Standard Practice for
Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Applications[1]

1. Scope*

1.1 This practice covers acoustic emission (AE) examination or monitoring of panel and plate-like composite structures made entirely of fiber/polymer composites.

1.2 The AE examination detects emission sources and locates the region(s) within the composite structure where the emission originated. When properly developed AE-based criteria for the composite item are in place, the AE data can be used for nondestructive examination (NDE), characterization of proof testing, documentation of quality control or for decisions relative to structural-test termination prior to completion of a planned test. Other NDE methods may be used to provide additional information about located damage regions. For additional information see X1.1 in Appendix X1.

1.3 This practice can be applied to aerospace composite panels and plate-like elements as a part of incoming inspection, during manufacturing, after assembly, continuously (during structural health monitoring) and at periodic intervals during the life of a structure.

1.4 This practice is meant for fiber orientations that include cross-plies, angle-ply laminates or two-dimensional woven fabrics. This practice also applies to 3-D reinforcement (for example, stitched, z-pinned) when the fiber content in the third direction is less than 5 % (based on the whole composite).

1.5 This practice is directed toward composite materials that typically contain continuous high modulus greater than 20 GPa [3 Msi] fibers.

1.6 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E543 Specification for Agencies Performing Nondestructive Testing
E976 Guide for Determining the Reproducibility of Acoustic Emission Sensor Response
E1067 Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels
E1106 Test Method for Primary Calibration of Acoustic Emission Sensors
E1316 Terminology for Nondestructive Examinations
E1781 Practice for Secondary Calibration of Acoustic Emission Sensors
E2533 Guide for Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications

2.2 *Other Documents:*

ANSI/ASNT CP-189 ASNT Standard for Qualification and Certification of Nondestructive Testing Personnel[3]
ISO 9712 Non-destructive Testing—Qualification and Certification of NDT Personnel[4]
NAS-410 NAS Certification and Qualification of Nondestructive Personnel (Quality Assurance Committee)[5]
SNT-TC-1A Recommended for Personnel Qualification and Certification of Nondestructive Testing Personnel[3]

3. Terminology

3.1 *Definitions*—See Terminology E1316 for general terminology applicable to this practice.

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[1] This practice is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.04 on Acoustic Emission Method.

Current edition approved June 1, 2015. Published July 2015. Originally approved in 2010. Last previous edition approved in 2010 as E2661/E2661M-10. DOI:10.1520/E2661_E1661M-15.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Ln., Columbus, OH 43228-0518, http://www.asnt.org.

[4] Available from International Organization for Standardization (ISO), 1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, http://www.iso.org.

[5] Available from Aerospace Industries Association of America, Inc., 1250 Eye St., NW, Washington, DC 20005.

***A Summary of Changes section appears at the end of this standard**

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *characteristic damage state*—transverse matrix cracking during the virgin loading of a composite; often resulting in reaching a limit of the crack density prior to reaching failure. Results in a reduction of stiffness of the composite. For additional information see X1.2.

3.2.2 *flat panel composite*—any fiber reinforced composite lay-up consisting of laminas (plies) with one or more orientations with respect to some reference direction that result in a two-dimensionally flat article of finite thickness (typically relatively thin).

3.2.3 *plate-like composite*—any fiber-reinforced composite lay-up consisting of laminas (plies), which is not strictly flat, but for purposes of the AE examination, can be considered as a two-dimensional (2-D) structural plate for wave propagation and for location of the region of AE source origin. Applies for a minimum radius of curvature of greater than about 2 m (6 ft), so curvature does not change group velocities.

3.2.4 *quasi-isotropic lay-up*—a plate where the group velocities of both the fundamental modes have been shown to be independent of propagation direction. For example: $[+45/-45/0/90]_s$[6].

3.2.5 *wideband AE sensors*—wideband (broadband) AE sensors, when calibrated according to E1106 or E1781, exhibit displacement or velocity response over several hundred kHz with a coefficient of variation of the response in dBs that does not exceed 10 %.

3.2.6 *wideband-based (modal) AE techniques*—AE techniques with wideband AE sensors that subject waveforms of the signals to combined time and frequency analysis to obtain mode-based arrival times (for source location calculations) and modal amplitudes for potential source identification. Note that mode-based arrival times can also be obtained with resonant sensors, but only at certain experimentally determined frequencies.

4. Summary of Practice

4.1 This practice consists of subjecting flat composite panels or plate-like composite structures to loading or stressing while monitoring with sensors that are sensitive to AE (transient displacement waves) caused by the creation of microdamage, growing flaws and friction-based sources. For additional information see X1.3.

4.2 This practice provides an approach to determine the local regions of origin of the AE sources and any potential local regions of large accumulation(s) of AE sources.

4.3 This practice can provide an approach to use AE-based criteria to determine the significance of flaws.

5. Significance and Use

5.1 This AE examination is useful to detect micro-damage generation, accumulation and growth of new or existing flaws. The examination is also used to detect significant existing damage from friction-based AE generated during loading or unloading of these regions. The damage mechanisms that can be detected include matrix cracking, fiber splitting, fiber breakage, fiber pull-out, debonding and delamination. During loading, unloading and load holding, damage that does not emit AE energy will not be detected.

5.2 When the detected signals from AE sources are sufficiently spaced in time so as not to be classified as continuous AE, this practice is useful to locate the region(s) of the 2-D test sample where these sources originated and the accumulation of these sources with changing load and/or time.

5.3 The probability of detection of the potential AE sources depends on the nature of the damage mechanisms, flaw characteristics and other aspects. For additional information see X1.4.

5.4 Concentrated damage in fiber/polymer composites can lead to premature failure of the composite item. Hence, the use of AE to detect and locate such damage is particularly important.

5.5 AE-detected flaws or damage concentrated in a certain region may be further characterized by other NDE techniques (for example, visual, ultrasonic, etc.) and may be repaired as appropriate. Repair procedure recommendations and the subsequent examination of the repair are outside the scope of this practice. For additional information see X1.5.

5.6 This practice does not address sandwich core, foam core or honeycomb core plate-like composites due to the fact that currently there is little in the way of published work on the subject resulting in a lack of a sufficient knowledge base.

5.7 Refer to Guide E2533 for additional information about types of defects detected by AE, general overview of AE as applied to polymer matrix composites, discussion of the Felicity ratio (FR) and Kaiser effect, advantages and limitations, AE of composite parts other than flat panels, and safety hazards.

6. Basis of Application—Personnel Qualification—Contractual Agreement

6.1 The following items are subject to contractual agreement between the parties using or referencing this practice.

6.2 *Personnel Qualification*—Unless contractually agreed otherwise, personnel performing examinations to this practice shall be qualified in accordance with a nationally or internationally recognized NDT personnel qualification practice or standard such as ANSI/ASNT-CP-189, SNT-TC-1A, NAS-410, ISO 9712, or a similar document. They shall be certified by the employer or certifying agency, as applicable. The practice or standard used and its applicable revision shall be identified in the contractual agreement between the using parties.

6.3 *Qualification of Nondestructive Agencies*—Unless contractually agreed otherwise, NDT agencies shall be qualified and evaluated as described in E543. The applicable edition of E543 shall be specified in the contractual agreement.

6.4 *Procedure and Techniques*—The procedures and techniques to be utilized shall be as specified in the contractual

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[6] Lei Wang, F.G. Yuan, "Group velocity and characteristic wave curves of Lamb waves in composites: Modeling and experiments," Composites Science and Technology 67 (2007) 1370–1384.

agreement. In particular, the contractual agreement should state whether full monitoring of the test sample is required or if only partial monitoring of certain expected critical areas is required.

6.5 *Timing of Examination*—The timing of examination shall be in accordance with 1.3, unless otherwise specified.

6.6 *Reporting Criteria*—Reporting criteria for the examination results shall be in accordance with Section 12, unless otherwise specified.

7. Apparatus

7.1 Refer to Fig. 1 for a typical AE system block diagram showing key components.

7.2 *AE Sensors:*

7.2.1 The selection of a wideband or resonant sensor is described here. For information on the frequency content of AE waves see X1.6. For a scientific method to select sensors whose best frequency response corresponds to the frequency range of the highest amplitudes of the AE waves see X1.7.

7.2.1.1 Wideband sensors can be used along with waveform recording to enhance AE data analysis by the application of wideband-based AE techniques. A wideband sensor should be chosen with relatively flat response (E1106 or E1781) from about 50 kHz to 400 kHz. For additional information see X1.7 for plates less than 2-mm thick and X1.8.

7.2.1.2 If resonant sensors are used, the best choice is a sensor with its primary resonance in the lower portion of a 50 kHz to 400 kHz frequency band. Sensors with a lower frequency resonance of about 25 kHz to 50 kHz can be used to increase sensor spacing (for example when a limited number of AE channels are available [see E1067]) in AE testing of composites, but such sensors increase the likelihood that unwanted extraneous noise will be recorded. To minimize the effects of airborne noise the lower resonant-frequency sensors can be wrapped with sound absorbing material.

7.2.2 Sensors should be shielded against electromagnetic interference (EMI) through proper design practice or differential (anti-coincidence) element design, or both.

7.2.3 Sensors should have omni-directional response, with directional variations not exceeding 4 dB from the average peak response of the set of sensors.

7.3 *Sensor Couplant:*

7.3.1 The sensors must be acoustically coupled (to remove air from between the sensor face and the composite surface) directly to the test sample. Commercially available couplants for ultrasonic flaw detection may be used. Silicone-based high-vacuum grease has been found to be particularly suitable, but it may not be desirable for all test locations and all test samples. Adhesives may also be used. Note: the sensor attachment procedure as well as the couplant or adhesive may require approval prior to sensor installation due to special requirements for materials placed in contact with composite structures (compatibility and/or contamination control).

7.3.2 Couplant selection should be made to minimize changes (for example, drying out of the couplant or movement of the couplant due to gravity over the range of test temperatures and test time duration) in coupling sensitivity during a complete examination.

7.4 *Sensor Attachment Apparatus:*

7.4.1 *Adhesives*—Various adhesives can be used to attach sensors and provide acoustic coupling. The bond line created

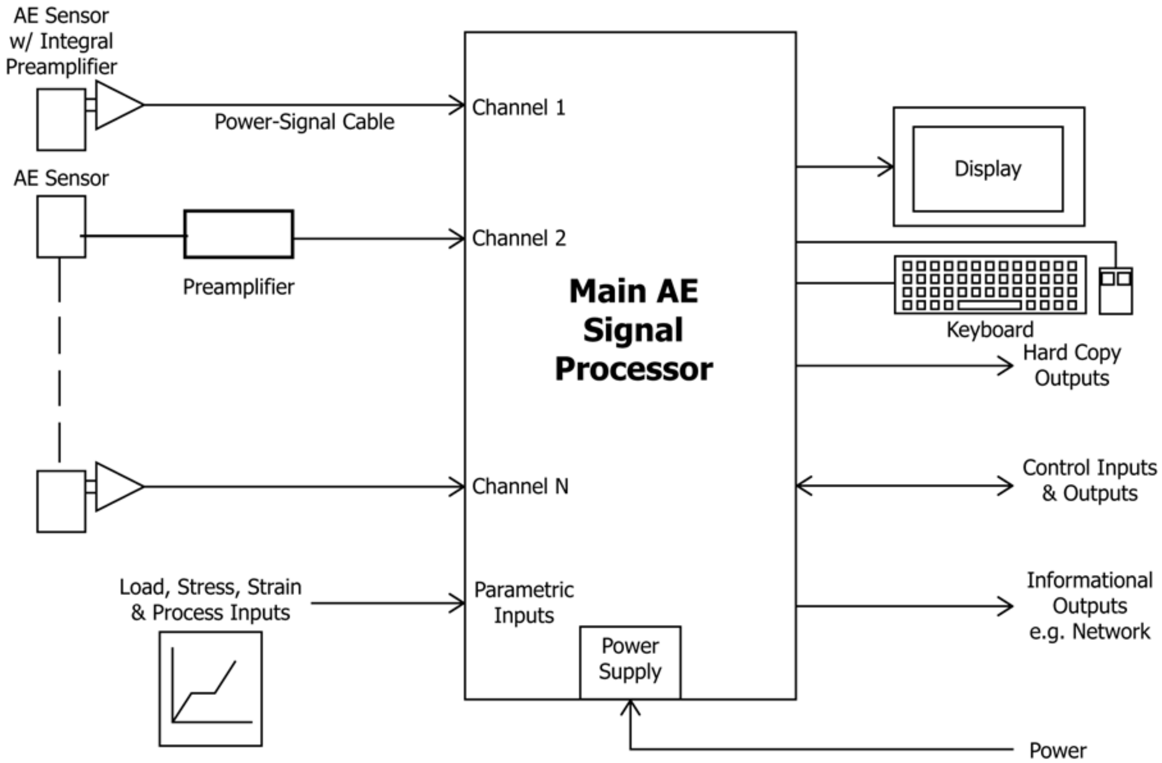

FIG. 1 AE System Block Diagram

by the adhesive must be much thinner than the shortest wavelengths of interest. Adhesives such as two-part epoxies, silicone adhesives, and cyanoacrylates have been successfully used for attaching sensors. Sensors attached with some adhesives can be difficult to remove without damaging the sensor or the examination sample. Also, due to the larger design deformations of composite materials (relative to metals designed to operate in their elastic range), adhesively bonded sensors may debond during test sample stressing or during thermal cycling of the test sample.

7.4.2 *Tape*—Elastic adhesive tapes have been successfully used for mounting transducers (for example, taping the sensors to one side of a large composite panel).

7.4.3 *Elastic Bands*—An elastic band (for example, rubber bands) can be placed over the sensor and anchored to the test sample to hold sensors in place.

7.4.4 *Spring Loaded*—Sensors may be spring loaded against the test sample by fixturing (that does not generate extraneous noise during testing). Such mounting must be able to accommodate the deformation of the test sample without losing acoustic coupling.

7.4.5 It is generally unacceptable to modify a composite by machining a "flat" to mount a sensor (creates potential damage). Thus, with surfaces that are rough, or have curvature, or both, it is typical that the sensors will have less sensitivity than when they are mounted on flat and smooth surfaces.

7.4.6 This practice does not address the use of waveguides for fiber/polymer composites.

7.5 *System Cabling:*

7.5.1 *Sensor Cable*—AE systems typically use a standard low noise shielded coaxial cable that is not susceptible to triboelectric noise (from mechanical movement of the cable) for this connection, due to its ability to shield the low level signal out of the sensor from electromagnetic interference. The cable should be kept short, 1-2 m [3-6 ft], to reduce attenuation of the signal, to reduce the length of cable possibly exposed to electromagnetic interference and to create the best signal-to-noise ratios. If it is absolutely necessary to use a longer length during testing, the effect of the longer length on the attenuation of signal amplitudes should be evaluated (for example, by PLBs with a short cable length versus the longer length). If the loss is greater than 6 dB, the measured loss should be compared to the signal amplitudes obtained during pre-testing to conclude whether the loss is acceptable. Note that integral preamplifier sensors eliminate issues resulting from sensor cables, but in some approaches such sensors increase the size and mass of the sensors and impact the mounting of this type of sensor.

7.5.2 *Power-Signal Cable*—The cable and connectors that provide power to the preamplifiers and conduct the preamp-amplified signals to the main processor shall be shielded against electromagnetic interference. The typical standard coaxial cabling used in AE testing is RG-58 at about 50 Ω impedance. Dual and quad shielded cable is also available to improve noise rejection in particularly noisy (electromagnetic) environments. When RG-58 is used, the maximum recommended length is 330 m [1000 ft] to avoid excessive signal attenuation. Smaller diameter cables, RG-174 (50 Ω impedance), can be used if the cable diameter is a concern for a bundle of cables, but the effects of possible EMI from external sources and cross talk between cables must be accounted for. Some systems may use 75 Ω coax cables such as RG-59. In all cases, the operator should follow the AE equipment manufacturer's recommendations.

7.6 *Preamplifier:*

7.6.1 The preamplifier converts the high impedance signal from the sensor to a low impedance signal and amplifies the signals to acceptable levels to allow the signal to be transmitted over longer distances of cable. The preamplifier also reduces the sensitivity to extraneous electromagnetic signals in the power-signal cable.

7.6.2 Integral preamplifiers (within the sensor case) reduce the sensitivity to extraneous electrical noise, and they perform as stated in 7.6.1.

7.6.3 The preamplifier should include a filter with a bandwidth that includes the useable frequency range of the sensors being used. Typically a filter bandwidth of 50 kHz to 400 kHz or high-pass filters with a low cut-off frequency in this range may be used (the low cut-off frequency is altered if a low frequency resonant sensor is used). If extraneous mechanical noise is present, then the lower frequency may need to be increased (but ideally it should remain at least 15 to 20 kHz below the resonant frequency of the sensor).

7.6.4 Preamplifier gain should vary not more than ±1 dB within the actual frequency and temperature ranges.

7.6.5 The input capacitance of the preamplifier should be low (typically less than 25 pf) to limit the loss of sensor sensitivity.

7.6.6 The preamplifier output should have a noise level not greater than 5 µV RMS (root-mean-square) (referred to a shorted input or a 50-ohm terminator at the input) within the actual frequency range.

7.6.7 The output impedance of the preamplifier should match the input impedance of the signal processing unit (typically 50 ohms).

7.6.8 Preamplifiers should be shielded from electromagnetic interference.

7.6.9 Due to possible high amplitude AE signals in some composites, care should be exercised to eliminate voltage saturation of the signals in the preamplifier. For example, if peak signal amplitudes are $\geq 97\ \mathrm{dB}_{AE}$, then a preamplifier that has 40 dB of gain and a maximum output of 20 Vpp into 50 Ω may experience saturation. In such a case, a preamplifier with a lower amplification gain should be used, for example 20 dB. Alternatively, lower sensitivity sensors can be used or preamplifiers with a larger maximum output voltage can be used.

7.7 *Power Supply:*

7.7.1 A stable, grounded, and reliable power supply that meets the signal processor manufacturer's specification should be used.

7.8 *Main AE Signal Processor:*

7.8.1 The main processor and computer with software (with sufficient independent channels) should have electronic circuitry and software through which signals from the sensors will be processed. The main processor normally adds additional gain and appropriate frequency filtering. It shall be capable of processing each AE hit to determine a threshold-based arrival time and the hits duration, counts, peak amplitude and energy on each independent channel. In addition, it should process the average signal level (ASL) or the root-mean-square (RMS) voltage on each channel. In order to record valid AE data, its capability, to process hits and store the processed AE hit data must exceed the rate at which AE hits will be generated in the examination. Finally, it should process and associate real-time parametric measurement values (for example, time-driven data such as load, strain, temperature, etc.) with each hit.

7.8.2 It may include hardware with sufficient dynamic range (at least 12-bit) and sufficient digitization rates to properly digitize each AE hit. It should provide capability to store the digitized waveform data and provide the ability to review the waveforms and perform appropriate data analysis. For this much greater amount of data, its capability to process hits and store the processed AE digitized data must exceed the rate at which AE hits will be generated in the examination in order to record valid AE data.

7.8.3 The electronic circuitry shall be stable within ±1 dB in the temperature range 4° to 49°C [40° to 120°F] (Based on manufacturer specifications).

7.8.4 The electronic circuit threshold shall be accurate within ±1 dB (Based on manufacturer specifications).

8. Calibration, System Performance Verification, Verification of Normal Sensor Response, and System Electronic Noise Characterization

8.1 Calibration of AE sensors, preamplifiers, acquisition system and AE electronic waveform generator (AE simulator, used for locally checking the performance of an AE system) should be carried out in accordance with the equipment manufacturer's specifications and requirements. For additional information see X1.9.

8.2 System performance verification must be conducted immediately before each AE examination. Performance verification uses a mechanical device (see 8.2.1 for the preferred technique for composite samples) to induce (with a fast rise time and short duration) displacement waves into the material under examination, at a specified distance (sufficient so that the preamplifier is not saturated by a very large signal) from each sensor. Induced displacement waves stimulate a sensor in a similar way as waves from real AE sources. Performance verifications verify performance of the entire system including the couplant.

8.2.1 (*a*) The preferred technique for conducting performance verifications is a pencil lead break (PLB). The lead should be broken (see Guide E976) on the material surface at a fixed distance of about 10 to 15 cm [4 to 6 in.] from each sensor. When the composite is not of quasi-isotropic construction, care should be taken so that the signal propagation path from the PLB to the sensor encounters the same fiber lay-up for each sensor. Guide E976 specifies 2H, 0.3-mm [0.012-in.] (or 0.5-mm [0.020-in.] providing a larger signal) diameter lead. The length of the lead should be 3 mm [0.12 in.]. Typically the peak amplitude of the signal from each sensor is recorded for three identical PLBs, and the results for each channel should have an average peak amplitude within ±4 dB from the average for all the channels. If a channel fails this test, it should be repeated after re-coupling the sensor for that channel, since improper coupling is a common problem. If the system still does not meet the performance requirements, the operator must determine the cause of the deficiency and take corrective action prior to the start of an examination. (*b*) In addition, a pencil lead should be broken in contact with the test sample surface at a location(s) such that the pulse generated leads to an AE hit at all the sensors intended for use in the application. The peak amplitudes from the signals from each sensor for three identical PLBs should be recorded along with the location of the PLB to provide data that provides a measure of attenuation of the wave propagation in the sample. When multiple samples are to be tested that are nominally the same, this attenuation data can be used to identify samples with better or worse attenuation than the average. Such data may be of use in the evaluation of differences in the AE generated in different test samples that are nominally the same. It also will provide a database for comparing relative signal strengths from a repeat set of PLBs after the AE examination.

8.2.2 An additional step may be useful in certain situations (for example when the sensors are covered with insulation after they are installed or when it is not safe to do the performance verifications during an AE test). This step consists of first following the description in 8.2.1. Then immediately conducting a performance verification by the use of an Auto Sensor Test (AST), where a pulse is applied successively to each sensor (which operates as a transducer or ultrasonic pulser) and the signals (typically the peak amplitude) from each of the adjacent sensors are collected. These results then provide a database that subsequent AST test results can be compared to when such tests are done at intermediate times during the AE examination and after the AE examination. This procedure also provides a database on the repeatability of wave propagation between the sensors for different test samples that are nominally the same.

8.3 Post system performance verification (by either or a combination of the techniques in 8.2.1 (*b*) and 8.2.2, selected so that a direct comparison can be made with the pretest results) is also to be completed immediately after the examination (when the test sample does not fail during the test) in order to verify that there were no significant changes in sensor coupling or system performance for each sensor and channel during the examination. However, in composites a variety of micro-damage or other test-induced damage can affect the post examination results due to changes in signal propagation characteristics. These changes may be observed and characterized by changes in the PLB or AST results.

8.3.1 If the post examination performance verification or any intermediate performance verification result shows that the system performance changed significantly (a loss of peak amplitude of more than 4 dB for any channel during the examination) the operator must note this in the report and determine if the system overall performance was still adequate. If not, then either the data analysis must be adjusted to account for the current system performance, or the test repeated with appropriate modifications (for example, if attenuation has increased significantly, then more sensors may be added to maintain sensitivity) to ensure valid results.

NOTE 1—It is not possible to repeat the AE generation from a virgin loading (that generates the characteristic damage state) of a composite sample during a subsequent retest.

NOTE 2—A repeated test must go to a higher load at least 10% above the first loading.

8.4 It is important to have a "reference geometry" for use in quickly verifying the performance of sensors suspected to be damaged. This can be done using a typical thickness quasi-isotropic composite plate (say 1 by 1 m (36 by 36 in.), to reduce edge reflections) upon which each sensor can be placed at a fixed location and subjected to the waves from a PLB at a fixed location. Comparing the PLB peak signal amplitude (and possibly the signal shape when waveform recording is being used) with previous data for that sensor (under the same conditions) may be used to identify faulty or non-performing sensors.

8.5 Characterization of system extraneous electronic noise is recommended by the following: (*i*) in a "quiet" environment away from significant electromagnetic noise sources (for example welding or operating overhead cranes; but not requiring a Faraday box or room) and mechanical noise sources, characterize the RMS (or equivalent ASL) noise level for each sensor/channel when each sensor is wrapped in foam (to eliminate any airborne noise) and not coupled to any solid; and (*ii*) in the same sensor environment determine the minimum threshold for each sensor/channel before consistent triggering on background electronic noise occurs. A typical value to define the minimum threshold would be a total of less than 10 hits per channel for a 15 minute time period. If there is more than a 3 dB difference in the noise level or the minimum threshold from the average of all channels, the faulty channel/sensor should be repaired.

8.6 Routine electronic evaluations must be performed any time there is concern about signal processor performance. An AE electronic waveform generator or simulator should be used in making such evaluations. Each signal processor channel must respond with peak amplitude reading within ±2 dB of the electronic waveform generator output.

9. Development of an AE Examination Plan

The AE examination plan includes the AE examination preparation. The examination plan is called out by the appropriate structural test plan for the component/structure to be examined.

9.1 *Number of Sensors, Spacing of Sensors, and Locations of Sensors:*

9.1.1 When determination of where AE sources originate is the primary goal, the number of sensors and their placement are determined differently depending on the AE technique used. If first-hit analysis is being used with resonant sensors, the maximum size of the regions to which it is desired to localize where the AE sources originated is approximately the total sample area being monitored divided by the number of sensors being used. If wideband sensors and wideband-based AE technology is being used, then the number of sensors is set by the discussion in 9.1.2.

9.1.2 When the primary goal is to effectively use AE to monitor the whole or a large part of a composite article, the number of sensors and their locations are best determined by attenuation measurements (with the selected sensor and selected electronic filters) on the composite article or on a test sample with the same materials, thickness and fiber lay-up. The attenuation measurements combined with the expected amplitudes of the AE sources of interest and the planned threshold (above the electronic or other background noise levels) determines how far apart the sensors can be located so that sources of interest do not have signals below the AE system threshold. Sensor spacing is normally decreased in the directions having higher attenuation (for example, in propagation directions perpendicular to a large percentage of the fibers). When basing the expected signal amplitudes from a database from small (25 mm [1 in.] wide) tensile or bending laboratory samples, the expected peak amplitudes should be reduced by about 10 to 12 dB to account for reinforcement of signal amplitude from edge reflections in small tab-type samples. For additional information see X1.10.

9.1.2.1 The desired method to characterize attenuation is the use of PLBs on the test sample edges. These PLBs with the axis of the pencil parallel to the plate surface should be done both on the test sample edge near the top or bottom surface and very near the mid-plane of the edge. The use of these two locations generates the full range of signal frequency (modal) dominance to be expected during testing. For additional information see X1.11. One sensor should be located very close to the PLB location (approximately within 6 mm [0.25 in.]) so that the attenuation information includes the near-field geometric attenuation. In this case, because a PLB is very close to the sensor, care must be taken that the AE signal from the nearest sensor (relative to the pencil lead break position) does not saturate the AE preamplifier. For additional information see X1.12. A series of additional sensors at several distances (up to or beyond the expected sensor spacing) from the source provide data (typically peak amplitude) to determine the loss of amplitude with increasing distance of propagation. To provide a true measure of attenuation for large test items, when a test sample of the same thickness and fiber layup (rather than the actual test article) is used for these wave propagation studies, the test sample should be of sufficient size sample (transverse dimensions should be at least two times the maximum propagation distance to be characterized) so that edge reflections do not significantly reinforce the direct path signals. Also, if the material is not quasi-isotropic, the propagation directions should include at a minimum the directions with the maximum and minimum in-plane and bending stiffness. In the case of a layup with large differences in the number of fibers in different directions, the attenuation measurements should also be made at different angles relative to the direction of the PLB force. In such cases modeling has shown there are both preferred propagation directions with less attenuation and non-preferred directions with higher attenuation.[7]

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[7] "Acoustic Emission Signals versus Propagation Direction for Hybrid Composite Layup with Large Stiffness Differences versus Direction," Marvin A. Hamstad and Markus G. R. Sause, 31st Conference of the European Working Group on Acoustic Emission (EWGAE), Paper We.1.A.1, Dresden, Germany, 2014.

9.1.3 When the primary goal is a comparison between the damage accumulations in virgin samples as a function of increasing stress level for different designs (material components and/or fiber lay-up) of the same item for well designed composite items (having relatively uniform stress fields without regions with stress concentrations), a single AE sensor typically is sufficient along with RMS (typically both averaging time and time-driven interval of 200 to 300 ms) (or its equivalent ASL) measurements of the AE to characterize the accumulation of the characteristic damage state as a function of applied load. The high hit rates may preclude the use of the measurement of standard hit features. If the hit rate is not too high then, the RMS data can be supplemented by the standard hit features. If the test sample does not meet the requirement of stress uniformity, then the technique for selection of the number and placement of sensors should follow 9.1.2. The measurement technique for the generated AE would remain the same for each channel. This AE data for different designs may demonstrate optimal designs (material components and/or fiber lay-ups) having the least accumulation of damage up to a given test level (or design load level).

9.1.4 For test articles with known stress concentrations, the AE test plan should emphasize placement of sensors in those regions. In other regions, a sufficient sensor density should be used to monitor for possible unknown flaws, or stress concentrations, or both.

9.1.5 Specific information about the model identification of the sensors (model designation, whether resonant, and the resonant frequency or wideband) to be installed on the structure and the sensor installation techniques (coupling and attachment) and the materials used for the sensor installation should be specified.

9.2 The test plan should include the planned settings of the preamplifier gains and their filter range.

9.3 The AE measurement system setup for proper data acquisition for the specific structural geometry and materials must be specified. This information includes parameters such as the threshold (and system gain prior to the signal reaching the threshold circuitry), filter range and other parameters that depend on the particular AE system. In addition, the choices of the test parameters (for example, load, pressure, test temperature, etc.) to be recorded by the AE system during the test should be specified.

9.4 A suitable loading profile for AE testing of composites may be relatively simple or it can be complicated, consisting of many load cases in tension, compression, bending, multi-axial loading, and it may include environmental effects (not to induce loads) such as high/low test temperatures, vacuum, etc. For additional information see X1.13. The specific loading recommendations are described here. For additional information see X1.14.

9.4.1 Since polymer matrices are normally viscoelastic at typical test temperatures, ramp portions (increasing and decreasing) of the loading/unloading schedule should have controlled rates, and hold times at load as well as rest times at zero or near zero load should be specific and uniform in length or match each other. The method used to control the loading/unloading rate should be specified.

9.4.2 At the beginning of the examination, there should be an initial low level loading in the range of 5 % to 10 % of the target maximum load (Note that this is not shown in Figs. 2-5). This loading is done to verify the functional performance of every part of the entire system including test controls, loading paths and instrumentation. This low-level load also helps verify the initiation of the load path. If this is the virgin loading of the test article, then AE will typically be generated from the start of the formation of the characteristic damage state. After the specified initial low level loading verification, the AE examination proceeds by increased stressing of the structure.

9.4.3 A common loading profile that is attractive, particularly for proof testing, is a load-hold-unload-rest-reload test cycle as illustrated in Fig. 2. The primary AE monitoring in this case is during the second loading (used to obtain the FR), the second hold and the second unload. The initial loading-holding-unloading portion serves to normalize the sample prior to the primary AE monitoring. A modification of this profile for quality control testing or testing to optimize materials and/or fabrication parameters is to terminate the test after the first unloading, and to focus the AE monitoring on the first loading and first hold.

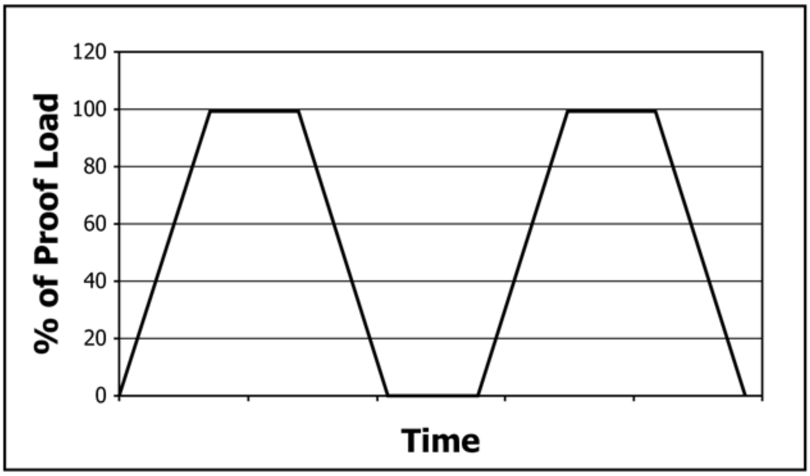

FIG. 2 Example of proof loading with holds and reload. All ramps and holds of equal duration.

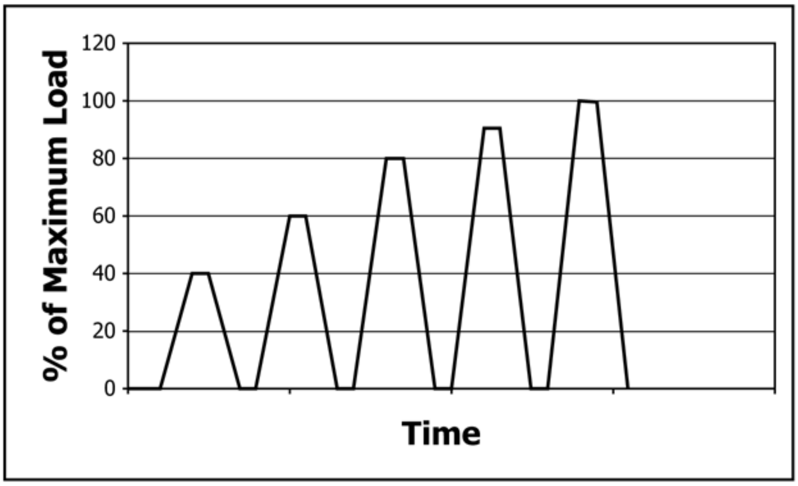

FIG. 3 Sequence of loading, hold and complete unloading. All ramps at equal rates and holds of equal duration.

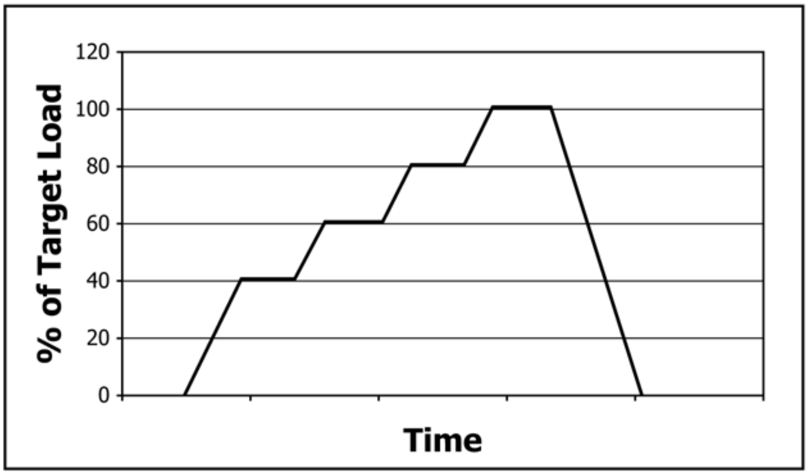

FIG. 4 Example of loading sequence in steps toward the target load. All ramps at equal rates and holds of equal duration.

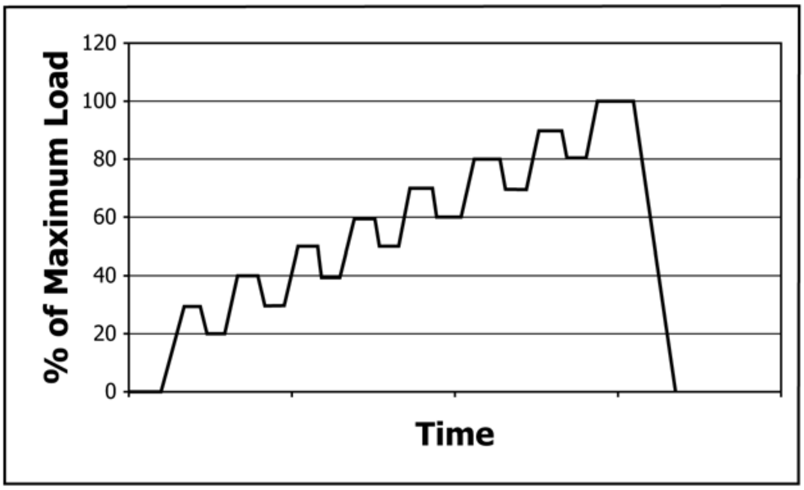

FIG. 5 Sequence of loading, hold and partial unloading. All ramps at equal rates and holds of equal duration.

9.4.4 Another loading profile is shown in Fig. 3 (Note that the magnitude of the steps may be adjusted to fit particular cases). This loading sequence is more time consuming due to the repeated unloading. This loading sequence is valuable due to: (*i*) its elimination of most of the AE signals from the formation of the characteristic damage state during each reloading up to near the previous maximum load; (*ii*) its enabling evaluation of the Felicity ratio for each successive loading; and (*iii*) its enabling of evaluation of the load-hold AE at successively higher stresses and iv) its providing the test manager with AE-based feedback on the state of the composite such that decisions to continue or stop loading can be made without generation of significant additional damage or catastrophic failure occurring.

9.4.5 A sequence of steps of load and then a hold as illustrated in Fig. 4 provides an alternate loading sequence (Note that the magnitude of the steps may be adjusted to fit particular cases). This sequence may be dictated by other considerations in a composite structural test. In this case it is better to use longer hold times so as to allow more relevant AE monitoring when the characteristic damage state (virgin loading of the test article) is not being formed. This profile also provides the test manager with AE-based feedback (from the hold portions) on the state of the composite such that decisions to continue or stop can be made without generation of significant additional damage or catastrophic failure occurring.

9.4.6 Another sequence of load steps, holds and partial unloads is shown in Fig. 5 (Note that the magnitude of the steps may be adjusted to fit particular cases). This sequence, while not as desirable (lacks sufficient unloads, such as shown in Fig. 1 and Fig. 2, to fully activate the FR), has the advantage of reducing the total test time.

9.5 Since many factors influence the nature and amount of AE in composite materials (fiber materials (includes fiber weaving and number of "ends"), matrix material, fiber volume, general internal macrostructure such as laminate lay-up, time between load cycles, loading rate, cure cycle, sample volume, subsequent loading cycles, porosity or void content, moisture content, history of load and temperature and test temperature), an AE characterization evaluation for a trial sample or preferably several trial samples may be needed to finalize details associated with the examination plan to determine the following:

9.5.1 Characteristics of AE wave propagation from real sources such as wave velocities (typically the velocity of the first arrival of the signal (hit)), attenuation and directional variations of these properties in the composite material. This information is used with other data to determine the final sensor spacing and sensor locations.

9.5.2 Characteristics of AE signals from the composite sample during loadings so as to enable distinguishing extraneous AE from AE signals of interest.

9.5.3 Characterization of typical AE amplitudes and AE event rates to provide guidance for the settings of AE system test parameters such as gains, thresholds and sensor spacing, as well as determination of any required modifications to the loading profile (for example the loading rate).

9.5.4 Development of appropriate acceptance/rejection criteria, when AE data is used in this role. Typically this AE application requires multiple "acceptable" and "unacceptable" test samples to establish the empirical criteria.

9.5.5 An evaluation of test environmental effects such as temperature, humidity and background noise, etc. should be specified in the test plan. Some typical sources of background extraneous noises are test fixturing, test grips, operating overhead cranes, hydraulic servo-valves, etc.

9.5.5.1 Specifically for background noise the following should be done. In the actual test environment with the sensors coupled to the test item the same two noise items specified in 8.5 should be measured for each channel. Comparing this data with that from the testing in section 8.5 can be used to identify and then correct any sensor/channel not consistent with average values for the actual test environment. For additional information see X1.15.

9.5.5.2 Specifically for humidity, due to the nature of the anticipated testing (not always well controlled laboratories) the control of the moisture content of test samples is not generally possible. If different test samples are expected to have significant changes in moisture content, then a series of tests with different moisture content is recommended to determine the effect of this variable on AE behavior.

9.6 Test samples should be identified based on sample type, sample condition, manufacturing characteristics, loading parameters, etc.

9.7 The AE data to be observed real time during the AE examination should be specified. The following is recommended.

9.7.1 Graph of total first hits (or counts from first hits) in each channel versus time and/or load as appropriate for the loading profile.

9.7.2 Graph of total hits (or total counts) from all channels versus time and/or load as appropriate for the loading profile.

9.7.3 Graph of total first-hit energy in each channel versus time and/or load as appropriate for the loading profile.

9.7.4 Graph of total-hit energy from all channels versus time and/or load as appropriate for the loading profile.

9.7.5 The graphs of 9.7.1 through 9.7.4 can be conveniently viewed as three dimensional plots of AE versus load or time versus channel number.

9.7.6 In addition three dimensional plots of RMS (or its equivalent ASL) versus load or time versus channel are also useful to monitor any changes in certain background noise levels during an examination.

9.8 AE-based criteria to determine when a premature halt to loading (based on the AE data) is required.

9.8.1 Emergency test stop criteria should be established if AE monitoring is required as a "go/no-go" decision factor relative to continued loading. This role for an AE examination requires real-time AE data review during loading (FR) or during load holds (see 10.11). The purpose of this real-time evaluation is to determine the significance of the AE data relative to the component's continued structural integrity under additional loading. The emergency stop criteria will determine if the examination should be terminated to prevent any additional damage. If the review reveals that the AE data has met the criteria, then, the loading needs to be immediately halted and followed by appropriate unloading.

9.9 The AE examination plan should be reviewed and approved by the appropriate authority and coordinated with those responsible for structural test engineering. It is desirable that those planning AE examinations of composites should be trained or experienced in both AE technology and testing of composite materials. Also they should possess knowledge of mechanical behavior of composite materials and their failure mechanisms.

10. AE Examination

10.1 Place the test sample in the load frame or load the article in-place. Insure that extraneous noise is kept to a minimum by isolating mechanical and electrical noise sources. For additional information see X1.16.

10.2 Install AE sensors at the planned locations with approved attachment techniques and materials.

10.3 Route cables and preamplifiers and secure them in place so they will not cause frictional AE during the test.

10.4 Set up the AE equipment in a safe place or a protective area as required.

10.5 Verify or adjust the planned data acquisition parameter settings for the best results in detecting acoustic emission of interest and filtering extraneous noises.

10.5.1 Check the ASL or RMS level for each channel. Record the values and compare with the values found in a "quiet" test environment (see 8.5). Make corrections if necessary. Also check the minimum threshold that can be set in each channel to identify any noisy channels (see 8.5). Record the minimum thresholds and compare with the values found in a "quiet" test environment (see 8.5). Make corrections as necessary. If unavoidable extraneous noise sources in the test environment require the AE threshold be raised a significant amount, then it may be necessary to add more sensors and reduce their spacing to maintain sensitivity to real AE sources in the test object. The threshold should be set at a minimum of 3 dB above the minimum threshold (as defined in subsection 8.5).

10.6 Perform an AE sensor sensitivity check and system verification (see 8.2) and record the data. Make corrections as necessary.

10.7 Record necessary information regarding the identification of the structural examination and loading cases. Prepare the AE data on-screen plots for real time monitoring and situational awareness as to the continuing structural integrity of the test sample.

10.8 Begin the examination by initiating the loading sequence and starting the recording of AE and parametric data, as specified.

10.9 Monitor the AE data for anomalies such as when AE test parameters need adjustment (in order for the test to be a valid AE examination) during the examination. Record any unexpected adjustments made during the test (any changes in loading rate, hold times, gain, frequency bandpass, threshold and data acquisition settings, data interruptions or procedure changes, etc.) and any other information that will help in post-test data analysis and results determination.

10.10 If appropriate (for example, during testing of items with unfamiliar AE generation characteristics), make sure a valid test is being performed.

10.10.1 (Validity of test) High event rates during loading that exceed the rate that the AE system can process or exceed an event rate such that typically the AE signals overlap each other in time so that they cannot be processed as discrete hits. If this applies, either terminate the examination or decrease the loading rate to decrease the event rate so that a valid AE examination can be done. Alternatively, limited AE data can be recorded by the use of RMS (see 9.1.3) (or ASL) measurement of the signals.

10.10.2 (Validity of test) Events from fixturing or the loading apparatus (as determined by a large number of first hits from sensors located nearest to the fixturing and/or loading apparatus). If possible, re-fixture the test sample to remove the extraneous noise sources, as these extraneous signals can obscure flaw or damage-based events.

10.11 If required, monitor the AE data as a factor to consider in a decision to terminate the examination before unacceptable damage to the test item occurs.

10.11.1 (Decision to terminate) Increasing rates of AE events as the hold-time increases particularly if the first-hits from these events are from sources originating from a particular region of the composite. This situation can be an indication of a progression of creep or stress rupture towards failure. Terminate the examination and perform follow-up NDE on the test sample to determine if significant damage has occurred.

NOTE 3—This follow-up may require access to a pristine undamaged test sample for a correct assessment of possible damage.

NOTE 4—A decision to terminate a test is highly dependent on the risk of failure that the test requestor is willing to tolerate. Ideally some "pathfinder" test item could be used to determine the conditions that require test termination. Further the actual conditions are highly dependent of composite variables such as fiber type, polymer and the layup of the fibers.

10.11.2 (Decision to terminate (see Note 4)) As loading proceeds, a concentration of events from a given localized region (as determined by a much larger number of first hits from a sensor in a particular location). A high concentration of events originating in a given region may be a possible indication of local flaw growth. Terminate the test and perform follow-up NDE (see 10.11.1) on the test sample to determine if significant damage has occurred.

10.11.3 (Decision to terminate (see Note 4)) Under repeated load cycles, if the FRs are decreasing significantly (as the load levels increase for subsequent cycles) for certain regions relative to other regions (or relative to previous like samples) this situation may be an indication of local flaw growth. An example of such a case, when the maximum of the load prior to the FR loading increased from 47 % of the expected strength to 59 % of the expected strength, the FR decreased by 15 %. Terminate the test and perform follow-up NDE (see Note 3) on the test sample to determine if significant damage has occurred.

10.11.4 (Decision to terminate (see Note 4)) As loading proceeds, a sharp change in the slope of the accumulation of AE (a "knee" in the curve of cumulative hits, hit energy or events versus load that indicates an exponential increase in AE) particularly from a local region (identified by first hits) may indicate a critical damage threshold has been crossed. Alternatively, if the AE software is programmed to overlay the cumulative AE with the rate of AE (so that when both are viewed on a single plot each parameter reaches full scale of the plot) versus time (under constant ramp loading) an exponential increase in AE can be identified. Terminate the test and perform follow-up NDE (see Note 3) on the test sample to determine if significant damage has occurred.

10.12 Report AE results to the test coordinator at specified time intervals or upon the development of abnormal situations, if required.

10.13 Transfer the raw data from the data acquisition computer to a storage media (more permanent than a floppy disc) and maintain the data in digital form for a specified period of time per requirement.

11. AE Data Analysis

11.1 As a primary basis for decisions use an available empirical database from comparative AE test results from "acceptable" versus "unacceptable" articles of the same design as the test item.

11.2 Record any known information as to previous load cycles and their stress fields (including the stress levels). Where appropriate use this information in the analysis of the current AE test data. Additionally, if available from previous load cycles, information on sample compliance, its changes with changes in load level and permanent deformation upon unloading should be added to the record and considered in the analysis.

11.3 Arrange the AE data by first-hit channel (sensor) or if source location can be done (see 11.5 and 11.6), then the AE data should be arranged by regions of origin. In either case only the first hit data is used for additional characterization.

11.4 The arranged AE data (first hit data) should be correlated by plots with the recorded parametric data such as load (or time for load holds) or strain, since the AE events represent the structure's damage response to their "driving force" (loading).

11.4.1 Use such data from multiple test samples to determine the relative damage status of different but nominally identical samples.

11.5 *Calculate Source Locations*—When wideband sensors and wideband-based AE are used, the single-velocity arrival times (for each hit of events) determined by time-frequency analysis can be used with directional-dependent group velocities (from theory or experiment) to determine the locations of AE sources when at least four sensors are hit. If fewer sensors are hit or if wideband-based AE is not in use then the technique of 11.6 must be used. For additional information see Appendix X1.17.

11.5.1 Use this data to prepare comparative plots of first hit data (number or rate of hits) by location clusters versus parametric information such as load or time.

11.5.2 *Hit-Energy Analysis*—Create comparative plots of hit-energy (cumulative sum or rate) by location clusters versus parametric information such as load or time.

11.6 *Zone (Area) Source Location*—Prepare data that groups the first hits for each sensor/channel. For additional information see X1.18.

11.6.1 Use this data to prepare comparative plots of first hit data (cumulative sum or rate) by channel versus parametric information such as load or time.

11.6.2 *Hit-Energy Analysis*—Create comparative plots of cumulative sum or rate of hit-energy (for the first hits) by channel versus parametric information such as load or time.

11.6.3 *Filtering Non-Useful AE*—Filter out any first-hit signals that hit only one channel and that have just one or two counts and have a peak amplitude of at least 12 dB above the threshold. For additional information see X1.19.

11.7 *Felicity Ratio*—If a loading profile results in a series of FR values at increasing load levels, then the FR for each region (either from source location clusters or from first hit defined regions) should be plotted as a function of the load (stress) in the reference load cycle for each FR. This data can identify regions where more damage is taking place with FRs that are significantly lower during the subsequent increasing load cycles of a particular test sample.

11.7.1 If the loading profile is the proof loading case, then the lowest individual FR for each test sample should be plotted relative to like items in a database that includes "acceptable" versus "unacceptable" items for which the residual strength is known. Published research has shown that the FR at a given proof-load level can be correlated with the residual strength of nominally identical composite items.

11.7.2 The determination of the onset of significant AE in order to define the FR can be operator dependent. Some techniques have been developed to make the determination non-subjective.[8]

11.8 *Events During Load Holds*—Typically increasing numbers of AE events or instability in the rate of AE events (particularly from a local region relative to other similarly fabricated and stressed regions) with increasing time during a load hold indicate potential growth of a flaw. In addition to creating plots of the cumulative or rate of hit energy versus the increasing time of the hold to identify higher damage regions other data can be developed for analysis. Plots of the cumulative or rate of hit energy versus the increasing time of the hold for clustered regions or first hit regions. In addition, this data from load holds for each region of the test sample can be analyzed by summing the product of the AE hit energy by the amount of hold time to when the event occurred (this approach emphasizes the AE during the later portions of the hold). Then the result of the sum can be compared from the different regions of the test sample as well as with the same data from different test samples. Regions of a test sample or different samples with damage that is identified by this technique should have follow-up NDE.

11.9 *Events During Unloading*—These potential AE events from frictional sources may indicate delamination, debonded areas or large fracture surfaces. A region based value[9], similar

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[8] "Correlation of Acoustic Emission Felicity Ratios and Hold-Based Rate Moment and Burst Strength," K.S. Downs and M.A. Hamstad, Journal of Acoustic Emission, Vol. 13, Nos. 3-4, pp. 45-55, 1995.

[9] "Acoustic Emission from Depressurization to Detect/Evaluate Significance of Impact Damage to Graphite/Epoxy Pressure Vessels," K.S. Downs and M.A. Hamstad, Journal of Composite Materials, Vol. 32, No. 3, 1998, pp. 258-307.

in concept to the FR, can be calculated. Regions of a test sample or different samples with damage that is identified by this technique should have follow-up NDE.

11.10 *AE During Virgin Loading*—Events from the formation of the characteristic damage state are not an indicator of structural deficiencies. Instead this emission can be used to provide a comparison between the damage accumulations as a function of increasing stress level for different designs (material components and/or fiber lay-up) of the same item. Plot of the RMS of the AE versus the load can be used to compare test samples with different designs. The lowest accumulation of AE (up to a given test level or design load level) and/or the test samples with the highest load at the initiation of damage may demonstrate optimal designs (material components and/or fiber lay-ups).

12. Report

12.1 On completion of the examination and any post examination analysis of the recorded data, all results should be summarized (in accordance with the test plan) in text, figures and tables. The AE result concerning the potential damage status or any acceptance/rejection status of the tested object(s) should be documented. This result should be based on a careful evaluation of all the factors from the AE measurements that led to the reported damage status or the acceptance/rejection recommendation.

12.2 The examiner should submit a signed report of the examination that includes the following:

12.2.1 Part description and identification should include:

12.2.1.1 Information regarding the component under examination including: part name, design model, serial number, composite fiber lay-up, fiber volume percentage, materials, size, shape and other pertinent structural details. For this report, it is recommended to take photographs of the test object prior to installation in any test fixture used and also after the AE sensors have been attached and connected to the cables and preamplifiers. Also photographs of the lead break positions for the overall signal propagation experiments. Finally, post-test photographs of the test object should be included.

12.2.1.2 Condition of part before and after examination as documented by visual inspection and other available information.

12.2.2 Identity and qualifications of examination personnel.

12.2.3 Date and time of examination.

12.2.4 Location of the examination and environmental conditions during the examination (e.g. temperature, humidity, inside or outside, etc.). Include the environmental conditions and the duration of this exposure prior to the AE examination.

12.2.5 The acoustic emission system and its characteristics (manufacturer, model and serial number, number of channels, frequency filter values, gain(s), system threshold, last calibration date, system verification information, software program name and version, preamplifier (model, gain, filter and serial number)).

12.2.6 The position in a relevant coordinate system of all sensors on the component being examined, as well as the sensor's manufacturer, model and serial numbers.

12.2.7 Method of acoustic coupling (including identification of the couplant) and the fixturing used to place the sensors against the component being examined.

12.2.8 Records of system in-situ verifications (see Section 10) carried out before and after the examination. This data should include the measured values as well as the AE system(s) data acquisition settings used.

12.2.9 Specific AE system setups (for example, settings used to determine hit durations and peak amplitudes) used to carry out the examination.

12.2.10 Parametric information recorded (scales and conversions of voltage to load, strain, etc.)

12.2.11 Specific steps that were taken to check for extraneous noise sources, and if applicable, what was done to eliminate their influence on the AE data.

12.2.12 A clear and specific description of the loading profile versus time during the examination. Alternatively, if stressing was accomplished by other stimulus such as thermal cycles, the stimulus parameter versus time should be specified in detail.

12.2.13 AE results and the analysis done.

12.2.14 Conclusions and recommendations.

13. Keywords

13.1 acoustic emission (AE); acoustic emission from composites; AE; aerospace composites; continuous fibers; fiber/polymer composites; flat panels; high modulus fibers; laminates; nondestructive testing (NDT); structural health monitoring (SHM)

APPENDIXES

(Nonmandatory Information)

X1. SUPPLEMENTARY INFORMATION FROM CORRESPONDING SECTIONS OF PRACTICE (NOTE SECTION NUMBERS REFER TO PARTS OF THE PRACTICE)

X1.1 (Section 1.2) Comments relative to uses of AE:

X1.1.1 Other uses of AE measurements include detection and location of the damage region of an impact-damaged plate with damage not apparent during visual inspection). In addition, the AE measurements can provide a record of the accumulation of micro-damage with increasing load applied to the structure (for materials studies or composite design studies), determine regions with high damage accumulation or monitor the accumulation of macro-damage with increasing load for a flawed structure. Other potential objectives of AE monitoring of composites include: detection of first damage during loading, failure warning, monitoring of fatigue cycles (to record the accumulation of damage) and structural health monitoring (to reduce or eliminate other nondestructive examinations).

X1.2 (Section 3.2.1) Comments relative to the characteristic damage state:

X1.2.1 In composite stiffness-governed designs where the design strain levels are very low, the formation of the characteristic damage state may not take place.

X1.2.2 The micro-damage from the formation of the characteristic damage state is not abnormal for many composites.

X1.2.3 AE from fiber/polymer composite structural items initiates on the virgin loading cycle at relatively load levels (as low as 10 % of the ultimate strength or at strains as low as 0.15 %). This AE is primarily related to sources generated by the formation of the characteristic damage state which is a consequence of the incompatibility of strains due to the large differences in the elastic modulus of the fibers compared to the polymer matrix and the large differences in the strength of the fibers compared to the matrix. Biaxial loading, which is normally the case in composite applications, results in significantly more of this AE as compared to uniaxial loading in the fiber direction of a unidirectional composite. In cases where the test temperature is above the glass-transition temperature of the polymer matrix or when the matrix is very flexible (modulus less than about 100 MPa [3 Msi]), the early AE is generally significantly reduced.

X1.3 (Section 4.1) Comments relative to micro-damage and friction-based AE sources:

X1.3.1 Micro-damage commonly refers to transverse cracking from the formation of the characteristic damage state during the virgin loading, and it can also include other AE sources (for example, individual fibers that fracture due to excessive or anomalous loads).

X1.3.2 Friction-based sources generally refer to damaged material interfaces interacting, particularly during unloading of the structure.

X1.4 (Section 5.3) Other aspects that the probability of detection depends upon:

X1.4.1 The energy emitted by the sources (for example the magnitude of energy released by the source and the time period of the operation of the source), the sensor sensitivity versus frequency, the sensor spacing, the distance from sources to the nearest sensor, the type of stress (for example, uniaxial versus biaxial), the direction of the stress relative to fiber lay-up, the attenuation of the AE waves with propagation distance and propagation direction relative to the fiber lay-up, the test sample's transverse dimensions, the threshold, the filter bandwidth, other settings of the AE system (for example, the event recognition settings), the preamplifier gain and the extraneous AE noise levels.

X1.5 (Section 5.5) Comment on characterization of AE detected sources:

X1.5.1 The potential need for further characterization of the sources of detected AE depends on the nature of the AE detected and on whether the test sample is designed for a stiffness driven application or for a strength driven application. For example, the presence of many relatively uniformly distributed AE sources of low amplitudes may be important for a stiffness-driven application (due to reduction in material stiffness). Alternatively, the presence of significant concentrated AE from a particular region may be important for a strength-driven application. When the AE levels are high, then the use of other NDE techniques may be indicated to characterize the damage.

X1.6 (Section 7.2.1) Comment on the frequency content of AE waves (signals) in fiber/polymer composites:

X1.6.1 The frequency content of a signal from a source depends first of all on the amount of time over which the source releases its energy. Even with a wideband sensor, the higher portion of the frequency content is only significant over a short propagation distance (200 to 250 mm [8 or 10 in.]) in a composite due to frequency-based attenuation and dispersion from the polymer matrix and the inhomogeneous microstructure of the composite. Further, as the wave propagates to distances beyond about five thicknesses of the composite, the dominant frequencies become those from the most energetic portions of the Lamb modes. These frequencies are directly dependent on the thickness of the composite sample and the depth of the source.

X1.7 (Section 7.2.1) Comment on selection of sensors with response that corresponds to the frequencies with the highest amplitudes in the AE waves:

X1.7.1 A scientific method to select sensors that will have high response at the frequencies that have the largest amplitudes in the AE waves in the plate sample is by use of in-plane pencil lead breaks (PLB) on the panel's edge. When this method is used, it is necessary to use a wideband (Test Method E1106 or Practice E1781) sensor (relatively flat from 50 kHz to 400 kHz; if the plate is very thin (2 mm [0.08 in.] or less) the frequency range should extend to 700 kHz or higher [some sensors that have this higher frequency response may lack significant response at lower frequencies]) and digitally record the signals. The wideband sensor should be located at a distance of at least 12 times the plate thickness from the PLB location. The signals obtained can be characterized for their primary frequency content by performing Fast Fourier Transforms (FFT) on the signals from PLBs at two locations on the plate edges. These locations are near the mid-plane and near either the top or bottom surface. The FFTs should be done on the regions of the signal that have the highest amplitudes. The primary frequency content identified by the FFTs can then be used to guide sensor selection. The selected sensor (wideband or resonant) should have significant response over the range of frequencies excited with the highest amplitudes. This signal evaluation can also be made by use of a wavelet transform or equivalent signal processing.

X1.8 (Section 7.2.1.1) Comments on Wideband AE sensors:

X1.8.1 Typically commercially available wideband sensors are less sensitive than resonant sensors.

X1.8.2 Due to the fact that AE sources in composites generally result in higher amplitude waves than AE sources in metals, the use of wideband sensors with their potential lower sensitivity is not generally a problem particularly if the wideband sensors have good response down to about 20 to 40 kHz.

X1.9 (Section 8.1) Comment on calibration of AE sensors used on fiber/polymer composites:

X1.9.1 Since AE sensors for testing composite plates are normally coupled to the plate surface, it should be noted that neither a standard practice nor standard guide for frequency-based calibration of sensitivity for AE sensors mounted on a low modulus material currently exists (Note that the composite stiffness in the out-of-plane direction is very close to the relatively low modulus of the polymer matrix, which is in contrast to the steel block used in Test Method E1106).

X1.10 (Section 9.1.2) Comments on the understanding and relevance of experimental attenuation data:

X1.10.1 The largest observable attenuation as a wave propagates from a source occurs in the immediate vicinity of the source. The reason is that this geometric attenuation of wave amplitudes in a plate depends on $1/\sqrt{r}$, where r is the distance from the epicenter of the source (located directly above the source) to the sensor (note that the wave energy falls off as 1/r).

X1.10.2 After propagating only about 50 mm [2 in.] the peak wave amplitude loss may be on the order of 30 dB or more (depending on the plate thickness). This observation is important for AE monitoring of composites as compared AE monitoring of metals. The difference is that in metals it is very unlikely that a sensor will be directly above a crack tip AE source, but with composite AE testing sensors are likely directly over some sources since AE events typically originate throughout a composite.

X1.10.3 Beyond the near-field large-attenuation region, the attenuation is dominated by a combination of $1/\sqrt{r}$, material-based absorption, lay-up-based direction of propagation effects, and dispersion. Total values of peak signal amplitude loss on the order of 1.5 to 2.5 dB per 25 mm [1 in.] have been observed.

X1.10.4 Also higher frequencies (above 150 kHz) are more rapidly attenuated due to the presence of the polymer and the non-homogenous microstructure.

X1.11 (Section 9.1.2.1) Comments relative to PLB locations:

X1.11.1 Pencil lead breaks with the two locations (near top or bottom surface and mid-plane) generate AE waves that best represent the "dipole-type" self-equilibrating real AE sources. Alternatively pencil lead breaks can be done on the top or bottom surface, but the user needs to be aware that such locations result in AE signals that have a much larger low frequency component (up to 20 dB or more depending on the AE system's bandwidth and sensor frequency response) as compared to real AE sources.

X1.12 (Section 9.1.2.1) Comments relative to saturation of the AE preamplifier):

X1.12.1 It is best to check for saturation by connecting the close sensor directly to a digital scope (with low input capacitance and high input resistance) to measure the input amplitude. Then using the gain of the preamplifier and its saturation voltage, it can be determined if the preamplifier will be saturated.

X1.13 (Section 9.4) Comments relative to different loadings:

X1.13.1 *Virgin Loading*—Typically upon the first (virgin) loading of a composite, a large amount of emission will occur (characteristic damage state emission) randomly generated throughout the composite. This emission is not normally an indication of approaching failure or critical damage. The AE from the virgin loading is useful in composite materials studies when different material parameters and/or laminate geometries are being examined to optimize the composite properties. Comparison of records of the AE accumulation versus load from different samples with such parameter changes is useful to distinguish optimized materials and/or composite designs. This loading is also useful to create a record (for example RMS of AE versus load) that demonstrates the production process for a certain composite item is repeatable from item to item.

X1.13.2 *Second Load Cycle or Felicity Ratio Loading*—This loading approach reduces the generation of AE that is relatively randomly generated throughout the test sample, and instead emphasizes the AE that may be generated from damaged or more highly stressed regions. The AE from such regions can effectively be "hidden" on the virgin load cycle due to the large amount of AE generated from the formation of the characteristic damage state. An obvious fact is that the number of AE events per added stress increment normally increases with increased loading during the second loading cycle. Hence, regions with stress concentrations (due to flaw initiation and growth or designed-in or unintended stress concentrations) will be at a higher stress level. Thus, these regions will generate more and earlier AE events per stress increment relative to areas in the composite item without stress concentrators, which experience more uniform stress fields. This earlier AE is more valuable in NDE-orientated AE examinations relative to the residual strength/life of the composite. In fiber/polymer composites, the FR is influenced by a number of factors: recent load and temperature history, test temperature, loading levels, unloading levels, loading/unloading rates, hold/rest times, sample geometry, the number of load cycles, peak load as a proportion of failure strength and construction materials.

X1.13.3 *Load Hold*—Load holds are used to determine if the composite is creeping or experiencing stress-rupture-based damage at a given load. A continuously increasing rate of events or instability in the rate of AE generation (near one or more than one sensor) as time increases during a load hold may be indicative of unstable flaw development and impending failure, and it is recommended that the examination be halted. The specification of criteria to halt a test depends strongly on the risk of failure that the test requesters are willing to tolerate. After halting an examination, follow-up NDE methods may be performed at the site(s) of interest (typically those regions of concentrated emission origins that are indicative of the presence of higher stresses in those regions) identified by the analysis of the AE data. A typical hold time for composites is about 4 to 10 minutes. The AE generated from different regions during the later part of the hold time is most valuable in comparing the damage status of composites of nominally the same design. The amount of AE generated during a load hold is less from a carbon fiber/polymer composite, most from a glass fiber/polymer composite, and mid-range from an organic fiber/polymer composite (due to different levels of sensitivity to stress rupture and different fiber stiffness).

X1.13.4 *Unloading*—Unloading of damaged composites may produce frictional emission that indicates fracture surfaces (for example, delaminations, etc.) rubbing against each other as the load is decreased. Investigation of these areas with other NDE techniques should be performed to characterize the damage in the AE located region.

X1.14 (Section 9.4) Comments relative to specific loading recommendations:

X1.14.1 Proper loading needs to be established to provide the necessary non-destructive stress to evaluate the component. The incorporation of second-load-cycle Felicity-ratio loading, hold AE and unload AE are particularly valuable in AE testing of composites. This aspect has been exploited in designing the loading profile and subsequent analysis of the AE during: (*i*) increasing second cycle loading, (*ii*) FR testing, and (*iii*) hold testing.

X1.15 (Section 9.5.5.1) Comment relative to superposition of background noise:

X1.15.1 Comparison of noise in the test environment compared to values in a "quiet" environment is necessary since real AE superimposes on background noise (electronic and extraneous). Excessive background noise will cause the AE in that sensor/channel to appear to be elevated compared to other channels when that is not the real case.

X1.16 (Section 10.1) Comments relative to techniques to minimize extraneous noise:

X1.16.1 Placement of rubber, or Teflon inserts, or both, into fixturing to reduce mechanical noise from contact between the test sample and the fixtures used to hold or load the sample. Since composites typically have higher design strain levels than metals during testing, relative movement can be a source of frictional extraneous AE not present with metal samples.

X1.16.2 Off-set hydraulic servo valves (from the actuators) by use of rubber hoses to reduce the continuous servo-based AE noise.

X1.16.3 Due to higher strain levels in composites (compared to metals) adhesively bonding sensors and/or other transducers, taping cables, preamplifiers, etc., to the composite may create extraneous AE noise sources.

X1.17 (Section 11.5) Comments relative to AE source location in fiber/polymer composites:

X1.17.1 Source location is useful to determine when AE sources are increasingly concentrated in a particular location. Such a case may be indicative of a localized flaw developing in that region.

X1.17.2 Location information about AE sources enhances the AE analysis techniques for composites since they are vulnerable to premature failure due to concentrated damage.

X1.17.3 Further in a well designed composite test sample that has not been flawed, it is not unusual for more than one region of the composite to have a larger number of sources than other regions particularly at higher stress levels.

X1.17.4 Also, AE source location results are useful to determine the regions of a composite article that may require inspection by other NDE methods.

X1.17.5 The determination of the two-dimensional location of AE sources by standard AE location algorithms (even with single-velocity signal arrival times) may not be possible due to the high attenuation resulting in the waves from the source not recording hits at the necessary four sensors (to eliminate false locations) in an array.

X1.17.6 Further, in composites threshold-determined arrival times do not normally correspond to a single velocity.

X1.18 (Section 11.6) Comments on Zone Source Location

X1.18.1 This recommended technique uses the accumulation of first hits as a function of the load or hold time for each individual sensor as a means of locating the regions or areas of the composite experiencing the most generation of AE.

X1.18.2 The size of each distinct area depends on the number of sensors used to monitor the test sample.

X1.18.3 Due to potential velocity and attenuation differences with propagation direction, the area that results in first hits for each sensor is not a simple circle around each sensor.

X1.18.4 This technique is also important to locate the regions of sources that do not hit sufficient sensors to make it possible to calculate a location.

X1.19 (Section 11.6.3) Comment on filtering of non-useful AE originating directly below a sensor:

X1.19.1 Signals originating from directly below a sensor are not as significant as they appear (based on the measured peak amplitude) relative to other detected signals since the near field geometric attenuation is very large.

X2. INTRODUCTION TO RELEVANT ASPECTS OF WAVE PROPAGATION

X2.1 Guided Wave Propagation—Finite Media

X2.1.1 Many of the structures encountered in testing are plate-like in nature, and this geometry will be primarily discussed here. The world of plates is divided into two regimes: thick and thin. The main types of waves propagating in the far-field (propagation distance greater than about five plate thicknesses) of a thick plate are Lamb waves, which are described by three-dimensional elasticity theory.

X2.1.2 The thin composite plate dominates in aerospace structure where weight is critical. Much of the impetus for the use of composite materials has come from the needs of aircraft and spacecraft. As it turns out, most of the energy in AE sources in sufficiently thin composite plates is propagated (far-field) by two types of waves which can be described by the same plate theory (laminated plate theory) used to develop the static properties of composites. Plate theory is essentially two dimensional.

X2.2 *Thick Plates*—The dispersion equation (a theoretical relation between wavelength, frequency and velocity) for Lamb wave theory is an extremely complicated transcendental equation. Since it contains frequency, Lamb waves are dispersive (each frequency component in a wave travels at a different velocity so the wave changes shape and length as it moves along the plate). In Lamb-wave theory, there are many displacement shapes through the plate thickness that the wave pulses can assume at a given frequency. These wave shapes are called modes (similar to vibration modes). Many Lamb modes can exist at a given frequency and the mode shape (the displacement profiles across the plate thickness) changes as a function of frequency within each mode. Modeling of AE signals in plates has shown that all the frequencies within a mode are not equally excited. Certain frequencies have higher amplitudes in the signal time domain. In addition, when higher signal frequencies are present in the AE signal, more Lamb modes can be present. These facts can make it difficult to distinguish the modes in an AE test. If wideband sensors are used, then when the appropriate group velocity curves are available along with an approximate propagation distance from the source to the sensor, the use of signal processing such as a wavelet transform or Choi Williams Distribution can be used to distinguish the modes in large plates where reflections from the plate edges do not interfere with the AE signals from the direct source to the sensor paths. The Lamb modes are designated S_0, S_1, S_2…, A_0, A_1, A_2…, SH_0, SH_1...and so forth, which is just a way of labeling the various modes from the simpler to the more complex mode shapes. In the above designation “S” stands for symmetric, “A” stands for anti-symmetric, and “SH” stands for shear horizontal. A complete explanation of Lamb waves is beyond the scope of this document. In principle the Lamb wave sinusoidals (Lamb modes are interchangeable jargon) can be superimposed to describe an acoustic pulse propagating in a plate. Extending the full Lamb wave theory to anisotropic composite laminate materials is difficult.

X2.2.1 *Group Velocities for Thick Plates*—Computer codes have been developed that allow the calculation of several of the lower Lamb modes for A, S, and SH.[10] The inputs required are the elastic properties, fiber direction, and thickness and density of each layer in the laminate. Then the phase and group velocities can be calculated for chosen directions of propagation.

X2.3 *Thin Composite Plates*—When the shortest wavelength of interest is greater (approximately) than the thickness of the plate, a two-dimensional plate wave theory can be used to describe acoustic emission in the far-field. This approach provides a simpler analysis than the application of Lamb wave theory, which applies to both thick and thin plates. From experiment, the AE waves found in many realistic structures, particularly composites, are these plate waves. There are three modes of propagation predicted by plate theory although, generally, just two are observed. One is called the extensional wave (mode), and the other is the flexural wave (mode). The correspondence with Lamb theory is respectively through the S_0 and A_0 modes. The third mode, which corresponds with the SH mode in Lamb theory, has its displacement motion in the plane of the plate while most AE sensors (primarily sensitive to motion perpendicular to their face or normal to the plate surface with the typical mounted orientation) do not respond significantly to this displacement. Hence, this mode is not typically observed, particularly when viscous couplants are used to couple the sensors.

X2.3.1 The equations of plate theory come from Newton’s laws of motion, but special assumptions about the geometry of the deformation can be made since the wavelength is so long.

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[10] Xue Qi and Xiaoliang Zho, “Ultrasonic Guided Wave Simulation Toolbox Development for Damage Detection in Composite.” AIP Conf. Proc., 1211, pp. 1095–1102, 2010. Implemented in “NDE Wave and Image Processor Software User Manual,” V. 3.0, D. J. Roth, 2010.

These assumptions simplify the equations of motion, and one of the first benefits is that the predicted dispersion equations are no longer transcendental. Instead they are simple algebraic expressions which can be readily understood. The characteristic displacement shapes (through the plate thickness) of the extensional and flexural modes are not evident until the modes have propagated several plate thicknesses from the source.

X2.3.2 For the extensional wave, the velocity in the x-direction (a direction of material symmetry of the layup), C_e, given by plate theory is:

$$C_e = \sqrt{\frac{A_{11}}{\rho h}} \tag{X2.1}$$

where C_e is the extensional plate wave velocity, A_{11} is the laminated plate stiffness in the x-direction, ρ is the density, and h is the thickness of the laminate. This velocity applies at relatively low frequencies where typical AE sensors have limited sensitivity. Note that the velocity in composite plates is dependent on direction of propagation (the numerator in Eq X2.1 changes and becomes more complex (due to additional plate stiffness terms and direction cosines) as the direction varies, and the wave is no longer purely extensional). In these cases, the mode is called quasi-extensional. This fact must be taken into account if accurate source location is to be performed. The largest displacement of this mode on the plate surfaces is in-plane, but due to the Poisson effect, there is an out-of-plane displacement propagating at this velocity as well.

X2.3.3 For the flexural wave, the velocity in the x-direction (a direction of material symmetry), C_f, given by plate theory is:

$$C_f = \left[\frac{D_{11}}{\rho h}\right]^{\frac{1}{4}} \sqrt{\omega} \tag{X2.2}$$

where $\omega = 2\pi f$ and f is the frequency, h is the laminated plate thickness, and D_{11} is the laminated plate bending stiffness in the x-direction. Note again that the velocity in composite plates is dependent on direction of propagation (note that the numerator in Eq X2.2 changes and becomes more complex—as indicated above—as the propagation direction varies with the presence of so-called quasi-flexural modes), and this fact must be taken into account if accurate source location is to be performed. As can be seen, the frequency is a variable in this equation, and thus this mode is dispersive (velocity depends on frequency). This dispersion means the pulse propagating in this mode will change shape as it propagates. The fact that the velocity varies throughout the pulse violates the usual assumption in AE source location of constant velocity pulses used by AE systems (threshold determination of arrival time) to trigger source location clocks. The largest displacement component on the plate surfaces of this mode is perpendicular to the plane of the plate.

X2.4 Information Relative to the Use of Plate Waves

X2.4.1 In thin plates only two types of waves are excited with any appreciable energy, these are the extensional plate wave and flexural plate wave. Since many of the structures monitored are of a plate shape, AE measurements can be based on theoretical foundations, which in turn, yield greater understanding of the detected signals.

X2.4.2 Experiments with thin composite plates have shown that for plate wave theory to apply, the thickness must be smaller than about one third of the wavelengths being measured. Depending on the source rise time, the one-third value can change. For longer source rise times it will be larger and for shorter source rise times it will be smaller. If this condition for plate waves is not violated, then in a thin plate typically only the two lowest modes (S_0 and A_0) have significant amplitudes.

X2.4.3 Compute the wavelength from (wavelength) = (velocity)/(frequency). When the velocity is in m/s and frequency is in Hz, the length will be in meters. The in-plane shear velocity for the medium divided by the highest frequency with appreciable amplitude in the AE signals will provide a reasonable approximation of the shortest wavelength. This wavelength can then be compared with the plate thickness. The in-plane bulk shear velocity, c_T, can be determined from $c_T = \sqrt{}G_{12}/\rho$, where G_{12} is the in-plane shear modulus of the composite lamina (subscript 1 is the fiber direction).

X2.4.4 The first arrival of an extensional wave in carbon/epoxy can travel at up to about 8 km/s [26,247 ft/s], (fiber direction in a unidirectional composite) depending on the layup of the material and the propagation direction. The fastest first arrival extensional wave velocity in more complex layups has been observed at about 6 km/s [78,700 ft/s]. And generally the first arrival of the flexural mode travels at a little less than about a quarter of the velocity of the extensional mode in its maximum velocity direction (Note, in a thin aluminum plate these mode differences in velocity only have a ratio of a little less than about half). A typical value for first arrival of the flexural mode in a carbon/polymer composite is about 1.6 to 1.7 km/s [21,000 to 22,300 ft/s], with only small changes due to different layups.[6]

X2.4.5 Near the source the extensional wave and flexural wave are mixed together. Farther from the source, say 10 to 20 times the plate thickness the extensional mode (complete pulse travels at the same velocity according to plate theory) will arrive well before the first arrival of the flexural mode.

X2.4.6 The flexural mode changes shape and lengthen as it propagates. In exact 3D theory, the extensional mode also changes shape and lengthens as it propagates as well.

X2.4.7 In composite materials, a detectable flexural wave propagates further than the extensional wave because it contains larger low frequency components (since there is less material attenuation at low frequencies).

X2.4.8 To study typical waveforms in a test sample, use a wideband sensor and preamplifier connected to a waveform recorder/digital oscilloscope to set up a test.

X2.4.9 It may be difficult to distinguish the two modes with a resonant transducer (unless the propagation distance is known and time frequency analysis is applied along with group velocity results).

X2.4.10 The two modes are part of the same event, but the flexural mode can produce a large amplitude signal which can look like a new event at longer propagation distances.

X2.4.11 Since AE sources radiate in all direction, there may be multiple paths for the waves from a single source to each AE sensor in plates with small transverse dimensions.

X2.4.12 In relatively thin plates there are two modes that dominate the waves and the resultant AE signals. Which of these two modes that is most dominate for a particular AE event depends on the depth of the point source below the plate surface, the lay-up, and the frequency sensitivity of the sensor (assuming an appropriate electronic bandwidth). For sources nearer one of the plate surfaces, the A_0, anti-symmetric, mode typically dominates the AE wave energy. This means that a later portion of the signal will have a higher amplitude than the initial portion. The converse applies for sources very near the plate mid-plane. In this case, the S_0, symmetric, mode carries more AE wave energy, and the initial portion of the signal typically will have an amplitude that matches or exceeds that of the latter portions of the signal. While this situation is influenced by the sensor frequency response and the electronic bandwidth used, it will have an effect on which portion of the AE signal will first penetrate the AE system threshold (providing a signal arrival time). For the same AE source, the differences in arrival time for the two different portions of the signal will be large since the velocities of the first arrivals of the two modes vary by nearly a factor of four.

X2.4.13 The thickness of the composite plate has two effects on the AE waves in the test sample.

X2.4.13.1 As the thickness of a particular composite plate (same materials and lay-up) decreases, the frequencies of the most energetic portions of the two modes increase approximately linearly. The converse occurs as the test plate thickness increases. This effect can most clearly be observed if the AE testing is done using non-resonant sensors with a sufficiently small diameter sensor element (sensor aperture).

X2.4.13.2 Also as the plate thickness increases, the amplitudes of the AE waves decrease due to the fact that the elastic energy released by the source is "spread" over more material. This spreading primarily occurs in the epicenter region of the sample where the geometric spreading (in three dimensions) of the signal is proportional to $1/r$, where r is the distance from the source. The typical maximum value of r for this dependence is $t/2 \leq r \leq t$, where t is the thickness of the composite plate.

X2.5 Source Location with Threshold-Based Systems with Plate Wave AE

X2.5.1 For some test situations, plate wave AE can be used to increase the location resolution of conventional AE instrumentation.

X2.5.2 For example, accurate linear location with the threshold triggered clock system in AE systems can be obtained by ensuring that it is always the arrival of the extensional mode that triggers the system. This can be accomplished by using a high gain and low threshold (the necessary threshold and gain can be determined at the beginning of the test by using a digital oscilloscope) when the extensional mode has sufficient amplitude.

X2.6 Source Location Based on the Dispersive Flexural Wave

X2.6.1 A source location method which takes into account the dispersive nature of this mode can be used. The method needs to be independent of threshold or gain settings since this mode changes shape as it propagates.

X2.6.2 Generally, a waveform-based AE system should be used in this case. And wideband sensors are generally required.

X2.6.3 More sophisticated signal processing techniques (such as cross-correlating the captured signals with a signal of known frequency or alternatively using a wavelet transform or the Choi Williams Distribution) are used to determine the arrival times of the particular frequency component of the flexural mode whose group velocity is known from theory or experiment.

X2.6.4 In the flexural pulse the frequency components look somewhat sinusoidal with the higher frequencies appearing on the digitally stored waveform ahead of the lower frequencies. The amplitude gradually increases with decreasing frequency provided the sensor has good low frequency response.

X2.6.5 If the composite plate has a quasi-isotropic lay-up, then for each mode their group velocities as a function of frequency do not change significantly as the propagation direction changes. Hence, conventional source location algorithms for two-dimensional location in isotropic materials can be used along with the arrival times obtained by the method in X2.6.3.

X2.6.6 If the composite plate is not quasi-isotropic, more complex algorithms must be used to account for the velocity changes with propagation direction.

X2.7 Identification of Composite AE Signal Sources in Composite Plates

X2.7.1 Identification of the type of source for each AE signal (by signal characteristics or other means) is generally not necessary for most AE applications.

X2.7.2 *Test Samples with Large Transverse Dimensions*— Using modeled AE signals in isotropic thin metal plate samples, different sources have been identified using the changes in the source-dependent radiation patterns. The technique depended on the use of wideband sensors to identify energetic portions of the two fundamental modes at different radiation angles. The technique applied even when the depth of the source changed. This technique could possibility be extended to apply to some composites, but to date this has not been shown.

X2.7.3 In the case of composite materials, the rapid growth of one source type can be identified by signal characteristics. This source is a delamination source, and it can be identified by AE signals with long durations with approximately constant amplitude of the envelope of the signal. The reason for this identifiable signal characteristic is that the rapid growth of this AE source is made up of a series of very closely spaced in time point AE sources which operate as the delamination initiates and very rapidly grows.[11]

X2.7.4 Techniques for acoustic emission signal identification have been developed using feature-based pattern recognition techniques.[12]

X2.8 Wave Propagation and Pencil Lead Breaks

X2.8.1 PLBs create the possibility to use them to provide information so as to estimate initial values of threshold and sensor spacing when composite samples of different fibers, matrices, lay-ups and thickness are to be tested along with different sensors and bandpasses. The PLB provides a common source that can be "moved" from one test situation, where the test parameters have been already determined, to another new situation. For example, by comparing the peak amplitude from a PLB at a certain distance on the previous sample (with the setup used for that sample) to the peak amplitude from a PLB at the same distance on the new sample (with the planned setup) a delta dB can be determined. This value can then be used to adjust the threshold and sensor spacing on the new sample to obtain approximately the same sensitivity.

X2.8.2 The signals from PLBs are not appropriate to demonstrate source location in composites with threshold-based arrival times due to their large amplitude, and in the case of out-of-plane PLBs the difference in the signal shape (modal emphasis of the A_0 mode relative to the S_0 mode of real AE sources) relative to real AE sources.

SUMMARY OF CHANGES

Committee E07 has identified the location of selected changes to this standard since the last issue (E2661/E2661M-10) that may impact the use of this standard.

(1) Added ISO 9712 to paragraph 6.2 and Section 2.
(2) The document was scrutinized extensively adding many small edits and some longer edits and additional text, to make the document clearer, more readable and more understandable. Technical content was not changed by these edits, only improved.

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[11] M. R. Gorman and T. H. Rytting, "Long Duration AE Events in Filament Wound Graphite/Epoxy in the 100-300 kHz Band Pass region," Proceedings of the 1st Intl. Symposium on Acoustic Emission from Reinforced Composites, Session 6, 11:05 – 11:20, SPI, pp 1-5, 1983.

[12] M.G.R. Sause , T. Müller , A. Horoschenkoff , S. Horn , "Quantification of failure mechanisms in mode-I loading of fiber reinforced plastics utilizing acoustic emission analysis," Composites Science and Technology 72, 2012, pp. 167–174.