Designation: ~~D3518/D3518M – 94 (Reapproved 2007)~~ D3518/D3518M – 13

Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a ±45° Laminate[1]

This standard is issued under the fixed designation D3518/D3518M; 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.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This test method determines the in-plane shear response of polymer matrix composite materials reinforced by high-modulus fibers. The composite material form is limited to a continuous-fiber-reinforced composite ±45° laminate capable of being tension tested in the laminate ~~χ~~x direction.

~~1.2 *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.*~~

1.2 The values stated in either SI units or inch-pound units are to be regarded separately as standard. Within the text the inch-pound units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system must be used independently of the other. Combining values from the two systems may result in nonconformance with the standard.

1.3 *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:*[2]

D883 Terminology Relating to Plastics
D3039/D3039M Test Method for Tensile Properties of Polymer Matrix Composite Materials
D3878 Terminology for Composite Materials
D5229/D5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials
E6 Terminology Relating to Methods of Mechanical Testing
E111 Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus
E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods
E456 Terminology Relating to Quality and Statistics
E1309 Guide for Identification of Fiber-Reinforced Polymer-Matrix Composite Materials in Databases
E1434 Guide for Recording Mechanical Test Data of Fiber-Reinforced Composite Materials in Databases
E1471 Guide for Identification of Fibers, Fillers, and Core Materials in Computerized Material Property Databases

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 standards.

3.2 *Definitions of Terms Specific to This Standard:*

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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 D30.04 on Lamina and Laminate Test Methods.

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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.

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, [Θ] for thermodynamic temperature, and [*nd*] for nondimensional 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.

3.2.1 *±45° laminate—in laminated composites*, a balanced, symmetric lay-up composed only of +45° plies and −45° plies. (See also *ply orientation*.)

3.2.2 *balanced, adj—in laminated composites*, having, for every off-axis ply oriented at +θ, another ply oriented at −θ that is of the same material system and form.

3.2.3 *lamina, n—pl. laminae, in laminated composites*, a single, thin, uniform layer that is the basic building block of a laminate. (Syn. *ply*).

3.2.4 *material coordinate system, n—in laminated composites*, a 123 Cartesian coordinate system describing the principle material coordinate system for a laminated material, where the 1-axis is aligned with the ply principal axis, as illustrated in Fig. 1. (See also *ply orientation, ply principal axis*, and *principal material coordinate system*.)

3.2.5 *nominal value, n*—a value, existing in name only, assigned to a measurable property for the purpose of convenient designation. Tolerances may be applied to a nominal value to define an acceptable range for the property.

3.2.6 *off-axis, adj—in laminated composites*, having a ply orientation that is neither 0 nor 90°.

3.2.7 *ply, n—in laminated composites*, synonym for *lamina*.

3.2.8 *ply orientation, n,* θ*—in laminated composites*, the angle between a reference direction and the ply principal axis. The angle is expressed in degrees, greater than −90° but less than or equal to +90°, and is shown as a positive quantity when taken from the reference direction to the ply principal axis, following the right-hand rule.

3.2.8.1 *Discussion*—The reference direction is usually related to a primary load-carrying direction.

3.2.9 *ply principal axis, n—in laminated composites*, the coordinate axis in the plane of each lamina that defines the ply orientation. (See also *ply orientation* and *material coordinate system*.)

3.2.9.1 *Discussion*—The ply principal axis will, in general, be different for each ply of a laminate. The angle that this axis makes relative to a reference axis is given by the ply orientation. The convention is to align the ply principal axis with the direction of maximum stiffness (for example, the fiber direction of unidirectional tape or the warp direction of fabric reinforced material).

3.2.10 *principal material coordinate system, n*—a coordinate system having axes that are normal to planes of symmetry within the material. (See also *material coordinate system*.)

3.2.10.1 *Discussion*—Common usage, at least for Cartesian coordinate systems (for example, 123 or *xyz*), aligns the first axis of the principal material coordinate system with the direction of highest property value; for elastic properties, the axis of greatest elastic modulus is aligned with the 1 or *x* axes.

3.2.11 *symmetric, adj—in laminated composites*, when the constituents, material form, and orientation for the plies located on one side of the laminate midplane are the mirror image of the plies on the other side of the midplane.

3.2.12 *transition region, n*—a strain region of a stress-strain or strain-strain curve over which a significant change in the slope of the curve occurs within a small strain range.

3.2.12.1 *Discussion*—Many filamentary composite materials exhibit a nonlinear stress/strain response during loading, such as seen in plots of either longitudinal stress versus longitudinal strain or transverse strain versus longitudinal strain. In certain cases, the nonlinear response may be conveniently approximated by a bilinear fit. There are varying physical reasons for the existence of a transition region. Common examples include matrix cracking under tensile loading and ply delamination.

3.3 *Symbols:*

3.3.1 *A*—cross-sectional area of a coupon.

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

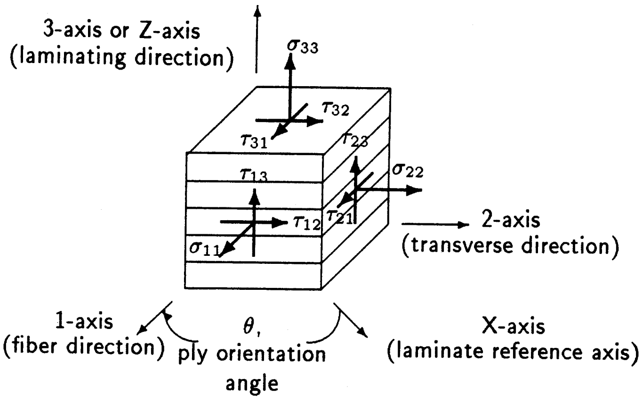


FIG. 1 Material Coordinate System

3.3.3 $F_{12}°$ *(offset)*—the value of the τ_{12} shear stress at the intersection of the shear chord modulus of elasticity and the ~~stress stress~~ stress-strain curve, when the modulus is offset along the engineering shear strain axis from the origin by the reported strain offset value.

3.3.4 G_{12}—in-plane shear modulus of elasticity.

3.3.4.1 *Discussion—*

Indices 1 and 2 indicate the fiber direction and transverse to the fiber direction in the plane of the ply, respectively, as illustrated in Fig. 2.

3.3.5 n—number of coupons per sample population.

3.3.6 P—~~load~~force carried by test coupon.

3.3.7 P^m—the ~~load~~force carried by test coupon that is the lesser of the (1) maximum ~~load~~force before failure or (2) ~~load~~force at 5 % engineering shear strain.

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

3.3.9 χ_i—test result for an individual coupon from the sample population for a given property.

3.3.10 x^{-}—mean or average (estimate of mean) of a sample population for a given property.

3.3.11 ε—general symbol for strain, whether normal strain or shear strain.

3.3.12 ε—indicated normal strain from strain transducer or extensometer.

3.3.13 τ_{12}—shear stress on the plane perpendicular to the 1-axis that acts parallel to the 2-axis.

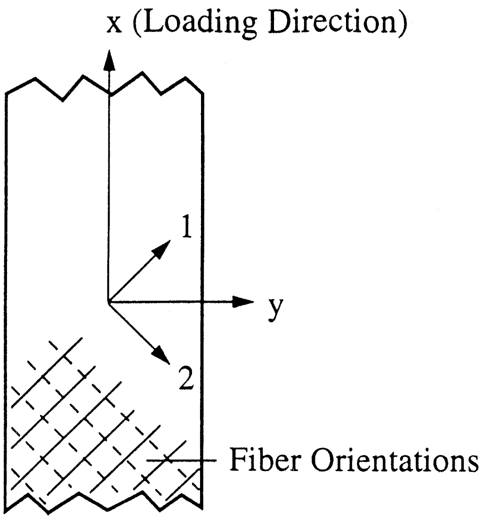
3.3.14 $\tau_{12}{}^m$—the calculated value of the τ_{12} shear stress taken at the lesser of (1) maximum shear stress before failure or (2) shear stress at 5 % engineering shear strain.

3.3.15 γ_{12}—engineering shear strain on the plane perpendicular to the 1-axis that acts parallel to the 2-axis.

3.3.16 $\gamma_{12}{}^m$—the value of the γ_{12} engineering shear strain at the maximum shear stress before failure, or 5 %, whichever is less.

4. Summary of Test Method

4.1 A uniaxial tension test of a ±45° laminate is performed in accordance with Test Method D3039/D3039M, although with specific restrictions on stacking sequence and thickness. Use of this test for evaluation of in-plane shear response was originally proposed by Petit[3] and was later improved by Rosen.[4] Using expressions derived from laminated plate theory, the in-plane shear



x and y represent the Specimen or Reference Axes, while
1 and 2 represent the Material or Local Axes

FIG. 2 Definition of Specimen and Material Axes

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[3] Petit, D. H., "A Simplified Method of Determining the In-plane Shear Stress/Strain Response of Unidirectional Composites," *Composite Materials: Testing and Design, ASTM STP 460*, American Society for Testing and Materials, 1969, pp. 83–93.

[4] Rosen, B. W., "A Simple Procedure for Experimental Determination of the Longitudinal Shear Modulus of Unidirectional Composites," *Journal of Composite Materials*, October 1972, pp. 552–554.

stress in the material coordinate system is directly calculated from the applied axial ~~load,~~force, and the related shear ~~stress~~strain is determined from longitudinal and transverse normal strain data obtained by transducers. This data is used to create an in-plane shear stress-shear strain curve.

5. Significance and Use

5.1 This test method is designed to produce in-plane shear property data for material specifications, research and development, quality assurance, and structural design and analysis. Factors that influence the shear response and should therefore be reported include the following: material, methods of material preparation and lay-up, specimen stacking sequence and overall thickness, specimen preparation, specimen conditioning, environment of testing, specimen alignment and gripping, speed of testing, time at temperature, void content, and volume percent reinforcement. Properties that may be derived from this test method include the following:

5.1.1 In-plane shear stress versus shear strain response,
5.1.2 In-plane shear chord modulus of elasticity,
5.1.3 Offset shear properties,
5.1.4 Maximum in-plane shear stress for a ±45° laminate, and
5.1.5 Maximum in-plane engineering shear strain for a ±45° laminate.

6. Interferences

6.1 *Impurity of Stress Field*—The material in the gage section of this specimen is not in a state of pure in-plane shear stress, as an in-plane normal stress component is present throughout the gage section and a complex stress field is present close to the free edges of the specimen. Although this test method is believed to provide reliable initial material response and can establish shear stress-shear strain response well into the nonlinear region, the calculated shear stress values at failure do not represent true material strength values and should only be used with caution. Despite attempts to minimize these effects, the shear stress at failure obtained from this test method, even for otherwise identical materials that differ only in cured ply thickness or fabric areal weight, may have differing failure modes and may not be able to be statistically pooled. The technical basis for the further discussion below is taken from the paper by Kellas et al.[5]

6.1.1 *Effects of In-Plane Normal Stress Field*—Of particular concern is the in-plane stress component normal to the fiber direction. This component of stress is present in all plies and throughout the gage section of the specimen. The effect of this stress on a given ply is minimized by the fiber reinforcement of the neighboring plies. Since the ply constraint is reduced with increasing ply thickness, the thickness of the individual plies is an important parameter that influences both the shear stress-shear strain response and the ultimate failure ~~load~~force of this specimen.[6] Moreover, the surface plies of a given specimen, being constrained by only one neighboring ply (as opposed to interior plies, which are constrained by a ply on each side), represent the weakest link in a ±45° specimen. During the tensile loading of this test coupon, the first ply failures consist primarily of normal stress (or mixed mode) failures, rather than pure shear failures. Because of this, the actual material shear strength cannot be obtained from this test. Except for the case of materials capable of sustaining large axial test coupon strains (greater than about 3.0 %), the shear stress at failure is believed to underestimate the actual material shear strength.

6.1.2 *Total Thickness Effects*—As a result of the failure processes discussed above, the shear stress-shear strain response at higher strain levels depends upon the total number of plies. As the total number of plies in the specimen configuration is increased, the relative contribution of the two weak surface plies to the total ~~load-carrying~~force-carrying capacity is decreased. After the surface plies of the laminate fail, their portion of the ~~load~~force is redistributed to the remainder of the intact plies. The higher the total number of plies, the greater the chance that the remaining plies will be able to carry the ~~load~~force without immediate ultimate failure of the coupon. However, with each successive ply matrix failure the number of remaining intact plies diminishes, to the point where the applied ~~load~~force can no longer be carried. Because of this process, higher ply count specimens tend to achieve higher failure ~~loads.~~forces. To minimize these effects, this test method requires the use of a homogeneous stacking sequence and requires a fixed number of plies, for which the only repeating plies are the two required for symmetry on opposite sides of the laminate mid plane.

6.1.3 *Effects of Large Deformation*—Note that extreme fiber scissoring can occur in this specimen for the cases of ductile matrices, weak fiber/matrix interfaces, thick specimens with a large number of repeated plies, or a combination of the above. Kellas et al suggest that a general rule of thumb for this specimen is that a fiber rotation of 1° takes place for every 2 % of axial strain (or every 3.5 % engineering shear strain for commonly tested materials). Such fiber scissoring, if left unbounded, would lead to an unacceptable violation of the assumption in this test method of a nominal ±45° laminate. This is the principal rationale for terminating this test at a large strain level, even if ~~load~~force is still increasing on the specimen. This test method terminates data reporting at 5 % calculated engineering shear strain; this limits fiber scissoring to about 1.5°, is approximately the limit of foil strain

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[5] Kellas, S., Morton, J., and Jackson, K. E., "Damage and Failure Mechanisms in Scaled Angled-Ply Laminates," *Fourth Composites Symposium on Fatigue and Fracture, ASTM STP 1156*, W. Stinchcomb and Ashbaugh, N. E., Eds., American Society for Testing and Materials, 1993, pp. 257–280.

[6] Repeating plies (adjacent plies at the same ply orientation) have an effect similar to thick plies, therefore, this test method prohibits constructions with repeating plies.

gage technology (if used), and is also well beyond the strain levels required for common engineering practice. Further details of the effects of stacking sequence, specimen geometry, and, in particular, specimen and ply thickness, are presented in the reference by Kellas et al.

6.1.4 *Effects of Edge Stresses*—Even though interlaminar stresses reach a maximum value near the free edges of this laminate, the effect of interlaminar stresses on the failure process of ±45° laminates is insignificant when compared to the effect of the normal stress component transverse to the fiber direction in the plane of the specimen. Therefore, the effect of specimen width is much less important than stacking sequence and specimen thickness effects.

6.1.5 *Effect of Axial Stress Nonuniformity*—Both the shear stress and the shear modulus calculations depend upon the uniformity of the applied axial stress. Since the average applied ~~load~~force is used to calculate the shear stress this will not necessarily correspond to the stress in the vicinity of the measured shear strain, unless the axial stress is uniform throughout the volume of the stressed material. Therefore, the greater the degree of material inhomogeneity, such as with coarsely woven fabrics or materials with significant resin-rich regions, the greater the potential for inaccuracies in the measured response.

6.2 *Other*—Additional sources of potential data scatter in testing of composite materials are described in Test Method D3039/D3039M.

7. Apparatus

7.1 Apparatus shall be in accordance with Test Method D3039/D3039M. However, this test method requires that ~~load-normal~~force-normal strain data be measured in both the longitudinal and transverse directions of the coupon.

8. Sampling and Test Specimens

8.1 *Sampling*—Sampling shall be in accordance with Test Method D3039/D3039M.

8.2 *Geometry*—The coupon geometry shall be in accordance with Test Method D3039/D3039M, as modified by the following:

8.2.1 The stacking sequence shall be $[45/-45]_{ns}$~~ns,~~, where $4 \leq n \leq 6$ for unidirectional tape (16, 20, or 24 plies) and $2 \leq n \leq 4$ for woven fabric (8, 12, or 16 plies). The recommended coupon width is 25 mm [1.0 in.], and the recommended coupon length range is 200 to 300 mm [8 to 12 in.], inclusive.

NOTE 2—Tabs, which are optional for the Test Method D3039/D3039M test coupon, are normally not required for successful conduct of this Practice.

8.3 *Specimen Preparation*—Specimen preparation shall be in accordance with Test Method D3039/D3039M.

9. Calibration

9.1 Calibration shall be in accordance with Test Method D3039/D3039M.

10. Conditioning

10.1 Conditioning shall be in accordance with Test Method D3039/D3039M.

11. Procedure

11.1 Perform a tension test on the ±45° laminate coupon in accordance with Test Method D3039/D3039M, with normal strain instrumentation in both longitudinal and transverse directions and continuous or nearly continuous ~~load-normal~~force-normal strain data recording. If ultimate failure does not occur within 5 % engineering shear strain, the data shall be truncated to the 5 % engineering shear strain mark (see 6.1.3 for the explanation). When the data is truncated, for the purpose of calculation and reporting, this 5 % engineering shear strain point shall be considered the maximum shear stress. Any truncation of data shall be noted in the report. Examples of typical shear stress-engineering shear strain plots are shown in Fig. 3 and Fig. 4.

12. Validation

12.1 Values for ultimate properties shall not be calculated for any specimen that breaks at some obvious flaw, unless such flaw constitutes a variable being studied. Retests shall be performed for any specimen on which values are not calculated.

12.2 A significant fraction of failures in a sample population exhibiting unacceptable failure modes shall be cause to reexamine the means of force introduction into the material. Factors considered should include the grip alignment, gaps between the grip and specimen, specimen thickness taper, and uneven machining.

13. Calculation

13.1 *Maximum Shear Stress/Shear Stress*— Calculate the maximum in-plane shear stress for the ±45° laminate using Eq 1 and report the results to three significant figures. If the shear modulus is to be calculated, determine the shear stress at each required data point using Eq 2.

$$\tau_{12}{}^{m} = \frac{P^{m}}{2A} \tag{1}$$

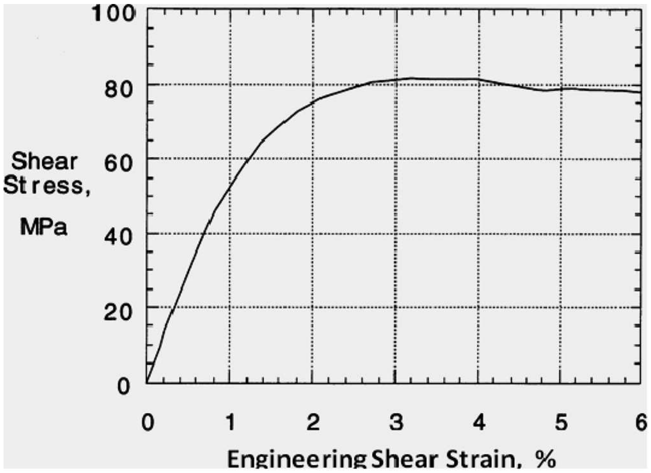

FIG. 43 Typical Shear Stress-Shear Strain Curve for PMC with Low-Ductility Matrix

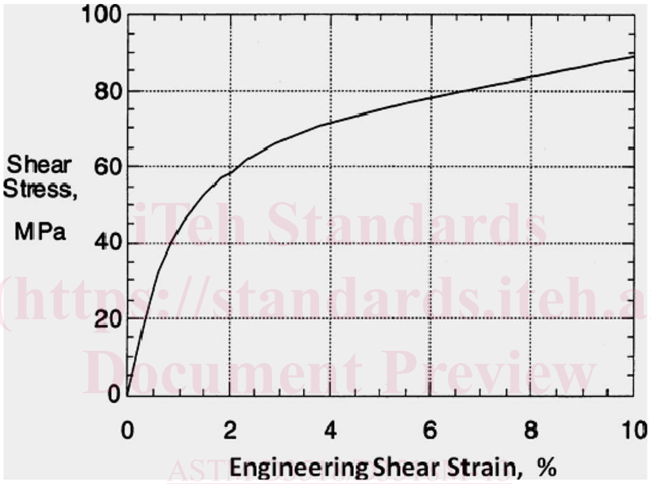

FIG. 54 Typical Shear Stress-Shear Strain Curve for PMC with Ductile Matrix

$$\tau_{12i} = \frac{P_i}{2A} \tag{2}$$

where:

$\tau_{12}{}^m$ = maximum in-plane shear stress, MPa [psi];
~~P^m = maximum load at or below 5 % shear strain, N [lbf];~~
P^m = maximum force at or below 5 % engineering shear strain, N [lbf];
τ_{12_i} = shear stress at *i*-th data point, MPa [psi];
~~P_i = load at *i*-th data point, N [lfb]; and~~
P_i = force at *i*-th data point, N [lbf]; and
A = cross-sectional area in accordance with Test Method D3039/D3039M, mm^2 [in.^{2}].

13.2 *Shear Strain/Maximum Shear Strain*— If shear modulus or maximum engineering shear strain is to be calculated, determine the engineering shear strain at each required data point using Eq 3. The maximum engineering shear strain is determined from Eq 4. Report the results to three significant figures.

$$\gamma_{12i} = \varepsilon_{\chi_i} - \varepsilon_{y_i} \tag{3}$$

$$\gamma_{12}{}^m = \min\begin{cases} 5\,\% \\ \gamma_{12} \text{ at maximum shear stress} \end{cases} \tag{4}$$

where:

γ_{12_i} = engineering shear strain at *i*-th data point, με;
ε_{χ_i} = longitudinal normal strain at *i*-th data point, με; and
ε_{y_i} = lateral normal strain at *i*-th data point, με; and
$\gamma_{12}{}^m$ = maximum engineering shear strain, με.