Designation: D 6416/D 6416M – 01

Standard Test Method for
Two-Dimensional Flexural Properties of Simply Supported Sandwich Composite Plates Subjected to a Distributed Load[1]

This standard is issued under the fixed designation D 6416/D 6416M; 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 two-dimensional flexural properties of sandwich composite plates subjected to a distributed load. The test fixture uses a relatively large square panel sample which is simply supported all around and has the distributed load provided by a water-filled bladder. This type of loading differs from the procedure of Test Method C 393, where concentrated loads induce one-dimensional, simple bending in beam specimens.

1.2 This test method is applicable to composite structures of the sandwich type which involve a relatively thick layer of core material bonded on both faces with an adhesive to thin-face sheets composed of a denser, higher-modulus material, typically, a polymer matrix reinforced with high-modulus fibers.

1.3 The values stated in either SI units or inch-pound units are to be regarded separately as standard. Within the text the inch-pound units are shown in brackets. 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 *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:*

C 274 Terminology of Structural Sandwich Constructions[2]
C 365 Test Methods for Flatwise Compressive Strength of Sandwich Cores[2]
C 393 Test Method for Flexural Properties of Flat Sandwich Constructions[2]
D 792 Test Methods for Density and Specific Gravity (Relative Density) and Density of Plastics by Displacement[3]
D 2584 Test Method for Ignition Loss of Cured Reinforced Resins[4]
D 2734 Test Method for Void Content of Reinforced Plastics[4]
D 3171 Test Method for Constituent Content of Composite Materials[2]
D 3878 Terminology for High-Modulus Reinforcing Fibers and Their Composites[2]
E 4 Practices for Force Verification of Testing Machines[5]
E 6 Terminology Relating to Methods of Mechanical Testing[5]
E 251 Test Methods for Performance Characteristics of Metallic Bonded Resistance Strain Gages[5]
E 1237 Guide for Installing Bonded Resistance Strain Gages[5]

2.2 *ASTM Adjunct:*

Sandwich Plate Test Fixture and Hydromat Pressure Bladder, ASTM D 6416/D 6416M[6]

3. Terminology

3.1 Terminology D 3878 defines terms relating to high-modulus fibers and their composites. Terminology C 274 defines terms relating to structural sandwich constructions. 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 terminology standards.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *bending stiffness*, *n*—the sandwich property which resists bending deflections.

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[1] This test method is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of Subcommittee D30.09 on Sandwich Construction.

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

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

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

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

[6] Detailed drawings for the fabrication of the 500–mm test fixture and pressure bladder shown in Fig. 3 and Fig. 4 are available from ASTM Headquarters. Order Adjunct No. ADJD6416.

3.2.2 *core*, *n*—a centrally located layer of a sandwich construction, usually low density, which separates and stabilizes the facings and transmits shear between the facings and provides most of the shear rigidity of the construction.

3.2.3 *face sheet*, *n*—the outermost layer or composite component of a sandwich construction, generally thin and of high density, which resists most of the edgewise loads and flatwise bending moments: synonymous with face, skin, and facing.

3.2.4 *footprint*, *n*—the enclosed area of the face sheet surface of a sandwich panel in contact with the pressure bladder during loading.

3.2.5 *hydromat*, *n*—a pressure bladder with a square perimeter fabricated from two square pieces of industrial belting which are superposed and clamped at the edges with through-bolted, mild steel bar stock.

3.2.6 *isotropic material*, *n*—a material having essentially the same properties in any direction.

3.2.7 *orthotropic material*, *n*—a material in which a property of interest, at a given point, possesses three mutually perpendicular planes of symmetry, which taken together define the principal material coordinate system.

3.2.8 *pressure bladder*, *n*—a durable, yet pliable closed container filled with water, or other incompressible fluid, capable of conforming to the contour of a normally loaded test panel when compressed against its face sheet surface by a test machine.

3.2.9 *shear stiffness*, *n*—the sandwich property which resists shear distortions: synonymous with shear rigidity.

3.2.10 *test panel*, *n*—a square coupon of sandwich construction fabricated for two-dimensional flexural testing: synonymous with sandwich panel, sandwich composite plate, sandwich composite panel, and panel test specimen.

3.3 *Symbols:*

3.3.1 a = support span of the test fixture or the length and width of the test panel structure between supports.

3.3.2 A_{eff} = effective contact area of the pressure bladder when compressed against the test panel.

3.3.3 B = test panel bending stiffness.

3.3.4 c = core thickness.

3.3.5 ϵ_x = normal face sheet strain, x component.

3.3.6 ϵ_y = normal face sheet strain, y component.

3.3.7 f = face sheet thickness.

3.3.8 F_m = total normal force applied to a test panel as measured by the test machine load cell.

3.3.9 h = average overall thickness of the test panel.

3.3.10 N = the number of included terms of the series.

3.3.11 P_m = experimentally measured bladder pressure.

3.3.12 ϕ = width of the unloaded border area of a test panel between the edge supports and the effective footprint boundary.

3.3.13 S = test panel shear stiffness.

3.3.14 ω_e = experimentally determined deflection at center of test panel.

4. Summary of Test Method

4.1 A square test panel is simply supported on all four edges and uniformly loaded over a portion of its surface by a water-filled bladder. Pressure on the panel is increased by moving the platens of the test frame. The test measures the two-dimensional flexural response of a sandwich composite plate in terms of deflections and strains when subjected to a well-defined distributed load.

4.2 Panel deflection at load is monitored by a centrally positioned LVDT which contacts the tension-side surface.

4.3 Load is monitored by both a crosshead-mounted load cell, in series with the test fixture, and a pressure transducer in the pressure bladder itself. Since the pressure bladder is also at all times in series with the load cell and test fixture, the effective contact area of the pressure field is continuously monitored as the load/pressure quotient.

4.4 Strain can be monitored with strategically placed strain gage rosettes bonded to the tension-side face-sheet surface. A typical arrangement has four rosettes equally spaced along one of the axes of symmetry of the plate.

5. Significance and Use

5.1 This test method simulates the hydrostatic loading conditions which are often present in actual sandwich structures, such as marine hulls. This test method can be used to compare the two-dimensional flexural stiffness of a sandwich composite made with different combinations of materials or with different fabrication processes. Since it is based on distributed loading rather than concentrated loading, it may also provide more realistic information on the failure mechanisms of sandwich structures loaded in a similar manner. Test data should be useful for design and engineering, material specification, quality assurance, and process development. In addition, data from this test method would be useful in refining predictive mathematical models or computer code for use as structural design tools. Properties that may be obtained from this test method include:

5.1.1 Panel surface deflection at load,

5.1.2 Panel face-sheet strain at load,

5.1.3 Panel bending stiffness,

5.1.4 Panel shear stiffness,

5.1.5 Panel strength, and

5.1.6 Panel failure modes.

6. Interferences

6.1 *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 in general. Specific material factors that affect sandwich composites include variability in core density and degree of cure of resin in both face sheet matrix material and core bonding adhesive. Important aspects of sandwich panel specimen preparation that contribute to data scatter are incomplete wetout of face sheet fabric, incomplete or nonuniform core bonding of face sheets, the non-squareness of adjacent panel edges, the misalignment of core and face sheet elements, the existence of joints or other core and face sheet discontinuities, out-of-plane curvature, and surface roughness.

6.2 *Test Fixture Characteristics*—Configuration of the panel edge-constraint structure can have a significant effect on test results. Correct interpretation of test data depends on the fixture supporting the test panel in such a manner that the boundary conditions consistent with simple support can be assumed to apply. Panel edge support journals must be coplanar and perpendicular to the loading axis. Given the fixture itself has sufficient rigidity, erroneous conclusions about panel strength and stiffness might be drawn if insufficient torque has been applied to the fasteners securing the lower panel edge support frame. In general, panels with more flexural rigidity and shear rigidity require more bolt torque to approach simple support.

6.3 *Pressure Bladder Characteristics*—When a pressure bladder is used to introduce normal load to a plate, the response of the plate is dependent on the resulting pressure distribution. The true function of the pressure bladder is to convert the absolute load applied by the test machine into a pressure field that can be specified by a relatively simple mathematical model. With the hydromat-style bladder, two simplifying assumptions are permitted: (*1*) the shape of the contact area is a readily definable geometric shape (or combination of shapes) and (*2*) the pressure is constant within the boundaries of the contact area. The pressure distribution is then characterized merely by the magnitude of the pressure and the size of the footprint. Obviously, the size and shape of the pressure bladder have a significant effect on test results in terms of the observed strains and deflections. Some errors in data interpretation are possible insofar as the actual pressure distribution differs from the simple mathematical model used in calculations.

NOTE 1—The error in the hydromat model has mainly to do with details of the footprint shape, since the effective contact area can be calculated at any time by dividing the absolute applied load by the bladder pressure. A secondary error arises from the non-zero bending stiffness of the fiber-reinforced industrial belting fabric that results in a narrow band of varying pressure at the very edge of the footprint. Calibration tests using a steel plate equipped with strain gages are recommended for each bladder unit to verify that the errors in the pressure distribution model are negligible (see Section 9).

6.4 *Tolerances*—Test panels need to meet the dimensional and squareness tolerances specified in 8.2 to ensure proper edge support and constraint.

6.5 *System Alignment*—Errors can result if the panel support structure is not centered with respect to the actuator of the test machine, or if the plane defined by the panel edge-bearing surfaces is not perpendicular to the loading axis of the test machine. Errors can also result if the pressure bladder is not centered properly with respect to fixture and actuator or if the edges of the bladder clamping bars are not parallel to the panel edge-support journals.

6.6 *Other System Characteristics*—When attempting to measure panel surface deflection, an error results which is an artifact of the test. It arises as normal load is applied, to the extent that the edges of the sandwich specimen are compressed from the reactive line loads generated by the upper and lower panel support structure. This direct rigid-body addition affects any LVDT positioned to contact the tension-side panel surface. To minimize the error, the edges of soft-core panels should be reinforced in accordance with 8.3.2.

7. Apparatus

7.1 *Procedures A, B, and C*—A schematic diagram illustrating the key components of the test method apparatus appears in Fig. 1.

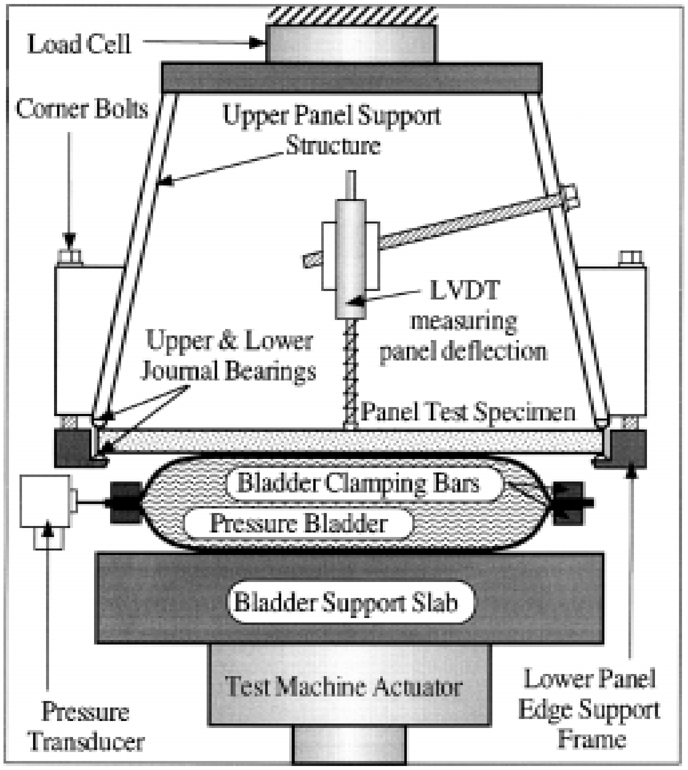

FIG. 1 Elements of the Two-Dimensional Sandwich Plate Flexural Test

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

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

7.1.1.2 *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 in accordance with 11.3.

7.1.1.3 *Load Indicator*—The testing machine load-sensing device shall be capable of indicating the total load being carried by the test specimen. This device shall be essentially 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. The load range(s) of interest may be fairly low for bending and shear modulus evaluation or much higher for strength evaluation, or both, as required.

7.1.2 *Loading Fixture*—As illustrated in the schematic diagram of Fig. 1, the loading fixture has two parts, a rigid, overhead upper panel support structure, which is attached to the load cell on the load frame crosshead, and a rigid lower panel edge support frame which bolts to the upper panel support structure at the corners. A square sandwich composite panel specimen is constrained at the edges when captured from above and below by these two fixture elements. All bearing surfaces are hardened steel rods with a circular cross-section, 12.7 mm [0.5 in.] in diameter. The support span for each dimension of the fixture is defined in Fig. 2. That the loading

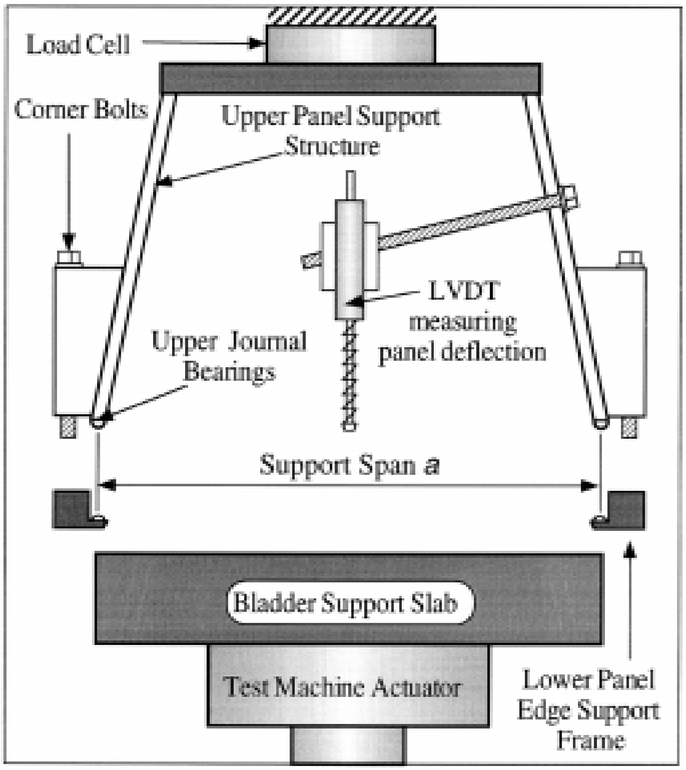

FIG. 2 Definition of Support Span for Specification of Panel Specimen Dimensional Tolerances

fixture constrains the test panel at all four edges is shown in the photographs of Figs. 3 and 4. Panel flexural response is thus two-dimensional under normal loading. The length of the support spans should be equal in both dimensions. Simply supported boundary conditions are approached as the lower panel edge support frame is drawn towards the upper panel support structure by tightening the four corner connecting bolts.

7.1.3 *Pressure Bladder*—Normal load is introduced to the test panel by means of a sealed water bladder which is compressed against the lower panel face by the bladder support slab that rests on the upward-moving lower platen. The bladder should be made of industrial belting, or other tough, flexible, waterproof fabric, and be capable of withstanding pressures of the order required to initiate failure in the test panel. Bladder skin should be of sufficient pliability to follow the contour of a test panel under a steadily increasing load, thus ensuring a uniform load distribution for the footprint. In Fig. 1, Fig. 3, and Fig. 4, through-bolted steel flatstock is used to clamp belting edges together to form the seal.

NOTE 2—The bladder size should be based on the inside dimensions of the test fixture rather than the outer dimensions of the test panel. It is important that during test loading the bladder contacts only the surface of the test panel. There must be no impingement of any part of the bladder on the lower panel edge support frame. It is recommended that the outer dimensions of any bladder clamping bar framework be less than the inside dimensions of the lower panel edge support frame so that clearance between the two will be maintained, even at significant panel deflections.

7.1.4 *Additional Instrumentation*—This test method requires bladder pressure and panel deflection sensors that shall meet the following requirements:

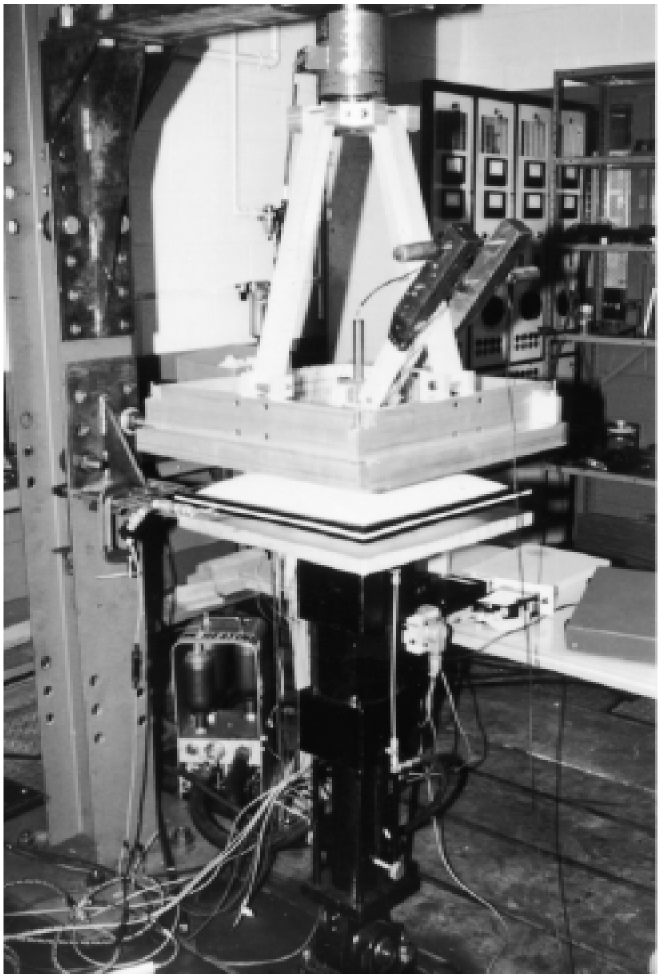

FIG. 3 Two-Dimensional Plate Flexural Test Apparatus

7.1.4.1 *Pressure Indicator*—The bladder pressure transducer must be in direct contact with the water by means of a tube that penetrates to the bladder interior. The connecting tube must be of sufficient diameter to permit pressure equilibrium with the interior without excessive lag time. The pressure transducer must be rated for the range of pressure magnitudes applied during the test and must respond with a precision of at least ±1 % of the full-scale value over the pressure range explored.

7.1.4.2 *LVDT*—The device for measuring the deflection of the test panel must be capable of measuring the displacement with a precision of at least ±1 %. The plunger that connects the panel surface with the LVDT core should be equipped with a spring return to ensure continued monitoring of the panel displacement even during an unloading cycle.

7.1.5 *Bonded Face-Sheet Resistance Strain Gages*—Strain gage selection is a compromise based on the procedure and the type of material to be tested. Strain gages should have an active grid length of 3 mm [0.125 in.] or less (1.5 mm [0.06 in.] is preferable). Gage calibration certification shall comply with Test Methods E 251. When testing woven fabric face sheet laminates, gage selection should consider the use of an active gage length which is at least as great as the characteristic repeating unit of the weave. Some guidelines on the use of

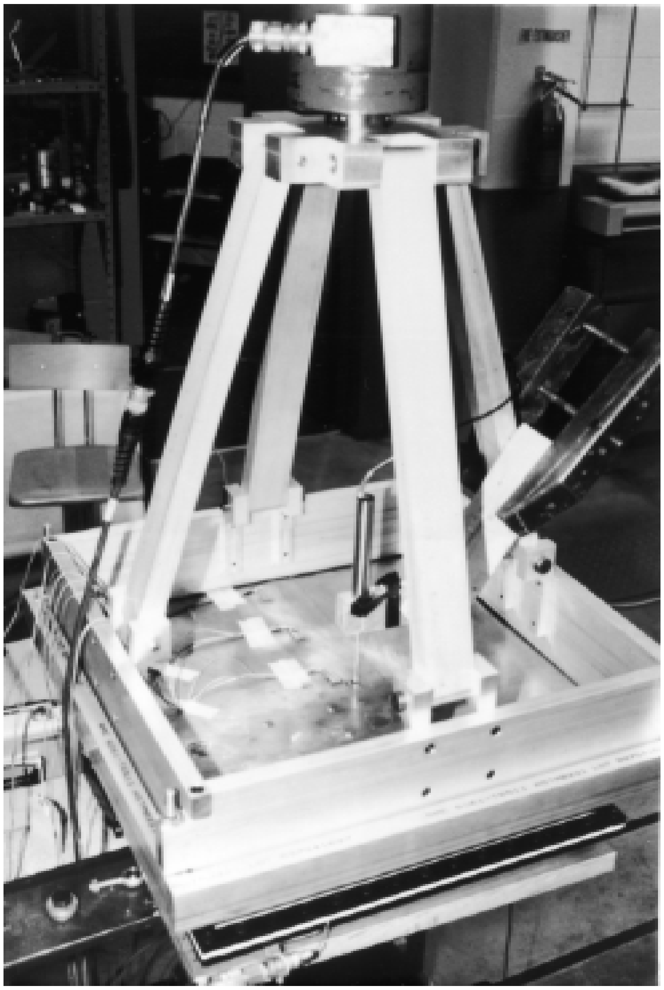

FIG. 4 Load Cell and Panel-Loading Fixture with Steel Calibration Plate

strain gages on composites are presented as follows, with a general discussion on the subject in reference.

7.1.5.1 Surface preparation of fiber-reinforced composites in accordance with Guide E 1237 can penetrate the matrix material and cause damage to the reinforcing fibers resulting in uncharacteristic local behavior. Reinforcing fibers shall not be exposed or damaged during the surface preparation process. Consult the strain gage manufacturer regarding surface preparation guidelines and recommended bonding agents for composites.

7.1.5.2 Select gages having larger resistances to reduce heating effects on low-conductivity materials. Resistances of 350 Ω or higher are preferred. Use the minimum possible gage excitation voltage consistent with the desired accuracy (1 to 2 V is recommended) to reduce further the power consumed by the gage. Heating of the substrate by the gage may affect the performance of the material directly, or it may affect the indicated strain as a result of a difference between the gage temperature compensation factor and the coefficient of thermal expansion of the coupon material.

7.1.5.3 Temperature compensation is recommended when testing at standard laboratory atmosphere. Temperature compensation is required when testing in nonambient temperature environments. When appropriate, use a traveler coupon (dummy calibration coupon) with identical lay-up and strain gage orientations for thermal strain compensation.

7.1.5.4 Consider the transverse sensitivity of the selected strain gage. Consult the strain gage manufacturer for recommendations on transverse sensitivity corrections. This is particularly important for a transversely mounted gage.

7.1.6 *Torque Wrench*—To effect simple support for test panels of varying shear and bending stiffness, tension in the four corner bolts that connect the lower panel edge support frame to the upper panel support structure needs to be controlled. Since bolt-tension requirements are typically fairly low, with correspondingly low torque requirements, a reliable microtorque wrench is recommended for adjusting the fixture.

7.1.7 *Line-Load Diffuser Strips*—It is recommended that test panels with wood face sheets, or face sheets of any easily indentable material, be protected on the upper edges, where they contact the hard-surface upper panel journal bearings. Narrow strips of thin spring steel should be placed around the edges of the upper surface of the panel before securing it in the loading fixture. Fig. 5 is a diagram that illustrates the proper placement of such strips, flush with the panel outer edges. The thickness of the strips should be on the order of 1.6 mm [0.063 in.], while width should be based on the fixture support span. (See Fig. 2.) Length of the strips should be on the order of one third the panel length or width, so that they do not inhibit the free rotation of the panel edges.

7.1.8 *Dial Calipers*—Dial calipers or conventional micrometers shall be sufficient for measuring panel thickness, provided they are accurate within ±0.025 mm [±0.001 in.].

8. Sampling and Test Specimens

8.1 *Sampling*—Because of the relatively large coupon size, one specimen per condition shall be considered sufficient.

NOTE 3—If specimens are to undergo environmental conditioning to equilibrium, and are of such type or geometry that the weight change of the material cannot be properly measured by weighing the specimen itself (such as when face sheets are bonded to a core), then a traveler coupon of

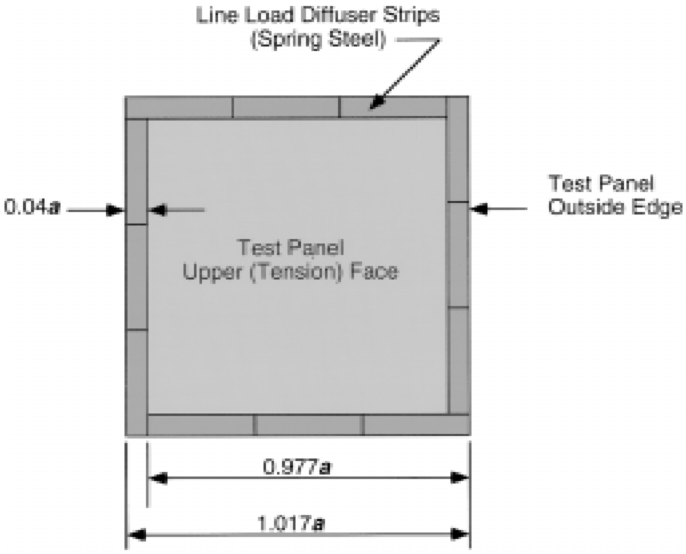

FIG. 5 Placement of Line Load Diffuser Strips

the same nominal face sheet thickness and appropriate size but masked on one side (to simulate the protective effect of the core) shall be used to determine when equilibrium has been reached for the specimens being conditioned.

8.2 *Geometry*—The test specimen shall be a uniform sandwich composite plate structure with a square perimeter and constant thickness. Dimensional tolerances must be based on the support span of the available test fixture. (See Fig. 2.)

8.2.1 *Specimen Thickness*—Specimen thickness *h* is the average thickness as measured to the nearest 0.025 mm [0.001 in.] at the center of each edge, h_1, h_2, h_3, and h_4. There should be no more than a ±2 % variation in the thickness of each edge with respect to the average thickness.

NOTE 4—There are no theoretical restrictions on the acceptable range of plate specimen thicknesses. However, to be an efficient load-bearing structure, the proportions of a simply supported sandwich plate should be such that the core material mainly carries shear load while the two face sheets mainly carry tension and compression loads, respectively. Therefore, for this test method to be the most helpful in optimizing sandwich structure, a thickness specification should be instituted which will enable a meaningful challenge to the constituent materials, in those terms, at small deflections. For example, if a panel specimen is too thin, small loads may induce large deflections where membrane effects become dominant. On the other hand, if a panel specimen is too thick, flexural response may be dominated by core shear properties. Since test machine capacities vary, it is advisable to recommend a range for specimen thickness based on the support span of the available test fixture. Therefore, for the testing of sandwich panels with the goal of learning how to optimize structural efficiency, the ratio of the support span to the average specimen thickness (*a/h*) should be between 10.0 and 30.0.

8.2.2 *Specimen Length and Width*—Specimen length and width should be 1.017 times the support span (1.017*a*) with a tolerance of ±0.0025*a*. See Fig. 6.

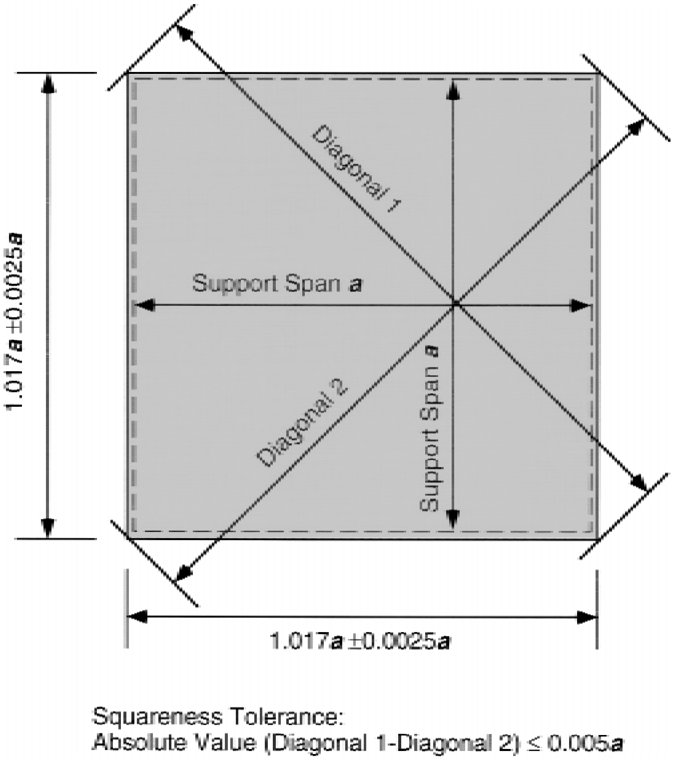

FIG. 6 Test Panel Length, Width, and Squareness Tolerances

NOTE 5—From a practical standpoint, a panel test specimen needs to be slightly longer and wider than its edge supports. But the amount of panel structure which extends beyond or "overhangs" the edge supports needs to be restricted, insofar as it constitutes a violation of simply supported boundary conditions. In effect, a specimen with a greater overhang will appear to be stiffer than an otherwise identical specimen with a lesser overhang.

8.2.3 *Specimen Squareness*—The difference between the length of the two opposite diagonals (measured from corner to corner) should be less than or equal to 0.005*a*. (See Fig. 6.)

8.3 *Test Specimen Fabrication*:

8.3.1 *Material and Process Documentation*—Although the need for complete and accurate documentation of test specimen composition and fabrication techniques is mentioned in Section 14, it is important to stress that construction details should be immediately recorded in a log after each step of the fabrication process. Composite construction is necessarily a complex process, and this test method can be effective in validating a particular fabrication method as well as the selection of constituent materials, if a detailed record exists. Enough information needs to be recorded and reported so that the experiment could be duplicated by any composites research facility. If possible, manufacturers' product numbers with actual lot numbers should be recorded. It is recommended that the core material piece which has been cut for specimen construction be carefully weighed and measured for density calculation before face sheet bonding in accordance with 11.2.2.

8.3.2 *Edge Reinforcement*—If the core material in the specimen has a compression modulus less than 300 MPa [43 512 psi] as determined in Test Method C 365, the edges should be reinforced by installing between the face sheets a border of higher-modulus material such as end-grain wood, having a compression modulus of at least 2240 MPa [325 000 psi]. The border should be of a width on the order of 0.016*a*, where *a* is the length of the support span. The overall length and width of the specimen is to remain as specified in 8.2.2. Preferably, this modification is to be included in the panel fabrication process and carried out before face sheet bonding, rather than done as a retrofit procedure.

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.

9.2 The bladder loading and panel edge support are critical components of the two-dimensional test fixture which is sometimes referred to as the hydromat test system. To ensure that the fixture is properly calibrated, use a steel calibration plate. The steel plate is of constant thickness, typically approximately 10 mm [0.4 in.], with a thickness tolerance of ±0.0125 mm [0.0005 in.]. Plate length is 505 mm [19.9 in.] with a tolerance of ±0.1 mm [0.004 in.] for the 500-mm [19.7-in.] size test fixture. Fix strain rosettes to the plate along the centerline of the plate, at the center and quarter points of the plate. Measure deflection at the center of the plate with an LVDT. For such a precise plate, the analytical solution is quite accurate. Any differences between theoretical and experimental deflections and strains must be in lack of calibration, or misuse of the test fixture. Find plate loading for the theoretical solution by assuming the measured bladder pressure acts uniformly over a centrally located square of area A_{eff} defined in Sections 3 and 13. The corner bolts, which draw the lower panel support frame up against the upper panel support frame, reduce clearance along the boundary edges, and the experimental center deflection should asymptotically approach that of the theoretical simply supported solution. Record the torque needed for the experimental deflection to asymptotically approach the theoretical simply supported deflection and use in subsequent panel tests with the proviso that soft-cored sandwich panels will need considerably less torque (over torquing will crush such a sandwich panel) to approach simple support. To be properly calibrated, it is expected that experimental deflections for the steel calibration plate will be within 2 % of the theoretical values and that experimental strains will be within 4 % of the theoretical values.

10. Conditioning

10.1 When the physical properties of the component materials are affected by moisture, bring the test specimens to constant weight (±1 %) before testing, preferably in a conditioning room with temperature and humidity control. Perform the test, preferably, in a room under the same conditions. A temperature of 23 ± 3°C [73 ± 5°F] and a relative humidity of 50 ± 5 % are recommended for standard control conditions.

11. Procedure

11.1 *Parameters to Be Specified Before Test*:

11.1.1 The test panel geometry.

11.1.2 The flexural properties and data reporting format desired.

NOTE 6—Determine specific material property, accuracy, and data reporting requirements before test for proper selection of instrumentation and data recording equipment. Estimate operating stress and strain levels to aid in transducer selection, calibration of equipment, and determination of equipment settings.

11.1.3 The environmental conditioning test parameters.

11.1.4 If performed, the sampling method, coupon geometry, and test parameters used to determine core density and face sheet reinforcement density and 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 as the test samples. For core density, it is recommended that the actual core piece cutout for panel specimen fabrication be carefully weighed and measured for density calculation before adhesive and face sheet application. After test, specific gravity and density may be evaluated in accordance with Test Methods D 792. Volume percent of the constituents may be evaluated by one of the matrix digestion procedures of Test Method D 3171, or, for certain reinforcement materials such as glass and ceramics, by the matrix burn-off technique of Test Method D 2584. Void content may be evaluated from the equations of Test Method D 2734 and are applicable to both Test Methods D 2584 and D 3171.

11.2.3 Condition the specimens, either before or after strain gaging, as required. Condition traveler coupons if to be used.

NOTE 7—Gaging before conditioning may impede moisture absorption locally underneath the strain gage or the conditioning environment may degrade the strain gage adhesive, or both. On the other hand, gaging after conditioning may not be possible for other reasons, or the gaging activity itself may cause loss of conditioning equilibrium. The timing on when to gage coupons is left to the individual application and shall be reported.

11.2.4 Following final specimen machining and any conditioning, but before the flexural testing, measure and report the specimen length and width, and thicknesses, h_1, h_2, h_3, and h_4 at the center of each edge, to the accuracy in 7.1.8. Weigh the specimen to the nearest 0.1 g. If using a platform scale, weigh the specimen on edge, so that disturbances from air currents can be minimized. Calculate the average panel thickness in millimetres [inches] and the area specific weight in units of grams per square metre [pounds per square foot] for each specimen.

11.2.5 Apply strain gages to the tension face of the specimen (see 4.4) if testing for shear stiffness, S, as well as bending stiffness, B.

11.3 *Speed of Testing*—If testing for quasistatic elastic properties, set the actuator or crosshead speed between 1.0 mm/min [0.050 in./min] and 2.5 mm/min [0.1 in./min]. For strength determination and failure initiation tests, select the actuator or crosshead speed so as to produce failure within 10 to 20 min from the beginning of load application. If the ultimate strength of the material cannot be reasonably estimated, conduct initial trials using standard speeds until the ultimate strain of the material and the compliance of the system are known, and the strain rate can be adjusted. The suggested standard speeds are:

11.3.1 *Constant Head-Speed Tests*—A standard crosshead displacement of 1.0 mm/min [0.050 in./min].

11.4 *Test Environment*—Condition the specimen to the desired moisture profile and, if possible, test under the same environment. Environmentally conditioned traveler coupons may be used to measure moisture loss during exposure to the test environment. Weigh a traveler coupon before testing and place it in the test chamber at the same time as the specimen. Remove the traveler coupon immediately after fracture and reweigh it to determine moisture loss. Record modifications to the test environment.

11.4.1 Store the specimen in the conditioned environment until test time, if the testing area environment is different than the conditioning environment.

11.4.2 If testing at other than standard conditions, monitor the test temperature by placing an appropriate thermocouple on the tension face of the panel in a location where it will not interfere with deflection or strain measurements. Maintain temperature of the specimen, and the traveler coupon, if one is being used for thermal strain compensation or moisture loss evaluation, within ±3°C [±5°F] of the required condition. Attaching thermocouple(s) to the test specimen (and the traveler) with vacuum-bagging sealant tape is an effective measurement method.

11.5 *Fixture Installation*:

NOTE 8—The following procedure is intended for vertical testing machines with an overhead load cell.

11.5.1 Ensure that the bearing surfaces of the fixture journals are polished and nick- and corrosion-free.

11.5.2 Verify that the fixture bearing surfaces are square and coplanar.

11.5.3 Attach the upper panel support structure to the load cell. The entire assembly must be centered on the line of action of applied load with the plane defined by the edge-support surfaces perpendicular to the line of action of applied load.

11.5.4 Install the LVDT which is to measure panel deflection. It should be in a position to contact the exact center of the tension surface of the specimen, with the plunger axis aligned with the line of action of the applied load.

11.5.5 On the platen opposite from the upper panel support frame place and center the pressure bladder support slab. The dimensions of the support slab must reasonably exceed those of the pressure bladder contact area or footprint.

11.5.6 Place the pressure bladder on the support slab with the clamping bars parallel to the edges of the upper panel support structure. If desired, protective rubber sheeting may be placed over the pressure bladder at this time.

NOTE 9—It is recommended to sandwich the rubber between two sheets of 0.127-mm [0.005-in.] tetrafluoroethylene polymer to reduce friction between the contact surfaces.

11.6 *Specimen Installation*:

11.6.1 Place a piece of 19-mm plywood large enough to support the lower panel edge support frame on top of the pressure bladder and its protective covering.

11.6.2 Ensure that the bearing surfaces of the lower panel edge support frame are polished and nick- and corrosion-free.

11.6.3 Verify that the lower frame bearing surfaces are square and coplanar.

11.6.4 Place the lower panel edge support frame on the plywood with the corner bolt holes aligned with the corresponding ones on the upper panel edge support structure.

11.6.5 Examine the test specimen for surface roughness, flatness, squareness, and dimensional tolerances. Check that panels with low-density cores have been reinforced at the edges for compressive line loads (see 8.3.2). If the specimen composition, weight, and dimensions have not been recorded, do so at this time.

11.6.6 With the intended tension side face up, place the panel specimen into the frame and center it with respect to the frame edges by inserting compressible spacers such as pipe cleaners into the gaps near the corners. Be sure the pipe cleaners are approximately parallel to the panel edges so that there will be no interference with the lower frame bearing surfaces. With a permanent marker, identify one edge as a reference for use in establishing actual orientation of panel with respect to the test fixture and also for documenting failure locations.

11.6.7 Place spring-steel line-load diffuser strips in position along all four edges of the test panel (as shown in Fig. 3). Strip edges should be flush with specimen edges.

11.6.8 Place a 3- by 32- by 32-mm [0.125- by 1.25- by 1.25-in.] wafer of birch plywood or any smooth-surfaced plastic in the exact center of the test panel to serve as a uniform platform for the LVDT plunger.

11.6.9 Tare the load cell to zero to deduct the weight of the upper panel support structure and LVDT assembly.

11.6.10 Move the actuator or crosshead to bring the test panel and lower frame in proximity to the upper panel support structure. Stop while there is still slight clearance between the LVDT plunger foot and the platform wafer. Start the four-corner bolts to bring the panel/lower frame assembly into exact alignment.

11.6.11 Move the panel/lower frame assembly into contact with the upper panel support structure taking care not to apply load greater than that represented by the combined weight of the panel and lower frame.

11.6.12 Check that the diffuser strip edges are still flush with specimen edges and then tighten the corner bolts alternately and evenly until just snug.

11.6.13 Move the actuator or crosshead away to create some clearance between the plywood sheet and the bottom edge of the lower panel edge support frame. Remove the plywood. Discharge any static electricity buildup before touching the controller equipment. Tare the load cell to zero to deduct the weight of the lower edge support frame/test panel assembly.

11.6.14 Bring the pressure bladder with protective cover into contact with the lower face of the test panel with a slight load, approximately 22 N [5 lbf]. Center the pressure bladder with respect to the edges of the lower panel edge support frame. A convenient way to accomplish this is to use a spacer or go-no-go gage which has dimensions equal to the correct distance between a straightedge placed vertically on the middle of the lower panel edge support frame and the outside edge of the pressure bladder clamping bars. The same spacer can be used to perform a clearance check at all four sides. The bladder can be considered to be centered when the spacer fits all the way around.

11.6.15 Apply appropriate torque in 1.8-Nm [16-in.–lbf] increments alternately to the nuts or bolts which secure the lower frame and test panel assembly.

NOTE 10—The application of fastener torque is crucial in achieving simply supported boundary conditions. In general, panels with greater flexural rigidity or shear rigidity, or both, require greater fastener torque in order for the fixture to effect simple support. When torque specifications are unavailable, perform successive displacement-controlled ramp tests with across-the-board torque increases in accordance with 11.7.1.

11.7 *Loading*

11.7.1 *Procedure A*—To determine a torque value which corresponds to simply supported boundary conditions, perform successive displacement-controlled ramp tests with across-the-board torque increases of 1.8 Nm [16 in.–lbf] for each repetition, starting with 1.8 Nm [16 in.–lbf]. Use a data acquisition system that simultaneously samples and records the bladder pressure, panel deflection, and strain transducers at intervals of not more than 3 s. First apply a standard initial load of 44 N [10 lbf] to seat all bearing surfaces. Zero the pressure transducer and panel LVDT. Record the torque applied to the lower panel edge support frame fasteners. Then ramp at an actuator/crosshead speed of 1.0 mm/min [0.050 in./min] to a small deflection safely within the linear/elastic response region of the panel structure. An approximate safe deflection limit estimate can be calculated by multiplying 1 mm times one tenth of the ratio of the support span to the panel thickness. Torque is sufficient when there has been less than a 1 % change (with respect to the immediately preceding ramp test) in the slope of the pressure versus deflection curve as determined by a least-squares fit.

11.7.2 *Procedure B*—To determine the load/pressure versus deflection response of a test panel for small deflections, use a data acquisition system that simultaneously samples and records the load cell, bladder pressure, panel deflection, and strain transducers at intervals of not more than 3 s. First apply a standard initial load of 44 N [10 lbf] to seat all bearing surfaces. Zero the bladder pressure transducer and panel LVDT. Record the torque applied to the lower panel edge support frame fasteners. Record the startup time. Then ramp at an actuator/crosshead speed of 1.0 mm/min [0.050 in./min] to a small deflection safely within the linear/elastic response region of the panel structure. An approximate safe deflection limit estimate can be calculated by multiplying 1 mm times one tenth of the ratio of the support span to the panel thickness. Repeat the procedure several times to allow any settling in to take place. After each test, return to the initial 44-N load and record the LVDT reading as an indication of permanent set. Record the time of the permanent set measurement. Rezero the pressure transducer and panel LVDT before each run. Plot the load versus panel deflection data and the bladder pressure versus panel deflection data. The slope of these curves is an indication of the relative two-dimensional flexural stiffness of the test specimen with respect to that of any other panel tested with the same equipment under the same conditions.

11.7.3 *Procedure C*—To determine the first failure strength of a panel specimen, use a data acquisition system that simultaneously samples and records the load cell, bladder pressure, panel deflection, and strain transducers at intervals of not more than 3 s. First apply a standard initial load of 44 N [10 lbf] to seat all bearing surfaces. Zero the bladder pressure transducer and panel LVDT. Record the torque applied to the lower panel edge support frame fasteners. Record the startup time. Then ramp at an actuator/crosshead speed of 1.0 mm/min [0.050 in./min] unless preliminary small-deflection tests have indicated that first failure is unlikely to occur within 10 to 20 min from the beginning of load application. In that case, adjust the speed. Report the actual actuator/crosshead speed. Continue the ramp until the load and pressure readings either cease to increase or start to decline. After the test, return to the initial 44-N [10-lbf] load and record the LVDT reading as an indication of permanent set. Record the time of the permanent set measurement.

NOTE 11—Since failures in sandwich panel structures are often subtle and noncatastrophic, it is recommended that appropriate load and displacement limits be set during ramp-to-first-failure tests to prevent overloading of the pressure bladder or fixture damage, or both.

11.8 *Data Recording*—Record ambient temperature and relative humidity during the test. Record load and pressure versus panel LVDT displacement (or strain) continuously or at frequent regular intervals. If a transition region or initial failures are noted, record the load, strains, and mode of damage at such points. If the specimen is to be loaded to large deflections, that is, deflections greater than half the panel thickness, record the maximum load, pressure, and the panel LVDT displacement (or strains). Since sandwich structures often contain materials that exhibit viscoelastic or other time-dependant behavior, record the time when loading begins. Record the time when permanent set readings are taken with the panel deflection LVDT.

NOTE 12—Other valuable data that can be useful in understanding testing anomalies include load versus head displacement data and load versus time data.

12. Verification

12.1 *Graphical Determination of Panel Strength*—Plot the load versus panel deflection data and the bladder pressure versus panel deflection data. Load and pressure values corresponding to first failure can be obtained through an analysis of the plots. For example, if a plot has a feature such as a peak formed by an abrupt decrease in load or pressure and a corresponding reversal in the sign of the slope, the load or pressure value at the peak can be considered the first-failure load. However, some significant sandwich panel failure mechanisms are more gradual in nature, such as delamination of face sheets, or yielding of the core in shear. In cases like these, the plot exhibits a region of smooth curvature with decreasing slope. Then the first failure strength cannot be precisely determined from a single test.

12.2 *Follow-Up Tests*—If no catastrophic failure has occurred, conduct a second ramp test to determine if the specimen has lost stiffness as manifested by a reduction in the slope of the pressure versus deflection curve. Determine the slope for both runs by executing a least-squares curve fit of all the data taken during the time between startup and the reaching of the "approximate safe deflection limit" as defined in Procedures A and B, 11.7.1 and 11.7.2. If there has been less than a 2 % reduction in slope with respect to that of the first ramp-to-failure attempt, no failure should be reported. If the slope reduction is 2 % or greater, and visual inspection confirms damage, the panel should be classified as permanently damaged. If the slope reduction is 2 % or greater, yet, the panel shows no visual evidence of damage, remove the panel from the fixture. After a period of two to seven days, reinstall the panel exactly as before and conduct a third ramp test to the approximate safe deflection limit to determine if any recovery has occurred. If the least-squares slope from the third test still shows a 2 % or more reduction with respect to the original ramp-to-failure test, then the panel can be considered permanently damaged and should be classified as such in the report. If the least-squares slope from the third test works out to be less than a 2 % reduction with respect to the original ramp-to-failure test, the panel has effectively recovered and should not be classified as permanently damaged or failed.

12.3 *Determination of Failure Modes*—Remove the test specimen from the fixture and examine. Record the modes and locations of failure for each specimen with respect to the reference edge. Some sandwich panel failure modes may not affect the external appearance of the specimen. If there is a permanent bend in a sandwich plate, it may be an indication of core shear failure, in which case, it is recommended to cut a quadrant from the panel that includes a cut made at 90° to the bend to expose the interior core.

12.3.1 *Acceptable Failure Modes*—Core shear failure, face sheet separation or delamination, face sheet buckling, or face sheet tension failure are all acceptable failure modes, providing the failure(s) initiate away from the panel edges.

12.3.2 *Unacceptable Failure Modes*—Unacceptable failure modes are those which are artifacts of the test method itself. For example, any type of failure which initiates less than one panel thickness away from a supported edge is unacceptable.

13. Calculation

13.1 *Calculation of In Situ Bending and Shear Stiffness*—In addition to the direct measurement of deflections and strains in a sandwich panel, the test device can be used to obtain the in situ bending and shear stiffnesses of the sandwich panel using a combined analytical/experimental approach.[7] The analytical solution assumes equal thickness, isotropic face sheets, an isotropic core, and follows the assumptions of classical sandwich plate theory. Because of simply supported boundary conditions, the Navier solution[8] (double Fourier series) can be used. Experimentally, the deflection is measured at a selected point x_d, y_d. The sum of the normal strain components $(\epsilon_x + \epsilon_y)$ is measured at a second selected point x_s, y_s. Therefore:

$$\omega_e = \frac{C_1}{B} + \frac{C_2}{S} \tag{1}$$

$$(\epsilon_x + \epsilon_y)_e = \left(\frac{c}{2} + f\right)\frac{C_2}{B} \tag{2}$$

where:

ω_e = experimentally determined deflection at x_d, y_d,
$(\epsilon_x + \epsilon_y)_e$ = experimentally determined sum of the normal strains at x_s, y_s,
B = bending stiffness,
S = shear stiffness,
c = core thickness,
f = face sheet thickness, and
C_1, C_2 = constants resulting from the Navier solution:

$$C_1 = \frac{16P_m a^4}{\pi^6} \sum_{m = 1, 3, 5}^{N} \sum_{n = 1, 3, 5}^{N} \frac{\cos\left(\frac{m\pi\phi}{a}\right)\cos\left(\frac{n\pi\phi}{a}\right)}{mn(m^2 + n^2)^2} \sin\frac{m\pi x_d}{a} \sin\frac{n\pi y_d}{a}$$

$$C_2 = \frac{16P_m a^2}{\pi^4} \sum_{m = 1, 3, 5}^{N} \sum_{n = 1, 3, 5}^{N} \frac{\cos\left(\frac{m\pi\phi}{a}\right)\cos\left(\frac{n\pi\phi}{a}\right)}{mn(m^2 + n^2)} \sin\frac{m\pi x_s}{a} \sin\frac{n\pi y_s}{a}$$

where:

P_m = experimentally measured bladder pressure,
a = length, width of square plate between supports,
ϕ = $\frac{1}{2}(a - \sqrt{A_{eff}})$,
A_{eff} = $\frac{F_m}{P_m}$ (effective pressure footprint area),
F_m = experimentally measured total load on the panel, and
N = number of included terms of the series.

It is useful to measure the deflections and strains experimentally in regions of low gradients, for example, near or at the center of the panel. A typical value of N to ensure convergence of the series is less than or equal to 20. Convergence is indicated when the $(S_N - S_{N\text{-}1})/S_N < \epsilon$. S_N is the sum of the series with N terms and ϵ is a predetermined difference. Typically, ϵ is chosen to be $\epsilon \approx 0.01$.

Eq 1 and 2 can be solved sequentially for B and S. With $(\epsilon_x + \epsilon_y)_e$ known, Eq 2 can be solved for B and with ω_e, B known, Eq 1 can be solved for S. Note that for orthotropic face sheets there are a total of three bending stiffnesses to be determined, and for an orthotropic core there are two shear stiffnesses. Five equations for the five unknown stiffnesses must be generated.

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):

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

14.1.2 The date(s) and location(s) of this test method.

14.1.3 The name(s) of the test method operator(s).

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

14.1.5 Identification of the all the materials constituent to the sandwich plate specimen tested, including for each: material specification, material type, manufacturer's material designation, manufacturer's lot or batch numbers, source (if not from manufacturer), dates of certification, expiration of certification, face sheet fiber filament diameter, tow or yarn filament count and twist, sizing, form or weave, fiber areal weight, matrix type, face sheet matrix content, and volatiles content. Also report measured core density in accordance with 11.2.2 and whatever details are known about its manufacture, such as blowing agent and aging sequence.

14.1.6 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.

14.1.7 Ply orientation stacking sequence of the laminate with respect to a reference plane which shall be the surface of the face actually contacted by the pressure bladder during testing.

14.1.8 Results of any nondestructive evaluation tests.

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

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[7] Bertelsen, W.D., Eyre, M.W., and Sikarskie, D.L., "Verification of the Hydromat Test System for Sandwich Panels," Third International Conference on Sandwich Construction, University of Southampton, Southampton, England, 1995.

[8] Zenkert, D., "An Introduction to Sandwich Construction," The Chameleon Press Ltd., London, United Kingdom, 1992.

14.1.10 Calibration dates and methods for all measurement and test equipment. In particular, results of the steel-plate calibration test (Section 9) should be included in the report, with a graph or tabulated relation of the effective contact area of the pressure bladder as a function of applied load when bearing against the standard steel reference plate.

14.1.11 Type of test machine, alignment results, and data acquisition sampling rate and equipment type.

14.1.12 Type, range, and sensitivity of LVDT(s) or any other instruments used to measure test panel deflection.

14.1.13 Type, range, and sensitivity of pressure transducer used to monitor bladder pressure.

14.1.14 Measured support span, *a*.

14.1.15 Results of system alignment evaluations, if any such were done.

14.1.16 Dimensions of each test specimen.

14.1.17 Weight of specimen and the area specific weight (adjusted to exclude any edge reinforcing materials).

14.1.18 Conditioning parameters and results, use of travelers and traveler geometry, and the procedure used if other than that specified in this test method.

14.1.19 Relative humidity and temperature of the testing laboratory.

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

14.1.21 Speed of testing.

14.1.22 Diameter, thread specifications, and torque applied for the four fasteners attaching the lower panel edge support frame to the upper panel support structure.

14.1.23 Transducer placement on the specimen and transducer type for each transducer used.

14.1.24 If strain gages were used, the type, resistance, size, gage factor, temperature compensation method, transverse sensitivity, lot number and batch number, lead-wire resistance, and any correction factors employed.

14.1.25 Pressure-deflection curves and pressure-strain curves and tabulated data of load and pressure versus deflection and load and pressure versus strain for each specimen.

14.1.26 Calculated small-deflection bending and shear stiffnesses.

14.1.27 Panel transition load and pressure and calculated core shear strength at panel transition pressure.

14.1.28 If panel transition strength is determined, the method of linear fit (if used) and the strain or deflection ranges, or both, over which the linear fit or chord lines were determined.

14.1.29 Failure mode and location of failure for each specimen with respect to reference edge (11.6.6).

15. Precision and Bias

15.1 *Precision*—The precision, defined as the degree of mutual agreement between individual measurements cannot yet be estimated because of an insufficient amount of data. Round-robin testing will take place as soon as volunteer laboratories can be equipped.

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

16. Keywords

16.1 bending; core; deflection; distributed load; face sheets; flexural properties; hydromat; hydrostatic loading; pressure bladder; sandwich composite; sandwich composite plate; sandwich structure; shear

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(**3**) Bertelsen, W.D., “Physical Testing of Marine Composites Using the Hydromat Testing System,” Fall Meeting, SNAME Great Lakes and Great Rivers Section, Ann Arbor, MI, 1994.

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