Designation: D6264/D6264M – 12

Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer-Matrix Composite to a Concentrated Quasi-Static Indentation Force[1]

This standard is issued under the fixed designation D6264/D6264M; 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 test method determines the damage resistance of multidirectional polymer matrix composite laminated plates subjected to a concentrated indentation force (Fig. 1). Procedures are specified for determining the damage resistance for a test specimen supported over a circular opening and for a rigidly-backed test specimen. The composite material forms are limited to continuous-fiber reinforced polymer matrix composites, with the range of acceptable test laminates and thicknesses defined in 8.2. This test method may prove useful for other types and classes of composite materials.

1.1.1 Instructions for modifying these procedures to determine damage resistance properties of sandwich constructions are provided in Practice D7766/D7766M.

1.2 A flat, square composite plate is subjected to an out-of-plane, concentrated force by slowly pressing a hemispherical indenter into the surface. The damage resistance is quantified in terms of a critical contact force to cause a specific size and type of damage in the specimen.

1.3 The test method may be used to screen materials for damage resistance, or to inflict damage into a specimen for subsequent damage tolerance testing. The indented plate can be subsequently tested in accordance with Test Method D7137/D7137M to measure residual strength properties. Drop-weight impact per Test Method D7136/D7136M may be used as an alternate method of creating damage from an out-of-plane force and measuring damage resistance properties.

1.4 The damage resistance properties generated by this test method are highly dependent upon several factors, which include specimen geometry, layup, indenter geometry, force, and boundary conditions. Thus, results are generally not scalable to other configurations, and are particular to the combination of geometric and physical conditions tested.

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

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

1.6 *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]

D792 Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement

D883 Terminology Relating to Plastics

D3171 Test Methods for Constituent Content of Composite Materials

D3878 Terminology for Composite Materials

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

D5687/D5687M Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation

D7136/D7136M Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event

D7137/D7137M Test Method for Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates

D7766/D7766M Practice for Damage Resistance Testing of Sandwich Constructions

[1] This test method 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, 2012. Published May 2012. Originally approved in 1998. Last previous edition approved in 2007 as D6264 – 07. DOI: 10.1520/D6264_D6264M-12.

[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.

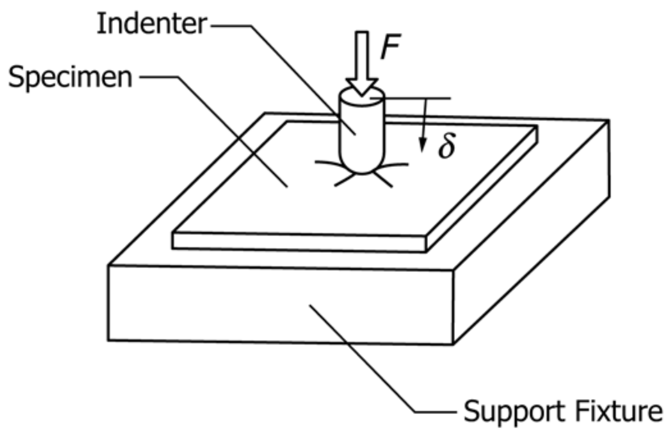

FIG. 1 Quasi-Static Indentation Test

E4 Practices for Force Verification of Testing Machines
E6 Terminology Relating to Methods of Mechanical Testing
E18 Test Methods for Rockwell Hardness of Metallic Materials
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
E1309 Guide for Identification of Fiber-Reinforced Polymer-Matrix Composite Materials in Databases
E1434 Guide for Recording Mechanical Test Data of Fiber-Reinforced Composite Materials in Databases
E1471 Guide for Identification of Fibers, Fillers, and Core Materials in Computerized Material Property Databases
E2533 Guide for Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications

2.2 *Military Standards:*

MIL-HDBK-17-3F Composite Materials Handbook, Volume 3—Polymer Matrix Composites Materials Usage, Design and Analysis[3]
MIL-HDBK-728/1 Nondestructive Testing[4]
MIL-HDBK-731A Nondestructive Testing Methods of Composite Materials—Thermography[4]
MIL-HDBK-732A Nondestructive Testing Methods of Composite Materials—Acoustic Emission[4]
MIL-HDBK-733A Nondestructive Testing Methods of Composite Materials—Radiography[4]
MIL-HDBK-787A Nondestructive Testing Methods of Composite Materials—Ultrasonics[4]

3. Terminology

3.1 *Definitions*—Terminology D3878 defines terms relating to composite materials. Terminology D883 defines terms relating to plastics. Terminology E6 defines terms relating to mechanical testing. 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.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 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.

3.2.2 *contact force, F* $[MLT^{-2}]$, *n*—the force exerted by the indenter on the specimen during the test, as recorded by a force indicator.

3.2.3 *dent depth, d* [*L*], *n*—residual depth of the depression formed by an indenter after removal of applied force. The dent depth shall be defined as the maximum distance in a direction normal to the face of the specimen from the lowest point in the dent to the plane of the surface that is undisturbed by the dent.

3.2.4 *indenter displacement,* δ [*L*], *n*—the displacement of the indenter relative to the specimen support.

3.2.5 *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.

3.2.6 *principal material coordinate system, n*—a coordinate system with axes that are normal to the planes of symmetry inherent to a material.

3.2.6.1 *Discussion*—Common usage, at least for Cartesian axes (123, *xyz*, and so forth), generally assigns the coordinate system axes to the normal directions of planes of symmetry in order that the highest property value in a normal direction (for elastic properties, the axis of greatest stiffness) would be 1 or *x*, and the lowest (if applicable) would be 3 or *z*. Anisotropic materials do not have a principal material coordinate system due to the total lack of symmetry, while, for isotropic materials, any coordinate system is a principal material coordinate system. In laminated composites, the principal material coordinate system has meaning only with respect to an individual orthotropic lamina. The related term for laminated composites is *reference coordinate system*.

3.2.7 *reference coordinate system, n*—a coordinate system for laminated composites used to define ply orientations. One of the reference coordinate system axes (normally the Cartesian *x*-axis) is designated the reference axis, assigned a position, and the ply principal axis of each ply in the laminate is referenced relative to the reference axis to define the ply orientation for that ply.

3.3 *Symbols:*

CV = coefficient of variation statistic of a sample population for a given property (in percent)

D = damage diameter (see Fig. 6)

d = dent depth (see 3.2.3)

[3] Available from U.S. Army Research Laboratory, Materials Directorate, Aberdeen Proving Ground, MD 21001.

[4] Available from U.S. Army Materials Technology Laboratory, Watertown, MA 02471.

E = energy calculated by integrating the contact force and indenter displacement curve

E_a = energy absorbed (inelastically) by the specimen during the test

E_{max} = energy at maximum indenter displacement

F = contact force (see 3.2.2)

F_{max} = the maximum contact force exerted on the specimen during a test

n = number of specimens per sample population

N = number of plies in laminate under test

s_{n-1} = standard deviation statistic of a sample population for a given property

x_i = test result for an individual specimen from the sample population for a given property

$\bar{x}$ = mean or average (estimate of mean) of a sample population for a given property

δ = indenter displacement (see 3.2.4)

δ_o = indenter displacement at initial specimen contact

δ_f = indenter displacement at the end of the unloading cycle

δ_{max} = maximum indenter displacement during the test

4. Summary of Test Method

4.1 A quasi-static indentation (QSI) test is used to measure the damage resistance on a balanced, symmetric laminated plate. Damage is imparted through an out-of-plane, concentrated force (perpendicular to the plane of the laminated plate) applied by slowly pressing a displacement-controlled hemispherical indenter into the face of the specimen (Fig. 1). The damage resistance is quantified in terms of the resulting size and type of damage in the specimen. The damage response is a function of the test configuration; comparisons cannot be made between materials unless identical test configurations, test conditions, etc. are used.

4.2 Procedures are specified for determining the damage resistance for a test specimen supported over a circular opening (edge supported) and for a rigidly-backed test specimen.

4.3 Preferred damage states are centered on the plate and are away from the plate edges.

5. Significance and Use

5.1 Susceptibility to damage from concentrated out-of-plane forces is one of the major design concerns of many structures made of advanced composite laminates. Knowledge of the damage resistance properties of a laminated composite plate is useful for product development and material selection.

5.2 QSI testing can serve the following purposes:

5.2.1 To simulate the force-displacement relationships of impacts governed by boundary conditions (**1-7**).[5] These are typically relatively large-mass low-velocity hard-body impacts on plates with a relatively small unsupported region. Since the test is run slowly in displacement control, the desired damage state can be obtained in a controlled manner. Associating specific damage events with a force during a drop-weight impact test is often difficult due to the oscillations in the force history. In addition, a specific sequence of damage events may be identified during quasi-static loading while the final damage state is only identifiable after a drop-weight impact test.

5.2.2 To provide an estimate of the impact energy required to obtain a similar damage state for drop-weight impact testing if all others parameters are held constant.

5.2.3 To establish quantitatively the effects of stacking sequence, fiber surface treatment, variations in fiber volume fraction, and processing and environmental variables on the damage resistance of a particular composite laminate to a concentrated indentation force.

5.2.4 To compare quantitatively the relative values of the damage resistance parameters for composite materials with different constituents. The damage response parameters can include dent depth, damage dimensions and through-thickness locations, F_{max} , E_a, and E_{max}, as well as the force versus indenter displacement curve.

5.2.5 To impart damage in a specimen for subsequent damage tolerance tests, such as Test Method D7137/D7137M.

5.2.6 To measure the indentation response of the specimen with and without bending using the two specimen configurations (edge supported and rigidly backed).

5.3 The properties obtained using this test method can provide guidance in regard to the anticipated damage resistance capability of composite structures of similar material, thickness, stacking sequence, etc. However, it must be understood that the damage resistance of a composite structure is highly dependent upon several factors including geometry, thickness, stiffness, mass, support conditions, etc. Significant differences in the relationships between force/energy and the resultant damage state can result due to differences in these parameters. For example, properties obtained using the specimen supported over a circular hole would more likely reflect the damage resistance characteristics of an un-stiffened monolithic skin or web than that of a skin attached to sub-structure which resists out-of-plane deformation. Similarly, test specimen properties would be expected to be similar to those of a panel with equivalent length and width dimensions, in comparison to those of a panel significantly larger than the test specimen, which tends to divert a greater proportion of the energy into elastic deformation.

5.4 The standard indenter geometry has a blunt, hemispherical tip. Historically, for the standard laminate configuration, this indenter geometry has generated a larger amount of internal damage for a given amount of external damage than is typically observed for similar indenters using sharp tips. Alternative indenter geometries may be appropriate depending upon the damage resistance characteristics being examined. For example, the use of sharp tip geometries may be appropriate for certain damage visibility and penetration resistance assessments.

5.5 Some testing organizations may desire to use this test method in conjunction with Test Method D7137/D7137M to assess the compression residual strength of specimens containing a specific damage state, such as a defined dent depth, damage geometry, etc. In this case, the testing organization should subject several specimens to multiple energy or force

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

levels using this test method. A relationship between energy or force and the desired damage parameter can then be developed. Subsequent QSI and compression residual strength tests can then be performed using specimens indented at an interpolated energy or force level that is expected to produce the desired damage state.

6. Interferences

6.1 This test may be useful in simulating the force-displacement relationships of large-mass low-velocity hard-body impacts on small plates. However, this test method does not address wave propagation and vibrations in the specimen, time-dependent material behavior, or inertia-dominated impact events.

6.2 The response of a laminated plate specimen to an out-of-plane force is dependent upon many factors, such as laminate thickness, ply thickness, stacking sequence, environment, geometry, indenter tip geometry, and boundary conditions. Consequently, comparisons cannot be made between materials unless identical test configurations, test conditions, and laminate configurations are used. Therefore, all deviations from the standard test configuration shall be reported in the results.

6.3 *Material and Specimen Preparation*—Poor material fabrication practices, lack of control of fiber alignment, and damage induced by improper specimen machining are known causes of high material data scatter in composites in general. Important aspects of plate specimen preparation that contribute to data scatter include thickness variation, out-of-plane curvature, surface roughness, and failure to maintain the dimensions specified in 8.2.

6.4 *Specimen Geometry and Indentation Location*—The size, shape, thickness, and stacking sequence of the plate, along with the indentation location, can affect the specimen deformation and damage formation behavior of the specimens significantly. The degree of laminate orthotropy can strongly affect the damage formation. Results can be affected if the indentation force is not applied perpendicular to the plane of the laminated plate.

6.5 *Support Fixture Characteristics*—Results are affected by the support fixture geometry, material, and bending rigidity.

6.6 *Non-Destructive Inspection*—Non-destructive inspection (NDI) results are affected by the particular method utilized, the inherent variability of the NDI method, the experience of the operator, etc.

6.7 The dent depth may "relax" or reduce with time or upon exposure to different environmental conditions.

6.8 Non-laminated, 3-D fiber-reinforced composites may form damage through different mechanisms than laminates.

7. Apparatus

7.1 *Micrometers and Calipers*—The accuracy of the instruments shall be suitable for reading to within 0.1 % of the measured value. The micrometer(s) shall use a 4 to 6 mm [0.16 to 0.25 in.] nominal diameter ball interface on irregular surfaces such as the bag side of a laminate, and a flat anvil interface on machined edges or very smooth tooled surfaces.

NOTE 1—For typical specimen geometries, a micrometer with an accuracy of ±0.0025 mm [±0.0001 in.] or better is desirable for thickness measurement, while a caliper with an accuracy of ±0.025 mm [±0.001 in.] or better is desirable for length, width and damage dimension measurement.

7.2 *Support Fixtures*—The damage resistance may be determined for a specimen that is edge supported or rigidly backed. For both configurations, the specimen's face shall be held normal to the axis of the indenter.

7.2.1 *Edge Supported Configuration*—The fixture shall consist of a single plate with a 125.0 ± 3.0 mm [5.00 ± 0.10 in.] diameter opening made from a structural metal such as aluminum or steel. The face of the plate shall be flat to within 0.1 mm [0.005 in.] in the area which contacts the test specimen. The top rim of the opening shall be rounded with a radius of 0.75 ± 0.25 mm [0.03 ± 0.01 in.]. The plate shall be sufficiently large to support the entire lower surface of the specimen, excluding the circular opening. The thickness of the plate shall be a minimum of 25 mm [1.0 in.] and greater than the expected maximum indenter displacement. A typical support fixture is shown in Figs. 2 and 3.

7.2.2 *Rigidly-Backed Configuration*—The specimen shall be placed directly on the flat rigid support that is mounted in the lower head of the testing machine. For this configuration, the support shall be made from steel with a minimum thickness of 12.7 mm [0.5 in.].

7.3 *Testing Machine*—The testing machine shall be in conformance with Practices E4 and shall satisfy the following requirements:

7.3.1 *Testing Machine Configuration*—The testing machine shall have both an essentially stationary head and a movable head. A short loading train shall be used with a flat platen on the lower head and a grip on the upper head.

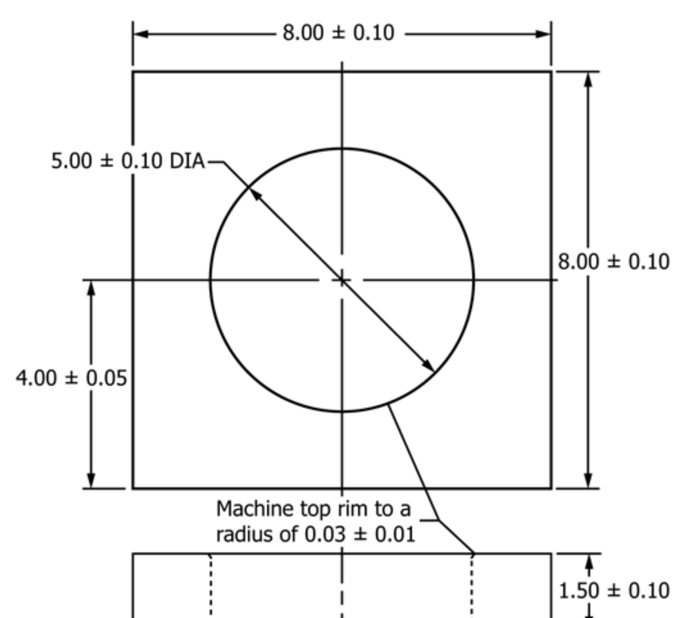

FIG. 2 Typical Fixture with Open Hole (Inch-Pound Version)

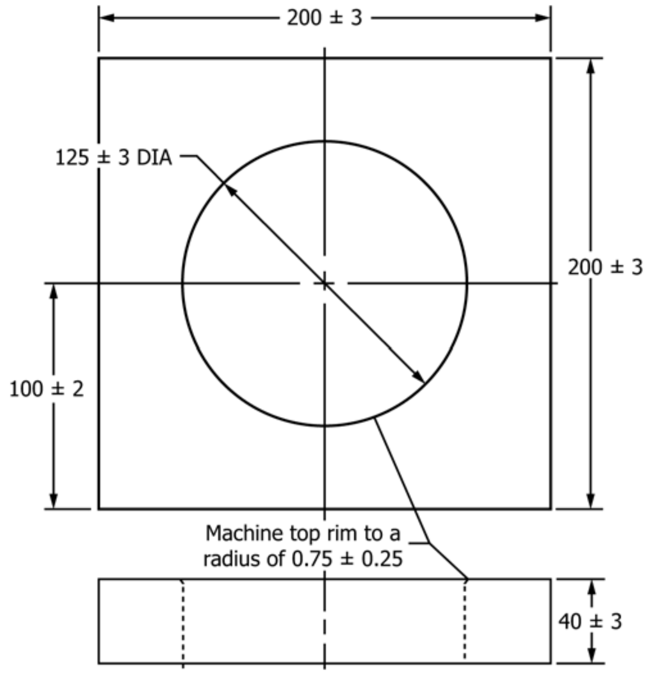

FIG. 3 Typical Fixture with Open Hole (SI Version)

7.3.2 *Grips*—The top head of the testing machine shall carry a grip to hold the indenter such that the direction of load applied to the specimen is coincident with the axis of travel. The grip shall apply sufficient pressure to prevent slippage of the indenter. The lower head shall have a means of attaching a flat platen.

7.3.3 *Flat Platen*—The test machine shall be mounted with a fixed (as opposed to spherical seat) flat platen on the lower head to support the specimen or test fixture. The support surface shall be normal to the axis of travel of the testing machine head and have a large enough surface to support completely the specimen or test fixture. A convenient means of providing this surface is through the use of a metal "T" in which the lower part of the "T" is clamped in the lower grips and the top part of the "T" provides the support surface. The lower platen may be marked to help center the test fixture between the platens. If the rigidly-backed configuration is to be used, this support shall be made from steel with a minimum thickness of 13 mm [0.5 in.].

7.3.4 *Drive Mechanism*—The testing machine drive mechanism shall be capable of imparting to the movable head a controlled velocity with respect to the stationary head. The velocity of the movable head shall be capable of being regulated as specified in 11.6.

7.3.5 *Force Indicator*—The testing machine force-sensing device shall be capable of indicating the total force being carried by the test specimen. This device shall be essentially free from inertia-lag at the specified rate of testing and shall indicate the force with accuracy over the force range(s) of interest of within ±1 % of the indicated value.

7.3.6 *Crosshead Displacement Indicator*—The testing machine shall be capable of monitoring and recording the crosshead displacement (stroke) with a precision of at least ±1 %. If machine and fixture compliance is significant, it is acceptable to measure the displacement of the movable head using a LVDT or similar device with ±1 % precision on displacement.

7.4 *Indenter*—The indenter shall have a smooth hemispherical tip with a diameter of 13.0 ± 0.3 mm [0.50 ± 0.01 in.] and a hardness of 60 to 62 HRC as specified in Test Methods E18. Alternate tip geometries may be used to study relationships between visible damage geometry (e.g., dent depth, dent diameter) and the internal damage state. If a different indenter is used as part of the testing, the shape and dimensions shall be noted.

7.5 *Conditioning Chamber*—When conditioning materials at non-laboratory environments, a temperature-/vapor-level controlled environmental conditioning chamber is required that shall be capable of maintaining the required temperature to within ±3°C [±5°F] and the required relative humidity level to within ±3 %. Chamber conditions shall be monitored either on an automated continuous basis or on a manual basis at regular intervals.

7.6 *Environmental Test Chamber*—An environmental test chamber is required for test environments other than ambient testing laboratory conditions. This chamber shall be capable of maintaining the test specimen at the required test environment during the mechanical test. The test temperature shall be maintained within ±3°C [±5°F] of the required temperature, and the relative humidity level shall be maintained to within ±3 % of the required humidity level.

7.7 *Data Acquisition Equipment*—Equipment capable of recording force and crosshead displacement is required.

7.8 *Dent Depth Indicator*—The dent depth can be measured using a dial depth gage, a depth gage micrometer, a tripod-mounted depth gage, or a properly calibrated displacement transducer. The measuring probe shall have a spherical tip with a maximum radius of curvature of 8.0 mm [0.35 in.]. An instrument with an accuracy of ±25 µm [±0.001 in.] is desirable for depth measurement.

8. Sampling and Test Specimens

8.1 *Sampling*—Test at least five specimens per test condition unless valid results can be gained through the use of fewer specimens, as in the case of a designed experiment. For statistically significant data the procedures outlined in Practice E122 should be consulted. The method of sampling shall be reported.

8.2 *Geometry:*

8.2.1 *Stacking Sequence*—The reference coordinate system shall coincide with the specimen edges. For comparison screening of the damage resistance of different materials, the standard specimen thickness shall be 4.0 to 6.0 mm [0.16 to 0.24 in.] and the laminate defined as follows:

8.2.1.1 *Unidirectional Tape*—Laminate construction shall consist of unidirectional plies with a stacking sequence of $[45/0/{-45}/90]_{NS}$ where N is a whole number. The recommended layups for various nominal cured ply thicknesses are provided in Table 1.

8.2.1.2 *Woven Fabric*—Laminate construction shall consist of fabric plies with a stacking sequence of $[(+45/{-45})/(0/90)]_{NS}$

TABLE 1 Recommended Layups for Various Nominal Cured Ply Thicknesses, Unidirectional Tape

Nominal Cured Ply Thickness		Ply Count	Layup
Minimum, mm [in.]	Maximum, mm [in.]		
0.085 [0.0033]	0.10 [0.004]	48	$[45/0/\text{-}45/90]_{6S}$
0.10 [0.004]	0.13 [0.005]	40	$[45/0/\text{-}45/90]_{5S}$
0.13 [0.005]	0.18 [0.007]	32	$[45/0/\text{-}45/90]_{4S}$
0.18 [0.007]	0.25 [0.010]	24	$[45/0/\text{-}45/90]_{3S}$
0.25 [0.010]	0.50 [0.020]	16	$[45/0/\text{-}45/90]_{2S}$
0.50 [0.020]	0.75 [0.030]	8	$[45/0/\text{-}45/90]_{S}$

where *N* is a whole number. The designations (+45/-45) and (0/90) represent a single layer of woven fabric with the warp and weft fibers oriented at the specified angles. Fabric laminates containing satin-type weaves shall have symmetric warp surfaces, unless otherwise specified and noted in the report. The recommended layups for various nominal cured ply thicknesses are provided in Table 2.

8.2.1.3 *Alternative Stacking Sequences*—Laminates fabricated using other layups or fiber orientations may be evaluated for damage resistance using this test method. Tests conducted using alternative stacking sequences must be designated as such, with the stacking sequence recorded and reported with any test results.

8.2.2 *Specimen Dimensions*—Specimens shall be 150.0 ± 3.0 mm [6.00 ± 0.10 in.] square, flat, and of constant thickness. The variation in thickness for any given specimen shall not exceed 0.1 mm [0.004 in.].

8.3 *Specimen Preparation*—Guide D5687/D5687M provides recommended specimen preparation practices and should be followed where practical.

8.3.1 *Panel Fabrication*—Control of fiber alignment is critical. Improper fiber alignment will affect the measured properties. Erratic fiber alignment will also increase the coefficient of variation. Report the panel fabrication method. Specimens shall be of uniform cross-section over the entire surface and shall not have a thickness taper greater than 0.08 mm [0.003 in.] in any direction across the length and width of the specimen. The coefficient of variation for thickness measurements taken in 11.2.5 should be less than 2 %.

8.3.2 *Machining Methods*—The use of diamond-tipped tooling (as well as water-jet cutting) has been found to be extremely effective for many material systems. Take precautions when cutting specimens from large panels to avoid notches, undercuts, rough or uneven surfaces, or delaminations due to inappropriate machining methods. If subsequent residual strength testing is to be performed, final dimensions should be obtained by water-lubricated precision sawing, milling, or grinding such that edges are flat and parallel. Record and report the specimen cutting methods.

8.3.3 *Labeling*—Label the plate specimens so that they will be distinct from each other and traceable back to the raw material and will neither influence the test nor be affected by it.

TABLE 2 Recommended Layups for Various Nominal Cured Ply Thicknesses, Woven Fabric

Nominal Cured Ply Thickness		Ply Count	Layup
Minimum, mm [in.]	Maximum, mm [in.]		
0.085 [0.0033]	0.10 [0.004]	48	$[(45/\text{-}45)/(0/90)]_{12S}$
0.10 [0.004]	0.13 [0.005]	40	$[(45/\text{-}45)/(0/90)]_{10S}$
0.13 [0.005]	0.15 [0.006]	32	$[(45/\text{-}45)/(0/90)]_{8S}$
0.15 [0.006]	0.18 [0.007]	28	$[(45/\text{-}45)/(0/90)]_{7S}$
0.18 [0.007]	0.20 [0.008]	24	$[(45/\text{-}45)/(0/90)]_{6S}$
0.20 [0.008]	0.25 [0.010]	20	$[(45/\text{-}45)/(0/90)]_{5S}$
0.25 [0.010]	0.36 [0.014]	16	$[(45/\text{-}45)/(0/90)]_{4S}$
0.36 [0.014]	0.50 [0.020]	12	$[(45/\text{-}45)/(0/90)]_{3S}$
0.50 [0.020]	1.00 [0.040]	8	$[(45/\text{-}45)/(0/90)]_{2S}$
1.00 [0.040]	1.50 [0.060]	4	$[(45/\text{-}45)/(0/90)]_{S}$

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 specimen condition is effective moisture equilibrium at a specific relative humidity as established by Test Method D5229/D5229M; however, if the test requester does not explicitly specify a pre-test conditioning environment, conditioning is not required and the test specimens may be tested as prepared.

NOTE 2—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.

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

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

11. Procedure

11.1 *Parameters to be Specified Prior to Test:*

11.1.1 The specimen sampling method, specimen type and geometry, and conditioning travelers (if required).

11.1.2 The damage resistance properties and data reporting format desired.

11.1.3 The environmental conditioning test parameters.

11.1.4 The specimen support configuration.

11.1.5 If performed, sampling method, plate specimen geometry, and test parameters used to determine density and reinforcement volume.

11.2 *General Instructions:*

11.2.1 Report any deviations from this test method, whether intentional or inadvertent.

11.2.2 If specific gravity, density, reinforcement volume, or void volume are to be reported, then obtain these samples from the same panels being tested. Specific gravity and density may be evaluated by means of Test Method D792. Volume percent of the constituents may be evaluated by one of the procedures of Test Methods D3171.

11.2.3 Following final specimen machining, but before conditioning, perform a baseline non-destructive inspection of the specimen to detect flaws or defects which may exist prior to testing. A variety of NDI techniques are available for detecting both surface and interior flaws in composites. Visual inspection and liquid penetrant methods can be used for identifying surface defects, while more sophisticated techniques are required for detecting internal flaws such as cracks, splits and delaminations. These techniques include ultrasonics, radiography, thermography, acoustic emission, modal analysis (such as instrumented tap testing) and eddy-current testing. Guidance on available techniques and selection of appropriate methods for specific composite applications is provided in Guide E2533, as well as section 7.4.2 of MIL-HDBK-17-3F. Basic principles and procedures for these methods are covered in the MIL-HDBK-728/1 series, while more specific information on the theory and interpretation of data can be found in MIL-HDBK-731A for thermography, MIL-HDBK-732A for acoustic emission, MIL-HDBK-733A for radiography, and MIL-HDBK-787A for ultrasonics. Record the method(s), specification(s) and parameters used in the NDI evaluation(s).

NOTE 3—The NDI techniques discussed in Guide E2533 and MIL-HDBK-17-3F each have particular attributes in regard to sensitivity to different damage types, ability to detect different types of damage in three dimensions, and so forth. It may be necessary to utilize a combination of NDI techniques to properly characterize the three-dimensional damage state in some instances (for example, when multiple-layer delaminations and matrix cracks are present).

11.2.4 Condition the specimens as required. Store the specimens in the conditioned environment until test time, if the test environment is different than the conditioning environment.

11.2.5 Following final specimen machining and any conditioning, but before all testing, measure the specimen width and length at two locations in the vicinity of the location to be damaged. The thickness of the specimen shall be measured at four locations near the indentation location, and recorded as the average of the four measurements. The accuracy of all measurements shall be within 1 % of the dimension. Record the dimensions to three significant figures in units of millimeters [inches].

11.3 *Test Environment*—If possible, test the specimen under the same fluid exposure level used for conditioning. However, cases such as elevated temperature testing of a moist specimen place unrealistic requirements on the capabilities of common environmental chambers. In such cases the mechanical test environment may need to be modified, for example, by testing at elevated temperature with no fluid exposure control, but with a specified limit on time to test after withdrawal from the conditioning chamber. Record any modifications to the test environment.

11.4 *Testing Machine Preparation*—Mount the appropriate fixture and indenter containing the hemispherical tip in the testing machine. Ensure that the specimen support fixture is centered under the indenter. Prepare force and displacement measurement instrumentation as required.

11.5 *Specimen Installation*—Place the specimen on the support fixture, making sure that the specimen's center is aligned with both the center of the fixture's opening (if applicable) and the centerline of the indenter. The distance between the centerline of the indenter and centers of the specimen and support fixture shall not exceed 1.0 mm [0.04 in.]. If a single specimen is going to be loaded in intervals, alignment marks should be made on the specimen and fixtures such that the original alignment can be maintained. Unless otherwise specified, indent the tool side of the specimen.

11.6 *Speed of Testing*—Set the speed of testing to reach the maximum force within 1 to 10 min. The suggested standard crosshead displacement rates are 1.25 mm/min [0.05 in./min] for the edge-supported configuration and 0.25 mm/min [0.01 in./min] for the rigidly-backed configuration.

11.7 *Loading*—Apply the indentation force to the specimen at the specified rate while recording data. Monitor the force and observe damage development. When the desired contact force, desired displacement, or the desired damage state has been reached, the specimen shall be unloaded and the test machine stopped. Unless specimen penetration is specifically desired, the test should be terminated before penetration so as to prevent masking of the failure modes in order to provide a more representative failure mode assessment. The unloading rate shall be the same as the loading rate.

NOTE 4—A test to penetration should not be conducted on a rigidly-backed specimen.

11.8 *Data Recording*—Record force versus crosshead displacement continuously, or at frequent regular intervals; for this test method, a minimum sampling rate of 2 data recordings per second, and a target minimum of 100 data points per test are recommended. If a compliance change or damage is noted, record the force, displacement, and mode of damage at such points. If the specimen is to be penetrated, record the maximum force and the crosshead displacement at, or as near as possible to, the moment of penetration. Load and displacement shall be recorded throughout the test including the unloading cycle.

11.8.1 Examples of recorded contact force versus displacement curves for the edge-supported configuration and for the rigidly-backed configuration are shown in Figs. 4 and 5. The onset of specimen-indenter contact is noted by the detection of a non-zero contact force. For the edge-supported configuration, the indenter will flex the specimen and form a local depression as the contact force increases. Sharp drops in recorded contact force typically represent damage processes that result in a sudden loss of stiffness.

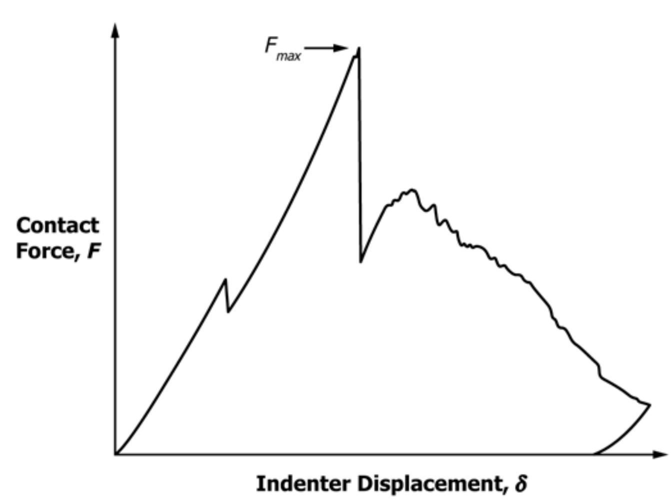

FIG. 4 Typical Force-Displacement Response for Edge-Supported Configuration

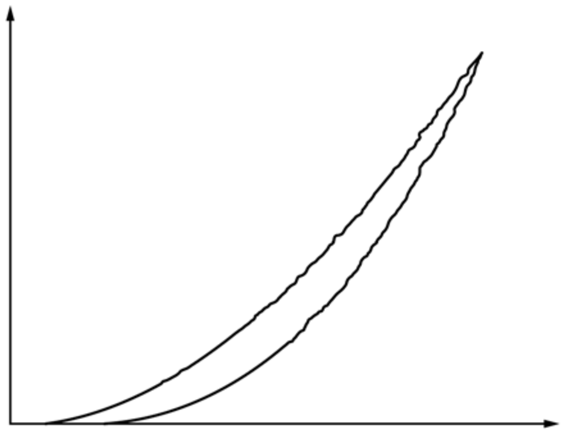

FIG. 5 Typical Force-Displacement Response for Rigidly-Backed Configuration

11.8.2 Some parameters, such as F_{max} and δ_{max}, may be determined directly from the contact force versus displacement curve(s) after the test. Other parameters, such as E_{max} and E_a, must be determined with additional calculations (see 13.1).

11.9 *Dent Depth*—Measure the dent depth, as defined in 3.2.3, using a suitable dent depth indicator as defined in 7.8. The dent shall be measured immediately after the force is removed. If distances are measured relative to a fixed point, the dent depth will be the difference between the lowest point in the dent and the plate surface. The distance to the plane of the specimen's surface shall be the average of four measurements spaced 90º apart and at least 25 mm [1.0 in.] from the indentation point to provide a sufficient distance away from the dent to not influence the measurement. If the depth is measured directly using a depth gage, the depth shall be the average of two measurements with the gage rotated 90º between measurements. The base of the depth gage shall be at least 50 mm [2.0 in.] and sufficiently large to span over the region affected by the dent. These requirements also apply if the depth is measured using a tripod-mounted depth gage (one which bases its reference surface on a micrometer holder that touches the surface at three points on a prescribed diameter). The dent depth shall be measured to the nearest 0.03 mm [0.001 in.].

11.10 *Stepped Loading*—In many cases, it may be desirable to load a specimen in a series of steps since dent measurements and NDI can not be performed on a loaded specimen. This technique may be useful in minimizing the amount of material needed for a damage resistance assessment. If a stepped loading procedure is used, it shall be reported with the results. For each step in the loading series, the specimen shall be loaded to a greater indenter displacement than the previous step. The same zero point for the indenter displacement shall be maintained for the entire series of loading steps. Alignment marks on the fixture shall be used to ensure that the specimen maintains the same center for each load step.

11.11 *Dent Relaxation*—Over time or under environmental exposure, the dent depth may decrease due to relaxation of the composite material. If information on short-term dent relaxation is desired, measure the dent depth 7 days after testing as in 11.9. Record the dent depth, the time duration after testing that the measurement was taken, and the environmental conditions prior to measurement.

11.12 *Non-Destructive Inspection:*

11.12.1 Evaluate the extent of damage using non-destructive inspection (NDI) techniques. Utilize NDI method(s), specification(s) and parameters consistent with those used to evaluate the specimen prior to testing in 11.2.3. Record the method(s), specification(s) and parameters used in the NDI evaluation(s).

11.12.2 Measure and record geometric dimensions for the detected damage, using a suitable instrument as defined in 7.1. Using Fig. 6 as a guide, determine locations of the eight indicated points relative to the center of the specimen and the reference coordinate system. Also determine the damage width, damage length, and maximum damage diameter. Alternative measurement locations may be required to characterize the extent of damage for non-standard layups or fiber orientations. Alternatively, automated algorithms may be used to define the extent of damage and to calculate the two-dimensional damage area using digital NDI data.

NOTE 5—Dimensional tolerances for the measured damage width, length and diameter are dependent upon the NDI method(s) utilized.

11.12.3 Record the damage mode(s) observed for each specimen, and the surface(s) and location(s) at which the damage modes are observed. More than one damage mode may be present in a damaged specimen. Fig. 7 illustrates commonly observed damage modes.

12. Validation

12.1 Property values shall not be calculated for any specimen that forms damage or 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 If a significant number of specimens in a sample population exhibit damage originating or extending significantly away from the indentation location, the support conditions shall be re-examined. Factors considered should include fixture alignment, indenter alignment, gaps between the specimen and fixture, and specimen thickness taper.

13. Calculation

13.1 *Energy*—The energy at any indenter displacement, δ, may be calculated from the contact force versus indenter displacement curve using Eq 1. Record the calculated energy to three significant figures. A positive displacement value represents downward motion of the indenter. Common numerical integration algorithms used in this application include the trapezoidal rule and Simpson's rule (2 and 3 point Newton-Cotes formulas, respectively (**8**)).

$$E(\delta) = \int_{\delta_o}^{\delta} F(\delta)d\delta \quad (1)$$

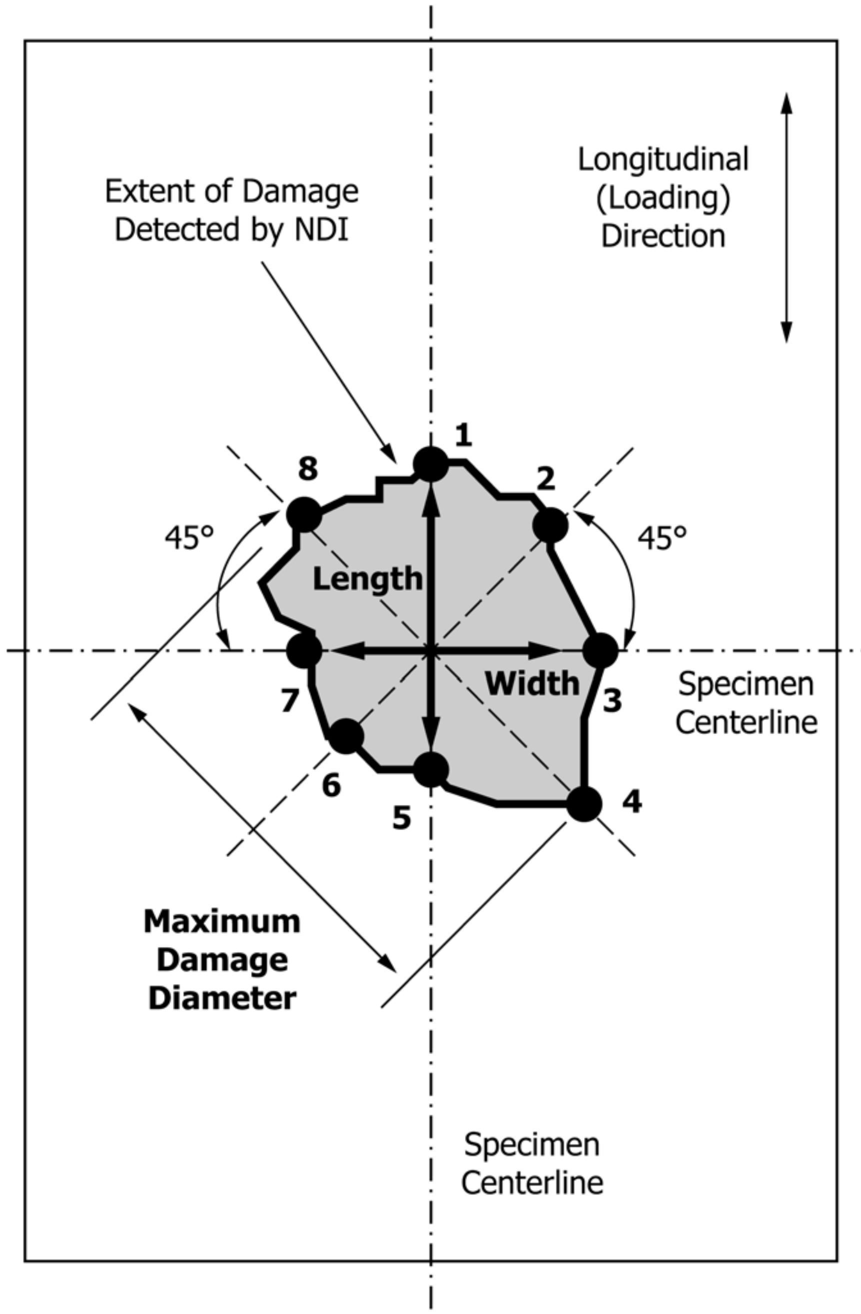

FIG. 6 Measurement of Extent of Damage

where:

E = energy at displacement δ, N-m [in.-lbf],
δ = indenter displacement during the test, m [in.],
δ_o = indenter displacement at initial specimen contact, m [in.], and
F = measured contact force at indenter displacement δ, N [lbf].

13.1.1 *Energy* E_{max}—The energy required for the indenter to reach its maximum displacement on the force-displacement curve may be calculated.

$$E_{max} = E(\delta_{max}) = \int_{\delta_o}^{\delta_{max}} F(\delta)d\delta \qquad (2)$$

where:

δ_{max} = maximum indenter displacement, m [in.].

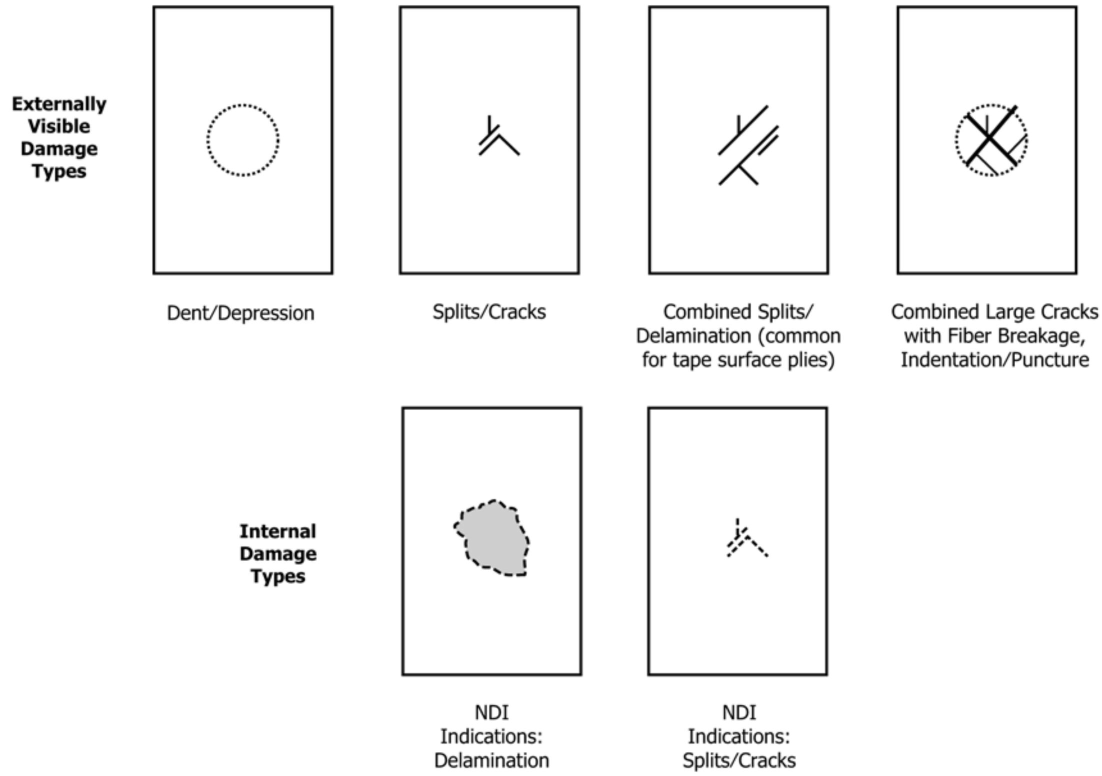

FIG. 7 Commonly Observed Damage Modes from Out-of-Plane Loading

13.1.2 *Absorbed Energy* E_a—The energy absorbed (inelastically) during a complete loading cycle (loading and unloading). The absorbed energy is represented as the area bounded by the loading and unloading curves.

$$E_a = E(\delta_f) = \int_{\delta_o}^{\delta_f} F(\delta) d\delta \quad (3)$$

where:

δ_f = indenter displacement at the end of the unloading cycle, m [in.].

13.2 *Statistics*—For each series of tests, calculate the average value, standard deviation, and coefficient of variation (in percent) for each property determined:

$$\bar{x} = \frac{\left(\sum_{i=1}^{n} x_i\right)}{n} \quad (4)$$

$$s_{n-1} = \sqrt{\left(\sum_{i=1}^{n} x_i^2 - n\bar{x}^2\right) / (n-1)} \quad (5)$$

$$CV = 100 \times s_{n-1} / \bar{x} \quad (6)$$

where:

$\bar{x}$ = sample mean (average),
s_{n-1} = sample standard deviation,
CV = sample coefficient of variation, %,
n = number of specimens, and
x_i = measured or derived property.

14. Report

14.1 Report 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):

NOTE 6—Guides E1309, E1434 and E1471 contain data reporting recommendations for composite materials and composite materials mechanical testing.

14.1.1 The revision level or date of issue of this test method.

14.1.2 The name(s) of the test operator(s).

14.1.3 Any variations to this test method, anomalies noticed during testing, or equipment problems occurring during testing.

14.1.4 Identification of all the applicable constituent information, including: material specification, material type, manufacturer's material designation, manufacturer's batch or lot number, source (if not from manufacturer), date of certification, expiration of certification, filament diameter, tow or yarn filament count and twist, sizing, form or weave, fiber areal weight, matrix type, matrix content and volatiles content.

14.1.5 Description of the fabrication steps used to prepare the parent laminate including: fabrication start date, fabrication end date, process specification, cure cycle, consolidation method, and a description of the equipment used.

14.1.6 Ply orientation and stacking sequence of the laminate.

14.1.7 If requested, report density, volume percent reinforcement, and void content test methods, specimen sampling method and geometries, test parameters and test results.

14.1.8 Method of preparing the test specimen, including specimen labeling scheme and method, specimen geometry, sampling method, and specimen cutting method.

14.1.9 Calibration dates and methods for all measurements and test equipment.

14.1.10 Type and configuration of test machine, data acquisition equipment, data sampling rate, crosshead displacement rate.

14.1.11 Measured length, width, and thickness for each specimen (prior to and after conditioning, if appropriate).

14.1.12 Conditioning parameters and results.

14.1.13 Relative humidity and temperature of the testing laboratory.

14.1.14 Environment of the test machine environmental chamber (if used) and soak time at environment.

14.1.15 Number of specimens tested.

14.1.16 Diameter of hemispherical indenter tip.

14.1.17 Results of nondestructive evaluation tests, including method, specification, inspection parameters and operator, both before and after testing.

14.1.18 Damage geometry, including positions of the eight specified measurement points, damage width, damage length, maximum damage diameter, damage area (if calculated), and through-thickness location in the reference coordinate system.

14.1.19 Damage modes and locations observed for each specimen.

14.1.20 Individual dent depths reported as a function of maximum contact force.

14.1.21 If dent relaxation is evaluated, individual dent depths after relaxation, along with the time duration after testing and the environmental conditions prior to measurement.

14.1.22 Contact force versus indenter displacement curves for each test/specimen.

14.1.23 Maximum force and maximum indenter displacement.

14.1.24 Maximum and absorbed energies for each specimen so evaluated, along with method of numerical integration utilized.

15. Precision and Bias

15.1 *Precision*—The data required for the development of a precision statement is not available for this test method.

15.2 *Bias*—Bias cannot be determined for this test method as no acceptable reference standard exists.

16. Keywords

16.1 composite materials; damage resistance; delamination; dent; impact; quasi-static indentation

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