INTERNATIONAL

Designation: D6873/D6873M − 17

Standard Practice for Bearing Fatigue Response of Polymer Matrix Composite Laminates[1]

This standard is issued under the fixed designation D6873/D6873M; 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 bearing test methods to determine the fatigue behavior of composite materials subjected to cyclic bearing forces. 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 Method D5961/D5961M with provisions for testing specimens under cyclic loading. Several important test specimen parameters (for example, fastener selection, fastener installation method, and 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 are not exact equivalents; therefore, each system must be used independently of the other. Combining values from the two systems may result in nonconformance with the standard.

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 and health 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

D5961/D5961M Test Method for Bearing Response of Polymer Matrix Composite Laminates

E4 Practices for Force Verification of Testing Machines

E6 Terminology Relating to Methods of Mechanical Testing

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

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

[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.

Current edition approved April 1, 2017. Published April 2017. Originally approved in 2003. Last previous edition approved in 2014 as D6873/D6873M – 08(2014). DOI: 10.1520/D6873_D6873M-17.

[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.

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 *bearing force, P [MLT^{-2}], n*—the total force carried by a bearing coupon.

3.2.2 *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.

3.2.3 *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.

3.2.4 *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 *hole elongation, ΔD [L], n*—the permanent change in hole diameter in a bearing coupon caused by damage formation, equal to the difference between the hole diameter in the direction of the bearing force after a prescribed loading and the hole diameter prior to loading.

3.2.7 *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.

3.2.8 *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.

3.2.9 *residual strength, [MLT^{-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.

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

3.2.11 *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).

3.2.12 *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.

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

3.3 *Symbols:*

d = fastener or pin diameter
D = specimen hole diameter
D_i = measured hole diameter prior to fatigue loading
D_N = measured hole diameter after N fatigue cycles
h = specimen thickness
k = calculation factor used in bearing equations to distinguish single-fastener tests from double-fastener tests
K_i = joint stiffness prior to fatigue loading
K_N = joint stiffness after N fatigue cycles
N = number of constant amplitude cycles
P = force carried by specimen
P^{max} = greater of the absolute values of the peak and valley values of force
P^{min} = lesser of the absolute values of the peak and valley values of force
δ = crosshead or extensometer translation
δ_i = fastener translation prior to fatigue loading
δ_N = fastener translation after N fatigue cycles
δ_{Nc} = crosshead or extensometer displacement at zero force after quasi-static compressive loading
δ_{Nt} = crosshead or extensometer displacement at zero force after quasi-static tensile loading
ΔD_N = hole elongation after N fatigue cycles
ΔK_N = percent reduction in joint stiffness after N fatigue cycles
ΔP = change in force over joint stiffness range under quasi-static loading
$\Delta\delta$ = change in crosshead or extensometer displacement over joint stiffness range under quasi-static loading
σ^{alt} = alternating bearing stress during fatigue loading
σ^{brm} = maximum cyclic bearing 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 hole elongation and joint stiffness, given by the greater of the absolute values of σ^{max} and $0.5 \times \sigma^{min}$
σ^{mean} = mean bearing 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 hole elongation and joint stiffness, given by the greater of the absolute values of σ^{min} and $0.5 \times \sigma^{max}$

4. Summary of Practice

4.1 In accordance with Test Method D5961/D5961M, but under constant amplitude fatigue loading, perform a uniaxial test of a bearing specimen. Cycle the specimen between minimum and maximum axial forces (stresses) at a specified frequency. At selected cyclic intervals, determine the hole elongation either through direct measurement or from a force (stress) versus deformation curve obtained by quasi-statically loading the specimen through one tension-compression cycle. If hole elongation is determined from a force (stress) versus deformation curve, also determine the percent joint stiffness reduction using the force versus deformation data. Determine the number of force cycles at which failure occurs, or at which a predetermined hole elongation or percent joint stiffness reduction is achieved, for a specimen subjected to a specific force (stress) ratio and bearing stress magnitude.

5. Significance and Use

5.1 This practice provides supplemental instructions for using Test Method D5961/D5961M to obtain bearing 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 bearing specimen. The loss in strength associated with fatigue damage may be determined by discontinuing cyclic loading to obtain the static strength using Test Method D5961/D5961M.

NOTE 2—This practice may be used as a guide to conduct spectrum 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 bearing 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), fastener-hole clearance, fastener type, fastener geometry, fastener installation method, fastener torque (if appropriate), countersink depth (if appropriate), specimen conditioning, environment of testing, time at temperature, type of mating material, number of fasteners, type of support fixture, specimen alignment and gripping, test frequency, force (stress) ratio, bearing stress magnitude, void content, and volume percent reinforcement. Properties that result include the following:

5.3.1 Hole elongation versus fatigue life curves for selected bearing stress values.

5.3.2 Percent joint stiffness reduction versus fatigue life curves for selected bearing stress values.

5.3.3 Bearing stress versus hole elongation curves at selected cyclic intervals.

5.3.4 Bearing stress versus percent joint stiffness reduction curves at selected cyclic intervals.

5.3.5 Bearing stress versus fatigue life curves for selected hole elongation values.

5.3.6 Bearing stress versus fatigue life curves for selected percent joint stiffness reduction values.

6. Interferences

6.1 *Force (Stress) Ratio*—Results are affected by the force (stress) ratio under which the tests are conducted. Specimens loaded under tension-tension or compression-compression force (stress) ratios develop hole elongation damage on one side of the fastener hole, whereas specimens loaded under tension-compression force (stress) ratios can develop damage on both sides of the fastener hole. Experience has demonstrated that reversed (tension-compression) force ratios are critical for bearing fatigue-induced hole elongation, with fully reversed tension-compression ($R = -1$) being the most critical force ratio (**1-3**).[3]

6.2 *Loading Frequency*—Results are affected by the loading frequency at which the test is conducted. High cyclic rates may induce heating due to friction within the joint, and may cause variations in specimen temperature and properties of the composite. 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 *Fastener Torque/Pre-load*—Results are affected by the installed fastener pre-load (clamping pressure). Laminates can exhibit significant differences in hole elongation behavior and failure mode due to changes in fastener pre-load under both tensile and compressive loading. Experience has demonstrated that low fastener torque/clamp-up is generally critical for bearing fatigue-induced hole elongation. (**1, 2, 4**). It should be noted that in some instances, low torque testing of single shear specimens has proven unsuccessful due to loosening of the fastener nut/collar during fatigue loading caused by deformation of the pin/bolt.

6.4 *Debris Buildup and Removal*—Results are affected by the buildup of fiber-matrix debris resulting from damage associated with hole elongation, and whether such debris is removed during the test. The presence of debris may mask the actual degree of hole elongation, and can increase both the friction force transfer and temperature within the specimen under fatigue loading. Experience has demonstrated that non-reversed force ratios (especially compression-compression force ratios) exhibit greater debris buildup than reversed force ratios. Fastener and debris removal can facilitate a more accurate measurement of hole elongation (**1, 2, 4**). In general, removing fastener(s) and cleaning the specimen hole(s) prior to measurement is recommended to ensure conservatism of hole elongation data to account for the potential removal of debris over time (due to fluid exposure, for example). However, fastener and debris removal during the test may result in an unrepresentative measurement of hole elongation growth behavior; thus, fastener and debris removal requirements shall be specified by the test requestor. Fasteners such as blind bolts and lockbolts are not practical to remove during fatigue testing; use of such fasteners may preclude cleaning of the specimen hole(s).

6.5 *Environment*—Results are affected by the environmental conditions under which the tests are conducted. Laminates tested in various environments can exhibit significant differences in hole elongation behavior, joint stiffness response and failure mode. Experience has demonstrated that elevated temperature, humid environments are generally critical for

[3] The boldface numbers in parentheses refer to the list of references at the end of this standard.

bearing fatigue-induced hole elongation (**1-4**). However, critical environments must be assessed independently for each material system, stacking sequence, and torque condition tested.

6.6 *Fastener-Hole Clearance*—Bearing fatigue test results are affected by the clearance arising from the difference between hole and fastener diameters. Small changes in clearance can change the number of cycles at which hole elongation initiates, and can affect damage propagation behavior (**1**). For this reason, both the hole and fastener diameters must be accurately measured and recorded. A typical aerospace tolerance on fastener-hole clearance is +75/-0 µm [+0.003/-0.000 in.] for structural fastener holes.

6.7 *Fastener Type/Hole Preparation*—Results are affected by the geometry and type of fastener utilized (for example, lockbolt, blind bolt) and the fastener installation procedures. Results are also affected by the hole preparation procedures.

6.8 *Method of Hole Elongation and Joint Stiffness Measurement*—Results are affected by the method used to monitor hole elongation and joint stiffness. Direct measurement of hole elongation permits an accurate examination of the extent of damage and elongation local to the hole surface. However, the measured elongation may not be uniform through the thickness of the laminate and may be uneven along the surface of the hole. Additionally, fasteners such as blind bolts and lockbolts are not practical to remove during fatigue testing; use of such fasteners precludes direct measurement of hole elongation. Force versus deformation data provide an "average" through-thickness measurement of hole elongation, as well as an indication of joint stiffness degradation due to damage formation. However, the accuracy of such measurements for hole elongation is affected by factors such as strain indicator accuracy, signal noise and slippage, grip slippage (for crosshead deflection data), friction within the joint specimen, fastener deformation, bearing deformation of load plates, and so forth. In some circumstances, it may be more useful and appropriate to monitor joint stiffness rather than hole elongation, for example when fatigue damage to both the composite laminate(s) and fastener(s) may be expected, or when testing joints with fasteners with high clamp-up forces (for example, lockbolts) which tend to exhibit low levels of hole elongation. It is recommended that joint stiffness changes be monitored using an extensometer unless it is demonstrated that changes measured using crosshead deflection data are consistent with those obtained from extensometer data. This is due to the additional sources of stiffness measurement error inherent to crosshead deflection data (grip slippage, support fixture deformation and friction).

6.9 *Reuse or Replacement of Fastener(s)*—Results are affected by whether fastener(s) are reused after hole cleaning and elongation measurement, or whether they are replaced. Both techniques have been used in industry, with reuse being the more common practice. Reuse requires less hardware and ensures a constant fastener diameter (and fastener-hole clearance) is maintained. The removal of thread lubricant during repeated torquing can decrease preload for a given torque level; as lower preload produces more hole elongation, reuse should produce conservative results. Also, fastener degradation is part of the fatigue process, and replacement could be considered non-conservative. However, if the fastener(s) deforms during test, reuse requires that it be replaced in the same "deformed" position as it was prior to removal. Also, replacement ensures that consistent torque and preload levels are used throughout the test. The technique used during fastener re-installation (reuse or replacement) shall be recorded. It is recommended to vary hole inspection intervals to aid in assessing whether fastener removal and reinstallation affects hole elongation behavior.

6.10 *Support Fixture Wear*—Results can be affected by wear and degradation of the holes, fasteners and pins of the support fixture (when utilized) under repeated use. This is especially important for specimens tested using the Procedure B and Procedure D configurations when compressive loadings are applied, as fixture wear can result in reduced specimen support and stabilization. Ensure the support fixture pins and fasteners are tight tolerance in accordance with Test Method D5961/D5961M requirements.

6.11 *Other*—Additional sources of potential data scatter are documented in Test Method D5961/D5961M.

7. Apparatus

7.1 *General Apparatus*—General apparatus shall be in accordance with Test Method D5961/D5961M. The micrometer or gage used shall be capable of determining the hole and fastener diameters to ±8 µm [±0.0003 in.].

7.2 *Testing Machine*—In addition to the requirements described in Test Method D5961/D5961M, 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 sinusoidal 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 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 % of true forces.

7.2.3 *Grips*—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 hole elongation, a support fixture shall be used to stabilize the specimen. The support fixture shall be in accordance with that described in Test Method D5961/D5961M Procedure B for single shear specimens, and with that described in Test Method D5961/D5961M Procedure D for double shear specimens.

7.4 *Thermocouple and Temperature Recording Devices,* capable of reading specimen temperature to ±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 Method D5961/D5961M, the specimen geometry shall satisfy the following requirements:

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 Method D5961/D5961M with the following restrictions:

8.2.2.1 *Tensile Loadings Only*—Procedure A (double shear), Procedure B (single shear, two-piece specimen), and Procedure C (single shear, one-piece specimen) configurations may be utilized. For Procedure B, both the single fastener joint and the double fastener joint geometries may be utilized. If the support fixture is used, the length of each specimen half and doubler must be adjusted to accommodate loading with the fixture. Direct measurement of hole diameter(s) is required to determine hole elongation.

8.2.2.2 *Compressive Loadings Applied*—Both the Procedure B (single shear) and Procedure D (double shear) configurations and corresponding support fixtures may be utilized. For Procedure B, both the single fastener joint and the double fastener joint geometries may be utilized; the length of each specimen half and doubler must be adjusted to accommodate loading with the support fixture. Hole elongation may be determined through either direct measurement or quasi-static loadings; joint stiffness may also be determined.

8.2.3 *Adhesive*—For specimens with bonded doublers, the adhesive should have sufficient durability as to withstand fatigue loading for the duration of the test.

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

8.3 *Specimen Preparation*—Specimens shall be prepared in accordance with Test Method D5961/D5961M. 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 specific 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 so that unintended changes in 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 hole elongation (and joint stiffness if applicable) is to be measured, method of measuring hole elongation, fastener and debris removal requirements, quasi-static peak and valley forces for hole elongation and joint stiffness measurement (if applicable), hole elongation level or percent joint stiffness reduction at which fatigue loading shall cease, and run-out cycles. Historically, bearing fatigue testing has ceased after the hole elongation level has reached 10 to 25 % of the initial hole diameter, or after joint stiffness has been reduced by 10 to 25% from the initial stiffness.

11.1.3 All other parameters documented in Test Method D5961/D5961M.

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, assembly, and fastener torquing in accordance with Test Method D5961/D5961M.

11.3 *Test Procedure:*

11.3.1 *Supported Specimen Installation*—If the specimen is to be tested with support fixture, install the test specimen into the support fixture as described in Test Method D5961/D5961M.

11.3.2 *Temperature Monitoring*—Attach temperature recording device in a manner not to influence the dynamic response of the specimen. It is recommended to attach the device to a fastener, as fatigue loading will typically cause a greater increase in fastener temperature than in laminate temperature. The device may be attached to the fastener 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] has demonstrated measurable degradation of material properties.

NOTE 4—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 D5961/D5961M, insert the specimen and support fixture (as applicable) into the test machine.

NOTE 5—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*—Attach extensometer(s) to the edges of the specimen in accordance with Test Method D5961/D5961M.

NOTE 6—It is recommended that joint stiffness changes be monitored using an extensometer. Crosshead deflection data may be used if it is first demonstrated that percent joint stiffness reduction measurements are consistent with those obtained from extensometer data.

11.3.5 *Quasi-Static Loading*—If force versus deformation data is being used to determine hole elongation and joint stiffness, 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*—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. 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. A hysteresis curve, 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 minimum sampling rate of 2 to 3 data recordings per second, and a target minimum of 50 data points per hysteresis cycle, are recommended.

NOTE 7—In some instances, the applied tensile and compressive forces may not be high enough to overcome friction at the fastener hole. When this occurs, hole elongation will be relatively small, and it is recommended to measure hole elongation directly (if possible) in addition to taking force versus deformation data.

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

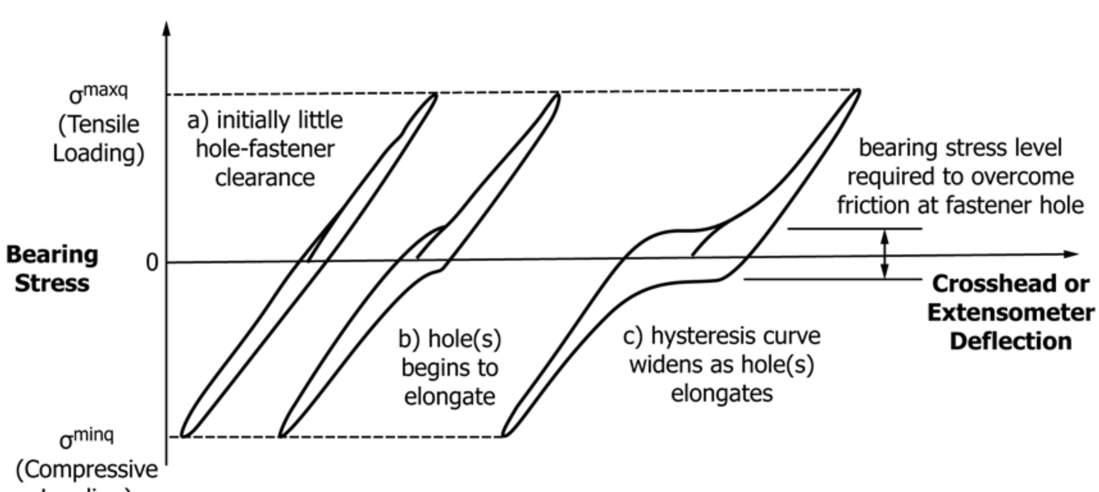

FIG. 1 Typical Bearing Stress versus Deflection Plots Depicting Shape of Hysteresis Curve

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 *Hole Elongation and Joint 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. Remove the specimen (and fixture if appropriate) from the test machine.

11.4.2 *Fastener Torque Measurement and Removal*—If debris removal is specified by the test requestor and the fastener(s) is to be reused, mark the direction of loading on the fastener head(s). Determine the torque level(s) of the fastener(s) prior to removal by first tightening the nut (holding the pin/bolt fixed) until resistance is overcome and the nut begins to rotate. Increase the torque level an additional 0.25 N-m (2 in.-lb) and record the measured value. Subtract 0.25 N-m (2 in.-lb) from the measured value, and record this value as the torque level prior to removal. Torque measurement by loosening the nut is not recommended, as static friction under the nut contributes to the loosening torque level and is highly variable, especially after fatigue loading. If debris removal is specified by the test requestor, remove the fastener(s) from the specimen.

11.4.3 *Debris Removal*—If debris removal is specified by the test requestor, clean the specimen hole(s), removing powdery debris in accordance with the specified hole preparation procedures.

NOTE 8—In general, cleaning the specimen hole(s) prior to measurement is recommended to ensure conservatism of hole elongation data.

11.4.4 *Hole Measurement*—If direct measurement is being used to determine hole elongation, measure the diameter of the hole(s) in the direction of the bearing force using micrometer or gage.

11.4.5 *Fastener Re-installation*—If the fastener(s) and debris were removed, clean the specimen hole(s) and surrounding clamping area as was done prior to loading. Clean the fastener/pin shank(s). If a replacement fastener(s) is to be used, measure the fastener/pin diameter(s) at the bearing surface location. In accordance with Test Method D5961/D5961M, install the fastener(s), and torque to the lesser of the initial installation torque or the torque level prior to removal as determined in 11.4.2. If the fastener(s) is being reused, ensure the marks on the head(s) are aligned with the loading direction. Record the technique of fastener re-installation (reuse or replacement).

11.4.6 *Specimen Re-insertion*—Re-insert the specimen (and fixture, if appropriate) into the test machine as in 11.3.3. Re-attach extensometer(s) as in 11.3.4 if appropriate.

11.4.7 *Quasi-Static Loading*—If force versus deformation data is being used to determine hole elongation and joint stiffness, perform a quasi-static loading cycle as in 11.3.5.

11.4.8 *Re-Initiate Fatigue Loading*—Commence applying fatigue forces again, as in 11.3.6.

11.5 *Failure*—Record the number of loading cycles at which specimen fracture occurred, at which the designated hole elongation or percent joint stiffness reduction was achieved, or at run-out. Depending upon the purpose for which the test is being conducted a specific loss in dynamic stiffness rather than fracture or hole elongation may constitute failure.

11.5.1 *Failure Mode*—Record the mode and location of failure of the specimen in accordance with Test Method D5961/D5961M.

12. Validation

12.1 Fatigue properties shall not be calculated for any specimen that breaks at some obvious flaw, unless such flaw constitutes a variable being studied. Retests shall be performed for any specimen on which values are not calculated.

12.2 A significant fraction of failures in a sample population occurring away from the fastener hole(s) shall be cause to re-examine the means of force introduction into the material. Factors considered should include the specimen alignment, fixture alignment (if appropriate), grip pressure, grip alignment, separation of fixture halves, specimen thickness taper, and uneven machining of specimen ends.

12.3 Initial fatigue cycles will often demonstrate a high friction force level, which will typically decrease to a steady-state level. If specimens are tested without debris removal, debris accumulation may increase the friction force level near the end of life. As this condition may provide an indication of reduced hole elongation, it is recommended that hole elongation data obtained after the friction force increases above the steady state level be considered invalid.

13. Calculations

13.1 *Geometric Calculations*—Calculate the specimen width to diameter ratio, the edge distance ratio, the diameter to thickness ratio, and the countersink depth to thickness ratio (if appropriate) in accordance with Test Method D5961/D5961M. Both the nominal ratio calculated using nominal values and the actual ratio calculated with measured dimensions shall be reported.

13.2 *Bearing Stresses*—Calculate the maximum magnitude of cyclic bearing stress using Eq 1, the mean bearing stress using Eq 2, and the alternating bearing stress using Eq 3. Report the results to three significant digits.

$$\sigma^{brm} = P^{max}/(kDh) \quad (1)$$

$$\sigma^{mean} = (P^{max} + P^{min})/(2kDh) \quad (2)$$

$$\sigma^{alt} = (P^{max} - P^{min})/(2kDh) \quad (3)$$

where:

σ^{brm} = maximum cyclic bearing stress magnitude, MPa [psi],
σ^{mean} = mean bearing stress during fatigue loading, MPa [psi],
σ^{alt} = alternating bearing stress during fatigue loading, MPa [psi],
P^{max} = greater of the absolute values of the peak and valley values of force, N [lbf],
P^{min} = lesser of the absolute values of the peak and valley values of force, N [lbf],
D = hole diameter, either nominal value or measured value prior to fatigue loading, mm [in.],
h = specimen thickness, mm [in.], and
k = force per hole calculation factor: 1.0 for single fastener or pin tests and 2.0 for double fastener tests.

NOTE 9—Referenced studies (**1-4**) have compared hole elongation and joint stiffness data on the basis of maximum bearing stress magnitude, mean bearing stress and alternating bearing stress. Generally, maximum bearing stress magnitude has been found to be the most useful basis for comparison of hole elongation and joint stiffness data under various fatigue force ratios.

13.3 *Hole Elongation, Direct Measurement*—Calculate the hole elongation at each prescribed fatigue interval at which diameter measurements were taken using Eq 4. Report the results to three significant digits. For specimens with two fastener holes, report the results for the hole exhibiting greater elongation.

$$\Delta D_N = D_N - D_i \quad (4)$$

where:

ΔD_N = hole elongation after N fatigue cycles, mm [in.],
D_N = measured hole diameter after N fatigue cycles, mm [in.], and
D_i = measured hole diameter prior to fatigue loading, mm [in.].

13.4 *Hole Elongation, Force Versus Deformation Data*—Plot the force (stress) versus crosshead deflection data and the force (stress) versus extensometer data to produce hysteresis curves as in Fig. 2. For each set of data at each prescribed fatigue interval, calculate the fastener translation at zero force as shown in Fig. 2, using Eq 5.

$$\delta_N = \delta_{Nt} - \delta_{Nc} \quad (5)$$

where:

δ_N = fastener translation after N fatigue cycles, mm [in],
δ_{Nt} = crosshead or extensometer displacement at zero force after quasi-static tensile loading, mm [in], and
δ_{Nc} = crosshead or extensometer displacement at zero force after quasi-static compressive loading, mm [in].

NOTE 10—Referenced reports (**1, 2**) defined fastener translation by extrapolating the elastic (linear) portion of the hysteresis curve to zero force for both tension and compression. Hole elongation was then considered as the difference between the resulting zero force intercepts. A subsequent study tracked hole elongation using this procedure, as well as by using the hysteresis curve zero force intercepts as defined for Eq 5 (**5**). The study concluded that both definitions provide equivalent measurements of hole elongation. Based upon this finding, it is recommended to use the hysteresis curve zero force intercepts for procedural simplicity.

The hole elongation at each prescribed fatigue interval may then be calculated using Eq 6.

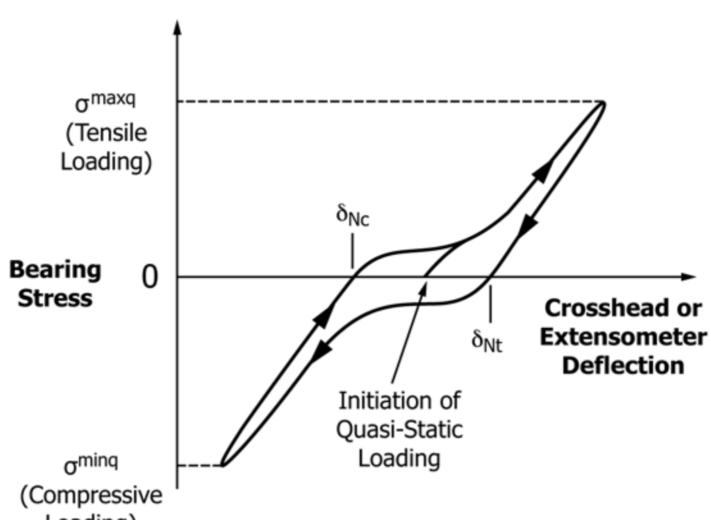

FIG. 2 Hysteresis Curve Parameters for Fastener Translation Calculations

$$\Delta D_N = \delta_N - \delta_i \tag{6}$$

where:

ΔD_N = hole elongation after N fatigue cycles, mm [in.],
δ_N = fastener translation after N fatigue cycles, mm [in.], and
δ_i = fastener translation prior to fatigue loading, mm [in.].

13.5 *Percent Joint Stiffness Reduction Data*—Plot the force versus crosshead deflection data and the force versus extensometer data to produce hysteresis curves as in Fig. 3. For each set of data at each prescribed fatigue interval, calculate the joint stiffness as shown in Fig. 3, using Eq 7.

$$K_N = \Delta P / \Delta\delta \tag{7}$$

where:

K_N = joint stiffness after N fatigue cycles, N/mm [lbf/in.],
ΔP = change in force over joint stiffness range under quasi-static loading, N [lbf], and
$\Delta\delta$ = change in crosshead or extensometer displacement over joint stiffness range under quasi-static loading, mm [in].

NOTE 11—The joint stiffness calculation is intended to provide a computationally simple means for monitoring changes in effective joint force versus displacement response at a specified loading ratio resulting from hole elongation, fastener deformation, or both. The calculated joint stiffness may be influenced by the applied loading ratio and the degree of hole elongation.

NOTE 12—The initial portion of the force/displacement curve will usually have substantial variations in the force/displacement response due to seating of the specimen within the grips or test fixture. The joint stiffness points should be determined after this behavior has dissipated. Because of these variations it is often most practical to use force end points to determine the joint stiffness.

The percent change in joint stiffness at each prescribed fatigue interval may then be calculated using Eq 8.

$$\Delta K_N = [(K_N - K_i)/K_i] \times 100 \tag{8}$$

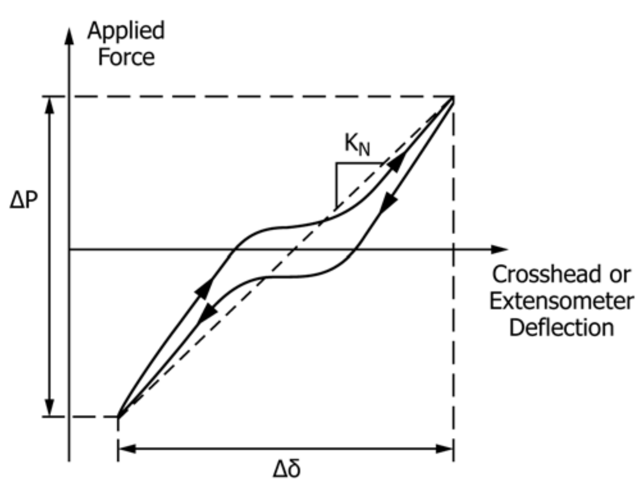

FIG. 3 Hysteresis Curve Parameters for Joint Stiffness Calculations

where:

ΔK_N = percent reduction in joint stiffness after N fatigue cycles, %,
K_N = specimen joint stiffness after N fatigue cycles, N/mm [lbf/in], and
K_i = specimen joint stiffness prior to fatigue loading, N/mm [lbf/in].

13.6 *Fatigue Life Distribution:*

13.6.1 *Log-Normal Distribution*—The use of a log-normal distribution is presented in Practice E739 for the representation of constant amplitude fatigue life data.

13.6.2 *Weibull Distribution*—The two parameter Weibull distribution is commonly used to represent constant amplitude fatigue life data. A two parameter Weibull distribution density function for fatigue life may be expressed as:

$$f(N) = \frac{\beta}{\alpha}\left(\frac{N}{\alpha}\right)_{\beta-1} \exp\left[-\left(\frac{N}{\alpha}\right)_{\beta}\right] \tag{9}$$

The Weibull distribution cumulative function for fatigue life may be given as:

$$F(N) = 1 - \exp\left[-\left(\frac{N}{\alpha}\right)_{\beta}\right] \tag{10}$$

One method of determining the Weibull scale and shape parameters, α and β, is the maximum likelihood technique (**6**).

13.7 *S-N Curve*—As described in Practice E739.

14. Report

14.1 The report shall include all appropriate parameters in accordance with Test Method D5961/D5961M.

14.2 In addition, the report shall include the following information, or references pointing to other documentation containing this information, to the maximum extent applicable (reporting of items beyond the control of a given testing laboratory, such as might occur with material details or panel fabrication parameters, shall be the responsibility of the requestor):

14.2.1 The revision level or date of issue of this practice.

14.2.2 Any variations to these test methods, anomalies noticed during testing, or equipment problems occurring during testing.

14.2.3 Description of the loading including: minimum and maximum test forces, force ratio, frequency, wave form, average number of fatigue loading transition cycles, technique of fastener re-installation (reuse or replacement), torque levels prior to fastener removal, re-installation torque values, and instances in which the loading was not within 2 % of the desired peak and valley values.

14.2.4 Hole elongation versus fatigue cycles data, force-deflection data (if appropriate). Typical hole elongation versus fatigue cycles behavior is shown in Fig. 4.

14.2.5 Percent joint stiffness reduction versus fatigue cycles data. Typical joint stiffness versus fatigue cycles behavior is shown in Fig. 5.

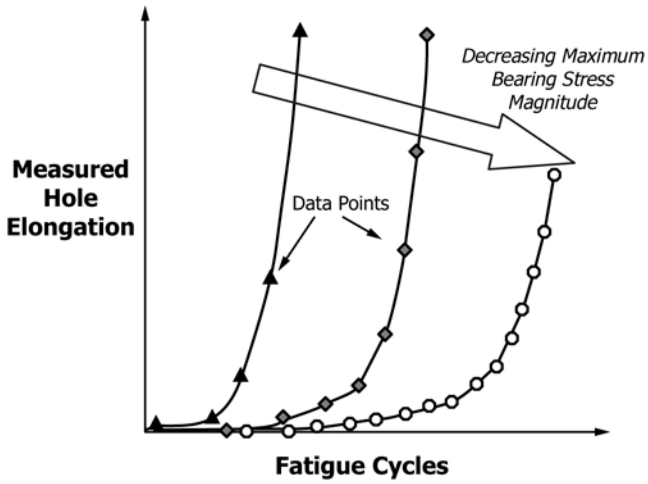

FIG. 4 Typical Hole Elongation versus Fatigue Cycles Behavior

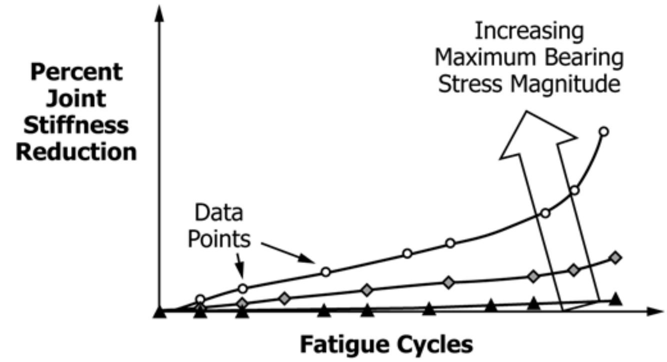

FIG. 5 Typical Percent Joint Stiffness Reduction versus Fatigue Cycles Behavior

14.2.6 Number of cycles to failure, specified hole elongation or percent joint stiffness reduction, or run-out.

14.2.7 Specimen failure modes. If a failure criterion such as stiffness loss, excessive creep, edge delamination, etc. is used, it should be noted.

15. Precision and Bias

15.1 *Precision*—The data required for the development of a precision statement is not available for these methods.

15.2 *Bias*—Bias cannot be determined for these methods as no acceptable reference standards exist.

16. Keywords

16.1 bearing fatigue; bolted joints; composite materials; compression testing; fastener; hole elongation; tension testing

REFERENCES

(1) Baldini, S. and Badaliance, R., "Compression Fatigue Life Prediction Methodology for Composite Structures, Volume II—Test Data and Damage Tracking," Report No. NADC-83061-60, Naval Air Development Center, Warminster, PA, 1982.

(2) Grant, P., Nguyen, N., and Sawicki, A., "Bearing Fatigue and Hole Elongation in Composite Bolted Joints," *Proceedings of American Helicopter Society 49th Annual Forum*, St. Louis, MO, May 1993.

(3) Ramkumar, R. L. and Tossavainen, E. W., "Strength and Lifetime of Bolted Laminates," *Fatigue in Mechanically Fastened Composite and Metallic Joints, ASTM STP 927*, J. M. Potter, Ed., American Society for Testing and Materials, Philadelphia, PA, 1986, pp. 251-273.

(4) Crews, J. H., Jr., "Bolt-Bearing Fatigue of a Graphite/Epoxy Laminate," *Joining of Composite Materials, ASTM STP 749*, K. T. Kedward, Ed., American Society for Testing and Materials, Philadelphia, PA, 1981, pp. 131-144.

(5) Sawicki, A., "V-22 EMD Fastener Variables and Manufacturing Defects Evaluation," Bell-Boeing Report No. 901-930-680, 1996.

(6) Talreja, R., "Estimation of Weibull Parameters for Composite Material Strength and Fatigue Life Data," *Fatigue of Fibrous Composite Materials, ASTM STP 723*, American Society for Testing and Materials, Philadelphia, PA, 1981, pp. 291-311.