This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

Designation: D7905/D7905M – 19ε1

Standard Test Method for Determination of the Mode II Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites[1]

This standard is issued under the fixed designation D7905/D7905M; 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—Editorial changes were made to Table 1 in November 2019.

1. Scope

1.1 This test method covers the determination of the mode II interlaminar fracture toughness, G_{IIc}, of unidirectional fiber-reinforced polymer matrix composite laminates under mode II shear loading using the end-notched flexure (ENF) test (Fig. 1).

1.2 This method is limited to use with composites consisting of unidirectional carbon-fiber- and glass-fiber-reinforced laminates. This limited scope reflects the experience gained in round robin testing. This test method may prove useful for other types and classes of composite materials; however, certain interferences have been noted (see Section 6).

1.3 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system are not necessarily exact equivalents; therefore, to ensure conformance with the standard, each system shall be used independently of the other, and values from the two systems shall not be combined.

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

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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

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

D883 Terminology Relating to Plastics

D2584 Test Method for Ignition Loss of Cured Reinforced Resins

D2734 Test Methods for Void Content of Reinforced Plastics

D3171 Test Methods for Constituent Content of Composite Materials

D3878 Terminology for Composite Materials

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

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

D7264/D7264M Test Method for Flexural Properties of Polymer Matrix Composite Materials

E4 Practices for Force Verification of Testing Machines

E6 Terminology Relating to Methods of Mechanical Testing

E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E456 Terminology Relating to Quality and Statistics

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)[3]

[1] This test method is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of Subcommittee D30.06 on Interlaminar Properties.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

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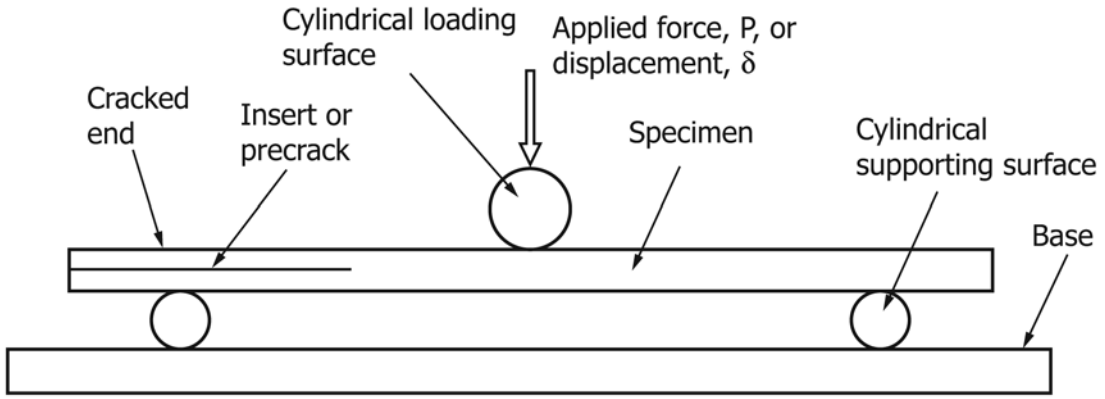

FIG. 1 ENF Test Fixture and Specimen Nomenclature

E1434 Guide for Recording Mechanical Test Data of Fiber-Reinforced Composite Materials in Databases (Withdrawn 2015)[3]

E1471 Guide for Identification of Fibers, Fillers, and Core Materials in Computerized Material Property Databases (Withdrawn 2015)[3]

3. Terminology

3.1 Terminology D3878 defines terms relating to high-modulous 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 conflict between terms, Terminology D3878 shall have precendence over the other terminology standards.

NOTE 1—If the term represents a physical quantity, its analytical dimensions are stated immediately following the term (or letter symbol) in fundamental dimension form, using the following ASTM standard symbology for fundamental dimensions, shown within square brackets: [*M*] for mass, [*L*] for length, [*T*] for time, [*u*] for thermodynamic temperature, and [*nd*] for non-dimensional quantities. Use of these symbols is restricted to analytical dimensions when used with square brackets, as the symbols may have other definitions when used without the brackets.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *compliance calibration (CC) method*—the method of data reduction where the relationship between specimen compliance [T^2/M] and delamination length [*L*] is determined prior to testing by measuring specimen compliance [T^2/M] at multiple simulated delamination lengths.

3.2.2 *mode II interlaminar fracture toughness, G_{IIc} [M/T^2]*—the critical value of strain energy release rate, *G*, [M/T^2] for delamination growth [*L*] due to an in-plane shear force [M/T^2] or displacement [*L*] oriented perpendicular to the delamination front.

3.2.3 *non-precracked (NPC) toughness [M/T^2]*—an interlaminar fracture toughness value that is determined from the preimplanted insert.

3.2.4 *precracked (PC) toughness [M/T^2]*—an interlaminar fracture toughness value that is determined after the delamination has been advanced from the preimplanted insert.

3.2.5 *strain energy release rate, G [M/T^2]*—the loss of strain energy, *dU* [ML^2/T^2], in the test specimen per unit of specimen width [*L*] for an infinitesimal increase in delamination length, *da* [*L*], for a delamination growing self-similarly under constant displacement [*L*]; in mathematical form,

$$G = -\frac{1}{B}\frac{dU}{da} \quad (1)$$

where:

U = total elastic strain energy in the specimen;
a = delamination length; and
B = specimen width.

3.3 *Symbols:*

A—intercept of the linear fit of compliance versus crack length cubed data

a—delamination length

a_{calc}—crack length calculated from an unloading curve after the NPC test

a_i—insert length in the trimmed specimen

a_j—the j^{th} crack length used during compliance calibration ($j = 1,2$)

a_o—delamination length used in fracture test

a_{PC}—actual crack length used during the PC test

a_{vis}—visually determined crack length after the NPC test

B—specimen width

C—specimen compliance

C_0—specimen compliance during load-up of the fracture test (see Figure 6 in 13.1)

C_u—specimen compliance from unloading after the non-precracked test

δ—displacement of loading roller during testing perpendicular to the plane of the specimen (Fig. 1)

E_{1f}—flexural modulus of the specimen

G—total strain energy release rate

G_{IIC}—mode II interlaminar fracture toughness

G_Q—candidate mode II interlaminar fracture toughness

$\%G_Q$—peak percentage of G_Q achieved during compliance calibration

h—specimen half-thickness (Fig. 2)

L—specimen half-span (Fig. 2)

L_c—distance from the center of the support roller at the cracked end of the specimen to the cracked end of the specimen (Fig. 2)

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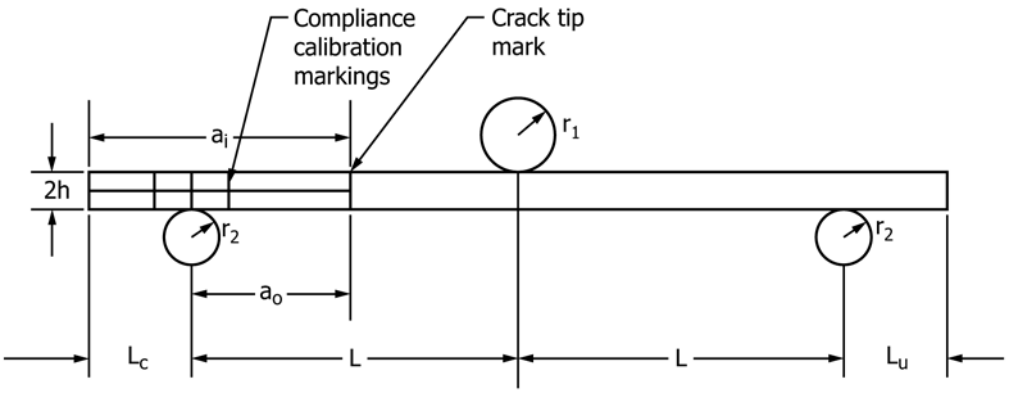

FIG. 2 ENF Specimen, Fixture, and Dimensions

L_u—distance from the center of the support roller at the uncracked end of the specimen to the uncracked end of the specimen (Fig. 2)

m—slope of the linear fit of compliance versus crack length cubed data

P—force applied to center loading roller and perpendicular to the plane of the specimen (Fig. 1)

P_c—critical force for mode II fracture

P_j—the compliance calibration force used at crack length a_j

P_{Max}—maximum value of force on the force-displacement curve

r_1—radius of the loading roller (Fig. 2)

r_2—radius of the support rollers (Fig. 2)

r^2—correlation coefficient of linear fit of compliance versus crack length cubed

Δs—maximum measured difference in crack length along the delamination front of the precrack

U—total elastic strain energy in the specimen

4. Summary of Test Method

4.1 The ENF specimen shown in Fig. 1 consists of a rectangular, uniform thickness, unidirectional laminated composite specimen containing a non-adhesive insert at the midplane that serves as a delamination initiator. Forces are applied to the specimen through an ENF fixture under displacement controlled loading.

4.2 Delamination growth is not stable in the ENF test. A method is presented so that the initiation values of the mode II interlaminar fracture toughness are obtained from the preimplanted insert as well as from a precrack.

4.3 A record of the applied force versus center roller displacement is to be obtained using an *x-y* recorder or equivalent real-time plotting device, or else it may be obtained and stored digitally. The mode II interlaminar fracture toughness, G_{IIc}, is obtained using the compliance calibration (CC) method. This is the only acceptable method of data reduction for this test (**1**).[4]

4.4 This standard recommends that static mode II precracking is performed and a recommended method is described. Other precracking methods may be used provided that a record of the shape of the precracked delamination front is obtained prior to the PC test. Precracking methods that typically leave crack front markings for post-test evaluation of these values include mode I and fatigue mode II.

5. Significance and Use

5.1 Susceptibility to delamination is one of the major design concerns for many advanced laminated composite structures. Knowledge of a laminated composite material's resistance to interlaminar fracture is useful for product development and material selection. Furthermore, a measurement of the mode II interlaminar fracture toughness that is independent of specimen geometry or method of force introduction is useful for establishing design allowables used in damage tolerance analyses of composite structures. Knowledge of both the non-precracked and precracked toughnesses allows the appropriate value to be used for the application of interest.

5.2 This test method can serve the following purposes:

5.2.1 To establish quantitatively the effect of fiber surface treatment, local variations in fiber volume fraction, and processing and environmental variables on G_{IIc} of a particular composite material;

5.2.2 To compare quantitatively the relative values of G_{IIc} for composite materials with different constituents;

5.2.3 To compare quantitatively the values of G_{IIc} obtained from different batches of a specific composite material, for example, to use as a material screening criterion or to develop a design allowable; and

5.2.4 To develop delamination failure criteria for composite damage tolerance and durability analyses.

6. Interferences

6.1 Linear elastic behavior is assumed in the calculation of G used in this method. This assumption is valid when the zone of damage or nonlinear deformation at the delamination front, or both, is small relative to the smallest specimen dimension, which is typically the specimen's thickness for the ENF test.

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

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6.2 G_{IIc} is obtained for both non-precracked and precracked specimens based on the maximum load point. G_{IIc} based on the nonlinear load point or other measures, such as a compliance offset, may also be obtained if desired. However, definitions of this type have not been related to any specific physical occurrences in the ENF test.

6.3 The three loading noses in the ENF test fixture may be fixed, rotatable, or rolling. Fixed loading noses or pins supported in a v-groove are recommended, and loading noses of this type were used in the interlaboratory test program that was conducted in support of this standard. The type of supports that are used is to be reported as described in Section 14. The loading noses should uniformly contact the specimen across its width. Lack of uniform contact can affect results, most commonly due to non-uniform loading across the width of the specimen. Formulas used in this standard assume a uniform line loading across the entire specimen width at the loading nose and at the specimen supports; deviations from this type of loading are beyond the scope of this standard.

6.4 There is an inherent error associated with the use of Eq 7 to obtain the calculated crack length, and it is not expected that the calculated crack length will exactly correspond to the true length of the precrack. However, since toughness is computed by CC, it has been shown **(2)** that this error in crack length will not affect the accuracy of the computed toughness provided that the recommended approach is followed.

6.5 For very tough composites, large deformations at the onset of delamination growth could affect the accuracy of the ENF test. For typical unidirectional glass and carbon reinforced unidirectional composites, it has been shown **(1)** that the combined effects of friction and geometric nonlinearities will affect the accuracy of the recommended approach by approximately 2.5 % or less for glass-reinforced polymer matrix composites with toughnesses up to 1.45 kJ/m^2 [8.28 in.-lbf/in.^{2}] and by 3 % or less for polymer matrix composites with carbon reinforcement with toughnesses up to 2.10 kJ/m^2 [12.0 in.-lbf/in.^{2}]. Testing of composites that exhibit greater toughness may produce somewhat larger errors. One means of checking for nonlinearities is to examine the difference between the nonlinear point and the maximum load point. If this is found to be greater than approximately 5 % of P_{Max}, further investigations may be in order to determine the reason for the discrepancy, for example, material nonlinearity, geometric nonlinearity, or subcritical crack advance. The results of this investigation may be used to choose a new test geometry, for example to eliminate geometric nonlinearities, or to choose a definition of critical load that is different from P_{Max}, for example in the case of subcritical crack advance.

6.6 A precracking method that only produces a short crack "jump," for example, by positioning a specimen with a crack tip close to the center loading roller, may produce precracked toughness values that are significantly higher than those that will be produced for a long crack jump following the recommended procedure **(2, 3)**.

6.7 The toughness measured using this method is sensitive to reinforcement volume and void content. Consequently, the test results may reflect manufacturing quality as much as material properties.

6.8 *Number of Points for CC*—The use of a three-point CC was studied extensively in References **(2, 4)** and resulted in the recommended approach (11.9). However, equivalent results will be obtained with a five-point CC, and one may use this approach following Note 4 (11.9).

6.9 The toughness values obtained by this test method for delamination growth at 0°/0° interfaces may not be representative of the toughness required for delamination growth at interfaces with different relative ply orientations.

7. Apparatus

7.1 *Testing Machine*—A properly calibrated test machine shall be used which can be operated in a displacement control mode with a constant displacement rate in the range from 0.025 to 1.6 mm/min [0.001 to 0.063 in./min]. The testing machine will conform to the requirements of Practices E4.

7.2 The testing machine shall be equipped with a loading fixture as shown in Fig. 1 and Fig. 2.

7.2.1 A fixture geometry with a nominal specimen span length (*2L*) of 100 mm [4 in.] and a nominal half-span length (*L*) of 50 mm [2 in.] is required.

7.2.2 The cylindrical loading surface shall have a radius, r_1, in the range of 4.7 to 9.6 mm [0.185 to 0.378 in.]. The cylindrical supporting surfaces shall have the same radius, r_2, which shall be in the range of 3.0 to 6.4 mm [0.118 to 0.250 in.]. The loading surface shall be centered between the two supporting surfaces (Fig. 2). All load and support surfaces shall be finely ground and free of indentation and burrs with all sharp edges relieved, with a hardness of 55 HRC or greater. Loading and support surfaces may be arranged in a fixed, rotatable, or rolling arrangement, where rotation may occur only about the cylindrical surfaces' center points as viewed in the orientation of Fig. 1 and Fig. 2. All other movement of the supporting surfaces shall be restrained, and loading surface shall only be free to move vertically when viewed in the orientation of Fig. 1 and Fig. 2 (that is, perpendicular to the plane of the specimen).

7.2.3 The system compliance, defined as the compliance of the load frame with the test fixture installed, shall be less than 3 % of the measured compliance of the specimens that are tested. The system compliance shall be determined by using an essentially rigid calibration bar with the ENF test fixture and a span length (*2L*) of 100 mm [4.0 in.]. It is recommended that the calibration bar is at least as stiff as a steel bar with a moment of inertia, *I*, equal to 6 cm^4 [0.144 in.^{4}]. When this is the case, the system compliance can be determined as the slope of the deflection versus force data from the test of the calibration bar in the ENF fixture. For calibration bars with a lower moment of inertia, the bar's compliance should be accounted for. Here, the system compliance may be computed as the slope of the deflection versus force data from the test of

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the calibration bar minus the compliance of the calibration bar, defined as $L^3/(6EI)$, where L is the half-span length and E and I are the Young's modulus and moment of inertia, respectively, of the calibration bar. The system compliance shall then be compared to the minimum compliance from all specimens tested to ensure that the 3 % requirement is met. It is recommended that the system compliance tests be performed with a nominal loading rate of 0.05 mm/min [0.002 in./min], but rates in the range of 0.02 to 0.08 mm/min [0.0008 to 0.003 in./min] are acceptable.

7.2.4 The fixture cannot have rotational bearings that allow rotation about an axis parallel to the length direction of the specimen.

7.2.5 It is recommended that the test fixture be equipped with alignment features to ensure that *(1)* the loading and support rollers are parallel, and *(2)* the longitudinal direction of the specimen is perpendicular to the roller direction **(3)**.

7.3 *Force Indicator*—The testing machine's force-sensing device shall be capable of indicating the total force carried by the test specimen. This device shall be essentially free from inertia-lag at the specified rate of testing and shall indicate the force with an accuracy over the force range(s) of interest of within ±1 % of the indicated value. Forces are dependent on the specimen geometry and toughness. A method to calculate the expected forces can be found in Annex A1.

7.4 *Load Point Displacement Indicator*—The load point displacement may be obtained from the crosshead separation of the load frame provided that the compliance requirement of 7.2.3 is satisfied. Otherwise, the load point displacement shall be taken from a properly calibrated external gauge or transducer or a stiffer test fixture, or both, or load frame should be used, or both. The load point displacement indicator shall indicate the load point displacement with an accuracy of ±1 % at the displacement at which delamination growth occurs.

7.5 *Force versus Load Point Displacement Record*—A digital record of force versus load point displacement shall be stored for subsequent post-processing.

7.6 *Micrometers and Calipers*—A micrometer with a 4 to 7 mm [0.16 to 0.28 in.] nominal diameter ball interface or a flat anvil interface shall be used to measure the specimen thickness. A ball interface is recommended for thickness measurements when at least one surface is irregular (for example, a course peel ply surface, which is neither smooth nor flat). A micrometer or caliper with a flat anvil interface shall be used for measuring length, width, and other machined surface dimensions. The use of alternative measurement devices is permitted if specified (or agreed to) by the test requestor and reported by the testing laboratory. The accuracy of the instrument(s) shall be suitable for reading to within 1 % of the specimen dimensions. For typical specimen geometries, an instrument with an accuracy of ±0.0025 mm [±0.0001 in.] is adequate for thickness measurements, while an instrument with an accuracy of ±0.025 mm [±0.001 in.] is adequate for measurement of length, width, and other machined surface dimensions.

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 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 *Specimen and Test Configuration*—Test laminates must contain an even number of plies and must be unidirectional, with delamination growth occurring in the 0° (zero degree) direction. Specimen dimensions shall conform to those presented in Fig. 3 and Fig. 4, which are chosen such that placement of the specimen within the fixture will be as defined in Table 1 and Fig. 2.

8.3 *Manufacturing:*

8.3.1 A flat composite plate shall be manufactured with a preimplanted non-adhesive film insert. Specimens are to be cut from these plates as shown in Fig. 3 and Fig. 4. Fabrication and machining are to be performed following Guide D5687/D5687M.

8.3.2 A non-adhesive film insert shall be implanted at the midplane of the laminate during layup to form an initiation site for the delamination (Fig. 3 and Fig. 4). The film thickness shall be no greater than 13 µm [0.0005 in.]. A polymer film is recommended for the insert to avoid problems with folding or crimping at the cut end of the insert. For epoxy matrix composites cured at or below 177 °C [350 °F], a thin film made of polytetrafluoroethylene (PTFE) is recommended. For composites with polyimide, bismaleimide, or thermoplastic matrices that are manufactured at relatively high temperatures, that is, greater than 177 °C [350 °F], a thin polyimide film is recommended. If a polyimide film is used, the film shall be painted or sprayed with a mold release agent before it is inserted in the laminate. Caution should be used, as mold release agents containing silicone may contaminate the laminate by migration through the individual layers. It is often helpful to coat the film at least once and then bake the film before placing the film on the composite. This will help to prevent silicone migration within the composite. It also is often necessary to decohere the light bond that might form between the insert and the composite **(2)**. For materials outside the scope of this standard, different film materials and procedures may be required.

8.3.3 The plate shall be made in such a way that the specimen dimensions presented in Fig. 3 and Fig. 4 may be achieved. Manufacturing large panels with a full-width insert in the center of the length direction is recommended to prevent thickness variations in the test specimens. After manufacture, these panels are cut width-wise along the centerline of the insert to create two plates, each with an edge view as shown in Fig. 3 and Fig. 4. A typical panel would be 400 mm [16 in.] long in the 0° direction with a 100 mm [4 in.] insert. Depending on the saw blade and amount trimmed at the edges, this will yield two plates that are approximately 200 mm [8 in.] long with an initial insert length (a_i) of approximately 50 mm [2 in.].

8.3.4 Prior to cutting the plate into specimens, the end of the insert should be accurately located and marked, and markings

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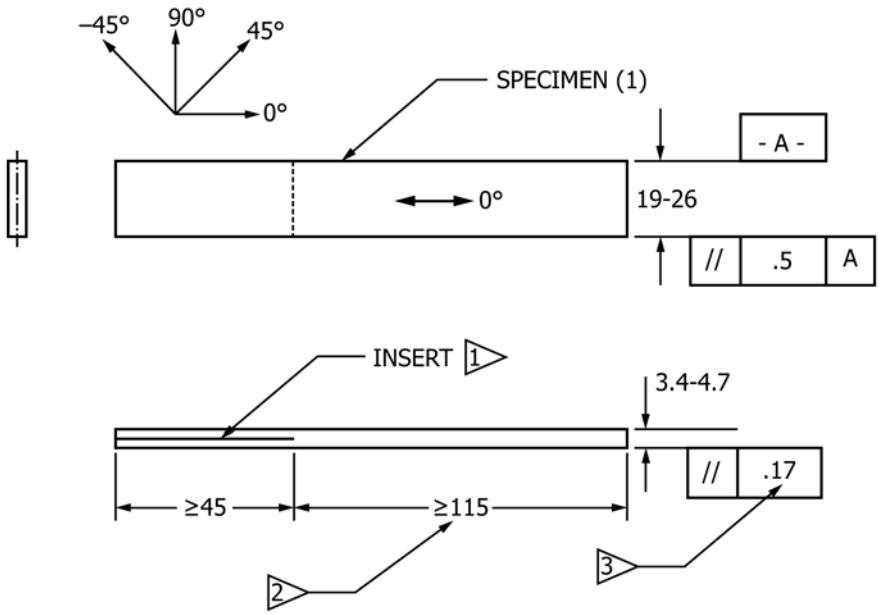

FIG. 3 Specimen—ENF Test (SI Units)

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should be placed on the plate such that location of each specimen relative to the original plate geometry will be identifiable subsequent to cutting.

8.3.5 Individual specimens are to be cut such that they fall within the range of allowable lengths and widths specified in Fig. 3 and Fig. 4.

8.3.6 Subsequent to cutting, measure the width, *B*, at the three points of each specimen that will correspond to the contact locations of the three rollers when the specimen is tested in the non-precracked configuration. Measure the thickness, *2h*, of each specimen at six points, with two thickness measurements at each of the points where the width was measured; one on the left side and one on the right side. The individual and average values of the three width measurements and the six thickness measurements shall be recorded. The variation in specimen width among all measurements shall not exceed 0.5 mm [0.02 in.], and the variation in specimen thickness shall not exceed 5 % of the mean value.

8.4 *Labeling*—Label the specimens so that they will be distinct from each other and traceable back to the raw material, and in a manner that will both be unaffected by the test and not influence the test.

8.5 *Void Content*—It is recommended that void content and fiber volume be reported. Void content may be determined using Test Methods D2734 and fiber volume fraction may be determined using Test Methods D3171.

9. Calibration

9.1 The accuracy of all measuring equipment shall have certified calibrations that are current at the time of use of the equipment.

10. Conditioning

10.1 The recommended pre-test condition is effective moisture equilibrium at a specific relative humidity as established by Test Method D5229/D5229M; however, if the test requestor does not explicitly specify a pre-test conditioning environment, no conditioning is required and the test specimens may be tested as prepared.

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

NOTE 2—The term "moisture," as used in Test Method D5229/D5229M, includes not only the vapor of a liquid and its condensate, but the liquid itself in large quantities, as for immersion.

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

11. Procedure

11.1 *Parameters to be Specified Prior to Test:*

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