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Standard Practice for Open-Hole Fatigue Response of Polymer Matrix Composite Laminates[1]

This standard is issued under the fixed designation D7615/D7615M; 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 provides instructions for modifying static open-hole tensile and compressive strength test methods to determine the fatigue behavior of composite materials subjected to cyclic tensile or compressive forces, or both. The composite material forms are limited to continuous-fiber reinforced polymer matrix composites in which the laminate is both symmetric and balanced with respect to the test direction. The range of acceptable test laminates and thicknesses are described in 8.2.

1.2 This practice supplements Test Methods D5766/D5766M and D6484/D6484M with provisions for testing specimens under cyclic loading. Several important test specimen ~~parameters (for example, fatigue force(stress) ratio)~~ parameters, for example fatigue force (stress) ratio, are not mandated by this practice; however, repeatable results require that these parameters be specified and reported.

1.3 This practice is limited to test specimens subjected to constant amplitude uniaxial loading, where the machine is controlled so that the test specimen is subjected to repetitive constant amplitude force (stress) cycles. Either engineering stress or applied force may be used as a constant amplitude fatigue variable. The repetitive loadings may be tensile, compressive, or reversed, depending upon the test specimen and procedure utilized.

1.4 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~~are not ~~be~~necessarily exact equivalents; therefore, to ensure conformance with the standard, each system shall be used independently of the ~~other. Combining~~other, and values from the two systems ~~may result in non-conformance with the standard.~~shall not be combined.

1.4.1 Within the text the inch-pound units are shown in brackets.

1.5 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D883 Terminology Relating to Plastics

D3878 Terminology for Composite Materials

D5229/D5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials

D5766/D5766M Test Method for Open-Hole Tensile Strength of Polymer Matrix Composite Laminates

D6484/D6484M Test Method for Open-Hole Compressive Strength of Polymer Matrix Composite Laminates

E4 Practices for Force Verification of Testing Machines

E6 Terminology Relating to Methods of Mechanical Testing

E83 Practice for Verification and Classification of Extensometer Systems

[1] This practice is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of Subcommittee D30.05 on Structural Test Methods.

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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.

E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process
E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods
E456 Terminology Relating to Quality and Statistics
E467 Practice for Verification of Constant Amplitude Dynamic Forces in an Axial Fatigue Testing System
E739 Practice for Statistical Analysis of Linear or Linearized Stress-Life (***S-N***) and Strain-Life (ε-***N***) Fatigue Data
~~E1309 Guide for Identification of Fiber-Reinforced Polymer-Matrix Composite Materials in Databases (Withdrawn 2015)[3]~~
~~E1434 Guide for Recording Mechanical Test Data of Fiber-Reinforced Composite Materials in Databases (Withdrawn 2015)[3]~~
E1823 Terminology Relating to Fatigue and Fracture Testing

3. Terminology

3.1 *Definitions*—Terminology D3878 defines terms relating to high-modulus fibers and their composites. Terminology D883 defines terms relating to plastics. Terminology E6 defines terms relating to mechanical testing. Terminology E1823 defines terms relating to fatigue. Terminology E456 and Practice E177 define terms relating to statistics. In the event of a conflict between terms, Terminology D3878 shall have precedence over the other standards.

NOTE 1—If the term represents a physical quantity, its analytical dimensions are stated immediately following the term (or letter symbol) in fundamental dimension form, using the following ASTM standard symbology for fundamental dimensions, shown within square brackets: [*M*] for mass, [*L*] for length, [*T*] for time, [θ] for thermodynamic temperature, and [nd] for non-dimensional quantities. Use of these symbols is restricted to analytical dimensions when used with square brackets, as the symbols may have other definitions when used without the brackets.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *constant amplitude loading, n—in fatigue*, a loading in which all of the peak values of force (stress) are equal and all of the valley values of force (stress) are equal.

3.2.2 *fatigue loading transition, n—in the beginning of fatigue loading*, the number of cycles before the force (stress) reaches the desired peak and valley values.

3.2.3 *force, P* $[MLT^{2}]$, *n*—the total force carried by a test specimen.

3.2.4 *force (stress) ratio, R [nd], n—in fatigue loading*, the ratio of the minimum applied force (stress) to the maximum applied force (stress).

3.2.5 *frequency, f* $[T^{1}]$, *n—in fatigue loading*, the number of force (stress) cycles completed in 1 s (Hz).

3.2.6 *nominal value, n*—a value, existing in name only, assigned to a measurable property for the purpose of convenient designation. Tolerances may be applied to a nominal value to define an acceptable range for the property.

3.2.7 *peak, n—in fatigue loading*, the occurrence where the first derivative of the force (stress) versus time changes from positive to negative sign; the point of maximum force (stress) in constant amplitude loading.

3.2.8 *residual strength,* $[ML^{-1}T^{-2}]$, *n*—the value of force (stress) required to cause failure of a specimen under quasi-static loading conditions after the specimen is subjected to fatigue loading.

3.2.9 *run-out, n—in fatigue*, an upper limit on the number of force cycles to be applied.

3.2.10 *spectrum loading, n—in fatigue*, a loading in which the peak values of force (stress) are not equal or the valley values of force (stress) are not equal (also known as variable amplitude loading or irregular loading).

3.2.11 *valley, n—in fatigue loading*, the occurrence where the first derivative of the force (stress) versus time changes from negative to positive sign; the point of minimum force (stress) in constant amplitude loading.

3.2.12 *wave form, n*—the shape of the peak-to-peak variation of the force (stress) as a function of time.

3.3 *Symbols:*

A = Cross-sectional area of a specimen
D = specimen hole diameter
h = specimen thickness
K = specimen chord stiffness, P/δ
K_i = specimen chord stiffness prior to fatigue cycles
K_N = specimen chord stiffness after N fatigue cycles
~~D = specimen hole diameter~~
~~h = specimen thickness~~
N = number of constant amplitude cycles
Δ_N = change in chord stiffness after N fatigue cycles
P = force carried by specimen
P^{maxq} = peak force under quasi-static loading for measurement of stiffness
P^{minq} = valley force under quasi-static loading for measurement of stiffness
w = specimen width

δ = crosshead or extensometer translation
σ^{alt} = alternating open hole stress during fatigue loading
~~σ^{ohm} = maximum cyclic open hole stress magnitude, given by the greater of the absolute values of σ^{max} and σ^{min}~~
σ^{max} = value of stress corresponding to the peak value of force (stress) under constant amplitude loading
σ^{maxq} = value of stress corresponding to the peak value of force (stress) under quasi-static loading for measurement of stiffness, given by the greater of the absolute values of σ^{max} and $0.5 \times \sigma^{min}$
σ^{mean} = mean normal stress during fatigue loading
σ^{min} = value of stress corresponding to the valley value of force (stress) under constant amplitude loading
σ^{minq} = value of stress corresponding to the valley value of force (stress) under quasi-static loading for measurement of stiffness, given by the greater of the absolute values of σ^{min} and $0.5 \times \sigma^{max}$
σ^{ohm} = maximum cyclic open hole stress magnitude, given by the greater of the absolute values of σ^{max} and σ^{min}

4. Summary of Practice

4.1 In accordance with Test Methods D5766/D5766M or D6484/D6484M, but under constant amplitude fatigue loading, perform a uniaxial test of an open-hole specimen. Cycle the specimen between minimum and maximum axial forces (stresses) at a specified frequency. At selected cyclic intervals, determine the specimen stiffness from a force versus deformation curve obtained by quasi-statically loading the specimen through one tension, compression, or tension-compression cycle as applicable. Determine the number of force cycles at which failure occurs (or at which a predetermined change in specimen stiffness is ~~observed),~~ observed) for a specimen subjected to a specific force (stress) ratio and stress magnitude.

5. Significance and Use

5.1 This practice provides supplemental instructions for using Test Methods D5766/D5766M or D6484/D6484M to obtain open-hole fatigue data for material specifications, research and development, material design allowables, and quality assurance. The primary property that results is the fatigue life of the test specimen under a specific loading and environmental condition. Replicate tests may be used to obtain a distribution of fatigue life for specific material types, laminate stacking sequences, environments, and loading conditions. Guidance in statistical analysis of fatigue data, such as determination of linearized stress life (S-N) curves, can be found in Practice E739.

5.2 This practice can be utilized in the study of fatigue damage in a polymer matrix composite open-hole specimen such as the occurrence of microscopic cracks, fiber fractures, or delaminations. The change in strength associated with fatigue damage may be determined by discontinuing cyclic loading to obtain the static strength using Test Methods D5766/D5766M or D6484/D6484M.

NOTE 2—This practice may be used as a guide to conduct variable amplitude loading. This information can be useful in the understanding of fatigue behavior of composite structures under spectrum loading conditions, but is not covered in this standard.

5.3 Factors that influence open-hole fatigue response and shall therefore be reported include the following: material, methods of material fabrication, accuracy of lay-up, laminate stacking sequence and overall thickness, specimen geometry, specimen preparation (especially of the hole), specimen conditioning, environment of testing, type of support fixture, specimen alignment and gripping, test frequency, force (stress) ratio, normal stress magnitude, void content, and volume percent reinforcement. Properties that result include the following:

5.3.1 Specimen stiffness versus fatigue life curves for selected normal stress values.

5.3.2 Normal stress versus specimen stiffness curves at selected cyclic intervals.

5.3.3 Normal stress versus fatigue life curves for selected stress ratio values.

6. Interferences

6.1 *Force (Stress) Ratio*—Results are affected by the force (stress) ratio under which the tests are conducted. Experience has demonstrated that reversed (tension-compression) force ratios are critical for fatigue-induced damage in open hole specimens, with fully reversed tension-compression (R = –1) being the most critical force ~~ratio~~ ratio. ~~(1)~~[3]~~.~~

6.2 *Loading Frequency*—Results are affected by the loading frequency at which the test is conducted. High cyclic rates may induce heating within the specimen that may cause variations in specimen temperature and properties of the composite as discussed in 11.3.2. The temperature of the specimen should be monitored, and the frequency should be kept low enough to avoid significant temperature variations, unless that is a factor to be studied during the test. For example, loading frequencies up to ~~5Hz~~5 Hz have been used successfully. Varying the cyclic frequency during the test is generally not recommended, as the response may be sensitive to the frequency utilized and the resultant thermal history.

6.3 *Environment*—Results are affected by the environmental conditions under which the tests are conducted. Laminates tested in various environments can exhibit significant differences in both strength and failure mode. Experience has demonstrated that

[3] ~~The last approved version of this historical standard is referenced on www.astm.org.~~Han, H., Bartley-Cho, J., and Lim, S., "The Effect of Loading Parameters on Fatigue of Composite Laminates, Part II," Report No. DOT/FAA/AR-96/76, U.S. Department of Transportation, Washington, DC, 1997.

elevated temperature, humid environments are generally critical for open hole fatigue-induced ~~damage~~damage.[3] ~~(1).~~However, critical environments must be assessed independently for each material system, stacking sequence, and loading condition tested.

6.4 *Method of Stiffness Measurement*—Results are affected by the method used to monitor specimen stiffness. Force versus deformation data provide an indication of specimen stiffness change due to damage formation. However, the accuracy of such measurements is affected by factors such as strain indicator accuracy, signal noise, ~~gage~~gauge length and extensometer slippage, extensometer placement/location, grip slippage, ~~and~~ load frame stiffness (for crosshead deflection data), and so forth.

6.5 *Hole Preparation*—Results are affected by the hole preparation procedures.

6.6 *Other*—Additional sources of potential data scatter are documented in Test Methods D5766/D5766M and D6484/D6484M.

7. Apparatus

7.1 *General Apparatus*—General apparatus shall be in accordance with Test Method D5766/D5766M Configuration A for tension-tension fatigue loading, and in accordance with Test Method D6484/D6484M Procedure A for tension-compression and compression-compression fatigue loading. The micrometer or ~~gage~~gauge used shall be capable of determining the hole diameter to ~~± 0.025 mm [± 0.001~~ ±0.025 mm [±0.001 in.].

7.2 *Testing Machine*—In addition to the requirements described in Test Methods D5766/D5766M or D6484/D6484M, the testing machine shall be in conformance with Practice E467 and shall satisfy the following requirements:

7.2.1 *Drive Mechanism and Controller*—The velocity of the movable head shall be capable of being regulated under cyclic force (stress) conditions. The drive mechanism and controller shall be capable of imparting a continuous loading wave form to the specimen. It is important to minimize drift of the fatigue loading away from the maximum and minimum values. Achieving such accuracy is critical in the development of reliable fatigue life data since small errors in loading may result in significant errors in fatigue life. It is recommended that the test controller be equipped with a Test Amplitude controller, capable of monitoring the fatigue forces at least once every three cycles.

7.2.2 *Force Indicator*—The force indicator shall be in compliance with ~~Practice~~Practices E4. The fatigue rating of the force indicator shall exceed the forces at which testing will take place. Additionally, this practice recommends compliance with Practice E467 for the development of a system dynamic conversion for the verification of specimen forces to within ~~1 %~~ 1 % of true forces.

7.2.3 *Extensometers*—The extensometer ~~gage~~gauge length shall be 25 mm [1.0 in.]. Extensometers shall satisfy, at a minimum, Practice E83, Class B-1 requirements for the strain range of interest, and shall be calibrated over that range in accordance with Practice E83. The extensometers shall be essentially free of intertia lag at the specified speed of testing.

7.2.4 *Grips*—As described in Test ~~Methods~~Method D5766/D5766M for tension-tension fatigue loading or Test Method D6484/D6484M Procedure A for tension-compression and compression-compression fatigue loading, where use of hydraulic grips is recommended for fatigue loading. The grips shall have sufficient fatigue rating for forces at which testing will take place.

7.3 *Support Fixture*—If compressive forces are applied, either during fatigue loading or during quasi-static loading to determine residual strength or monitor specimen stiffness, a support fixture shall be used to stabilize the specimen. The support fixture shall be in accordance with that described in Test Method D6484/D6484M.

7.4 *Thermocouple and Temperature Recording Devices,* capable of reading specimen temperature to ~~± 0.5°C [± 1.0°F].~~ ±0.5 °C [±1.0 °F].

8. Sampling and Test Specimens

8.1 *Sampling*—For statistically significant data, the procedures outlined in Practice E122 should be consulted. From the number of tests selected a statistically significant distribution of data should be obtained for a given material, stacking sequence, environment, and loading condition.

8.1.1 *Sample Size for S-N Curve*—The recommended minimum number of specimens in the development of S-N data is described in Table 1. A minimum of three different force (stress) levels is recommended in development of S-N data. For additional procedures consult Practice E739.

8.2 *Geometry*—In addition to the requirements described in Test Methods D5766/D5766M and D6484/D6484M, the specimen geometry shall satisfy the following requirements:

TABLE 1 Number of Specimens Required for Each S-N Curve

Type of Test	Minimum Number of Test Specimens
Preliminary and exploratory	6
Research and development testing	12
Design allowables data	24
Reliability data	24

8.2.1 *Stacking Sequence*—The stacking sequence should be evaluated for free edge effects to minimize the likelihood of edge delamination initiation.

8.2.2 *Specimen Configuration*—The test specimen configuration shall be in accordance with Test Methods D5766/D5766M Configuration A for tension-tension loading or D6484/D6484M for tension-compression and compression-compression loading.

8.3 *Specimen Preparation*—Specimens shall be prepared in accordance with Test Method D5766/D5766M or Test Method D6484/D6484M. Special care should be taken to ensure that specimen edges are sufficiently free of obvious flaws as determined by visual inspection. Such flaws may lead to premature failure due to edge delamination.

9. Calibration

9.1 The accuracy of all measuring equipment shall have certified calibrations that are current at the time of use of the equipment.

10. Conditioning

10.1 The recommended pre-test condition is effective moisture equilibrium at a specified relative humidity as established by Test Method D5229/D5229M; however, if the test requestor does not explicitly specify a pre-test conditioning environment, no conditioning is required and the test specimens may be tested as prepared.

10.2 The pre-test specimen conditioning process, to include specified environmental exposure levels and resulting moisture content, shall be reported with the test data.

NOTE 3—The term moisture, as used in Test Method D5229/D5229M, includes not only the vapor of a liquid and its condensate, but the liquid itself in large quantities, as for immersion.

10.3 If no explicit conditioning process is performed, the specimen conditioning process shall be reported as "unconditioned" and the moisture content as "unknown."

10.4 Maintaining testing environment is critical to obtaining consistent fatigue data since testing for long periods of time (days or weeks) is not uncommon. For unattended tests, ~~it is desirable to monitor the test system~~ the test environment shall be monitored so that unintended changes in the test environment result in suspension of the test. Report the testing environment for the duration of the test.

11. Procedure

11.1 *Parameters to Be Specified Prior to Test:*

11.1.1 The specimen sampling method, specimen type and geometry, minimum and maximum test forces (stresses) σ^{min} and σ^{max} for each test, force (stress) ratio for each test, test frequency and wave form of the fatigue loading. For the purpose of development of an S-N curve, all specimens shall be tested at the same frequency and wave form unless that is a factor to be studied in the test.

11.1.2 Fatigue cycle counts at which stiffness is to be measured, method of measuring stiffness, quasi-static peak and valley forces for stiffness measurement (if applicable), stiffness level at which fatigue loading shall cease, and run-out cycles.

NOTE 4—Fatigue damage accumulation curves are "S" shaped requiring more data points at earlier cycles and again closer to failure (the latter requires some estimate of N at failure) to capture the damage accumulation behavior. For example, during a 2 million cycle test, stiffness may be checked at the following intervals: N = 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, 10 000, 20 000, 50 000, and every 100 000 cycles thereafter. The final interval is typically constant and should be one order of magnitude less than the anticipated N at failure.

11.1.3 All other parameters documented in Test Methods D5766/D5766M or D6484/D6484M.

11.2 *General Instructions:*

11.2.1 Any deviations from these procedures, whether intentional or inadvertent, shall be reported.

11.2.2 Perform general instructions for conditioning, measurement, cleaning, and assembly in accordance with Test Methods D5766/D5766M or D6484/D6484M.

11.3 *Test Procedure:*

11.3.1 *Supported Specimen Installation*—If the specimen is to be tested in tension-compression or compression-compression fatigue loading, a support fixture in accordance with that described in Test Method D6484/D6484M shall be used to stabilize the specimen. Install the test specimen into the support fixture as described in Test Method D6484/D6484M.

11.3.2 *Temperature Monitoring*—Attach temperature recording device in a manner not to influence the dynamic response of the specimen. The device may be attached to the specimen using adhesive, tape, or a spring clip; when utilizing a spring clip, use insulating material to isolate the temperature recording device from the spring clip. The temperature of the specimen shall be monitored, and the frequency should be kept low enough to avoid significant temperature variations, unless that is a factor to be studied in the test. Caution is recommended when selecting loading frequencies; high cyclic rates may cause variations in specimen temperature and properties of the composite. For some material systems a change in ~~10°C [18°F]~~10 °C [18 °F] has demonstrated measurable degradation of material properties.

NOTE 5—When testing a conditioned specimen at elevated temperature with no fluid exposure control, the percentage moisture loss of the specimen prior to test completion may be estimated by placing a conditioned traveler coupon of known weight within the test chamber at the same time the specimen is placed in the chamber. Upon completion of the test, the traveler coupon is removed from the chamber, weighed, and the percentage weight loss calculated and reported. It should be noted that specimen moisture loss may differ from the traveler moisture loss due to cyclic loading-induced heating of the specimen.

11.3.3 *Specimen Insertion*—In accordance with Test Method D5766/D5766M Configuration A or Test Method D6484/D6484M Procedure A, insert the specimen (for unsupported specimens) or the fixture (for supported specimens) into the test machine.

NOTE 6—Monitor the specimen for the occurrence of slippage or crushing as a result of the grips or fixture. Should either slippage or crushing occur and lead to premature specimen failure, this data should not be reported as valid.

11.3.4 *Extensometer Installation*—If an extensometer is being used to measure deformation data, attach extensometer(s) to the edges of the specimen in accordance with Test Method D5766/D5766M or Test Method D6484/D6484M.

11.3.5 *Quasi-Static Loading*—If force versus deformation data is being used to determine stiffness degradation, perform an initial quasi-static loading cycle.

11.3.5.1 *Quasi-Static Forces*—The quasi-static tension and compression forces shall be those corresponding to σ^{maxq} and σ^{minq} as defined in 3.3.

11.3.5.2 *Loading*—For tension-tension and tension-compression fatigue specimens, from zero force, apply tensile force to the specimen quasi-statically up to the force (stress) corresponding to σ^{maxq}, then return to zero force. For tension-compression and compression-compression fatigue specimens, apply compressive force to the specimen up to the force (stress) corresponding to σ^{minq}, then return to zero force. Force (stress) versus crosshead deflection and extensometer deflection shall be recorded during the quasi-static force cycle. Hysteresis curves, similar to those shown in Fig. 1, should be observed after graphically plotting the force (stress) versus deflection data. The quasi-static loading should be conducted under force control with a low loading rate (such that a typical hysteresis cycle takes approximately 20 to 30 s to complete). A sampling rate of 2 to 3 data recordings per second, and a target minimum of 50 data points per hysteresis cycle, are recommended.

11.3.5.3 *Extensometer Removal*—Remove extensometer(s) from the specimen prior to fatigue loading.

11.3.6 *Fatigue Loading:*

11.3.6.1 *Method A (Amplitude Loading)*—This approach of transitioning force to the specimen consists of quasi-statically increasing the force until reaching the desired mean force (stress), in other words the set point, and slowly increasing the force (stress) amplitude, in other words the span, until the desired peak and valley values are obtained. In this approach, a fatigue loading transition occurs before the desired peak and valley values are reached. The number of loading cycles corresponding to this transition shall be reported.

11.3.6.2 *Method B (Direct Loading)*—This approach of transitioning force to the specimen consists of quasi-statically increasing the force to either the maximum or minimum force (stress) followed by immediate cycling between maximum and minimum force using a haversine wave form (for which the valley values will not decrease below the minimum force). This approach eliminates the fatigue loading transition associated with amplitude loading and is only possible with modern signal generators and controllers.

11.3.6.3 *Monitoring Force*—Following the fatigue force transition, the peak and valley force values should be monitored periodically. If required, the settings of the force controller should be adjusted to achieve the desired loading. It is common for the peak and valley force values to drift during fatigue loading due to changes in compliance of the specimen. Report instances in which the loading was not within 2 % of the desired peak and valley values.

11.4 *Stiffness Measurement:*

11.4.1 *Halt Fatigue Loading*—After a prescribed number of fatigue cycles have been conducted, halt the fatigue loading and return the specimen to zero force.

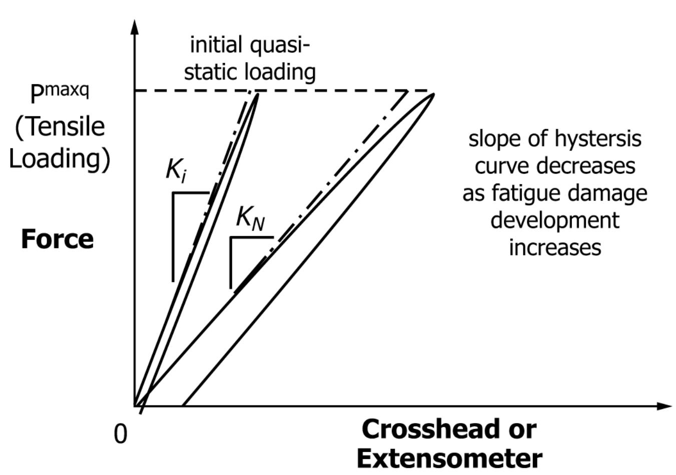

FIG. 1 Typical Tensile Force versus Deflection Plots depicting Hystersis Curve Shape and Parameters