Designation: E1922/E1922M – 22

Standard Test Method for Translaminar Fracture Toughness of Laminated and Pultruded Polymer Matrix Composite Materials[1]

This standard is issued under the fixed designation E1922/E1922M; 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 covers the determination of translaminar fracture toughness, K_{TL}, for laminated, molded, or pultruded polymer matrix composite materials of various fiber orientations using test results from monotonically loaded notched specimens. If the material response is such that the K_{TL} calculation is not valid, alternate reporting methods are provided.

1.2 This test method is applicable to room temperature laboratory air environments.

1.3 Composite materials that can be tested by this test method are not limited by thickness or by type of polymer matrix or fiber, provided that the specimen sizes and the test results meet the requirements of this test method. This test method was developed primarily from test results of various carbon fiber – epoxy matrix laminates and from additional results of glass fiber – epoxy matrix, glass fiber-polyester matrix pultrusions and carbon fiber – bismaleimide matrix laminates (**1-4**, **5**, **6**).[2]

1.4 A range of eccentrically loaded, single-edge-notch tension, ESE(T), specimen sizes with proportional planar dimensions is provided, but planar size may be variable and adjusted, with associated changes in the applied test load. Specimen thickness is a variable, independent of planar size.

1.5 Specimen configurations other than those contained in this test method may be used. It is particularly important that the requirements discussed in 5.1 and 5.4 regarding contained notch-tip damage be met when using alternative specimen configurations in conjunction with the K_{TL} calculation.

1.6 *Units*—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.

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

1.7 *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.*

1.8 *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:*[3]

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

D883 Terminology Relating to Plastics

D3039/D3039M Test Method for Tensile Properties of Polymer Matrix Composite Materials

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

D5528/D5528M Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites

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

E4 Practices for Force Calibration and Verification of Testing Machines

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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 D30.05 on Structural Test Methods.

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

[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.

E6 Terminology Relating to Methods of Mechanical Testing
E83 Practice for Verification and Classification of Extensometer Systems
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
E399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness of Metallic Materials
E456 Terminology Relating to Quality and Statistics
E1823 Terminology Relating to Fatigue and Fracture Testing

3. Terminology

3.1 *Definitions:*

3.1.1 Terminology D3878 defines terms relating to composite materials. Terminology D883 defines terms relating to plastics. Terminology E6 defines terms relating to mechanical testing. Terminology E1823 defines terms relating to fracture testing. Terminology E456 and Practice E177 define terms relating to statistics. In the event of a conflict between terms, Terminology D3878 shall have precedence over the other standards.

3.2 *Definitions of Terms Specific to This Standard:*

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

3.2.2 *normalized notch size [nd], n*—the ratio of notch length, a_n, to specimen width, *W*.

3.2.3 *notch-mouth displacement [L], n*—the Mode I (also called opening mode) component of crack or notch displacement due to elastic and permanent deformation. The displacement is measured across the mouth of the notch on the specimen edge (see Fig. 1).

3.2.4 *notch length [L], n*—the distance from a reference plane to the front of the machined notch. The reference plane depends on the specimen form, and normally is taken to be either the boundary, or a plane containing either the load line or the centerline of a specimen or plate. The reference plane is defined prior to specimen deformation (see Fig. 2).

3.2.5 For additional information, see Terminology D883 and Test Methods D3039/D3039M, D5229/D5229M, and D5528/D5528M.

3.3 *Symbols:*

a_n—notch length

B—specimen thickness

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

K—applied stress intensity factor

K_{TL}—translaminar fracture toughness

P—applied force

P_{max}—maximum applied force achieved during test

S_{n-1}—standard deviation statistic of a sample population for a given property

V_n—notch-mouth displacement

W—specimen width

x_{i}—test result for an individual specimen from the sample population for a given property

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

α—normalized notch size

4. Summary of Test Method

4.1 This test method involves tension testing of eccentrically loaded, single-edge-notch, ESE(T), specimens in opening mode loading. Force versus displacement across the notch at the specimen edge, V_n, is recorded. The force corresponding to a prescribed increase in normalized notch length is determined, using the force-displacement record. The translaminar fracture toughness, K_{TL}, is calculated from this force using equations that have been established on the basis of elastic stress analysis of the modified single-edge notched specimen. When the assumptions upon which the K_{TL} calculation is based are violated, results are instead reported in terms of applied force/width, geometry, and observed distributed damage.

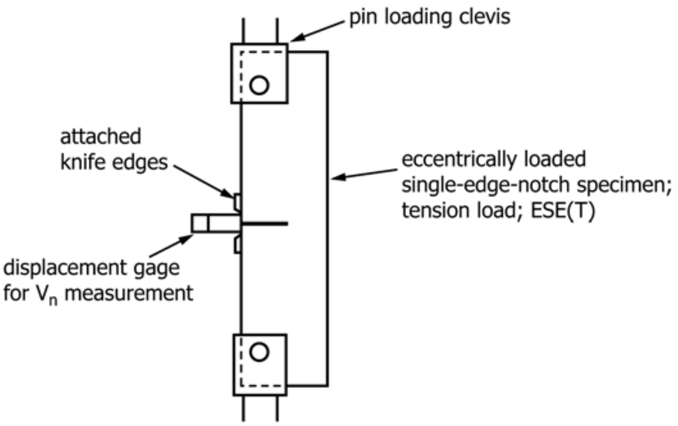
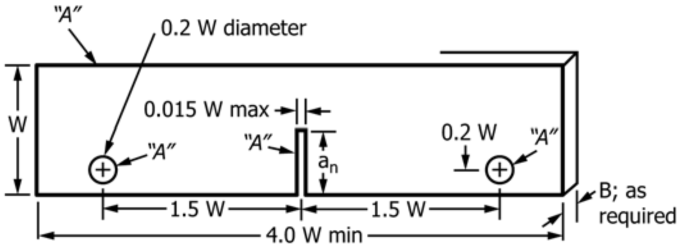


FIG. 1 Test Arrangement for Translaminar Fracture Toughness Tests



NOTE 1—All dimensions +/– 0.01 *W*, except as noted.

NOTE 2—All surfaces perpendicular and parallel as applicable within 0.01 *W*.

FIG. 2 Translaminar Fracture Toughness Test Specimen

4.2 The validity of translaminar fracture toughness, K_{TL}, determined by this test method depends on maintaining a relatively contained area of damage at the notch tip. To maintain this suitable notch-tip condition, the allowed increase in notch-mouth displacement near the maximum force point of the tests is limited to a small value. Small increases in notch-mouth displacement are more likely for relatively thick samples and for samples with a significant proportion of the near surface reinforcing fibers aligned parallel to the direction of the notch, or inherently brittle material response, or both.

4.3 For material response in which the damage is not limited to the local crack tip region, this test method results in a structural failure response that is strongly dependent on specimen geometric details (in addition to length, width, and notch geometry) such as fiber orientations, stacking sequence if laminated, weave architecture if woven, manufacturing process if liquid-molded or containing discontinuous fibers, etc. In these cases, the relevant reported data is not K_{TL} but rather then global observed structural response of the coupon, for example, the force-displacement history as a function of observed damage events (crack branching, delaminations, local fiber failures, etc).

5. Significance and Use

5.1 The parameter K_{TL} determined by this test method is a measure of the resistance of a polymer matrix composite laminate to notch-tip damage and effective translaminar crack growth under opening mode loading. The result is valid only for conditions in which the damage zone at the notch tip is small compared with the notch length and the in-plane specimen dimensions. Alternately, for materials exhibiting distributed damage in a larger volume, observed force-displacement and discrete damage events are still valid structural responses for certain specific engineering applications.

5.2 This test method can serve the following purposes. In research and development, (*a*) K_{TL} data can quantitatively establish the effects of fiber and matrix variables and stacking sequence of the laminate on the translaminar fracture resistance of composite laminates; and (*b*) quantified distributed damage measurements can be used to validate progressive composite damage models. In structural design, K_{TL} data can, within the constraints of the specimen geometry and loading, be used to assess composite laminate resistance to damage growth from edge flaws and notches.

5.3 The translaminar fracture toughness, K_{TL}, as well as distributed damage observations, determined by this test method may be a function of the testing speed and temperature. This test method is intended for room temperature and quasi-static conditions, but it can apply to other test conditions provided that the requirements of 13.2 and 13.3 are met. Application of K_{TL} in the design of service components should be made with awareness that the test parameters specified by this test may differ from service conditions, possibly resulting in a different material response than that seen in service. Distributed damage observations are also limited to the material and geometry tested, but may be more generally applied to a variety of structural analysis validation applications.

5.4 Not all types of laminated polymer matrix composite materials experience the contained notch-tip damage and effective translaminar crack growth of concern in this test method. In such circumstances, the force-displacement and discrete damage observations – not K_{TL} – shall be used.

5.5 The reporting section requires items that tend to influence translaminar fracture toughness and discrete damage progression to be reported; these include the following: material, methods of material fabrication, accuracy of lay-up orientation, laminate stacking sequence and overall thickness, specimen geometry, specimen preparation, specimen conditioning, environment of testing, void content, volume percent reinforcement, size and method of notch preparation, specimen/fixture alignment, and speed of testing.

6. Interferences

6.1 *Material and Specimen Preparation*—Poor material fabrication practices, lack of control of fiber alignment, and damage induced by improper specimen machining are known causes of high material data scatter in composites in general. Important aspects of specimen preparation that contribute to data scatter include thickness variation, out-of-plane curvature, surface roughness, and failure to meet the dimensional and squareness tolerances (parallelism and perpendicularity) specified in 8.2.2.

6.2 *Notch Preparation*—Because of the dominating presence of the notch, results from this test method are relatively insensitive to parameters that would be of concern in an unnotched tensile property test. However, since the notch dominates the response, consistent preparation of the notch is important to meaningful results. Damage caused by notch preparation can affect the calculated translaminar fracture toughness.

6.3 *Geometry*—Results are affected by the ratio of notch length to specimen width, as well as the ratio of notch width to specimen width. The ratios should be maintained as specified in 8.1, unless the experiment is investigating the influence of these ratios.

6.4 *Material Behavior*—The inherent damage progression from the relatively blunt machined notch in this test specimen design determines whether or not the K_{TL} calculation is valid. It is the joint responsibility of the test requester and test operator to determine the validity of the calculated fracture toughness value and report the final data in an appropriate manner.

6.5 *System Alignment*—Errors can result if the test fixture is not centered with respect to the loading axis of the test machine.

7. Apparatus

7.1 *Micrometers and Calipers*—A micrometer with a 4 to 8 mm [0.16 to 0.32 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 coarse 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, other machined surface dimensions.

7.2 *Test Fixture*—Pin-loading clevises of the type used in Test Method E399 shall be used to apply force to the specimen. A typical arrangement is shown in Fig. 1.

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

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

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

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

7.4 *Displacement Gage*—A displacement gage shall be used to measure the displacement at the notch mouth during loading. An electronic displacement gage of the type described in Test Method E399 can provide a highly sensitive indicator of notch-mouth displacement for this purpose. The gage is attached to the specimen using knife edges affixed to the specimen or integral knife edges machined into the specimen. Integral knife edges may not be suitable for relatively low strength materials. Other types of gages and attachments may be used if it can be demonstrated that they will accomplish the same result. The accuracies of the displacement measuring and recording devices should be such that the displacement can be determined with an accuracy of ±1 %. (For additional information, see Practice E83.)

7.5 *Full-Field Strain Measurement Equipment*—For quantification of distributed discrete damage events remote from the notch tip, full field strain measurement methods such a Digital Image Correlation (DIC), high-speed photography, Moire Fringe methods, etc. may be required. Required resolution of such methods are dependent on damage events being measured and shall be determined by the test requester for specific materials and specimen geometries.

7.6 *Data Acquisition Equipment*—Equipment capable of recording force and notch mouth displacement is required. Full-field strain measurement is optional.

8. Sampling and Test Specimens

8.1 *Sampling*—It is required that enough tests be performed to obtain three valid replicate test results for each material condition. If material variations are expected, five tests are required. For statistically significant data, the procedures outlined in Practice E122 should be consulted. The method of sampling shall be reported.

8.2 *Geometry:*

8.2.1 *Stacking Sequence*—The specimen shall have multidirectional fiber orientations (fibers oriented in a minimum of two directions), with the 0° fiber orientation aligned with the lengthwise (long) dimension. A thickness as small as 2 mm has been found to work well. However, too small a thickness can cause out-of-plane buckling, which invalidates the test. The 0° fiber orientation of the specimen before testing shall be aligned to within 2° of the intended loading axis. For example, a K_{TL} test of a $[0/90]_{5S}$ laminate would involve the testing of a 20 ply specimen with the fibers in the 0° plies aligned within 2° of the loading axis of the specimen.

8.2.2 *Specimen Configuration*—The required test and specimen configurations are shown in Fig. 1 and Fig. 2. The notch length, a_n, shall be between 0.5 and 0.6 times the specimen width, W. The notch width shall be 0.015 W or thinner (see Fig. 2). The specimen thickness, B, is the full thickness of the composite material to be tested. The specimen width is selected by the user. A value of W between 25 and 50 mm has been found to work well. Other specimen dimensions are based on specimen width.

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

8.3.1 *Panel Fabrication*—Control of fiber alignment is critical. Improper fiber alignment will reduce the measured properties. The panel must be flat and of uniform thickness to assure even loading. Erratic fiber alignment will also increase the coefficient of variation. Report the panel fabrication method.

8.3.2 *Machining Methods*—Specimen preparation is extremely important for this specimen. Take precautions when cutting specimens from large panels to avoid nicks, undercuts, rough or uneven surfaces, or delaminations due to inappropriate machining methods. Obtain final dimensions by water-lubricated precision sawing, milling, or grinding. The use of diamond-tipped tooling (as well as water-jet cutting) has been found to be extremely effective for many material systems. Edges should be flat and parallel within the specified tolerances. Holes should be drilled undersized and reamed to final dimensions. Take special care to ensure that creation of the pin holes does not delaminate or otherwise damage the material surrounding the holes. The dimensional tolerances shown in Fig. 2 shall be followed in the specimen preparation. Record and report the specimen machining methods.

8.3.3 *Notch Preparation*—The notch can be prepared using any process that produces the required narrow slit. Prior tests (**1, 2**) show that a notch width less than 0.015 W gives consistent results regardless of notch tip profile. A diamond impregnated copper slitting saw or a jewelers saw have been found to work well. Use caution to prevent splitting or delamination of the surface plies near the notch tip. Record and report the notch preparation method.

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

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

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 1—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 type and geometry, and conditioning travelers (if required).

11.1.2 The translaminar fracture properties, discrete damage types to be monitored, and data reporting format desired.

NOTE 2—Determine specific material property, accuracy, and data reporting requirements prior to test for proper selection of instrumentation and data recording equipment. Estimate the specimen response to aid in transducer selection, calibration of equipment, and determination of equipment settings.

11.1.3 The environmental conditioning test parameters.

11.1.4 Test displacement rate, in terms for displacement per time.

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

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

11.3 *Specimen Measurement*—Three specimen measurements are necessary to calculate applied K: notch length, a_n; thickness, B; and width, W. Complete separation of the specimen into two pieces often occurs during a test, so it is required that the specimen measurements be done prior to testing. Also, exercise care to prevent injury to test personnel. Record the dimensions to three significant figures.

11.3.1 Measure the notch length, a_n, to the nearest 0.1 mm [0.004 in.] on each side of the specimen. Use the average of the two notch length measurements in the calculations of applied K.

11.3.2 Measure the thickness, B, to the nearest 0.002 W, at no fewer than three equally spaced positions around the notch. Record the average of the three measurements as B for that specimen.

11.3.3 Measure the width, W, to the nearest 0.05 mm [0.002 in.].

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

NOTE 3—The test requester may request that additional measurements be performed after the machined specimens have gone through any conditioning or environmental exposure.

11.5 *Speed of Testing*—Set the speed of testing such that the time from zero to peak force is between 30 and 100 s.

11.6 *Specimen and Instrumentation Installation*—Install the specimen into the test fixture as shown in Fig. 1, with the displacement gage located at the notch mouth on the edge of the specimen and, if required, additional full-field strain measurement instruments.

11.7 *Loading*—Apply tensile force to the specimen/fixture assembly at the specified displacement rate while recording