Standard Practice for Determining Damage-Based Design Stress for Glass Fiber Reinforced Plastic (GFRP) Materials Using Acoustic Emission[1]

This standard is issued under the fixed designation E2478; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice details procedures for establishing the direct stress and shear stress damage-based design values for use in the damage-based design criterion for materials to be used in GFRP vessels and other GFRP structures. The practice uses data derived from acoustic emission examination of four-point beam bending tests and in-plane shear tests (see ASME Section X, Article RT-8).

1.2 The onset of lamina damage is indicated by the presence of significant acoustic emission during the reload portion of load/reload cycles. "Significant emission" is defined with historic index.

1.3 *Units*—The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units which are provided for information only and are not considered standard.

1.4 *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]

D790 Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials

D4255/D4255M Test Method for In-Plane Shear Properties of Polymer Matrix Composite Materials by the Rail Shear Method

D3846 Test Method for In-Plane Shear Strength of Reinforced Plastics

E543 Specification for Agencies Performing Nondestructive Testing

E976 Guide for Determining the Reproducibility of Acoustic Emission Sensor Response

E1316 Terminology for Nondestructive Examinations

E2374 Guide for Acoustic Emission System Performance Verification

2.2 *ASME Documents:*[3]

ASME Section X, Article RT-8 Test Method for Determining Damage-Based Design Criterion

ASME Section V, Article 11 Acoustic Emission Examination of Fiber-Reinforced Plastic Vessels

2.3 *Other Standards:*

ANSI/ASNT-CP-189 Qualification and Certification of Nondestructive Testing Personnel[4]

SNT-TC-1A Recommended Practice for Personnel Qualification and Certification in Nondestructive Testing[4]

NAS-410 Certification and Qualification of Nondestructive Test Personnel[5]

3. Terminology

3.1 Definitions of terms related to conventional acoustic emission are in Terminology E1316, Section B.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *historic index*—a measure of the change in MARSE (or other AE feature parameter such as AE Signal Strength) throughout an examination.

3.2.2 *knee in the curve*—a dramatic change in the slope of the cumulative AE (MARSE or Signal Strength) versus time curve.

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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.

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[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 of Mechanical Engineers (ASME), ASME International Headquarters, Three Park Ave., New York, NY 10016-5990, http://www.asme.org.

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

[5] Available from Aerospace Industries Association of America, Inc. (AIA), 1000 Wilson Blvd., Suite 1700, Arlington, VA 22209-3928, http://www.aia-aerospace.org.

3.2.3 *measured area of the rectified signal envelope (MARSE)*—a measure of the area under the envelope of the rectified linear voltage time signal from the sensor. (see ASME Section V, Article 11)

3.2.4 *significant emission*—a level of emission that corresponds to the first time during reloading that the historic index attains a value of 1.4.

4. Summary of Practice

4.1 This practice uses acoustic emission instrumentation and examination techniques during load/reloading of materials being examined, to determine the onset of significant acoustic emission. The onset of significant emission is related to the damage-based design stress by the Felicity ratio.[6,7]

5. Significance and Use

5.1 The damage-based design approach will permit an additional method of design for GFRP materials. This is a very useful technique to determine the performance of different types of resins and composition of GFRP materials in order to develop a damage tolerant and reliable design. This AE-based method is not unique, other damage-sensitive evaluation methods can also be used.

5.2 This practice involves the use of acoustic emission instrumentation and examination techniques as a means of damage detection to support a destructive test, in order to derive the damage-based design stress.

5.3 This practice is not intended as a definitive predictor of long-term performance of GFRP materials (such as those used in vessels). For this reason, codes and standards require cyclic proof testing of prototypes (for example, vessels) which are not a part of this practice.

5.4 Other design methods exist and are permitted.

6. Basis of Application

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

6.1.1 *Personnel Qualification*—If specified in the contractual agreement, 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, or a similar document and 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.

6.1.2 *Qualification of Nondestructive Agencies*—If specified in the contractual agreement, NDT agencies shall be qualified and evaluated as described in Practice E543. The applicable revision of Practice E543 shall be specified in the contractual agreement.

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

6.1.4 *Timing of Examination*—The timing of examination shall be in accordance with 12.4 unless otherwise specified.

6.1.5 *Extent of Examination*—The extent of examination shall be in accordance with Sections 9 and 10 unless otherwise specified.

6.1.6 *Reporting Criteria*—Reporting criteria for the examination results shall be in accordance with 15.1 unless otherwise specified.

7. Apparatus

NOTE 1—Refer to Fig. 1 for AE system block diagram showing key components of the AE system. It is recommended to use two AE sensors to monitor the specimen, evaluated on a per channel basis.

7.1 *AE Sensors*

7.1.1 AE sensors shall be resonant in a 100 to 300 kHz frequency band.

7.1.2 Sensors shall have a peak sensitivity greater than –77 dB (referred to 1 volt per microbar, determined by face-to-face ultrasonic examination) within the frequency range 100 to 300 kHz. Sensitivity within the 100 to 300 kHz range shall not vary more than 3 dB within the temperature range of intended use.

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

7.1.4 Sensors shall have omni-directional response, with variations not exceeding 2 dB from the peak response.

7.2 *Couplant*

7.2.1 Commercially available couplants for ultrasonic flaw detection may be used. Silicone-based high-vacuum grease has been found to be particularly suitable. Adhesives may also be used.

7.2.2 Couplant selection should be made to minimize changes in coupling sensitivity during a complete examination. Consideration should be given to the time duration of the examination and maintaining consistency of coupling throughout the examination.

7.3 *Sensor-Preamplifier Cable*

7.3.1 The cable connecting the sensor to the preamplifier shall not attenuate the sensor peak voltage in the 100 to 300 kHz frequency range more than 3 dB (6 ft (1.8 m) is a typical length). Integral preamplifier sensors meet this requirement. They have inherently short, internal, signal cables.

7.3.2 The sensor-preamplifier cable shall be shielded against electromagnetic interference. Standard low-noise coaxial cable is generally adequate.

7.4 *Preamplifier*

7.4.1 The preamplifier shall have a noise level no greater than five microvolts rms (referred to a shorted input) within the 100 to 300 kHz frequency range.

7.4.2 Preamplifier gain shall vary no more than ±1 dB within the 100 to 300 kHz frequency band and temperature range of use.

7.4.3 Preamplifiers shall be shielded from electromagnetic interference.

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[6] Ramirez, G., Ziehl, P., Fowler, T., 2004, "Nondestructive Evaluation of FRP Design Criteria with Primary Consideration to Fatigue Loading", *ASME Journal of Pressure Vessel Technology*, Vol. 126, pp. 1–13.

[7] Ziehl, P. and Fowler, T., 2003, "Fiber Reinforced Polymer Vessel Design with a Damage Approach", Journal of Composite Structures, Vol. 61, Issue 4, pp. 395-411.

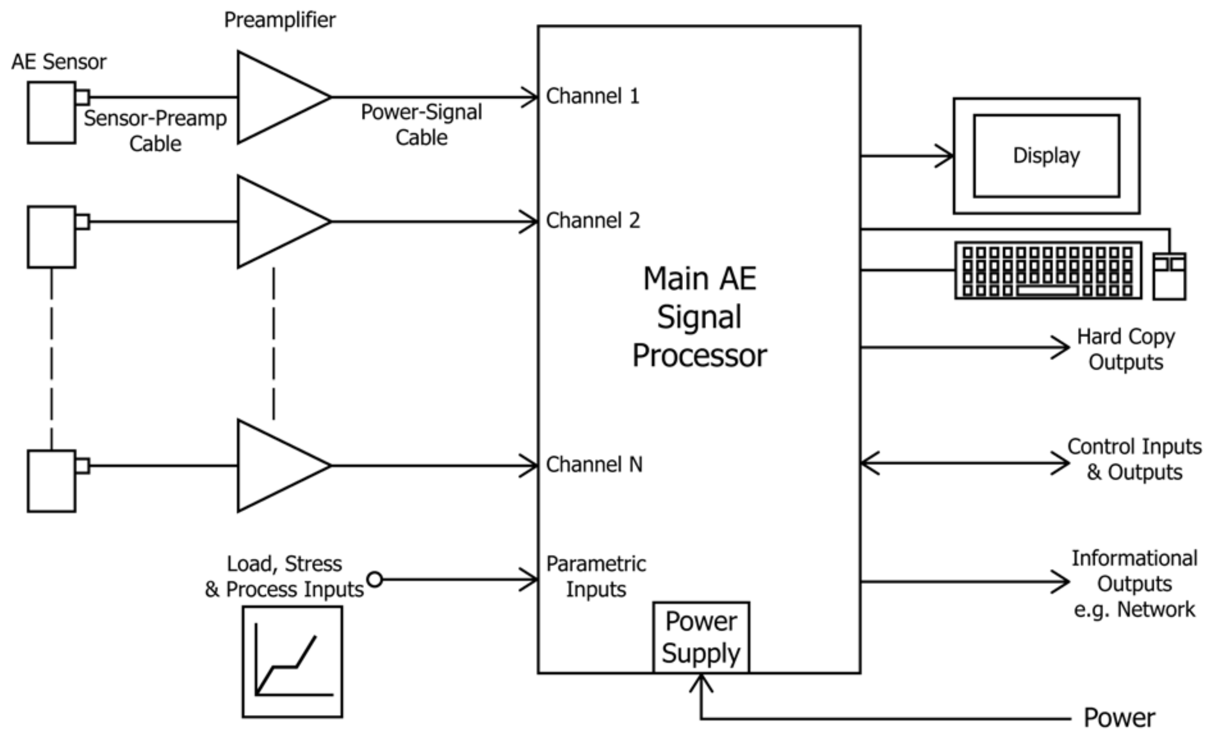

FIG. 1 AE System Block Diagram

7.4.4 Preamplifiers of differential design shall have a minimum of 40 dB common-mode rejection.

7.4.5 Preamplifiers shall include a bandpass filter with a minimum bandwidth of 100 kHz to 300 kHz. Note that the crystal resonant characteristics provide additional filtering as does the bandpass filter in the signal conditioner.

7.4.6 It is preferred that the preamplifier be mounted inside the sensor housing.

7.5 *Power-Signal Cable*

7.5.1 The cable and connectors that provide power to preamplifiers, and that conduct amplified signals to the main processor, shall be shielded against electromagnetic interference. Signal loss shall be less than 3 dB over the length of the cable.

7.6 *Power Supply*

7.6.1 A stable, grounded, power supply that meets the signal processor manufacturer's specification shall be used.

7.7 *Main Signal Processor*

7.7.1 The main processor shall have circuitry through which sensor data will be processed. It shall be capable of processing hits, hit arrival time, duration, counts, peak amplitude, and MARSE (or similar AE feature parameters such as Signal Strength) on each channel.

7.7.2 Electronic circuitry shall be stable within ±1 dB in the temperature range 40 to 100°F (4 to 38°C).

7.7.3 Threshold shall be accurate within ±1 dB.

7.7.4 MARSE shall be measured on a per channel basis and shall have a resolution of 1 % of the value obtained from a one millisecond duration, 150 kHz sine burst having an amplitude 25 dB above the data analysis threshold. Usable dynamic range shall be a minimum of 40 dB.

NOTE 2—Instead of MARSE, other AE feature parameters such as "Signal Strength" may be used.

7.7.5 Amplitude shall be measured in decibels referenced to 0 dB as 1 microvolt at the preamplifier input. Usable system dynamic range shall be a minimum of 60 dB with 1 dB resolution over the frequency band of 100 to 300 kHz, and the temperature range of 40 to 100°F (4 to 38°C). Not more than ±1 dB variation in peak detection accuracy shall be allowed over the stated temperature range.

7.7.6 Hit duration (AE signal duration) shall be accurate to ±5 µs and is measured from the first threshold crossing to the last threshold crossing of the AE signal.

7.7.7 Hit arrival time shall be recorded globally for each channel accurate to within one millisecond, minimum.

7.7.8 The system deadtime of each channel of the system shall be no greater than 200 µs.

7.7.9 The hit definition time shall be 400 µs.

7.7.10 The examination threshold shall be set at 40 dB (depending on background noise of the system setup when subjected to a constant load of 10 % or less of the estimated failure load). Threshold should remain constant during the entire examination.

8. Calibration and Verification

8.1 Annual calibration and verification of AE sensors, preamplifiers (if applicable), signal processor, and AE electronic waveform generator (or simulator) should be performed. Equipment should be adjusted so that it conforms to equipment manufacturer's specifications. Instruments used for calibrations must have current accuracy certification that is traceable to the National Institute for Standards and Technology (NIST).

8.2 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 evaluations. Each signal processor channel must respond with peak amplitude reading within ±2 dB of the electronic waveform generator output.

8.3 A system performance verification must be conducted immediately before, and immediately after, each examination. A performance verification uses a mechanical device to induce stress waves into the material under examination, at a specified distance from each sensor. Induced stress waves stimulate a sensor in the same way as emission from a flaw. Performance verifications verify performance of the entire system (including couplant). (Refer to Guide E2374 for AE system performance verification techniques).

8.3.1 The preferred technique for conducting a performance verification is a pencil lead break (PLB). Lead should be broken on the material surface at a specified distance from each sensor. The 2H lead, 0.012-in. (0.3-mm) diameter, and 0.079–0.118-in. (2 to 3-mm) long should be used (see Fig. 5 of Guide E976 and Guide E2374).

8.3.2 *Auto Sensor Test (AST)*—An electromechanical device such as a piezoelectric pulser (and sensor which contains this function) can be used in conjunction with pencil lead break (8.3.1) as a means to assure system performance. This device can be used to replace the PLB post examination, system performance verification (8.3). (Refer to Guide E2374.)

9. Test Methods

9.1 The evaluation setup, loading arrangement, and specimen dimensions for the flexure test shall be in accordance with Procedure B of Test Methods D790. Specimen thickness may be dictated by the type of laminate being tested. Otherwise, specimens will be typically ⅜-in. (9.5-mm) thick and shall have sufficient width, clearance, and overhang to permit mounting of an acoustic emission sensor. Sensors should not be mounted in the middle third of the specimen.

9.2 The evaluation setup, loading arrangement, and specimen dimensions for the in-plane shear test shall be in accordance with Procedure B of Test Method D4255/D4255M.

10. Evaluation Specimens

10.1 Specimens representative of the lamina used (or to be used) in the design (for example, a vessel) are required. This necessitates specimens of representative fiber types, constructions, and volume percentage. Specimens shall be fabricated with the resin to be used in the design (for example, a vessel). If more than one resin is used, specimens of each of the resins shall be evaluated.

10.1.1 *Flexural Specimens*—The specimens shall be fabricated as facing lamina on a random mat carrier. The random mat carrier shall have 1.5 oz (44.4 mL) per square foot chopped or random fiber, shall be 0.25 ± 0.063 in. (6.35 ± 1.6 mm) and shall be faced on each side with a minimum thickness of 0.063 in. (1.6 mm) of the lamina to be evaluated.

10.1.2 *Shear Specimens*—The specimens shall be entirely of the lamina construction being evaluated. For a lamina with unidirectional fibers, specimens shall be prepared and evaluated with the load applied in both the direction of the fibers and perpendicular to the fibers.

11. Examination Temperature

11.1 For applications with a design operating temperature between 0°F (-18°C) and 120°F (49°C), the temperature of the examination shall be within the range of 0°F (-18°C) and 120°F (49°C).

11.2 For applications with a design operating temperature above 120°F (49°C), the temperature of the examination shall be within the range of 50°F (10°C) and 120°F (49°C).

11.3 The design and examination temperatures (±5 %) shall be reported in the test results.

12. Examination Procedure

12.1 The loading procedure for determining the presence of the Felicity effect is important and is detailed in Fig. 2. Increasing the load at a constant rate of strain is acceptable.

12.2 Load shall be monitored continuously to an accuracy of ±1 % during loading and unloading. Strain can also be monitored but is not necessary for determination of the damage-based design stress.

12.3 An estimate of the ultimate load is required. Typically, this is obtained by loading a specimen directly to failure without acoustic emission monitoring. The estimate should have an accuracy of –10 to +10 %.

12.4 The loading schedule shown in Fig. 2 shall be used. Additional load/unload cycles shall be used until a Felicity ratio of less than 0.98 is obtained.

12.5 The first load shall be to 15 % of the estimated ultimate load. Each subsequent load/unload cycle is increased 5 % above the previous cycle.

12.6 Polymers are strain rate dependent and the loading should not result in a rate of load increase greater than 1 % of the estimated ultimate load per second. The procedure shall be conducted in load control.

12.7 A conditioning period of at least 12 hours is required between each loading cycle.

12.8 Load/unload cycles shall continue until the Felicity ratio falls below 0.98. This will generally occur in the linear range of mechanical behavior.

12.9 Acoustic emission shall be monitored continuously during reload to the previous maximum load. Acoustic emission can be monitored during unloading and for new increments of load, but is not used for determination of the damage-based design criterion.

12.10 It is recommended that three specimens be tested with averaging the results.

13. Data Analysis

13.1 *Overview*—The onset of significant acoustic emission shall be determined by applying historic index analysis to the

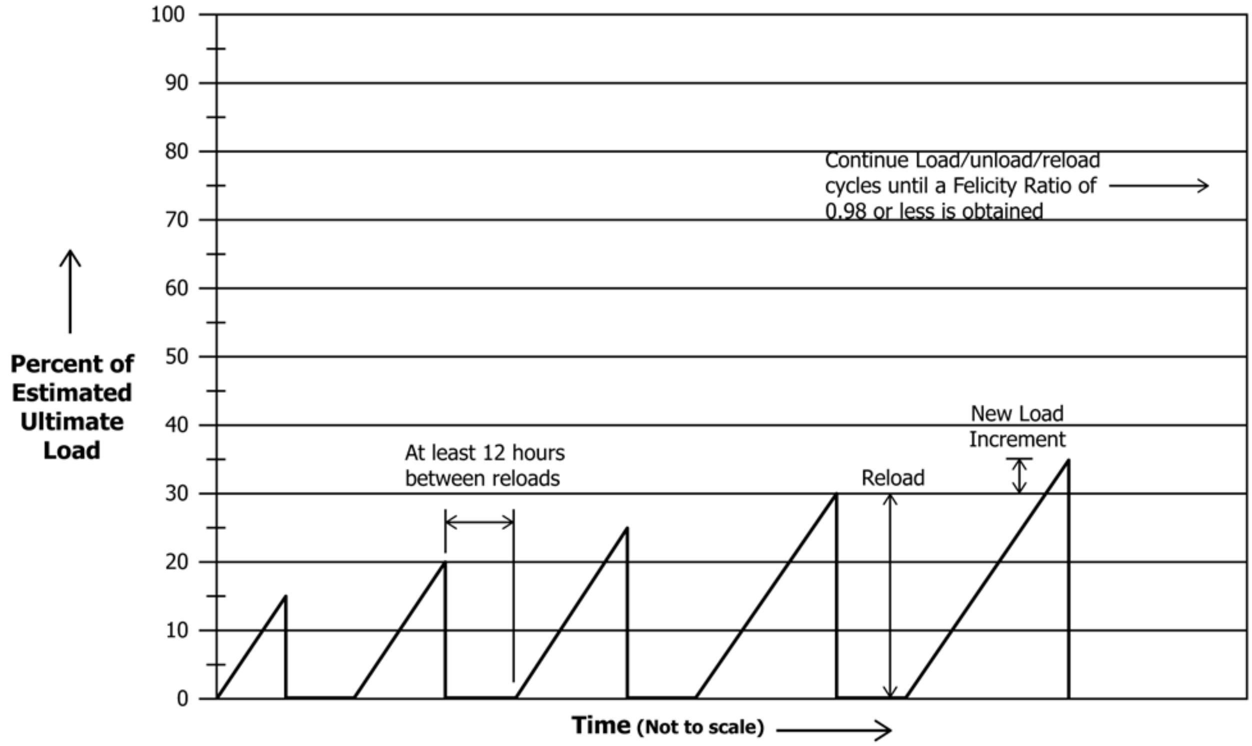

FIG. 2 Loading Schedule

cumulative MARSE versus time curve. Time must be correlated to stress. The load data should be gathered simultaneously with the acoustic emission data and displayed on the same plot as the cumulative MARSE versus time.

NOTE 3—Instead of MARSE, other AE feature parameters such as Signal Strength may be used.

13.2 *Stress*—Stress shall be calculated using the procedures given in the Test Methods D790 and Test Method D3846. The measured dimensions of the specimen shall be used for these calculations. For the flexural specimens with a facing lamina on a random mat carrier, the properties of the cross section shall be transformed relative to the elastic modulus of the facing lamina in order to take account of the different elastic moduli of the constituent layers.

13.3 *Acoustic Emission Data Set*—Acoustic emission data shall be analyzed for each reload cycle to determine if the damage-based design stress has been reached. Each cycle shall be analyzed independently of data from other reloads. AE should be analyzed on a per channel basis using the lowest damage-based design stress.

13.4 *Historic Index*—The historic index shall be used to establish the onset of significant acoustic emission. Onset of significant acoustic emission is defined as the stress when the historic index value first becomes equal to or greater than 1.4. The historic index is defined by:

$$H(t) = \frac{N}{N-K} \frac{\sum_{i=K+1}^{i=N} S_{Oi}}{\sum_{i=1}^{i=N} S_{Oi}} \quad (1)$$

$H(t)$ = the historic index at time t.
N = the number of hits (ordered by time) up to and including time t.
S_{Oi} = the MARSE value of the i*th* hit.
K = an empirically derived factor that varies with the number of hits. Values for K are given in Table 1.

TABLE 1 K Factor for Historic Index

Number of Hits, N	K
<20	Not applicable
20 to 100	0
101 to 500	0.8N
>500	N - 100

Historic index has been found to be a sensitive method of detecting a change in slope in the cumulative MARSE versus time curve. This change in slope is often referred to as the "knee in the curve". In the vicinity of the knee, the historic index will increase sharply. This will be followed by a decline in value until another knee is encountered. Historic index is particularly valuable for determining onset of new damage mechanisms and is essentially independent of specimen size. Historic index is a form of trend analysis, and is performed continuously for each hit. The greater the number of hits on a channel the more accurate will be the results. An analysis requires a minimum number of data points, and is not valid when only a small number of hits are recorded. The historic index is set to unity if a channel has 100 or fewer hits.

14. Felicity Ratio

14.1 When this loading procedure is followed, a Felicity ratio between 0.90 and 1.00 will normally be obtained. Occasionally, a lower Felicity ratio will be obtained. If the

Felicity ratio falls below 0.85, the results shall be discarded and a new test conducted. It is important to use only data from the reloading.

15. Damage-Based Design Stress

15.1 The damage-based design stress shall be taken as the maximum stress during the load cycle previous to the reload cycle that resulted in the onset of significant emission. This information should be documented in a test report as specified by the contractual agreement. The damage-based design stress should not be confused with an allowable stress. It is not intended to be used for purposes of design without appropriate modifications factors. Appropriate modification factors and design criteria are determined by and specified in the governing design codes.

16. Keywords

16.1 acoustic emission; damage based design criterion; direct stress damage-based design; composite material characterization; FRP material characterization; shear stress damage based design