing toward a stable state and is similar to that observed in Refs. 10 and 11. Lightly damaged material (2.24 J, Sensor 3) AE behavior is similar, except the event rates are much higher initially and slightly higher at the end of the hold. The difference in event rates between Sensor 1 output and Sensor 3 output is the contribution caused by progression of damage in the impacted area.

The event rate produced by heavily damaged material (16.24 J, Sensor 3) is initially of the same level as that produced by the lightly damaged material. This all changes at approximately 120 s into the hold when very large and unstable event rates (as high as 80 s^{-1}) appeared. The large event rates and their instability imply that significant damage progression is occurring. Supporting this conclusion is the fact that this specimen failed at only ~60% of the design strength.

Visual differentiation between the behaviors recorded in Figs. 15 a and b is easy, but the differences are not so easily discerned with less damaged specimens. A numerical means to quantify the event rate behavior, known as the event rate moment, was presented in Ref. 17. It is defined as the summation, over a period of static load, of the quantities produced by multiplying the number of first hits detected by a designated sensor during a fixed time interval by the time elapsed from initiation of the static load. To accommodate the large range of event rates observed, the cumulative event-rate moment was normalized by dividing by the event summation over the same period. Thus, for sensor X first hits, the normalized cumulative event-rate moment becomes:

$$M_X = \frac{\sum_{i=1}^n t_i N_i}{\sum_{i=1}^n N_i} \quad \text{Eq. 1}$$

Over a 10 min hold, and using a 1 s counting interval, $n = 600$. To a first approximation, the effect of impact-damage related AE can be isolated by subtracting M_1 for the undamaged specimen (S/N 3234) from M_3 for a damaged specimen. When this was done as a function of time for all the damaged specimens, the results in Fig. 16 were obtained. Positive differences occurred when the value for the damaged specimen was greater; this occurred on Specimens 0780, 0781, 0784, and 0785 which were also the ones which exhibited unstable rate behavior. Specimens 0779 and 0782 exhibited stable rate behavior and, thus, a generally negative-trending difference. Because of a single instability, the difference for Specimen 0783 was initially positive, but it was rapidly decreasing as the hold closed.

Correlations between the normalized moment and specimen strength were sought to validate the usefulness of the normalized moment technique. Since several of the holds were terminated early, it wasn't possible to use the full 10 min hold period. Instead, the normalized moments were determined for two periods, i.e., 0 to 6 min and 0 to 9 min, and the results plotted against strength in Fig. 17. The results are divided into two general groupings in each time period. Specimens exhibiting stable event rate behavior compose the lower group and have M_3 values consistently below 105 s for the shorter monitoring period and 125 s for the longer monitoring period. The lower

Fig. 16 The difference between stable and unstable AE behavior can be quantified by use of the normalized cumulative event rate moment technique during static loading.

groupings show only slight correlations between M_3 and strength. Specimens exhibiting unstable rate behavior produced the results in the upper groupings; they can be correlated with strength. The longer hold period produced larger M_3 values and, consequently, a stronger correlation. Thus, the normalized event rate moment technique can distinguish between specimens exhibiting stable and unstable rate behavior and for the latter can provide a prediction of strength trends.

Fig. 17 Stable and unstable AE rate behavior can be separated by use of the Normalized Cumulative Moment. Correlations improve with length of hold.

Distributions of event durations for first hits were obtained; representative Channel 3 first hit data are shown in Fig. 18. Once again, the 0 to 2 min and 2 to 6 min time periods were used. Duration scales were limited to $2000\ \mu\text{s}$ for convenience, although durations as long as $40,000\ \mu\text{s}$ occurred. The distributions in Fig. 18a demonstrate that, during the first two minutes of a hold, the durations of both undamaged and damaged specimens were in approximately the same range, generally $\leq 1000\ \mu\text{s}$. However, later in the hold, the damaged specimens produced many events with durations $\geq 1000\ \mu\text{s}$, while the undamaged specimen produced very few. Using the approach of Gorman and Rytting [12], the events with durations $\geq 1000\ \mu\text{s}$ were termed Long Duration Events (LDE). The LDEs in the longer time frame were totaled for each specimen and plotted against strength in Fig. 19. Once again, a segregation between stable and unstable behavior is evident. Stable specimens always produced fewer than ten LDEs, while unstable specimens always produced more than ten LDEs. A strong relationship between LDE total and strength exists for the unstable specimens. The dry bands specimen is again an outlier. In this case, the interaction of damage and dry bands changes the character (duration) of the emission.

Fig. 18 The occurrence of longer duration events increased with hold length and damage level.
(a. 0-2 min; b. 2-6 min)

Fig. 19 Total static pressure LDE correlates with residual strength for specimens exhibiting unstable rate behavior.

5. CONCLUSIONS

An extensive series of experiments was performed on impact-damaged spherical composite test specimens. The overarching goals of the work were to evaluate the AE response of the specimens under a variety of loads and establish, if possible, correlations between the emission and strength of the specimens. These goals were more than sufficiently met. The primary conclusions of the work are:

1. Damage modes induced in composite structures subjected to localized impact loading include cracks, fiber buckling, composite/liner disbonding, delaminations, and liner deformation. Specimen strength decreased linearly with an increase in the amount of energy absorbed during impact. Ultimate failure always occurred at the site of impact.
2. When thermally cycled, both undamaged and damaged composite material produced thermo-AE, but damaged material produced ~50% more. More heavily damaged material produced more AE than less heavily damaged material. Damaged material produced AE during heating and cooling portions of all thermal cycles, but the effect was not repeatable.

3. In a similar manner, when damaged specimens were subjected to biaxial loading (i.e., pressurization) both undamaged and damaged material produced AE and damaged material produced significantly more AE than did undamaged material. AE was produced in response to rising load on each loading cycle. However, emission always reinitiated at a load lower than that reached on the immediately preceding cycle which is evidence that the Felicity effect was active. FRs were calculated from the various loading cycles. Linear relationships were developed between FR values and impact damage level and failure strength, P_f . The sensitivity of the FR - P_f relationship was affected by separation between the damage site and the receiving sensor.
4. AE was also produced during static loading. Once again, damaged material produced more emission than did undamaged material and more severely damaged specimens produced more emission. More severely damaged specimens produced very high and widely varying event rates when held under static load. A quantity known as the normalized event-rate moment was used to quantify the static load event-rate behavior. For specimens exhibiting unstable event-rate behavior, the normalized event rate moment was inversely related to failure strength. A correlation between failure strength and total long duration events was also developed for those specimens.

6. REFERENCES

1. Brosey, W. D., M. T. Calfee, J. W. Whittaker, D. A. Waldrop, E. G. Henneke, D. Post, K. L. Reifsnider, and R. A. Blake. "Evaluation of Nondestructive Evaluation Techniques for Determination of Flawed Conditions and the Effects of Flaws on the Burst Pressure in Kevlar-Epoxy Filament-Wound Spherical Test Specimens," Report No. Y-2428, Dec. 1989, Oak Ridge Y-12 Plant, Martin Marietta Energy Systems, Inc., Oak Ridge, TN.
2. Brosey, W. D., M. T. Calfee, J. W. Whittaker, E. G. Henneke, II, D. Post, K. L. Reifsnider, and R. A. Blake. "Nondestructive Evaluation Performance in Predicting Failure Strength of Spherical Composite Specimens with Implanted Flaws," *Materials Evaluation*, Vol. 48, No. 3, Sept. 1990, pp 1090-1095.
3. Whittaker, J. W., W. D. Brosey, and M. A. Hamstad. "Felicity Ratio Behavior of Pneumatically and Hydraulically Loaded Spherical Composite Test Specimens," *Journal of Acoustic Emission*, Vol. 9, No. 2, 1990, pp 75-83.
4. Whittaker, J. W., W. D. Brosey, and M. A. Hamstad. "Correlation of Felicity Ratio and Strength Behavior of Impact-Damaged Spherical Composite Test Specimens," *Journal of Acoustic Emission*, Vol. 9, No. 2, 1990, pp 84-90.
5. Sato, N., T. Kurauchi, and O. Kamigato. "Detection of Damage in Composite Materials by Thermo-Acoustic Emission Technique," *Progress in Acoustic Emission III*, 1986, pp 620-629.
6. Sato, N., T. Kurauchi, and O. Kamigato. "Thermo-Acoustic Emission from Damaged Composite," *SAMPE Journal*, Vol. 23, Sept.-Oct., 1987, pp 48-52.

7. Fowler, T. J. and E. Gray. "Development of an Acoustic Emission Test for FRP Equipment," Preprint 3583, American Society of Civil Engineers, New York; presented at the ASCE Convention, Boston, MA (April. 2-6, 1979).
8. Hamstad, M. A. "Quality Control and Nondestructive Evaluation Techniques for Composites - Part VI: Acoustic Emission - A State-of-the-Art Review," AVRADCOM Report No. TR 83-F-7, University of Denver, Department of Physics, Denver, CO (1983).
9. Hamstad, M. A. "A Discussion of the Basic Understanding of the Felicity Effect In Fiber Composites," *Journal of Acoustic Emission*, Vol. 5, No. 2, 1986, pp 95-102.
10. Jinen, E. "Acoustic Emission of Single Notched Short Carbon Fiber Reinforced Nylon 6 (FRPT) under Constant Tensile Load," *Engineering Fracture Mechanics*, Vol. 21, No. 1, 1985, pp 49-61.
11. McNally, D. J., "Inspection of Composite Rocket Motor Case Using Acoustic Emission," *Materials Evaluation*, Vol. 43, No. 5, 1985, pp 728-739.
12. Gorman, M. R. and T. H. Rytting, "Long Duration AE Events in Filament Wound Graphite/Epoxy in the 100-300 KHz Bandpass Region," *Proceedings, First International Symposium on Acoustic Emission from Reinforced Composites, San Francisco, CA, July 19 -21, 1983*. New York: Society of the Plastics Industry, Inc.
13. Gorman, M. R., "Burst Prediction by Acoustic Emission in Filament-Wound Pressure Vessels," *Journal of Acoustic Emission*, Vol. 9, No. 2, 1990, pp 131-139.
14. Hamstad, M. A., and R. G. Patterson, "Considerations for Acoustic Emission Monitoring of Spherical Kevlar/Epoxy Composite Pressure Vessels", in *Composites in Pressure Vessels and Piping*, ASME Publication PVP-PB-021, American Society of Mechanical Engineers, New York, 1977, pp 141-163.
15. Whittaker, J. W., W. D. Brosey, O. Burenko, and D. A. Waldrop, "Acoustic Emission Propagation and Source Location in Small, Spherical Composite Test Specimens," *Journal of Acoustic Emission*, Vol. 7, No. 1, 1988, pp 31-40.
16. Dostal, C. A., Editor, *Engineered Materials Handbook, Volume 1: Composites*, Section 4, ASM International, Metals Park, Ohio, 1987, pp 196-198.
17. Hamstad, M. A., J. W. Whittaker, and W. D. Brosey, "Correlation of Residual Strength with Acoustic Emission from Impact-Damaged Composite Structures under Constant Biaxial Load," *Journal of Composite Materials*, Vol. 26, No. 15, 1992, pp 2307-2328.

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