Designation: D6641/D6641M – 16$^{\varepsilon 1}$

Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture[1]

This standard is issued under the fixed designation D6641/D6641M; 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.

ε[1] NOTE—A label in Figure 3 was corrected editorially in March 2017.

1. Scope

1.1 This test method determines the compressive strength and stiffness properties of polymer matrix composite materials using a combined loading compression (CLC) (**1**)[2] test fixture. This test method is applicable to general composites that are balanced and symmetric. The specimen may be untabbed (Procedure A) or tabbed (Procedure B), as required. One requirement for a successful test is that the specimen ends do not crush during the test. Untabbed specimens are usually suitable for use with materials of low orthotropy, for example, fabrics, chopped fiber composites, and laminates with a maximum of 50 % 0° plies, or equivalent (see 6.4). Materials of higher orthotropy, including unidirectional composites, typically require tabs.

1.2 The compressive force is introduced into the specimen by combined end- and shear-loading. In comparison, Test Method D3410/D3410M is a pure shear-loading compression test method and Test Method D695 is a pure end-loading test method.

1.3 Unidirectional (0° ply orientation) composites as well as multi-directional composite laminates, fabric composites, chopped fiber composites, and similar materials can be tested.

1.4 The values stated in either SI units or inch-pound units are to be regarded separately as standard. Within the test 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.

NOTE 1—Additional procedures for determining the compressive properties of polymer matrix composites may be found in Test Methods D3410/D3410M, D5467/D5467M, and D695.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D695 Test Method for Compressive Properties of Rigid Plastics
D883 Terminology Relating to Plastics
D3410/D3410M Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading
D3878 Terminology for Composite Materials
D5229/D5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials
D5379/D5379M Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method
D5467/D5467M Test Method for Compressive Properties of Unidirectional Polymer Matrix Composite Materials Using a Sandwich Beam
D5687/D5687M Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation
E4 Practices for Force Verification of Testing Machines
E6 Terminology Relating to Methods of Mechanical Testing
E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process
E132 Test Method for Poisson's Ratio at Room Temperature

[1] This test method is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of Subcommittee D30.04 on Lamina and Laminate Test Methods.

Current edition approved Nov. 1, 2016. Published November 2016. Originally approved in 2001. Last previous edition approved in 2014 as D6641/D6641M-14. DOI: 10.1520/D6641_D6641M-16E01.

[2] Boldface numbers in parentheses refer to the list of references at the end of this test method.

[3] 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.

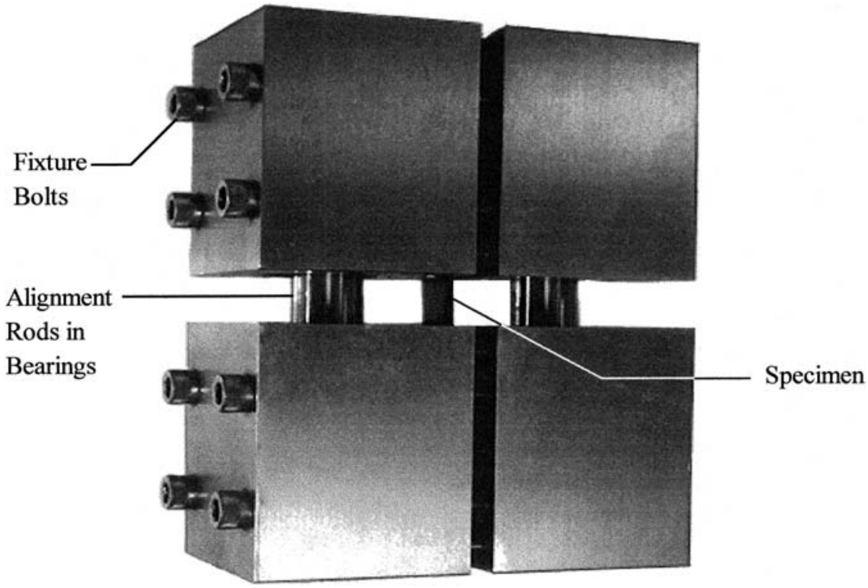


FIG. 1 Photograph of a Typical Combined Loading Compression (CLC) Test Fixture

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods
E456 Terminology Relating to Quality and Statistics
E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
E1309 Guide for Identification of Fiber-Reinforced Polymer-Matrix Composite Materials in Databases (Withdrawn 2015)[4]
E1434 Guide for Recording Mechanical Test Data of Fiber-Reinforced Composite Materials in Databases (Withdrawn 2015)[4]
E1471 Guide for Identification of Fibers, Fillers, and Core Materials in Computerized Material Property Databases (Withdrawn 2015)[4]

2.2 *ASTM Adjunct:*
Combined Loading Compression (CLC) Test Fixture, D 6641/D6641M[5]

3. Terminology

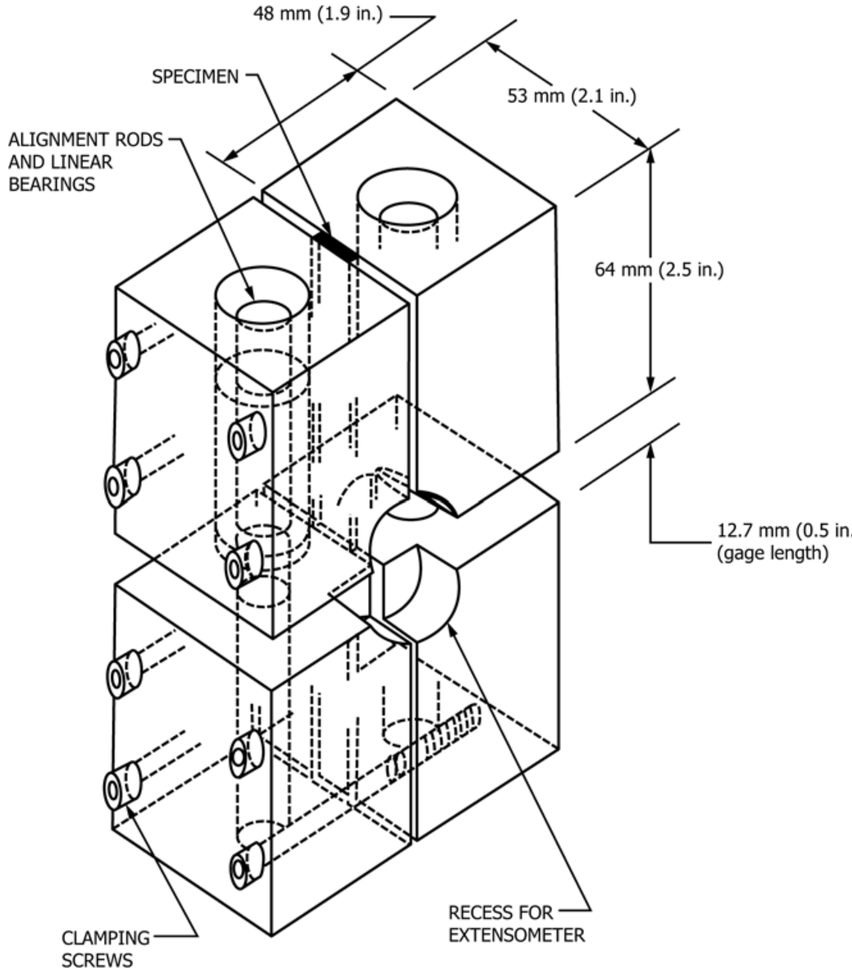
3.1 *Definitions*—Terminology D3878 defines terms relating to high-modulus fibers and their composites. Terminology D883 defines terms relating to plastics. Terminology E6 defines terms relating to mechanical testing. Terminology E456 and Practice E177 define terms relating to statistics. In the event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

3.2 *Symbols: A*—cross-sectional area of specimen in gage section
B_y—face-to-face percent bending in specimen
CV—sample coefficient of variation, in percent
E^c—laminate compressive modulus
F^{cu}—laminate ultimate compressive strength
F^{cr}—Euler buckling stress
G_{xz}—through-thickness shear modulus of laminate
h—specimen thickness
I—moment of inertia of specimen cross section
l_g—specimen gage length
n—number of specimens
P—load carried by test specimen
P^f—load carried by test specimen at failure
s—as used in a lay-up code, denotes that the preceding ply description for the laminate is repeated symmetrically about its midplane
s_{n-1}—sample standard deviation
w—specimen gage width
$\bar{x}$—sample mean (average)
x_i—measured or derived property
ε—indicated normal strain from strain transducer
ε_x—laminate axial strain
ε_y—laminate in-plane transverse strain
$\varepsilon_1, \varepsilon_2$—strain gage readings
$\nu_{xy}{}^c$—compressive Poisson's ratio

4. Summary of Test Method

4.1 A test fixture such as that shown in Figs. 1 and 2, or any comparable fixture, can be used to test the untabbed (Procedure A) or tabbed (Procedure B) straight-sided composite specimen of rectangular cross section shown schematically in Fig. 3. A typical specimen is 140 mm [5.5 in.] long and 13 mm [0.5 in.] wide, having an unsupported (gage) length of 13 mm [0.5 in.] when installed in the fixture. A gage length greater or less than 13 mm is acceptable, subject to specimen buckling considerations (see 8.2). The 13-mm [0.5 in.] gage length provides sufficient space to install bonded strain gages when they are required. The fixture, which subjects the specimen to combined end- and shear-loading, is itself loaded in compression between flat platens in a universal testing machine. Load-strain data are collected until failure occurs (or until a specified strain level is

[4] The last approved version of this historical standard is referenced on www.astm.org.
[5] A detailed drawing for the fabrication of the test fixture shown in Figs. 1 and 2 is available from ASTM Headquarters. Order Adjunct No. ADJD6641.



Note: Using standard M6×1 (¼-28 UNF) screws, the bolt torque required to test most composite material specimens successfully is typically between 2.5 and 3.0 N-m [20 and 25 in.-lb.].

FIG. 2 Dimensioned Sketch of a Typical Combined Loading Compression (CLC) Test Fixture

achieved if only compressive modulus or Poisson's ratio, or both, are to be determined, and not the complete stress-strain curve to failure).

5. Significance and Use

5.1 This test method is designed to produce compressive property data for material specifications, research and development, quality assurance, and structural design and analysis. When tabbed (Procedure B) specimens, typically unidirectional composites, are tested, the CLC test method (combined shear end loading) has similarities to Test Methods D3410/D3410M (shear loading) and D695 (end loading). When testing lower strength materials such that untabbed CLC specimens can be used (Procedure A), the benefits of combined loading become particularly prominent. It may not be possible to successfully test untabbed specimens of these same materials using either of the other two methods. When specific laminates are tested (primarily of the $[90/0]_{ns}$ family, although other laminates containing at least one 0° ply can be used), the CLC data are frequently used to "back out" 0° ply strength, using lamination theory to calculate a 0° unidirectional lamina strength (**1, 2**). Factors that influence the compressive response include: type of material, methods of material preparation and lay-up, specimen stacking sequence, specimen preparation, specimen conditioning, environment of testing, speed of testing, time at temperature, void content, and volume percent reinforcement. Composite properties in the test direction that may be obtained from this test method include:

5.1.1 Ultimate compressive strength,

5.1.2 Ultimate compressive strain,

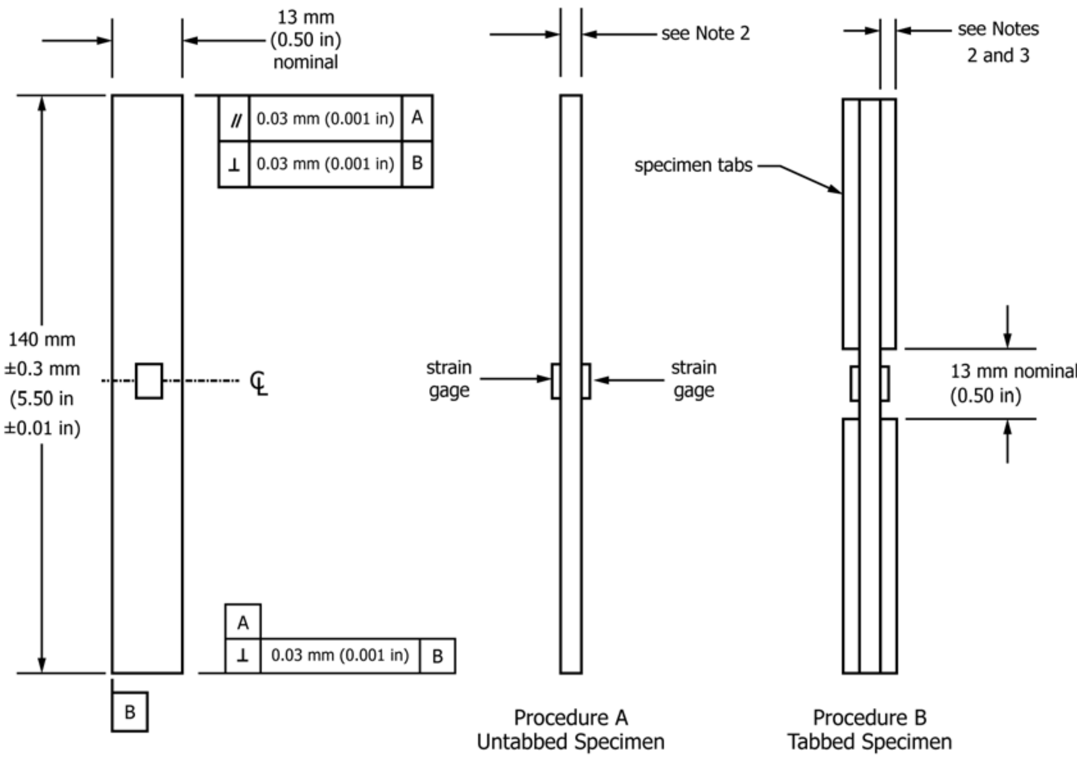
5.1.3 Compressive (linear or chord) modulus of elasticity, and

5.1.4 Poisson's ratio in compression.

6. Interferences

6.1 Because of partial end loading of the specimen in this test method, it is important that the ends of the specimen be machined flat, parallel to each other, and perpendicular to the long axis of the coupon (see Fig. 3), just as for Test Method D695. Improper preparation may result in premature end crushing of the specimen during loading, excessive induced bending, or buckling, potentially invalidating the test.

6.2 Erroneously low laminate compressive strengths will be produced as a result of Euler column buckling if the specimen is too thin in relation to the gage length (see 8.2). In such cases,



(1) The specimen ends must be parallel to each other within 0.03 mm [0.001 in.] and also perpendicular to the longitudinal axis of the specimen within 0.03 [0.001 in.], for both Procedures A and B.

(2) Nominal specimen and tabbing thickness can be varied, but must be uniform. Thickness irregularities (for example, thickness taper or surface imperfections) shall not exceed 0.03 mm [0.001 in.] across the specimen or tab width or 0.06 mm [0.002 in.] along the specimen grip length or tab length.

(3) Tabs are typically square-ended and on the order of 1.6 mm [0.06 in.] thick, but thickness can be varied as required, as discussed in 8.2.

(4) The faces of the specimen may be lapped slightly to remove any local surface imperfections and irregularities, thus providing flatter surfaces for more uniform gripping by the fixture.

FIG. 3 Typical Test Specimen Configuration

the specimen thickness must be increased or the gage length reduced. A practical limit on reducing gage length is maintaining adequate space in which to attach strain gages, if required. A gage length of at least about 9 mm [0.35 in.] is typically required for this purpose. Bending or buckling, or both, can usually only be detected by the use of back-to-back strain gages mounted on the faces of the specimen (**3**). Bending and buckling are not visually obvious during the test, or from an examination of the specimen failure mode.

6.3 For a valid test, final failure of the specimen must occur within the gage section. Which failure modes are deemed acceptable will be governed by the particular material, configuration, and application (see 12.1).

6.4 Untabbed (Procedure A) specimens of continuous-fiber-reinforced laminates having more than 50 % axially oriented (0°) plies may require higher than acceptable fixture clamping forces to prevent end crushing. Excessive clamping forces induce at the ends of the gage section local stress concentrations that may produce erroneously low strength results (see 11.2.7). In such cases, the specimen must be tabbed (Procedure B).

6.5 If the outermost plies of a laminate are oriented at 0°, the local stress concentrations at the ends of the specimen gage section may lead to premature failure of these primary load-bearing plies, producing erroneously low laminate strength results. This is particularly true for specimens with low numbers of plies, since then the outer plies represent a significant fraction of the total number of plies (**1**).

6.6 The compressive strength and stiffness properties of unidirectional composites as well as all laminate configurations may be determined using this test method, subject to some limitations (**1**). One limitation is that the fixture clamping forces induced by the applied bolt torques required to successfully fail the composite before specimen end crushing must not induce significant stress concentrations at the ends of the gage section (**4**). Such stress concentrations will degrade the measured compressive strength. For example, testing an untabbed high-strength unidirectional composite is likely to be unsuccessful because of the excessive clamping forces required to prevent specimen end crushing, whereas a lower strength unidirectional composite may be successfully tested using acceptable clamping forces. The use of a tabbed specimen to increase the bearing area at the specimen ends is then necesary (**1, 5**). An untabbed thickness-tapered specimen, although nonstandard, has also been used to successfully test high-strength unidirectional composites (**5**).

6.7 In multidirectional laminates, edge effects can affect the measured strength and modulus of the laminate.

7. Apparatus and Supplies

7.1 *Micrometers and Calipers*—A micrometer having a suitable-size 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, shall be used. A caliper of suitable size can also be used on machined edges or very smooth tooled surfaces. The accuracy of these instruments shall be suitable for reading to within 1 % of the sample length, width and thickness. For typical specimen geometries, an instrument with an accuracy of ±2.5 µm [±0.0001 in.] is desirable for thickness and width measurement, while an instrument with an accuracy of ±25 µm [±0.001 in.] is desirable for length measurements.

7.2 *Torque Wrench*—Calibrated within the torque range required.

7.3 *Testing Machine*—A calibrated testing machine shall be used which can be operated at constant crosshead speed over the specified range. The test machine mechanism shall be essentially free from inertial lag at the crosshead speeds specified. The machine shall be equipped with an appropriate force-measuring device (for example, a load cell). The accuracy of the test machine shall be in accordance with Practices E4.

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

7.5 *Environmental Chamber*—A chamber capable of enclosing the test fixture and specimen while they are mounted in the testing machine, and capable of achieving the specified heating/cooling rates, test temperatures, and environments, shall be used when nonambient conditions are required during testing. This chamber shall be capable of maintaining the gage section of the test specimen within ±3°C [±5°F] of the required test temperature during the mechanical test. In addition, the chamber may have to be capable of maintaining environmental conditions such as fluid exposure or relative humidity during the test.

7.6 *Compression Fixture*—A test fixture such as that shown in Figs. 1 and 2, or a comparable fixture, shall be used. The fixture shown introduces a controllable ratio of end loading to shear loading into the specimen, by controlling the torque applied to the clamping screws.

7.7 *Strain-Indicating Device*—Longitudinal strain shall be simultaneously measured on opposite faces of the specimen to allow for a correction as a result of any bending of the specimen, and to enable detection of Euler (column) buckling. Back-to-back strain measurement shall be made for all five specimens when the minimum number of specimens allowed by this test method are tested. If more than five specimens are to be tested, then a single strain-indicating device may be used for the number of specimens greater than the five, provided the total number of specimens are tested in a single test fixture and load frame throughout the tests, that no modifications to the specimens or test procedure are made throughout the duration of the tests, and provided the bending requirement (see 12.3 and 12.4) is met for the first five specimens. If these conditions are not met, then all specimens must be instrumented with back-to-back devices. When Poisson's ratio is to be determined, the specimen shall be instrumented to measure strain in the lateral direction using the same type of transducer. The same type of strain transducer shall be used for all strain measurements on any single coupon. Strain gages are recommended because of the short gage length of the specimen. Attachment of the strain-indicating device to the coupon shall not cause damage to the specimen surface.

7.8 *Data Acquisition Equipment*—Equipment capable of recording force and strain data is required.

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, such 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*—The test specimen is an untabbed (Procedure A) or tabbed (Procedure B) rectangular strip of the composite to be tested, as shown in Fig. 3. A guide to preparation of flat composite panels, with processing guidelines for specimen preparation, is presented in Guide D5687/D5687M. Specimen dimensions and tolerances must be in compliance with the requirements of Fig. 3. As noted also in 6.6, for materials with a sufficiently high compressive strength in the direction of loading, end crushing or an untabbed specimen cannot be prevented by increasing fixture clamping force alone. It then becomes necessary to use tabs, to increase the load-bearing area at the specimen ends. While tapered tabs would be potentially beneficial in reducing stress concentrations in the specimen at the tab ends, they increase the effective unsupported length (gage length) of the specimen, increasing the possibility of inducing specimen buckling. Thus, untapered (square-ended) tabs are recommended. For many polymer-matrix composites, glass fabric/epoxy tabs have been found to perform well (**1, 4**). This material has a favorable combination of compliance, shear strength and toughness. Note that tabs having a low stiffness, yet sufficiently strong to transmit the induced forces, are desired. Thus, tabs of the same material as the specimen are normally not desired, contrary to common beliefs (**6**). For specimen thicknesses on the order of 2.5 mm [0.10 in.] thick or less, tabs on the order of 1.6 mm [0.06 in.] thick have been found to be adequate (**1, 4**). For thicker specimens, thicker tabs may be required, a tab thickness limit being reached when the tab adhesive is no longer able to transfer the induced shear forces. In this case, the practical solution it to reduce the specimen thickness. If axial strain is to be measured (for example, to monitor specimen bending, to determine the axial compressive modulus, or to obtain a stress-strain curve), two single-element axial strain gages or similar transducers are typically mounted back-to-back on the faces of the specimen, in the center of the gage section, as shown in Fig. 3 (see also Section 12). If in-plane transverse strain is also to be measured (for example, to calculate the in-plane compressive Poisson's ratio), an additional single-element strain gage oriented in the transverse direction on one face of the specimen may be used. Alternatively, one or more strain gage rosettes may be used.

8.2.1 *Specimen Width*—The nominal specimen width shall be 13 mm [0.50 in.]. However, other widths may be used. For example, the fixture shown in Figs. 1 and 2 can accommodate specimens up to a maximum width of 30 mm [1.2 in.]. In order to maintain a representative volume of material within the gage section, specimens narrower than 13 mm [0.50 in.] are not typically used. It is sometimes desirable to use specimens wider than nominal, for example, if the material architecture is coarse (as for a coarse-weave fabric), again to maintain a representative gage section volume of material being tested.

8.2.2 *Specimen Thickness*—Although no specific specimen thickness is required, some limitations exist. The thickness must be sufficient to preclude Euler column buckling of the specimen. Eq 1 may be used to estimate the minimum thickness to be used for strength determinations (see also Test Method D3410/D3410M). As indicated in Eq 1, the minimum specimen thickness required depends on a number of factors in addition to gage length (**1, 4**).

$$h \geq \frac{l_g}{0.9069\sqrt{\left(1-\frac{1.2F^{cu}}{G_{xz}}\right)\left(\frac{E^f}{F^{cu}}\right)}} \quad (1)$$

where:

h = specimen thickness, mm [in.],
l_g = length of gage section, mm [in.],
F^{cu} = expected ultimate compressive strength, MPa [psi],
E^f = expected flexural modulus, MPa [psi], and
G_{xz} = through-the-thickness (interlaminar) shear modulus, MPa [psi].

NOTE 2—Eq 1 is derived from the following expression for the Euler buckling stress for a pin-ended column of length l_g (an assumption which is strictly not valid for the specimen gage length l_g), modified for shear deformation effects. The E^f in Eq 1 and Eq 2 is the flexural modulus of the specimen. For the intended purpose, the approximation of using the compressive modulus E^c in place of the flexural modulus E^f may be valid.

8.2.2.1 Eq 1 may be rewritten in the form of Eq 2 (**7**).

$$F_{cr} = \frac{\pi^2 E^f}{\frac{l_g^2 A}{I} + 1.2\pi^2 \frac{E^f}{G_{xz}}} \quad (2)$$

where:

F_{cr} = predicted Euler buckling stress, MPa [psi],
A = specimen cross-sectional area, mm^2 [in.^{2}], and
I = minimum moment of inertia of specimen cross section, mm^4 [in.^{4}].

8.2.2.2 Eq 2 can be used to estimate the applied stress, F_{cr}, on the test specimen at which Euler buckling is predicted to occur for the specific specimen configuration of interest. Practical experience has shown that Eq 1 and Eq 2 are reliable for conventional fiber/polymer matrix composites, and that as a general guide, keeping the predicted value F_{cr} of buckling stress at least 30 % above the expected compressive strength is usually sufficient (**1, 4**).[6] Other composites may require different percentages.

8.2.2.3 The through-the-thickness (interlaminar) shear modulus, G_{xz}, as required in Eq 1 and 2, can be measured, for example, by using Test Method D5379/D5379M. If G_{xz} is not available in the form of experimental data, assuming value of G_{xz} of approximately 4 GPa [0.60 Msi] is a reasonable estimate for most polymer matrix composite materials tested at room temperature (**4**). In any case, this is offered only as an estimate, to serve as a starting point when designing a test specimen of a material with an unknown G_{xz}. Also, this assumed value may not be reasonable for configurations such as stitched laminates or 3D woven composites, in which case it will be necessary to measure G_{xz} directly. The absence of specimen buckling must eventually be verified experimentally. The specimen can be thinner if only modulus is being determined, as the required applied force may then be significantly lower than the buckling force. There is no specific upper limit on specimen thickness. For Procedure A (untabbed specimens), one practical limitation is the increasing difficulty of applying a uniform pressure over the ends of a specimen of progressively larger cross-sectional area. Another is the need to apply increasing clamping forces to prevent end crushing as the specimen becomes thicker (by maintaining the desired ratio of end loading to shear loading). As discussed in 6.4, the induced stress concentrations in the specimen by the test fixture increase as the clamping force increases. Note that increasing the width of the specimen does not alleviate this condition. For Procedure B (tabbed specimens), the tab thickness must be increased as specimen thickness increases, to prevent end crushing. THe limit on specimen thickness is when the tab adhesive can no longer transmit the forces on the tab ends into the specimen via shear through the adhesive.

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*—Unless a different environment is specified as part of the experiment, condition the test specimens in accordance with Procedure C of Test Method D5229/D5229M, and store and test at standard laboratory atmosphere (23 ± 3°C [73 ± 5°F] and 50 ± 10 % relative humidity).

[6] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:D30-1007. Contact ASTM Customer Service at service@astm.org.

11. Procedure

11.1 *Before Test:*

11.1.1 Inspect the test fixture to ensure that it is operating smoothly and that the gripping and loading surfaces are not damaged and are free of foreign matter. Screw threads and fixture threads shall also be clean and lubricated. A powdered graphite lubricant is suggested; oils can spread onto the surfaces of the fixture, promoting the accumulation of debris on them during subsequent testing.

11.1.2 For nonambient temperature testing, preheat or precool the test chamber as required in the applicable specifications or test instructions.

11.1.3 Condition and store specimens in accordance with applicable specifications or test instructions.

11.1.4 Measure the specimen width and thickness to a precision of 0.0025 mm [0.0001 in.], recording the average of three measurements. The width and thickness measurements shall be made in the gage section of the specimen, taking care not to measure directly over the strain gage or gage adhesive. Measure the specimen length to a precision of 0.025 mm [0.001 in.].

11.2 *Specimen Installation When Using a Fixture of the Type Shown in Figs. 1 and 2:*

11.2.1 Loosen the screws in both halves of the test fixture sufficiently to accommodate the specimen thickness to be tested.

11.2.2 Remove the upper half of the fixture from the lower half. Place the lower half of the fixture on a flat surface with the alignment rods pointing upward. It is helpful to perform this operation on a granite surface plate or similar hard flat surface.

11.2.3 Place the test specimen in the test fixture. Ensure that the end of the specimen is flush with the bottom surface of the fixture and in contact with the flat surface plate while slightly tightening the four screws in the lower half of the fixture ("finger tight").

11.2.4 Turn the upper half of the fixture upside down and place it on the flat surface.

11.2.5 Turn the lower half of the fixture upside down and insert its alignment rods and the free end of the mounted specimen into the inverted upper half of the fixture. Make sure the end of the specimen is flush with the end of the upper half of the fixture and in contact with the flat surface plate. If the upper half will not slide freely into the lower half, slightly loosen the two screws in the lower half that are closest to the gage section, while restraining the upper half so that it does not slide down too far and damage the strain gages or other transducers, if present.

11.2.6 Slightly tighten the four screws in the upper half of the fixture (finger tight).

11.2.7 Place the assembled fixture on its side with the screws on top. Torque all eight of the 6-mm [0.25-in.] diameter screws to 2.5 to 3.0 N-m [20 to 25 in.-lb], in three or four approximately equal increments, using a diagonal tightening pattern at each end so the fixture surfaces are uniformly clamped against the surfaces of the test specimen.

NOTE 3—The required torque may vary depending on the type of material and the thickness of the specimen being tested. A torque of 2.5 to 3.0 N-m [20 to 25 in.-lb] has been found to be sufficient for most materials of typical specimen thicknesses, for example, 2.0 to 3.0 mm [0.080 to 0.120 in.] thick (**1, 4**). If the torque is too low for a given configuration, the ends of the specimen may crush. If the torque is excessive, the high clamping force will induce detrimental stress concentrations in the specimen at the ends of the gage section and lead to premature failures. Thus, a torque just sufficient to prevent end crushing should be used. This may require several trials when testing an unfamiliar material. However, it has been shown that the acceptable range of torque is very broad (**4**).

11.2.8 Place the assembled fixture between well-aligned, fixed (as opposed to spherical-seat) flat platens (platen surfaces parallel within 0.03 mm [0.001 in.] across the fixture base) in the testing machine. One fixed and one spherical seat platen can be used as an alternative, but is not the preferred configuration (**4**). If the platens are not sufficiently hardened, or simply to protect the platen surfaces, a hardened plate (with parallel surfaces) can be inserted between each end of the fixture and the corresponding platen.

11.2.9 If strain gages or other transducers are being used, attach the lead wires to the data acquisition apparatus. To determine the compressive modulus of the laminate, the laminate stress must be measured at two specified strain levels, typically 1000 and 3000 microstrain (see 11.2). Often back-to-back strain gages are used. If bending of the specimen is occurring at any strain level, the strains measured on the opposite faces of the specimen will not be equal. The average of these two values is the desired strain since the amount of bending does not affect the average strain. However, just as in the discussion of compressive strength (see 12.4), the percent bending must be kept to less than 10 % (see also Test Method D3410/D3410M).

11.3 *Loading*—Load the specimen in compression to failure at a nominal rate of 1.3 mm/min [0.05 in./min], while recording force, displacement, and strain data. Loading time to failure should be 1 to 10 min. If only modulus is being determined, load the specimen approximately 10 % beyond the upper end of the strain range being used to determine modulus.

11.4 *Data Recording*—Record load versus strain (or displacement) continuously or at frequent regular intervals. A sampling rate of 2 to 3 data recordings per second, and a target minimum of 100 data points per test is recommended. If a transition region or initial ply failures are noted, record the force, strain, and mode of damage at such points. If the specimen is to be failed, record the maximum force, the failure force, and the strain (or transducer displacement) at, or as near as possible to, the moment of failure.

12. Validation

12.1 Inspect the tested specimen and note the type and location of the failure. For valid tests, final failure of the specimen will occur within the gage section. The failure mode may be brooming, transverse or through-thickness shear, longitudinal splitting, or delamination, among possibly other forms (**3**). Which failure modes are deemed acceptable will be governed by the particular material, laminate configuration, and application. Acceptable failure modes are illustrated in Test Method D3410/D3410M. Minor end crushing before final failure in the gage section sometimes occurs. If this end crushing arrests, and a valid gage section failure ultimately is achieved, end crushing does not invalidate the test. In general, failures that initiate elsewhere within the gripped length do not arrest and hence invalidate the test.

12.2 The occurrence of Euler buckling invalidates the test. Euler buckling failures cannot be detected by visual inspection of the specimen during or after the test. Only the use of back-to-back strain gages or similar instrumentation provides a reasonable indication.

12.3 Although the specimen does not buckle, the induced bending may be excessive. This can be due to imperfections in the test specimen, the test fixture, or the testing procedure. Eq 3 is to be used to calculate percent bending. Additional details are given in Test Method D3410/D3410M.

$$B_y = percent\ bending = \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \varepsilon_2} \times 100 \quad (3)$$

where:

ε_1 = indicated strain from Gage 1 and
ε_2 = indicated strain from Gage 2.

The sign of the calculated Percent Bending indicates the direction in which the bending is occurring. This information is useful in determining if the bending is being induced by a systematic error in the test specimen, testing apparatus, or test procedure, rather than by random effects from test to test.

12.4 For the test results to be considered valid, percent bending in the specimen shall be less than 10 % as determined by Eq 3. Determine percent bending at the midpoint of the strain range used for chord modulus calculations (see 13.2). The same requirement shall be met at the failure strain for the strength and strain-to-failure data to be considered valid. This requirement shall be met for all five of the specimens requiring back-to-back strain measurement. If possible, a plot of percent bending versus average strain should be recorded to aid in the determination of failure mode.

12.4.1 Although extreme amounts of bending (greater than 40 to 50 %) will decrease the measured compressive strength, it has been found that as much as 30 to 40 % bending may have no significant effect on the compressive strength value obtained (**4**). However, the presence of large amounts of bending does suggest some irregularity in specimen preparation or testing procedure. Thus, achievement of less than 10 % bending at failure is required for the test to be considered valid (see also Test Method D3410/D3410M). The use of back-to-back strain gages on the first few specimens of a group (the gages being centered within the gage length on the opposite faces of the test specimen) provides a good indication of the general bending response of the group. However, it does not guarantee that all subsequent specimens of the group will fail at an acceptable level of bending. The use of back-to-back strain instrumentation on all specimens is the only way of ensuring this. However, if the back-to-back strain instrumentation used on a representative sample of the specimens indicates acceptable percent bending and the absence of Euler buckling (see 7.6), and the compressive strengths of all specimens tested are similar, there is reasonable assurance that bending and buckling did not influence the results (**4**).

12.5 Record the mode, area, and location of failure for each specimen. Choose a standard failure identification code based on the three-part code shown in Fig. 4. A multimode failure can be described by including each of the appropriate failure mode codes between the parentheses of the M failure mode. For example, a typical gage-section compression failure for a $[90/0]_{ns}$ laminate having elements of Angled, Kink-banding, and longitudinal Splitting in the middle of the gage section would have a failure mode code of M(AKS)GM. Examples of overall visual specimen failures and associated Failure Identification Codes (four acceptable and four unacceptable) are shown in Fig. 4.

12.5.1 *Acceptable Failure Modes*—The first character of the Failure Identification Code describes the failure mode. All of the failure modes in the "First Character" table of Fig. 4 are acceptable with the exception of end-crushing or Euler buckling. An Euler buckling failure mode cannot be determined by visual inspection of the specimen during or after the test. Therefore, it must be determined through inspection of the stress-strain or force-strain curves when back-to-back strain indicating devices are used (see 7.6).

12.5.2 *Acceptable Failure Test*—The most desirable failure area is the middle of the gage section since the gripping/tabbing influence is minimal in this region. Because of the short gage length of the specimens in this test method, it is very likely that the failure location will be near the grip/tab termination region of the gage section. Although not as desirable as the middle of the gage section, this is an acceptable failure area. If a significant fraction (>50 %) of the failures in the sample population occurs at the grip or tab interface, reexamine the means of force introduction into the specimens. Factors considered should include the tab alignment, tab material, tab adhesive, grip type, grip pressure, and grip alignment. Any failure that occurs inside the grip/tab portion of the specimen is unacceptable.

13. Calculation

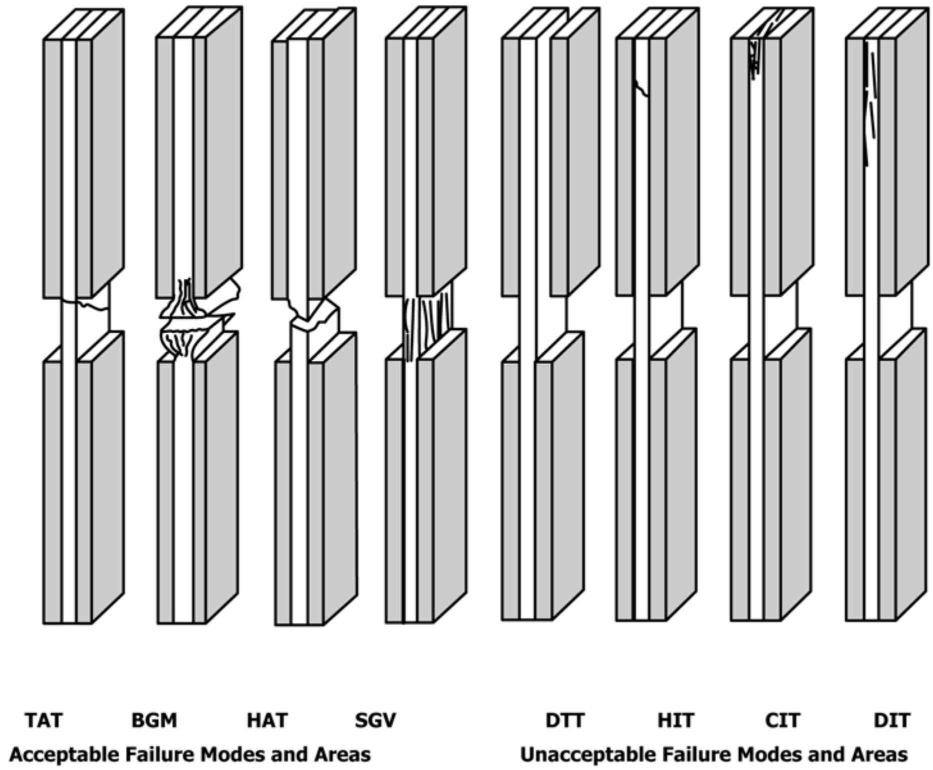
13.1 *Laminate Compressive Strength*—Calculate the compressive strength of the laminate using Eq 4:

$$F^{cu} = \frac{P_f}{wh} \quad (4)$$

where:

F^{cu} = laminate compressive strength, MPa [psi],
P_f = maximum load to failure, N [lbf],
w = specimen gage width, mm [in.], and
h = specimen gage thickness, mm [in.].

13.2 *Laminate Compressive Modulus*—A chord modulus is to be calculated over a range of axial strain, ε_x, of 1000 to 3000 microstrain and reported to three significant figures. This strain range is specified to represent the lower half of the stress-strain curve. For materials that fall below 6000 με, a strain range of 25 to 50 % of ultimate is recommended. However, for some materials another range may be more appropriate. Other definitions of chord modulus may be evaluated and reported at the user's discretion. If such data are generated and reported, report also the definitions used, the strain range used, and the results to three significant figures. Calculate this compressive modulus using Eq 5:



First Character

Failure Mode	Code
Angled	A
Brooming	B
end-Crushing	C
Delamination	D
Euler buckling	E
tHrough-thickness	H
Kink bands	K
Lateral	L
Multi-mode	M(xyz)
long.-Splitting	S
Transverse shear	T
eXplosive	X
Other	O

Second Character

Failure Area	Code
Inside grip/tab	I
At grip/tab	A
Gage	G
Multiple Areas	M
Tab adhesive	T
Various	V
Unknown	U

Third Character

Failure Location	Code
Bottom	B
Top	T
Left	L
Right	R
Middle	M
Various	V
Unknown	U

FIG. 4 Compression Test Specimen Three-Part Failure Identification Codes and Overall Specimen Failure Schematics

$$E^c = \frac{P_2 - P_1}{(\varepsilon_{x2} - \varepsilon_{x1})\, w\, h} \quad (5)$$

where:

E^c = compressive modulus, MPa [psi],
P_1 = load at ε_{x1}, N [lbf],
P_2 = load at ε_{x2}, N [lbf],
ε_{x1} = actual strain nearest lower end of strain range used,
ε_{x2} = actual strain nearest upper end of strain range used,
w = specimen gage width, mm [in.], and
h = specimen gage thickness, mm [in.]

13.3 *Compressive Poisson's Ratio:*

13.3.1 *Compressive Poisson's Ratio By Chord Method*—Use the same strain range as for calculating the laminate compressive modulus (see 11.2). Determine the transverse strain, ε_y, at each of the two ε_x strain range end points. Calculate Poisson's ratio using Eq 6 and report to three significant figures.

$$\nu_{xy}{}^c = -(\varepsilon_{y2} - \varepsilon_{y1})/(\varepsilon_{x2} - \varepsilon_{x1}) \quad (6)$$

Other definitions of Poisson's ratio may be evaluated and reported at the user's discretion. If such data are generated and reported, report also the definitions used, the strain range used, and the results to three significant figures. Test Method E132 provides additional guidance in the determination of Poisson's ratio.

NOTE 4—If bonded resistance strain gages are being used, the error produced by the transverse sensitivity effect on the transverse gage will generally be much larger for composites than for metals. An accurate measurement of Poisson's ratio requires correction for this effect. Contact the strain gage manufacturer for information on the use of correction factors for transverse sensitivity.

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

$$\bar{x} = \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right) \quad (7)$$

$$S_{n-1} = \sqrt{\frac{\left(\sum_{i=1}^{n} (x_i - \bar{x})^2\right)}{(n-1)}} \quad (8)$$

$$CV = 100 \cdot S_{n-1}/\bar{x} \quad (9)$$

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, if not previously provided:

14.1.1 Complete identification of the material, including lot and roll numbers (as applicable), and the laminate configuration.

14.1.2 Method of preparation of the test specimens, including process cycle(s).

14.1.3 Specimen pretest conditioning history.

14.1.4 Relative humidity and temperature conditions in the test laboratory.

14.1.5 Identification of test machine, load cell, test fixture, and data acquisition equipment.

14.1.6 Test parameters, including environment of the test and tolerances, dwell time at temperature and tolerances, fixture bolt torques used, and crosshead speed.

14.1.7 Dimensions of each specimen to at least three significant figures, including gage section width and thickness, and overall specimen length.

14.1.8 Nominal gage length (determined from fixture dimensions and nominal specimen overall length).

14.1.9 Force-strain data for each specimen for each strain gage used.

14.1.10 For strength and modulus tests: failure force, failure strain, calculated ultimate compressive strength (F^{cu}), and calculated compressive modulus (E^c). These values shall be reported to at least three significant figures.

14.1.11 For modulus only tests: maximum force applied, strain at maximum applied force, and calculated compressive modulus (E^c). These values shall be reported to at least three significant figures.

14.1.12 Strain range used for modulus calculation.

14.1.13 Description of failure mode and location (for strength tests).

14.1.14 Percent bending at strain range midpoint of chord modulus calculation (see 13.2), and at failure (if determined).

14.1.15 Identification of the facility and individuals performing the test.

14.1.16 Date of test.

14.1.17 Any deviations from this test method.

14.2 The information reported for this test method includes mechanical testing data; material and laminate identification data; and fiber, filler, and core material identification data. These data shall be reported in accordance with Guides E1434, E1309, and E1471, respectively. Each data item discussed is identified as belonging to one of the following categories: (VT) required for reporting of a valid test result, (VM) required for valid traceability, (RT) recommended for maximum test method traceability, (RM) recommended for maximum material traceability, or (O) for optional data items. The following information applies to the use of these documents for reporting data:

14.2.1 *Guide E1434:*

14.2.1.1 The response for Field A5, Type of Test, is "Compression."

14.2.1.2 Measured values will be reported for Fields F4 and F5. Nominal values are acceptable for Fields F7 to F9.

14.2.1.3 The failure identification code (in accordance with Test Method D3410/D3410M) will be reported in Fields H18 and K50. The failure location is optional in Fields H17 and K49 since the failure identification code includes this information.

14.2.1.4 Statistical parameters for specimen dimensions, maximum load, maximum transverse strain, and bending strain are optional. These include Fields K1 to K9, K19 to K21, and K30 to K34. The testing summary sub-block is also optional (Fields K14 to K18).

14.2.2 *Guide E1309:*

14.2.2.1 The consolidation method should be reported as the process stage type in Field E2.

14.2.2.2 The nominal cure cycle is required for valid material traceability in one set of process stage conditions in Field E4. The actual cure cycle is recommended in a second set of process stage conditions in Field E4.

14.2.3 *Guide E1471:*

14.2.3.1 Tow or yarn filament count and filament diameter should be included as dimension parameters in Field B2.

15. Precision and Bias[6]

15.1 *Round-Robin Results*—The precision of this test method is based on an interlaboratory study (ILS) of ASTM D6641/D6641M, Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture, conducted in 2007-2013. Four different materials (one in two different grades) and five lay-ups, resulting in 10 material/lay-up configurations as shown in Table 1, were tested. Both procedures (A and B), and both strength and modulus measurements were evaluated. Eleven laboratories participated. All the specimens of each configuration were fabricated from single large panels, and machined at one location to reduce processing and machining variability. An initial three-lab/six-configuration phase was conducted to interrogate the Round-Robin Test Protocol and identify any systemic issues. Phase 2 included all eleven labs and eight configurations. Each of the eleven laboratories received randomized samples for testing. All tests were performed at ambient laboratory conditions. The test

TABLE 1 Round-Robin Test Configurations

Mat ID	Material	Lay-Up	Thickness (in.)	1.2 x h_{crit}[B]	Spec/Lab	Labs/Mat'l
A[A]	Gr145 IM-Fiber/Epoxy Tape	$[45/90/-45/0]_{2s}$	0.0848	0.0818	4	11
B[A]	Gr145 IM-Fiber/Epoxy Tape	$[45/90/-45/0]_{2s}$	0.0848	0.0841	6	11
C	Gr145 IM-Fiber/Epoxy Tape	$[45/90/-45/0]_{3s}$	0.1272	0.0888	3	9
D	Gr228 IM-Fiber/Epoxy Tape	$[-45/0/45/90]_{2s}$	0.1328	0.0766	3–6	5
E	SM-Fiber/Epoxy Tape	$[90/0]_{3s}$	0.0756	0.0769	3	9
F[C]	SM-Fiber/Epoxy Tape	$[0]_8$	0.0504	0.0653	2–3	5
G	E-Glass/Epoxy Fabric	$[90]_8$	0.25	0.0821	3	3
H	E-Glass/Epoxy Fabric	$[0]_8$	0.25	0.0821	5	11
J	E-Glass/Vinyl-Ester Fabric	$[90]_8$	0.25	0.0894	2	3
K	E-Glass/Vinyl-Ester Fabric	$[0]_8$	0.25	0.0894	4	11

[A] Materials A and B were fabricated by different vendors from different material lots.
[B] 1.2 x h_{crit} was the recommended thickness limit to prevent buckling per D6641/D6641M section 8.2.2.2 at the time of the round-robin testing (since revised to 1.3 × h_{crit}), determined using measured E and F_{cu} and assumed G_{xz}=0.6 Msi.
[C] Material F was tested per Procedure B (tabbed). All others were per Procedure A.

results shown are based on calculations using actual (measured) specimen thickness and width. Note that two of the specimen configurations were of marginal thickness for buckling. The average results for each laboratory and each configuration are listed in Table 2 and Table 3. As seen by the notes in Table 2, reliable strength measurement is often difficult, whereas modulus measurement (Table 3) is more straightforward.

15.2 *Precision*—Defined in Practice E177 as the closeness of agreement between independent test results, precision is separated into within-laboratory repeatability and between-lab reproducibility. The metric for comparison of both is sample standard deviation, in an absolute sense and, given that composite properties vary greatly in magnitude, this is more usefully expressed relative to mean values as the coefficient of variation (CV). These round-robin statistics are summarized in Table 4. Except as noted, Practice E691 was followed for the design and analysis of the round-robin test data; the details are given in ASTM Research Report No. D30-1007.[6] Materials D, F, G, and J are included in Table 4 for information only, despite not meeting the Practice E691 requirement for minimum number of laboratories (D could perhaps have been included on an exception basis, F was the only interrogation of Procedure B, and G and J were only intended as part of the Phase 1 exploratory effort).

15.2.1 *Repeatability Coefficient of Variation* (s_r/X_{bar})—Defined to be within-lab precision on the same material, test method, and by the same lab and operator on essentially the same day. The percentage difference (*CV*) noted in Table 4 is one standard deviation. An additional, optional metric defined in Practice E691 is the Repeatability Limit, 2.8 x (s_r/X_{bar}). This value is the 95% confidence interval on (s_r/X_{bar}) and two average values from the same lab/operator/day differing by more than this amount are essentially certain to be from different populations (due to lab error, differences in materials, etc). By general convention in the composites testing field, differences of less than one standard deviation (more than 50% chance of being from same population) are considered equivalent, thus the Repeatability Limit is not tabulated. It is seen in Table 4 that these values range from 3.7–6.6% for strength and 2.4–3.2% for modulus, which are reasonable when compared to other D30 within-lab repeatability precision statements. Considering the four materials included for information-only, moduli values were within the overall ranges; Material D (lacking only one more lab for inclusion and suffering no data censors in Table 2) strength repeatability was above-average; Procedure B (Material F) was within the overall Procedure A range; and Materials G and J had much lower strength repeatability CVs, probably due to insufficient lab and specimen/lab sample-sizes.

15.2.2 *Reproducibility Coefficient of Variation* (s_R/x_{bar})—Defined to be between-lab precision on the same material, test method, but by a different lab and operator on a different day. The percentage difference (CV) noted in Table 4 is one standard deviation. An additional, optional metric defined in Practice E691 is the Reproducibility Limit, 2.8 x (s_R/x_{bar}). This value is the 95% confidence interval on (s_R/x_{bar}) and two average values from different labs differing by more than this amount are essentially certain to be from different populations. As above, differences of less than one standard deviation are considered equivalent. It is seen in Table 4 that these values range from 5.3–12.8% for strength and 4.0–4.4% for modulus. While the 12.8% strength reproducibility CV for Material A seems high relative to other materials, and Material A exhibited some data censure due to buckling/procedure/quality issues (see Table 2 notes), no reason could be found to censure the entire material set. The modulus range was reasonable when compared to other D30 between-lab reproducibility precision statements. Considering the four materials included for information-only, moduli values were within/lower-than/higher-than the overall ranges; Material D (lacking only one more lab for inclusion and suffering no data censors in Table 2) strength reproducibility was above-average; Procedure B (Material F) was within the overall Procedure A range; and Materials G and J again had much lower strength reproducibility CVs.

15.2.3 The above terms (repeatability coefficient of variation, repeatability limit, reproducibility coefficient of variation, and reproducibility limit) are used as specified in Practice E177.

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

16. Keywords

16.1 combined loading; composite materials; compressive modulus of elasticity; compressive properties; compressive

TABLE 2 Compression Strength Results Summary

Note 1—US Customary units *(ksi)* shown for mean strengths. To obtain SI units of *MPa*, multiply by 6.894757.

Lab	Material																			
	A[B]		B[B]		C		D[C]		E[D]		F		G		H		J		K	
	Mean (ksi)	CV (%)	Mean (ksi)	CV (%)	Mean (ksi)	CV (%)	Mean (ksi)	CV (%)	Mean (ksi)	CV (%)	Mean (ksi)	CV (%)	Mean (ksi)	CV (%)	Mean (ksi)	CV (%)	Mean (ksi)	CV (%)	Mean (ksi)	CV (%)
1	92.51	3.60	108.5	1.24	119.3	2.92	92.81	2.08	105.1	3.95	[A]		48.34	1.74	55.44	7.41	61.86	0.09	71.26	5.92
2	87.09	2.42	106.4	6.55	112.8	3.39	91.62	3.69	90.18	5.87	[A]		47.93	1.08	56.02	6.79	59.35	1.94	65.50	2.33
3	83.68	6.59	103.8	5.97	113.5	6.90	97.39	2.12	100.5	2.64	127.7	5.98	50.12	2.42	56.92	7.35	56.62	0.06	67.05	1.58
4	112.1	7.39	103.3	4.08	[A]		86.22	7.40	97.21	2.13	138.0	0.35	...		53.30	5.84	...		65.72	4.64
5	[A]		110.3	2.65	110.8	8.65	80.22	15.4	102.0	2.75	131.8	7.82	...		56.85	5.61	...		69.27	3.28
6	106.4	4.13	105.5	2.81	109.6	8.43	...		99.66	2.93	...		...		56.43	6.85	...		66.43	8.36
7	103.6	3.00	105.1	5.94	113.1	3.59	...		102.8	4.62	...		...		55.78	3.80	...		64.59	4.81
8	[A]		[A]		107.9	9.62	...		[A]		...		...		54.99	4.74	...		66.33	6.38
9	[A]		[A]		116.0	1.71	...		[A]		...		...		57.15	9.27	...		70.29	2.23
10	115.4	0.77	105.9	9.49	...		...		...		...		...		57.94	3.76	...		74.08	0.75
11	113.5	1.20	110.4	2.31	...		...		...		...		...		57.98	8.15	...		69.87	3.37
Overall Avg:	101.8		106.6		112.9		89.65		99.64		132.5		48.80		56.25		59.27		68.22	
Overall CV %		11.8		4.83		6.02		8.26		5.57		5.76		2.62		6.37		4.05		5.72

[A]Censored entire set due to buckling, test or specimen quality problems, or both.
[B] Censored one or more individual test results from one or more lab sets due to buckling, test or specimen, or both, quality problems.
[C]Censored three individual test results from one lab due to a test problem (fixture torque too low).
[D] Included seven individual test results from three labs despite buckling or failure-mode issues, because they were within-population of acceptable results.

TABLE 3 Compression Modulus Results Summary

Note 1—US Customary units (*Msi*) shown for mean moduli. To obtain SI units of *GPa*, multiply by 6.894757.

Lab	Material													
	A		B		D		E		F		G		J	
	Mean (Msi)	CV (%)	Mean (Msi)	CV (%)	Mean (Msi)	CV (%)	Mean (Msi)	CV (%)	Mean (Msi)	CV (%)	Mean (Msi)	CV (%)	Mean (Msi)	CV (%)
1	8.07	1.08	8.15	3.64	8.27	1.20	8.87	4.21	15.96	1.71	3.92	3.49	4.21	7.48
2	8.01	1.16	8.09	1.61	7.93	4.28	8.83	0.32	16.51	1.70	4.01	1.00	4.19	4.52
3	7.83	1.74	8.00	1.17	8.27	3.39	8.47	1.80	15.60	2.94	4.03	2.86	4.10	3.45
4	8.12	3.41	8.15	1.77	...		8.72	1.99	16.06	3.31	...		...	
5	7.97	2.76	8.03	1.73	...		8.90	4.31	16.20	3.28	...		...	
6	...		7.37	2.04	...		8.13	1.44	...		...		...	
7	8.07	2.92	8.09	2.47	...		8.72	1.45	...		...		...	
8	8.46	2.35	8.35	2.33	...		9.27	0.48	...		...		...	
9	7.54	4.47	7.90	5.76	...		8.32	1.77	...		...		...	
10	7.80	5.08	8.05	1.09	...		...		...		...		...	
11	7.90	4.44	8.18	3.38	...		...		...		...		...	
Overall Avg:	7.98		8.03		8.15		8.69		16.07		3.99		4.17	
Overall CV (%)		3.77		3.90		3.55		4.29		2.89		2.64		4.41

strength; Poisson's ratio

TABLE 4 Round-Robin Statistics

Mat ID	Material	Lay-Up	thk (in.)	Between-Observation Coefficients of Variation (%) Within-Lab Repeatability $(s_r/X_{bar}) \times 100$ Strength	Modulus	Between-Lab Reproducibility $(s_R/x_{bar}) \times 100$ Strength	Modulus
A	Gr145 IM-Fiber/Epoxy Tape	$[45/90/-45/0]_{2s}$	0.0848	4.20	3.19	12.80	4.19
B	Gr145 IM-Fiber/Epoxy Tape	$[45/90/-45/0]_{2s}$	0.0848	5.14	2.77	5.30	3.99
C	Gr145 IM-Fiber/Epoxy Tape	$[45/90/-45/0]_{3s}$	0.1272	5.86		5.86	
D[A]	Gr228 IM-Fiber/Epoxy Tape	$[-45/0/45/90]_{2s}$	0.1328	7.27	3.20	9.91	3.82
E	SM-Fiber/Epoxy Tape	$[90/0]_{3s}$	0.0756	3.71	2.41	5.74	4.41
F[A]	SM-Fiber/Epoxy Tape	$[0]_8$	0.0504	5.59	2.68	6.00	3.01
G[A]	E-Glass/Epoxy Fabric	$[90]_8$	0.250	1.85	2.66	2.83	2.66
H	E-Glass/Epoxy Fabric	$[0]_8$	0.250	6.57		6.57	
J[A]	E-Glass/Vinyl-Ester Fabric	$[90]_8$	0.250	1.12	5.46	4.49	5.46
K	E-Glass/Vinyl-Ester Fabric	$[0]_8$	0.250	4.47		5.80	
			Average:	4.99	2.79	7.01	4.20

[A]Shown for information only. Too few labs to be strictly valid. Not included in averages

REFERENCES

(1) Adams, D.F., and Welsh, J.S., "The Wyoming Combined Loading Compression (CLC) Test Method," *Journal of Composites Technology & Research*, Vol 19, No. 3, 1997, pp. 123-133.

(2) *CMH-17-1F*, "Polymer Matrix Composites, Volume 1–Guidelines for Characterization of Structural Materials," available from ASTM International, West Conshohocken, PA19428, www.astm.org, Section 2.4.2.

(3) Odom, E.M., and Adams, D.F., "Failure Modes of Unidirectional Carbon/Epoxy Composite Compression Specimens," *Composites*, Vol 21, No. 4, July 1990, pp. 289-296.

(4) Wegner, P.M., and Adams, D.F., "Verification of the Wyoming Combined Loading Compression Test Method," published by the Federal Aviation Administration Technical Center, Atlantic City, NJ, as Report No. UW-CMRG-R-98-116 (Composite Materials Research Group, University of Wyoming), September 1998.

(5) Adams, D.F., and Finley, G.A., "Experimental Study of Thickness-Tapered Unidirectional Composite Compression Specimens," *Experimental Mechanics*, Vol 36, No. 4, December 1996, pp. 348-355.

(6) Xie, M., and Adams, D. F., "Effect of Specimen Tab Configuration on Compression Testing of Composite Materials," *Journal of Composites Technology & Research* Vol 17, No. 2, April 1995, pp. 11-21.

(7) Timoshenko, S.P., and Gere, J.M., *Theory of Elastic Stability*, 2nd ed., McGraw-Hill Book Co., New York, 1961, pp. 132-135.