Designation: E 1922 – 97

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

This standard is issued under the fixed designation E 1922; 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 polymer matrix composite materials of various ply orientations using test results from monotonically loaded notched specimens.

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 and carbon fiber – bismaleimide matrix laminates **(1-4)**.[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, provided that stress intensity calibrations are available and that the test results meet the requirements of this test method. 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.

1.6 Values stated in SI units are to be regarded as the standard.

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

2. Referenced Documents

2.1 *ASTM Standards:*

D 883 Terminology Relating to Plastics[3]
D 3039 Test Method for Tensile Properties of Polymer Matrix Composite Materials[4]
D 3878 Terminology of High-Modulus Reinforcing Fibers and their Composites[4]
D 5229 Test Method for Moisture Adsorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials[4]
D 5528 Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites[4]
E 4 Practices for Force Verification of Testing Machines[5]
E 6 Terminology Relating to Methods of Mechanical Testing[5]
E 83 Practice for Verification and Classification of Extensometers[5]
E 399 Test Method for Plane-Strain Fracture Toughness of Metallic Materials[5]
E 1681 Test Method for Determining a Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials Under Constant Load[5]
E 1823 Terminology Relating to Fatigue and Fracture Testing[5]

3. Terminology

3.1 *Definitions:*

3.1.1 Terminology E 6, E 1823, and D 3878 are applicable to this test method.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *notch-mouth displacement, V_n [L]*—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 surface (see Fig. 1).

3.2.2 *notch length, a_n [L]*—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).
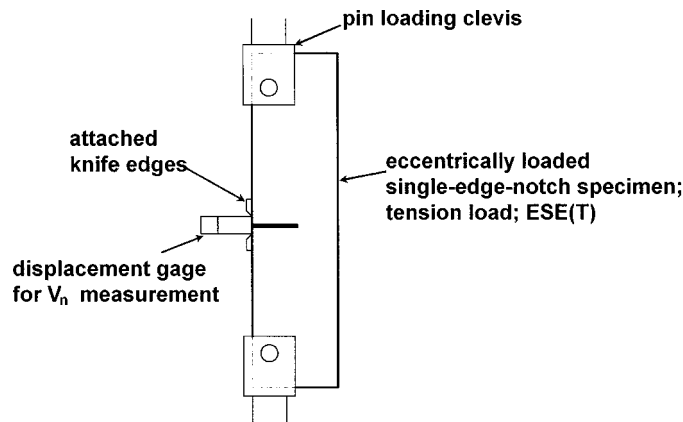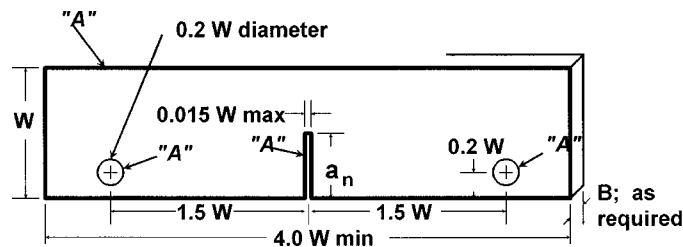

FIG. 1 Test Arrangement for Translaminar Fracture Toughness Tests

Note 1—All dimensions +/– 0.01 *W*, except as noted.
Note 2—A surfaces perpendicular and parallel as applicable within 0.01 *W*.

FIG. 2 Translaminar Fracture Toughness Test Specimen

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

3.2.4 For additional information, see Terminology D 883 and Test Methods D 3039, D 5229, and D 5528.

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. Load versus displacement across the notch at the specimen edge, V_n, is recorded. The load corresponding to a prescribed increase in normalized notch length is determined, using the load-displacement record. The translaminar fracture toughness, K_{TL}, is calculated from this load using equations that have been established on the basis of elastic stress analysis of the modified single-edge notched 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 load 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.

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.

5.2 This test method can serve the following purposes. In research and development, 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. In acceptance and quality control specifications, K_{TL} data can be used to establish criteria for material processing and component inspection.

5.3 The translaminar fracture toughness, K_{TL}, 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 9.2 and 9.3 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.

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. For example, the notch-tip damage may be more extensive and may not be accompanied by any significant amount of effective translaminar crack growth. Typically, lower strength composite materials and those with a significant proportion of reinforcing fibers aligned in a direction perpendicular to the notch axis may not experience the contained

notch-tip damage required for a valid test.

6. Apparatus

6.1 *Loading*—Specimens shall be loaded in a testing machine that has provision for simultaneous recording of the load applied to the specimen and the resulting notch-mouth displacement. A typical arrangement is shown in Fig. 1. Pin-loading clevises of the type used in Test Method E 399 are used to apply the load to the specimen. The accuracies of the load measuring and recording devices should be such that load can be determined with an accuracy of ±1 %. (For additional information see Practices E 4).

6.2 *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 E 399 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 E 83).

7. Specimen Configuration and Preparation

7.1 *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. 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 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.

7.2 *Specimen Orientation*—The load axis of the specimen before testing shall be aligned to within 2° with the intended laminate test direction. For example, a K_{TL} test of a $[0/90]_{5S}$ laminate would involve the testing of a twenty ply specimen with the fibers in the 0° plies aligned within 2° with the load axis of the specimen.

7.3 *Specimen Preparation*—The dimensional tolerances shown in Fig. 2 shall be followed in the specimen 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.

8. Procedure

8.1 *Number of Tests*—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.

8.2 *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.

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

8.2.2 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. Composite fabrication methods result in variations in specimen thickness, due to differences in volume fraction of matrix material. Therefore, the nominal average thickness calculated from the individual thickness of all the specimens tested from a given component shall be used in the calculation of applied *K*.

8.2.3 Measure the width, *W*, to the nearest 0.05 mm.

8.3 *Loading Rate*—Load the specimen at a rate such that the time from zero to peak load is between 30 and 100 s.

8.4 *Test Record*—Make a plot of load versus the output of the displacement gage. Choose plotting scales so that the slope of the initial linear portion of the record is between 0.7 and 1.5. Continue the test until the load has reached a peak and dropped to 50 % of the peak value.

9. Calculation or Interpretation of Results

9.1 *Calculation of Applied Stress Intensity Factor, K*—Calculate the applied *K* for the ESE(T) specimen from the following expression (**4, 5**);

$$K = [P/BW^{1/2}] \, \alpha^{1/2} \, [1.4 + \alpha] \, [3.97 - 10.88 \, \alpha + 26.25 \, \alpha^2 - 38.9 \, \alpha^3 + 30.15 \, \alpha^4 - 9.27 \, \alpha^5] / [1 - \alpha]^{3/2} \quad (1)$$

where:
K = applied stress intensity factor, MPa m$^{1/2}$,
P = applied load, MN,
α = a/W (dimensionless),
a_n = notch length as determined in 8.2.1, m,
B = specimen thickness as determined in 8.2.2, m,
W = specimen width as determined in 8.2.3, m,

and the expression is valid for $0 \leq \alpha \leq 1$, for isotropic materials and for a wide range of laminates (**1**).

9.2 *Validity Criteria for K_{TL}*—Translaminar fracture tests of carbon fiber/ polymer matrix laminates (**1-4**) have shown that materials with a relatively small damage zone, required for consistent K_{TL} measurements, also display relatively small amounts of additional notch-mouth displacement, ΔV_n, during fracture. A typical load versus notch-mouth displacement plot for a laminate is shown in Fig. 3. For a variety of materials, the maximum applied *K* value determined from the maximum load during the test provides a consistent measure of translaminar fracture toughness when the notch-mouth displacement values at maximum load are within the following criterion (**4**):

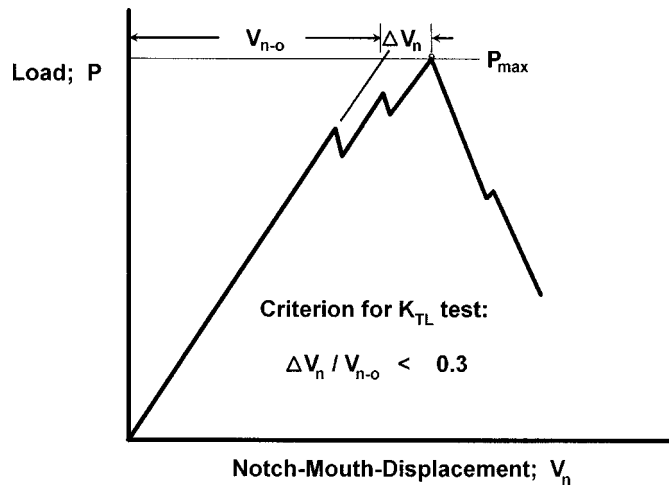$$\Delta V_n / V_{n-o} \leq 0.3 \quad (2)$$

FIG. 3 Typical Load Versus Notch-Mouth-Displacement Plot

where:

V_{n-o} = V_n at $P = P_{max}$ on the extension of the initial linear portion of the plot (see Fig. 3), and

ΔV_n = the additional notch-mouth displacement up to the P_{max} point.

9.3 *Determination of K_{TL}*—To determine the translaminar fracture toughness, use the following procedure.

9.3.1 Determine the maximum applied K value, K_{max}, corresponding to the maximum load during the test, P_{max}, using the equation in 9.1.

9.3.2 Determine the values of ΔV_n and V_{n-o} from the load versus notch-mouth displacement plot, using the procedure shown in Fig. 3.

9.3.3

If: $\Delta V_n / V_{n-o} \leq 0.3$, then $K_{max} = K_{TL}$.

If: $\Delta V_n / V_{n-o} > 0.3$, the extent of damage around the notch may be too large and it is not possible to obtain a measure of K_{TL}.

10. Report

10.1 Report the following information for each specimen tested:

10.1.1 The principal dimensions of the specimen, including thickness, width, and notch depth,

10.1.2 Descriptions of the test equipment and procedures, including testing machine, rate of loading, and displacement gages,

10.1.3 Description of the tested material, including the type of fiber and matrix and the ply sequence of the laminate,

10.1.4 The temperature and relative humidity at the time of the test and the relative humidity of the storage environment for the samples before the test,

10.1.5 Fracture appearance of the specimen following the test, including the extent and nature of damage and cracking on the outside surfaces of the specimen ahead of the notch, and

10.1.6 The translaminar fracture toughness, K_{TL}, determined as described in 9.3.

11. Precision and Bias

11.1 *Precision*—The precision of a K_{TL} determination is a function of the precision of the several specimen dimensions and the precision of the load and displacement measurements. In addition, significant variations in the K_{TL} value can result if the tested material is not homogeneous. It is difficult to assess the precision of the test with this number of variables. However, it is possible to derive useful information concerning the precision of a K_{TL} measurement from the results of an interlaboratory test program, (**4**), and from the results of other tests of various materials (**1-3**). In this program an attempt was made to choose homogeneous test material and test conditions that could be consistently achieved. The program, coordinated by ASTM Task Group E8.09.02, included eight replicate tests from two laboratories of 4.2 mm thick specimens of AS4/977-2 [90/-45/0/+45]$_{4S}$ carbon/epoxy laminates. The mean value of K_{TL} for the eight tests was 56.6 MPa m$^{1/2}$ with a standard deviation of 2.9 MPa m$^{1/2}$. Variations similar to those reported in (**4**) should be expected from future, closely controlled experiments.

11.2 *Bias*—There is no accepted standard value of K_{TL} for any material. In the absence of a fundamental value, no meaningful statement can be made concerning the bias of data.

REFERENCES

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(**3**) Underwood, J. H. and Kortschot, M. T., "Notch-Tip Damage and Translaminar Fracture Toughness Measurements from Carbon/Epoxy Laminates," *Proceedings of 2nd International Conference on Deformation and Fracture of Composites*, The Institute of Materials, London, 1993.

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