Designation: D 6264 – 98

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 D 6264; 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 A quasi-static indentation (QSI) test method is used to obtain quantitative measurements of the damage resistance of a continuous-fiber-reinforced composite material to a concentrated indentation force (Fig. 1). The indentation force is applied to the specimen by slowly pressing a hemispherical indenter into the surface. Procedures are specified for determining the damage resistance for a simply supported test specimen and for a rigidly backed test specimen. The damage resistance is quantified in terms of a critical contact force associated with a single event or sequence of events to cause a specific size and type of damage in the specimen. These tests may be used to screen materials for damage resistance or to inflict damage into a specimen for subsequent damage tolerance testing. This test method is limited to use with composites consisting of layers of unidirectional fibers or layers of fabric. This test method may prove useful for other types and classes of composite materials. Certain interferences, however, have been noted (see 6.7).

1.2 *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.*

1.3 The values stated in SI units are to be regarded as standard. The values given in parentheses are provided for information purposes only.

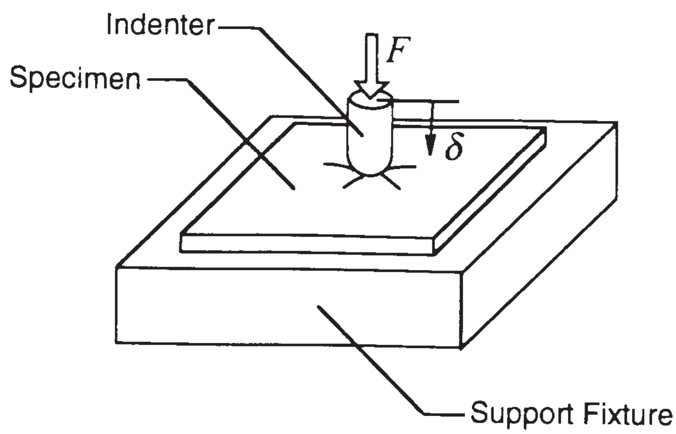

FIG. 1 Quasi-Static Indentation Test

2. Referenced Documents

2.1 *ASTM Standards:*

D 883 Terminology Relating to Plastics[2]

D 2734 Test Methods for Void Content of Reinforced Plastics[3]

D 3171 Practice for Fiber Content of Resin Matrix Composites by Matrix Digestion[4]

D 3878 Terminology of High-Modulus Reinforcing Fibers and Their Composites[4]

D 5229/D5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials[4]

D 5687/D5687M Guide for Preparation of Flat Composite Panels With Processing Guidelines for Specimen Preparation[4]

E 4 Practices for Force Verification of Testing Machines[5]

E 6 Terminology Relating to Methods of Mechanical Testing[5]

E 18 Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials[5]

E 122 Practice for Choice of Sample Size to Estimate a Measure of Quality for a Lot or Process[6]

3. Terminology

3.1 *Definitions*—Terminology D 3878 defines terms relating to high-modulus fibers and their composites. Terminology

[1] This standard is under the jurisdiction of ASTM Committee D-30 on Composite Materials and is the direct responsibility of Subcommittee D30.05 on Structural Test Methods.

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[2] *Annual Book of ASTM Standards*, Vol 08.01.

[3] *Annual Book of ASTM Standards*, Vol 08.02.

[4] *Annual Book of ASTM Standards*, Vol 15.03.

[5] *Annual Book of ASTM Standards*, Vol 03.01.

[6] *Annual Book of ASTM Standards*, Vol 14.02.

D 883 defines terms relating to plastics. Terminology E 6 defines terms relating to mechanical testing. In the event of a conflict between terms, Terminology D 3878 shall have precedence over the other standards.

3.2 *Definitions of Terms Specific to This Standard*—The terms in this test method may conflict with general usage. There is not yet an established consensus concerning the use of these terms. The following descriptions are intended only for use in this test method.

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 nondimensional 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.

3.2.1 *contact force, F* [MLT^{-2}], *n*—the total force applied normal to the face of the specimen by the indenter.

3.2.2 *damage, n—in structures and structural materials*, a structural anomaly in a material or structure created by manufacturing or service usage.

3.2.3 *damage resistance, n— in structures and structural materials*, a measure of the relationship between the force, energy, or other parameter(s) associated with an event or sequence of events and the resulting damage size and type.

3.2.4 *dent depth, d* [*L*], *n*—residual depth of the depression formed by an indenter after removal of load. 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 indented surface that is undisturbed by the dent.

3.2.5 *F_1 force, F_1* [MLT^{-2}], *n*—contact force at which the force/indenter displacement curve has a discontinuity in force or slope.

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

3.2.7 *maximum force, F_{max}* [MLT^{-2}], *n*—the maximum contact force a laminate will resist. This force is obtained from the *F*/δ curve after a point is reached where the contact force does not increase with increasing indenter displacement.

3.3 *Symbols:*

d	=	dent depth (see 3.2.4).
F	=	contact force (see 3.2.1).
F_1	=	F_1 force (see 3.2.5).
F_{max}	=	maximum force (see 3.2.7).
N	=	number of ply groups in a laminate's stacking sequence.
δ	=	indenter displacement (see 3.2.6).

4. Summary of Test Method

4.1 The quasi-static indentation (QSI) test is used to measure the damage resistance of a uniform-thickness laminated composite specimen. An indentation force is applied slowly by pressing a displacement-controlled hemispherical indenter into the face of the specimen. The displacement is increased until the desired damage state is reached. Procedures are specified for determining the damage resistance for a simply supported test specimen and for a rigidly backed test specimen. The damage response is a function of the test configuration.

4.2 A record of the applied contact force/indenter displacement (*F*/δ) is recorded on either an *X-Y* recorder, an equivalent real-time plotting device, or stored digitally and postprocessed.

5. Significance and Use

5.1 Susceptibility to damage from concentrated indentation forces is one of the major weaknesses of many structures made of advanced laminated composites. Knowledge of the damage resistance of a laminated composite material subjected to a concentrated indentation force is useful for product development and material selection.

5.2 The QSI test method can serve the following purposes:

5.2.1 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 quasi-static indentation force.

5.2.2 To compare quantitatively the relative values of the damage resistance parameters for composite materials with different constituents. The damage response parameters include *d*, F_1, and F_{max}, as well as the *F*/δ curve.

5.2.3 To place a controlled amount of damage in a specimen for subsequent damage tolerance tests.

5.2.4 To isolate and measure the indentation response of the specimen without bending (rigidly backed configuration).

6. Interferences

6.1 The QSI test simulates the force/displacement relationships of many impacts governed by boundary conditions **(1-7)**. These are typically relatively large-mass low-velocity hard-body impacts on plates with a relatively small unsupported region. 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 damage response of a specimen is dependent on many factors, including the indenter geometry and specimen support conditions. Consequently, comparisons cannot be made between materials unless identical test configurations, identical test conditions, and identical laminates are used. Therefore, all deviations from the standard test configuration should be reported in the results.

6.3 Force F_1 does not represent the initiation of damage, but generally represents when the displacement of the indenter is affected by large-scale damage formation. Typically, matrix cracks and small delaminations form before this force.

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

6.5 Treatment and interpretation of delamination growth are beyond the scope of this test method.

6.6 *Material and Specimen Preparation*— Poor material fabrication practices, lack of control of fiber alignment, and damage induced by improper coupon machining are known causes of high material data scatter in composites.

6.7 *Application to Other Materials, Lay-Ups, and Architectures*:

6.7.1 The QSI test primarily has been used for testing carbon-fiber-reinforced tape and fabric laminates with polymer matrices. For other materials, a quite different response may occur.

6.7.2 Nonlaminated, 3D fiber-reinforced, or textile composites may fail by different mechanisms than laminates. The most critical damage may be in the form of matrix cracking or fiber failure, or both, rather than delaminations.

7. Apparatus

7.1 *Testing Machine*—The testing machine shall be in conformance with Practices E 4 and shall satisfy the following requirements:

7.1.1 *Testing Machine Heads*—The testing machine shall have both an essentially stationary head and a movable head.

7.1.2 *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.

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

7.1.4 *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 rigid support.

7.2 *Flat Rigid Support*—A flat rigid surface shall be attached to the lower head and used 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. If the rigidly backed configuration is to be used, this support shall be made from steel with a minimum thickness of 12.7 mm (0.5 in.).

7.3 *Indenter*—The indenter shall have a smooth hemispherical tip with a diameter of 12.7 ± 0.1 mm (0.500± 0.003 in.) and a hardness of 60 to 62 HRC as specified in Test Methods E 18. If a different indenter is used as part of the testing, the shape and dimensions shall be noted.

7.4 *Indenter Displacement Indicator*— The axial displacement of the indenter relative to the support fixture may be estimated as the crosshead travel, provided the deformation of the testing machine and support fixture is less than 2 % of the crosshead travel. If not, the indenter displacement shall be obtained from a properly calibrated external gage or transducer located between the indenter and the support fixture or the rigid support surface. The displacement indicator shall indicate the displacement with an accuracy of ±1 % of the thickness of the specimen.

7.5 *Load Versus Indenter Displacement (F Versus* δ*) Record*—An *X-Y* plotter, or similar device, shall be used to make a permanent record during the test of load versus indenter displacement. Alternatively, the data may be stored digitally and postprocessed.

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

7.6.1 *Simply Supported Configuration*— The fixture shall consist of a single plate with a 127.0 ± 2.5 mm (5.00± 0.10 in.) diameter opening made from a structural metal such as aluminum or steel. 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 Fig. 2.

7.6.2 *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.).

7.7 *Micrometers*—The micrometer(s) shall use a suitable size diameter ball-interface on irregular surfaces such as the bag-side of a laminate, and a flat anvil interface on machined or very smooth tooled surfaces. The accuracy of the instruments shall be suitable for reading to within 1 % of the sample width and thickness. For typical specimen geometries, an instrument with an accuracy of ±2.5 µm [±0.0001 in.] is desirable for thickness measurement, while an instrument with an accuracy of ±25 µm [±0.001 in.] is desirable for width measurement.

7.8 *Dent Depth Indicator*—The dent depth can be measured using a dial depth gage, a depth gage micrometer, or a properly calibrated displacement transducer. The measuring probe shall have a hemispherical tip with a diameter between 1.5 and 5.0 mm (0.06–0.20 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 condition, unless valid results can be gained through the use of fewer specimens, such as in the case of a designed experiment. For statistically significant data, the procedures outlined in Practice E 122 should be consulted. Report the method of sampling.

8.2 *Specimen Lay-Up*—The laminate shall be flat and have a cross section of constant thickness.

8.2.1 For comparison screening of the damage resistance of different materials, the following laminate is suggested. A quasi-isotropic lay-up with a specimen thickness in the range of 3.5 to 5.0 mm (0.14 to 0.20 in.) with a target thickness of 4.2 mm (0.17 in.) shall be obtained as follows:

8.2.1.1 *Tape*—Laminate construction shall consist of the appropriate number of unidirectional plies to achieve a total cured thickness nearest to 4.2 mm (0.17 in.) with a stacking sequence of $[45/0/-45/90]_{NS}$ where *N* is a whole number. If the "nearest" thickness is less than 3.5 mm (0.14 in.), the next

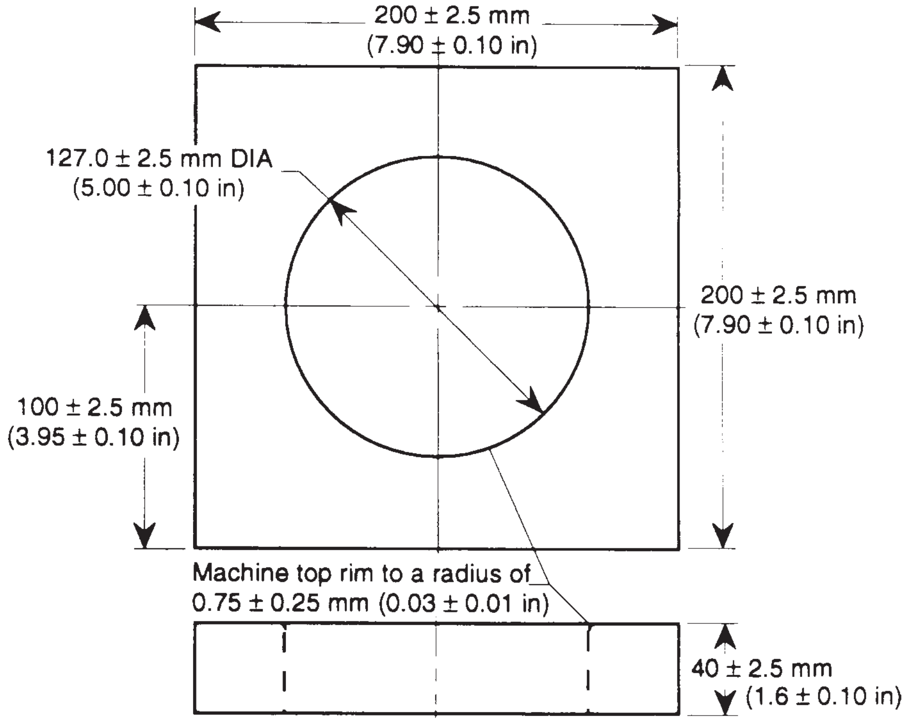

FIG. 2 Typical Fixture for the Simply Supported Configuration

value of *N* shall be used (*N* + 1). For a typical 145-grade tape, a 32-ply specimen shall be manufactured with a lay-up of $[45/0/-45/90]_{4S}$.

8.2.1.2 *Woven Fabric*—Laminate construction shall consist of the appropriate number of fabric plies to achieve a total cured thickness nearest to 4.2 mm (0.17 in.) with a stacking sequence of $[(+45/-45)/(0/90)]_{NS}$ where *N* is a whole number. If the "nearest" thickness is less than 3.5 mm (0.14 in.), the next value of *N* shall be used (*N* + 1). 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. If a satin weave is used, each layer shall be flipped such that the predominant tow direction on each side of the fabric corresponds to the specified lay-up.

8.3 *Specimen Dimensions*—Specimens shall be 152.0 ± 1.0 mm (6.00 ± 0.05 in.) square and of constant thickness. The variation in thickness for any given specimen shall not exceed 0.1 mm.

8.4 *Specimen Preparation*—Panels shall be fabricated and machined in accordance with Guide D 5687/D 5687M. Label the coupons so that they will be distinct from each other and traceable back to the raw material, and in a manner that will both be unaffected by the test and not influence the test.

8.5 *Void Content and Fiber Volume*— It is recommended that void content and fiber volume be reported. Void content may be determined using the equations of Test Method D 2734. The fiber volume fraction may be determined using matrix digestion per Practice D 3171.

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 *Standard Conditioning Procedure*— Condition specimen in accordance with Procedure C of Test Method D 5229/D 5229M unless other conditioning is specified as part of the experiment. Store and test specimens at Standard Laboratory Atmosphere (23 ± 3°C [73 ± 5°F] and 50 ± 10 % relative humidity). Nonstandard conditioning and nonstandard test environments shall be reported.

10.2 *Oven Drying*—If damage resistance data are desired for laminates in an oven-dried condition, use Procedure D of Test Method D 5229/D 5229M.

11. Procedure

11.1 Select either the simply supported or rigidly backed test configuration. Mount the appropriate fixture(s) in the testing machine. The following procedures are identical for the two test configurations. Report any deviations from this test method, whether intentional or inadvertent.

11.2 If fiber volume or void content are to be reported, then obtain these samples from the same panel being tested.

11.3 Mount the indenter in the testing machine such that the relative displacement between the specimen and indenter will be normal to the face of the specimen.

11.4 Measure the thickness of each specimen to the nearest 0.05 mm (0.002 in.) at several points around the edge of the specimen using a micrometer (7.7). The variation in thickness along the length of the specimen shall not exceed 0.1 mm (0.004 in.). The average value of the thickness measurements shall be recorded.

11.5 Mark the center of the specimen's face. For the simply supported configuration, 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 and the centerline of the indenter. For the rigidly backed configuration, place the specimen directly on the flat rigid support such that the specimen's center is aligned with 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 fixtures such that the original alignment can be maintained.

11.6 Apply load to the specimen in displacement control at a constant crosshead (or servohydraulic ram) displacement rate. The displacement rate should be selected so as to reach the maximum force within 1 to 10 min. Record the load versus displacement trace on an *X-Y* chart recorder or other appropriate recording device.

11.7 As load is increased, the indenter will press into the specimen forming a local depression and, for the simply supported configuration, flexing the specimen. Observe damage characteristics. Examples of a typical F/δ curve for the simply supported configuration and for the rigidly backed configuration are shown in Figs. 3 and 4.

11.8 When a desired milestone, such as F_{max} or the desired contact force or the desired damage state, has been reached, the specimen shall be unloaded and the test machine stopped. Load and displacement shall be recorded throughout the test including the unloading cycle. The unloading rate shall be the same as the loading rate.

11.9 Dent depth (*d*) is a function of contact force but cannot be obtained from a loaded specimen. Therefore, the specimen must be unloaded to perform this measurement. For example, to obtain *d* at contact force F', load specimen to $F = F' > 0$; unload to $F = 0$; perform measurement to obtain $d(F')$. Center the specimen on the fixture again according to the alignment marks and load the specimen to the next higher load, $F = F'' > F'$. The dent depth, as defined in 3.2.4, shall be measured using a suitable dent depth indicator as defined in 7.8. The dent shall be measured immediately after the load is removed from the specimen. 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 90° apart and at least 25 mm from the indentation point to provide a sufficient distance away from the dent to not influence the measurement. If the depth is measured directly by using a depth gage, the depth shall be the average of two measurements with the gage rotated 90° between measurements. The base of the depth gage shall be at least 50 mm and sufficiently large to span over the region affected by the dent. The dent depth shall be measured to the nearest 0.01 mm (0.001 in.).

11.10 The F_1 force and maximum force, F_{max}, can be determined from the contact force/indenter displacement (F/δ) curve(s) after the test. F_1 and F_{max} may not exist for the rigidly backed configuration.

12. Report

12.1 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 requester.

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

12.1.2 The date(s) and location(s) of the test.

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

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

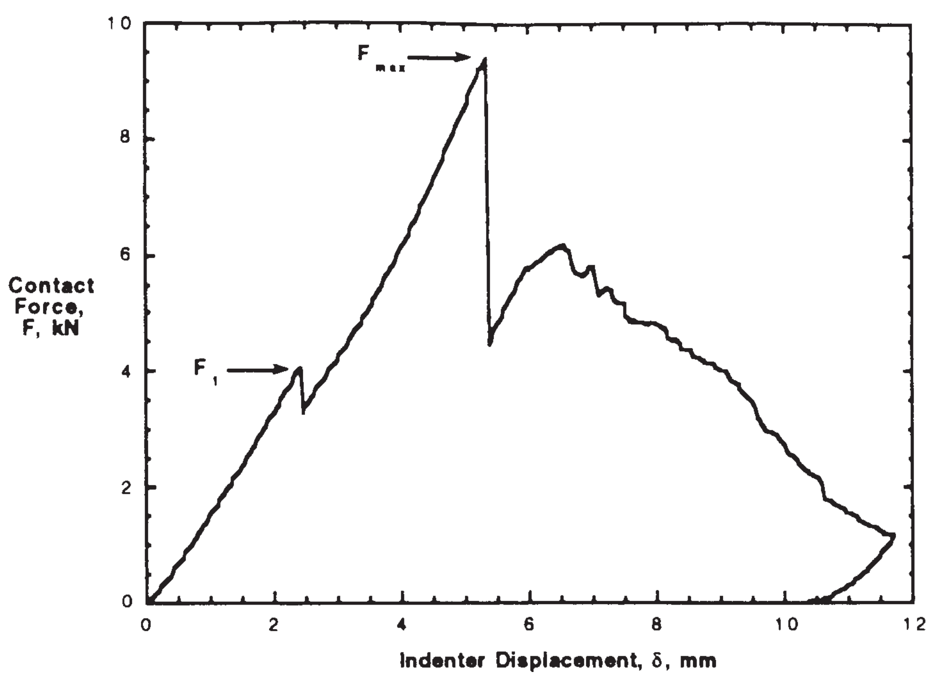

FIG. 3 Typical *F*/δ Response for the Simply Supported Configuration

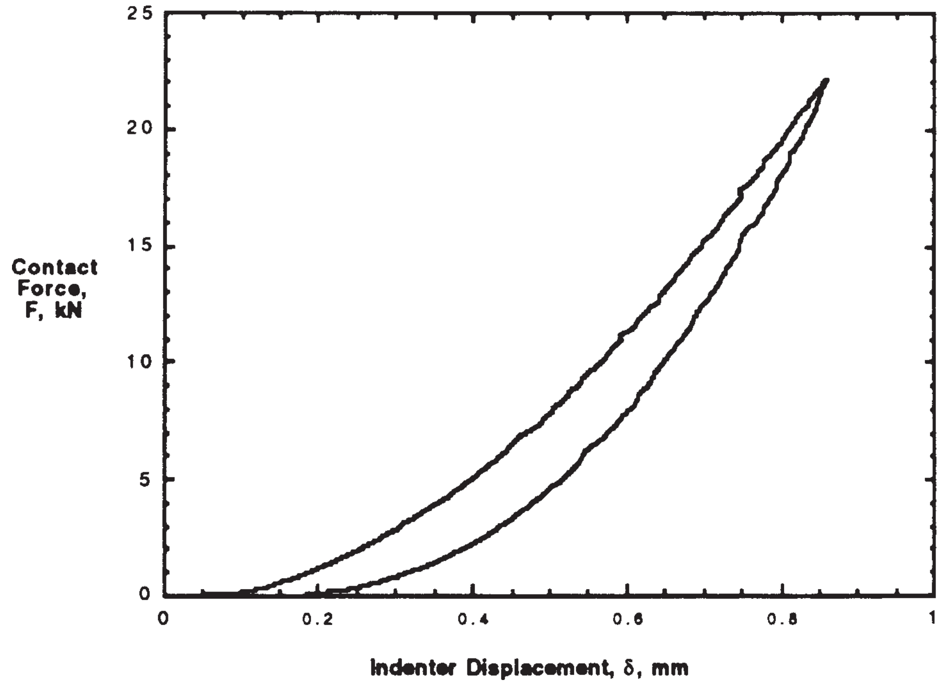

FIG. 4 Typical F/δ Response for the Rigidly Backed Configuration

12.1.5 Identification of the material tested, including: material specification, material type, material designation, manufacturer, manufacturer's lot or batch 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, prepreg matrix content, and prepreg volatiles content.

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

12.1.7 Ply orientation stacking sequence of the laminate.

12.1.8 Fiber volume fraction and void content, if measured. Include the method used to determine fiber volume fraction and void content.

12.1.9 Average ply thickness of the material.

12.1.10 Results of any nondestructive evaluation tests.

12.1.11 Method of preparing the test specimen, including specimen labeling scheme and sampling method.

12.1.12 Calibration dates and methods for all measurement and test equipment.

12.1.13 Type of test machine and data acquisition sampling rate and equipment type.

12.1.14 Dimensions of each test specimen. Include average nominal thickness of each specimen and maximum thickness variation along the edges of the specimen.

12.1.15 Conditioning parameters and results and the procedure used if other than that specified in the test method.

12.1.16 Relative humidity and temperature of the testing laboratory.

12.1.17 Speed of testing.

12.1.18 Displacement transducer placement, if used, and transducer type.

12.1.19 *Test results*:

12.1.19.1 Contact force/indenter displacement (F/δ) curves.

12.1.19.2 F_1, F_{max}, and d, if these parameters were measured. For dent depth (d) measurements, the results should be reported as a function of contact force.

12.1.19.3 Report the number of specimens tested and the individual values, mean, standard deviation, and coefficient of variation (standard deviation divided by the mean) of all measurements.

12.1.19.4 Any observations on damage characteristics that were made for each specimen.

13. Precision and Bias

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

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

14. Keywords

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

REFERENCES

(**1**) Bucinell, R. B., Nuismer, R. J., and Koury, J. L., "Response of Composite Plates to Quasi-Static Impact Events," *Composite Materials: Fatigue and Fracture (Third Volume), ASTM STP 1110*, T. K. O'Brien, Ed., American Society for Testing and Materials, Philadelphia, 1991, pp. 528–549.

(**2**) Elber, W., "Failure Mechanics in Low-Velocity Impacts on Thin Composite Plates," NASA TP 2152, May 1983.

(**3**) Jackson, W. C., and Poe, C. C., Jr., "The Use of Impact Force as a Scale Parameter for the Impact Response of Composite Laminates," *Journal of Composites Technology & Research*, Vol 15, No. 4, Winter 1993, pp. 282–289.

(**4**) Kwon, Y. S., and Sankar, B. V., "Indentation-Flexure and Low-Velocity Impact Damage in Graphite Epoxy Laminates," *Journal of Composites Technology & Research*, Vol 15, No. 2, Summer 1993, pp. 101–111.

(**5**) Lagace, P. A., Williamson, J. E., Tsang, P. H. W., Wolf, E., and Thomas, S., "A Preliminary Proposition for a Test Method to Measure (Impact) Damage Resistance," *Journal of Reinforced Plastics and Composites*, Vol 12, May 1993, pp. 584–601.

(**6**) Sjöblom, P. O., Hartness, J. T., and Cordell, T. M., "On Low-Velocity Impact Testing of Composite Materials," *Journal of Composite Materials*, Vol 22, Jan. 1988, pp. 30–52.

(**7**) Swanson, S. R., "Limits of Quasi-Static Solutions in Impact of Composite Structures," *Composites Engineering*, Vol 2, No. 4, 1992, pp. 261–267.