7

Lamina Shear Response

A shear test of a composite material is performed to determine the shear modulus or shear strength, or both. Ideally, both properties can be determined from the same test, but this is not always the case. In addition, the shear response of a composite material is commonly nonlinear, and full characterization thus requires generating the entire shear stress–strain curve to failure. However, many shear test methods are not capable of generating the entire curve, and sometimes not even a portion of it. Figure 7.1 defines the in-plane shear stress, τ_{12} (and τ_{21}) and shear strain, γ_{12} (and γ_{21}). The other shear stress and strain components are defined accordingly. The in-plane shear modulus is denoted by G_{12}, and the shear strength by S_6. Additional definitions and notation are presented in Chapter 2.

The major deficiency of all existing shear test methods for composite materials is the lack of a pure and uniform state of shear stress in the test section. Thus, compromises have to be made. Although many shear test methods are described in the literature [1,2], only a relatively few are in common use.

In particular, the torsional loading of a thin-walled, hoop-wound tube will not be detailed here. Most discussions of shear testing start with the statement, "The torsional loading of a thin-walled tube produces a uniform state of shear stress, but…" Then some or all of the following negative aspects of tube testing are enumerated. Fabrication of the tube, which is typically hoop-wound using the filament winding process, requires special equipment and expertise. Fabrication of a tube with fibers oriented along the axis of the tube is even more difficult. In both cases the resulting tube is relatively fragile.

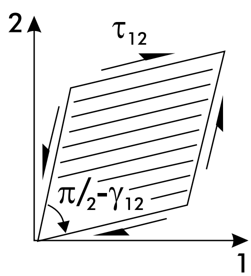

FIGURE 7.1
Definition of in-plane shear stress (τ_{12}) and shear strain (γ_{12}).

Equally important, a tube is usually not representative of the material form used in the eventual structural design. For example, because of the radical differences in the processes used to fabricate tubes vs. flat (or curved) panels or structural shapes in general, the material may not have the same strength properties. A torsional loading machine of sufficiently low torque capacity is required, and often not available. The tube specimen must be reinforced at each end in some manner so that it can be gripped within the torsion machine without damaging it. A hoop-wound tube in particular is very susceptible to inadvertent bending loads induced during testing because of nonaxial torsional loads. Any induced bending stresses combine with the shear stress to induce premature failure and thus low shear strength.

The five most popular current shear tests all happen to be ASTM standards. They include the Iosipescu shear test, ASTM D 5379 [3]; the two- and three-rail shear tests, ASTM D 4255 [4]; the $[\pm 45]_{ns}$ tension shear test, ASTM D 3518 [5]; and the short beam shear test, ASTM D 2344 [6]. These test methods are listed above in the order of their relative validity and versatility, and will be discussed in that order as well.

7.1 Iosipescu Shear Test Method (ASTM D 5379)

The Iosipescu shear test method and specimen configuration shown in Figure 7.2 are based on the original work with metals by Nicolai Iosipescu of Romania [7], from which the test method derives its name. The Composite Materials Research Group (CMRG) at the University of Wyoming led its application to composite materials [8,9]. The test method became an ASTM standard for composite materials in 1993 [3]. Analysis of the specimen under load reveals that a state of uniform shear stress exists in the center of the notched specimen on the cross section through the notches, although not in the immediate vicinity of the notch roots [9–11]. In addition, the normal stresses (the nonshear stresses) are low everywhere on this cross section. By orienting the specimen's longitudinal axis along any one of the three axes of material orthotropy, any one of the six shear stress components, representing the three independent shear stress components (see Chapter 2), can be developed.

For example, Figure 7.3 shows the required specimen orientations for measuring the two (nonindependent) in-plane shear stress components, τ_{12} and τ_{21}, for a unidirectional composite. However, note that a 0° orientation (fibers parallel to the long axis of the specimen) forms a much more robust specimen and is strongly preferred over a 90° orientation. A $[0/90]_{ns}$ (cross-ply) specimen is even more robust. Because there is no shear coupling between the plies of a $[0/90]_{ns}$ laminate (see Chapter 2), this orientation will theoretically produce the same shear properties as those of a unidirectional composite. In practice, it is likely to produce shear strengths closer to the

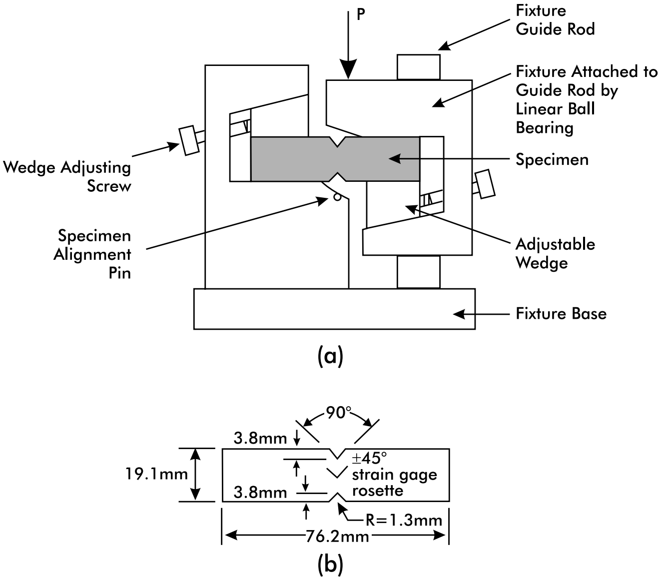

FIGURE 7.2
Sketches of (a) Iosipescu shear test fixture, and (b) test specimen.

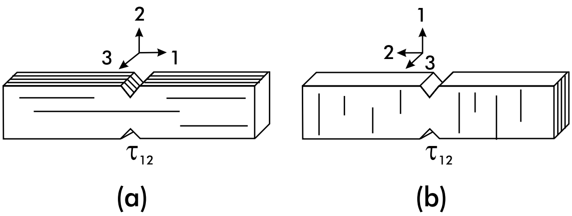

FIGURE 7.3
Iosipescu shear test specimens for in-plane shear testing: (a) 0° specimen, and (b) 90° specimen.

true shear strength of the composite material because premature failures are less likely to occur. That is, the cross-ply laminate is likely to produce more accurate (and in this case higher) shear strengths. However, note that presently, the 0° orientation unidirectional specimen is still much more commonly used, in part because a unidirectional laminate is more likely to be available for testing. This may change if the use of cross-ply laminates and back-out factors to determine unidirectional lamina compressive strength, as discussed in Section 6.7 of Chapter 6, increases in popularity.

When a strain gage is attached to one (or both) faces of the specimen in the central region between the notches, a complete shear stress–shear strain curve can be obtained. These attractive features, along with the relatively small specimen size and the general ease of performing the test, have made the Iosipescu shear test method very popular.

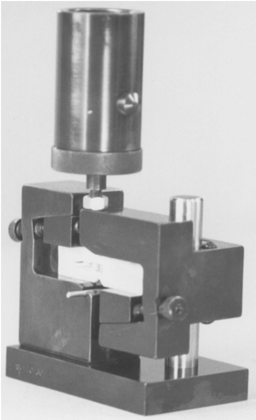

FIGURE 7.4
Photograph of an Iosipescu shear test fixture with specimen installed. (Photograph courtesy of Wyoming Test Fixtures, Inc.)

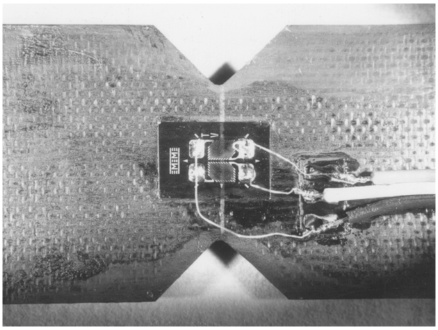

FIGURE 7.5
A ±45° biaxial strain gage rosette bonded to an Iosipescu shear test specimen.

The standard Iosipescu specimen is shown in Figure 7.2(b). The top and bottom edges must be carefully machined to be flat, parallel to each other, and perpendicular to the faces of the specimen, to avoid out-of-plane bending and twisting when the load is applied (see Figure 7.2(a)). The geometry of the notches is less critical [9]. The standard fixture, shown in Figure 7.4, can accommodate a specimen thickness up to 12.7 mm, although a thickness on the order of 2.5 mm is commonly used. For most composite materials it is convenient and economical to form the V-shaped notches using a shaped grinding wheel. The notch on one edge of a stack of specimens can be formed, the stack turned over, and the other notch formed.

If shear strain is to be measured, a two-element strain gage rosette with the elements oriented ±45° relative to the specimen longitudinal axis can be attached to the central test section region, such as shown in Figure 7.5, and the rosette wired in a half-bridge circuit. A single-element gage oriented at either plus or minus 45° can be used and wired in a quarter-bridge circuit, but this is not common practice. If out-of-plane bending and twisting of the specimen are a concern, back-to-back strain gages can be used to monitor these undesired effects [3,12]. However, this is normally not necessary.

The specimen should be centered horizontally in the test fixture using the specimen-centering pin (Figures 7.2(a) and 7.4). Vertical alignment is achieved by keeping the back face of the specimen in contact with the fixture while the wedge adjusting screws are finger-tightened to close any gap between the specimen and the fixture. Note that these wedges are not clamps and need not be tightened. They are provided to accommodate any tolerance in the width dimension of the specimen.

The upper half of the test fixture is loaded in compression through a suitable adapter, attaching it to the crosshead of the testing machine. The applied load and strain signals are monitored until the specimen fails.

The (average) shear stress across the notched section of the specimen is calculated using the simple formula

$$\tau = P/A \tag{7.1}$$

where P is the applied force, and A is the cross-sectional area of the specimen between the notches. For a unidirectional composite specimen tested in the 0° orientation, detailed stress analyses [9–12] indicate that an initially nonuniform elastic stress state exists. However, if any inelastic material response occurs, and particularly if there is initiation and arrested propagation of a crack parallel to the reinforcing fibers at each notch tip (which will occur well before the ultimate loading is attained), the local stress concentrations are significantly relieved. The stress distribution then becomes even more uniform across the entire cross section of the specimen, and increases further the accuracy of Equation (7.1).

Shear strain, γ, is simply calculated as the sum of the absolute values of the ±45° strain gage readings,

$$\gamma = |\varepsilon(45°)| + |\varepsilon(-45°)| \tag{7.2}$$

or, if only a single-element gage mounted at plus or minus 45° is used,

$$\gamma = 2|\varepsilon(45°)| \tag{7.3}$$

The shear modulus, G, is obtained as the initial slope of the shear stress–shear strain curve.

Premature damage in the form of longitudinal matrix cracks initiating from the notch roots is a common occurrence in 0° unidirectional specimens. Load decreases are observed at about two thirds of the eventual ultimate load when these cracks initiate and propagate, but they quickly arrest and the specimen then carries additional load until the true shear failure occurs, which involves multiple matrix cracks parallel to the fibers and concentrated in the region of the specimen between the two notches. Because 90° specimens often fail prematurely, particularly for brittle-matrix composites, as a result of stress concentrations and induced bending, they may not produce a representative failure stress. Figure 7.6 shows schematic stress–strain curves for unidirectional composites tested in the 90° and 0° directions. The 90° specimen usually fails suddenly, parallel to the fibers (Figure 7.7(a)). The 0°specimen fails in a more gradual manner. As noted, a small load decrease is often observed at approximately two thirds of the ultimate shear strength (Figure 7.6), because of cracking at the notch root, as indicated in Figure 7.7(b). Two decreases, relatively close to each other, will occur if the notch root cracks do not happen to occur simultaneously. These are stress-relieving mechanisms, as discussed above, and do not represent the shear strength. The stress that results in total failure across the test section, as shown in Figure 7.7(c), is the failure stress S_6. Figures 7.8 and 7.9 show typical

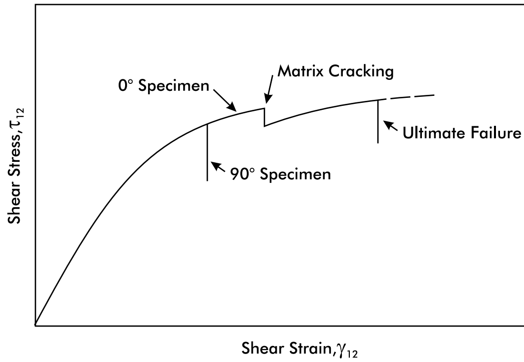

FIGURE 7.6
Schematic stress–strain curves for 0° and 90° Iosipescu shear test specimens.

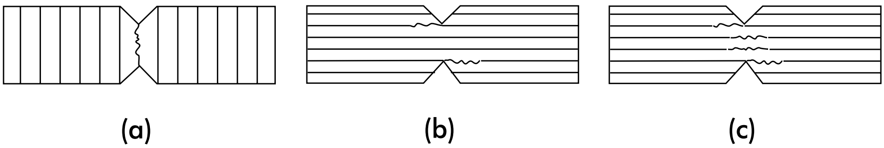

FIGURE 7.7
Failure modes of Iosipescu shear test specimens: (a) matrix cracking in a 90° specimen, and (b) and (c) matrix cracking in a 0° specimen.

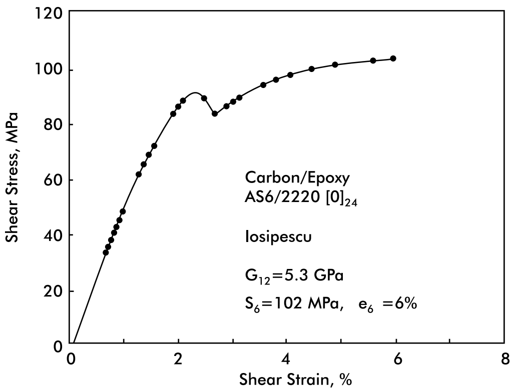

FIGURE 7.8
Shear stress–strain curve for a $[0]_{24}$ carbon/epoxy Iosipescu shear specimen.

stress–strain curves for 0° specimens of two different types of composite materials. Note that no load drop is evident in the shear stress–strain curve of Figure 7.9 because the polyphenylene sulfide (PPS) thermoplastic matrix is relatively ductile, relieving the local shear stress concentrations at the notch roots sufficiently to avert local failures. Additional examples of acceptable and unacceptable failure modes are presented in ASTM D 5379.

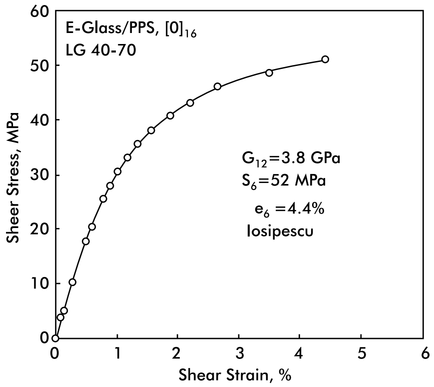

FIGURE 7.9
Shear stress–strain curve for a $[0]_{16}$ glass/PPS Iosipescu shear specimen.

7.2 Two-Rail Shear Test Method (ASTM D 4255)

This is an in-plane shear test method. Both the two- and three-rail shear tests are included in the same ASTM Standard D 4255 [4]. They will be discussed in separate sections here because they utilize different test fixtures and offer different advantages and disadvantages. Presently, these two test methods are used somewhat less frequently than the other three test methods. This is particularly true for the three-rail shear test method, for reasons to be discussed later. However, the two-rail shear test method is given a more prominent position in the present discussion because it has some very favorable technical attributes that the two test methods to be discussed next (the $[\pm 45]_{ns}$ tension shear and the short beam shear test methods) do not exhibit. That is, although presently it is not used as extensively as are the others, it has significant potential for future improvements and hence increased use.

The commonly used tensile-loading version of the two-rail shear test fixture is shown schematically in Figure 7.10(a). A compression-loading fixture also exists, but is not commonly used. The tensile-loading fixture has had a long history, and presumably is based on fixture designs originally developed even earlier (circa 1960) for the shear testing of plywood panels [13]. As a consequence, it contains some features that are not fully logical for use with composite materials. For example, note that in Figure 7.10(a), the specimen is loaded at a slight angle relative to its axis (indicated as 7° in ASTM D 4255). There does not appear to be a technical reason for this; rather, it is probably an artifact of a test fixture for plywood (ASTM 2719) developed in the early 1960s [14]. In that case, because of the type of loading apparatus used, it was convenient to apply the load to the large (610 × 430 mm) plywood test panel slightly off-axis.

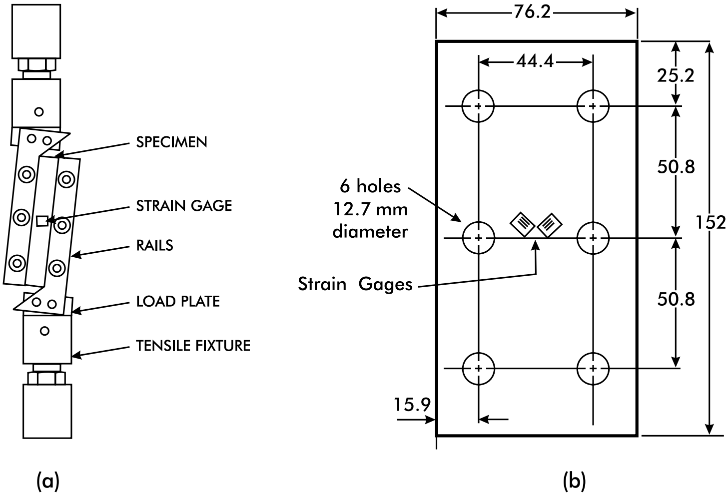

FIGURE 7.10
Two-rail shear test method: (a) fixture configuration, and (b) specimen geometry (all in mm).

The two-rail shear test specimen is shown in Figure 7.10(b). As indicated, the specimen is 76.2 × 152.4 mm, thus consuming eight times more test material than the Iosipescu shear specimen. Note also that there are six holes in the otherwise simple rectangular specimen. These are clearance holes for the six bolts that clamp the specimen to the rails. Not only do these holes potentially introduce stress concentrations in the test specimen, there is always some inherent concern about making holes in a composite material without introducing auxiliary damage. In addition, for very high shear strength composites the clamping forces have to be very high to avoid slipping of the rails during the test. A bolt torque of 100 N·m, which is a very high torque for the 9.5-mm-diameter bolts, is specified [4].

Despite these current deficiencies of the two-rail shear test method, there are distinct positive attributes of the method as well. The loading mode is actually much like that for the Iosipescu shear test method. That is, an essentially pure shear loading is applied to the gage section of the specimen (the 12.7-mm-wide portion of the specimen exposed between the rails). The shear stress along the length of the specimen (parallel to the rails) is relatively constant, except near the ends (which must be at a zero shear stress because they are free surfaces). Some extraneous normal (tensile and compressive) stresses are introduced by the presence of the rails, particularly near the boundaries of the gage section. Finite element analyses have been conducted to characterize these stresses [10,15], and undoubtedly specimen and fixture modifications can be made to significantly reduce, if not eliminate, them. Studies are currently in progress.

One previously stated advantage of the Iosipescu shear test method is the relatively small specimen size. Seemingly contradictory is the potential advantage of the two-rail shear test fixture, which can test larger specimens. When coupons taken directly from large structural components are tested, it is sometimes desirable to test a specimen of a more representative size.

For all of the reasons discussed here, the two-rail shear test method holds promise for increased usage as some of the present deficiencies are eliminated. More details are presented in Reference [15].

When a two-rail shear test is conducted, the specimen must first be properly prepared, heeding in particular the cautions already noted regarding formation of the required six clearance holes in the specimen without introduction of auxiliary damage. When a unidirectional lamina is tested, the fibers can be oriented either parallel (90° orientation) or perpendicular (0° orientation) to the rails. However, a fiber orientation perpendicular to the rails is much preferred, because extraneous bending and edge effects have much less influence on the measured properties and the specimen is much more robust [15]. In fact, testing a $[0/90]_{ns}$ (cross-ply) laminate may be even better; the specimen is even more robust than a unidirectional lamina with fibers oriented perpendicular to the rails. Because there is no shear coupling between the plies of a $[0/90]_{ns}$ laminate (see Chapter 2), this orientation will theoretically produce the same shear properties as a unidirectional composite. In practice, it is likely to produce shear strengths closer to the true shear strength of the composite material because premature failures are less likely to occur. That is, the cross-ply laminate is likely to produce more accurate (and in this case higher) shear strengths. Note that this same general logic was stated in Section 7.1 with reference to the Iosipescu shear test specimen.

The specimen to be tested is clamped between the pairs of rails, as indicated in Figure 7.10(a). It is important that the rails do not slip during the test. If they do slip, the clamping bolts can bear against the clearance holes in the specimen, inducing local stress concentrations leading to premature failure. This, of course, results in an unacceptable test. Most currently available fixtures have thermal-sprayed tungsten carbide particle gripping surfaces [16], although ASTM D 4255 does not specifically require them. The thermal-sprayed surfaces generally have much better holding power than the other types of grip surfaces listed in the standard, as discussed in Reference [15].

If shear strain is to be measured, a single-element or a dual-element strain gage is bonded to the specimen at the center of the gage section. If bending or buckling is suspected, back-to-back strain gages can be used, just as discussed for the Iosipescu shear test method in the previous section. Likewise, the calculations of shear stress, shear strain, and shear modulus are also the same; the cross-sectional area in the present case is the length of the specimen parallel to the rails times the specimen thickness.

In summary, the two-rail shear test method clearly has many attributes in common with the Iosipescu shear test method. In fact, it is conceivable that at some future time the two test methods will converge into one.

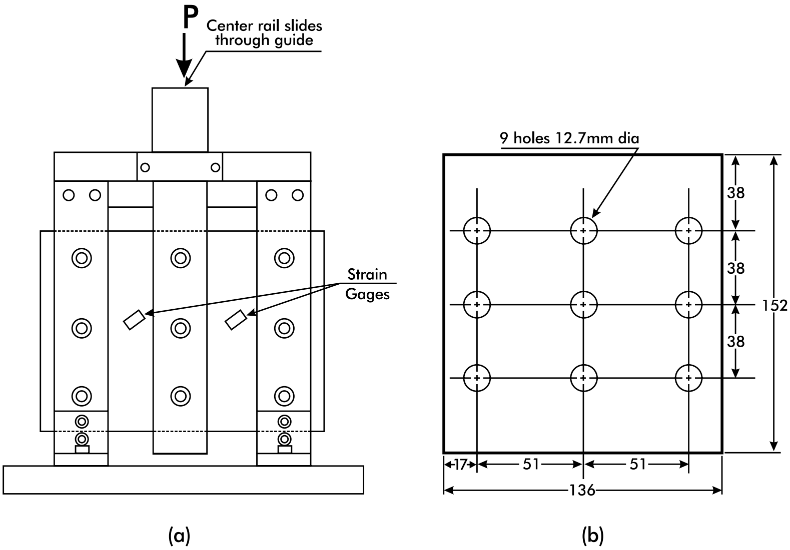

FIGURE 7.11
Three-rail shear test method: (a) fixture configuration, and (b) specimen geometry (all in mm).

7.3 Three-Rail Shear Test Method (ASTM D 4255)

Although the in-plane shear stress state induced in the three-rail shear test specimen is generally similar to that induced in the two-rail shear test specimen, there also are significant differences between the two test methods. In particular, the test fixtures are quite different. A sketch of the three-rail shear fixture is shown in Figure 7.11. The standard fixture shown is designed to be loaded in compression between the flat platens of a testing machine. Tensile loading is also permissible if the fixture is modified to permit attachment to the base and crosshead of the testing machine. However, in practice this is not commonly done. In fact, the fixture drawings available from ASTM only include the compression-loaded configuration.

Unlike the two-rail shear fixture, the three-rail shear fixture does shear load the specimen along its geometric axes. However, nine rather than six clearance holes must be cut into the specimen, and the size of the standard specimen is 136 × 152 mm rather than 76 × 152 mm, i.e., 1.8 times larger. These are both distinct disadvantages, i.e., causing increased specimen preparation time (and hence cost) and increased test material consumption, respectively. The (two) gage sections are each 25.4 mm wide, twice as wide as for the (single) gage section of the two-rail shear specimen, which could be an advantage in some cases, as discussed relative to the two-rail shear fixture. However, the gage width of the two-rail shear specimen could also simply be increased to 25.4 mm, if desired. In any case, the potential for buckling in the gage section is always a concern as the gage section width is increased.

The methods of specimen gripping, specimen strain gaging, and reducing the test data are essentially the same as for the two-rail shear test method, as detailed in Section 7.2.

In summary, the disadvantages of the three-rail shear test method relative to the two-rail shear test method generally outweigh the advantages. Thus it is presently used much less frequently [16].

7.4 $[\pm 45]_{ns}$ Tensile Shear Test Method (ASTM D 3518)

The $[\pm 45]_{ns}$ tensile coupon can be employed to determine the shear properties of the unidirectional lamina. These include the in-plane shear modulus, G_{12}, and the ultimate shear stress and strain, S_6 and e_6, respectively. The test specimen is relatively simple to prepare and requires no special test fixture other than standard tensile grips. The test method has been standardized as ASTM D 3518 [5].

The state of stress in each lamina of the $[\pm 45]_{ns}$ laminate is not pure shear. Each lamina contains tensile normal stresses, σ_1 and σ_2, in addition to the desired shear stress, τ_{12}. In addition, an interlaminar shear stress, τ_{xz}, is present near the laminate free edge [5], as discussed in Chapter 2. Normally, these considerations would lead to the rejection of this test geometry. However, there are mitigating circumstances that reduce these concerns. First, the shear stress–strain responses of many types of composite laminae are nonlinear, and may exhibit strain softening characteristics. Thus, although the biaxial state of stress present in the specimen likely causes the measured value of shear strength to be lower than the true value, the reduction may be small because of the nonlinear softening response. Second, the magnitudes of the interlaminar stresses for laminates containing laminae with high orthotropy ratios are a maximum at ply angles of 15 to 25°, and the interlaminar stresses are considerably smaller for 45° ply angles. Therefore, the $[\pm 45]_{ns}$ tensile shear test method may often be reliable in determining lamina shear strength and modulus.

The test specimen geometry for the $[\pm 45]_{ns}$ tensile shear coupon is shown in Figure 7.12. The width of the specimen typically is on the order of 25 mm. End tabs may not be required because the tensile strength of a $[\pm 45]_{ns}$ laminate is low relative to that of an axially loaded unidirectional composite. The $[\pm 45]_{ns}$ laminate tension test provides an indirect measure of the in-plane shear stress-strain response in the material coordinate system. The tensile specimen is instrumented with a 0°/90° biaxial strain gage rosette as shown in Figure 7.12. The specimen is prepared, and tested in tension to ultimate failure following the procedures outlined for the tension test in Chapter 5.

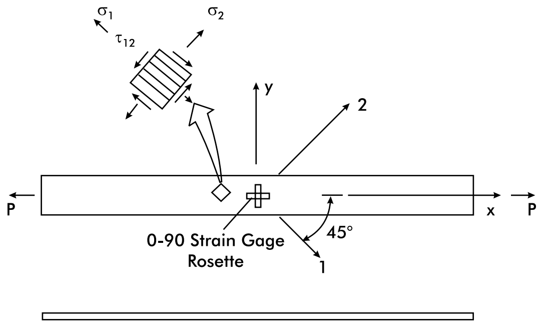

FIGURE 7.12
The $[\pm 45]_{ns}$ tensile specimen for evaluation of the shear stress–strain response of unidirectional composites, and the stress state in a ply.

Determination of the intrinsic (lamina) shear properties from the tension test results uses a stress analysis of the $[\pm 45]_{ns}$ specimen. The shear stress, τ_{12} (Figure 7.12), is simply [5]

$$\tau_{12} = \sigma_x/2 \tag{7.4}$$

where σ_x is the axial stress (P/A). The shear strain is

$$\gamma_{12} = \varepsilon_x - \varepsilon_y \tag{7.5}$$

where ε_x and ε_y are the axial and transverse strains, respectively ($\varepsilon_y < 0$). Hence, the in-plane shear modulus, G_{12}, is readily determined by plotting $\sigma_x/2$ vs. $(\varepsilon_x - \varepsilon_y)$ and establishing the slope of the initial portion of the curve. The ultimate shear stress, S_6, is defined as the maximum value of $\sigma_x/2$. Figures 7.13 and 7.14 show typical shear stress–shear strain curves for the lamina as determined from the laminate tensile test.

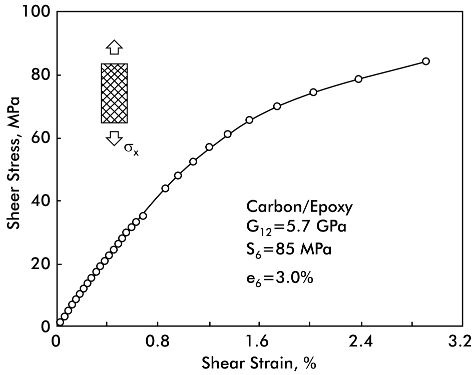

FIGURE 7.13
Shear stress–strain curve obtained from a tensile test of a $[\pm 45]_{2s}$ carbon/epoxy test specimen.

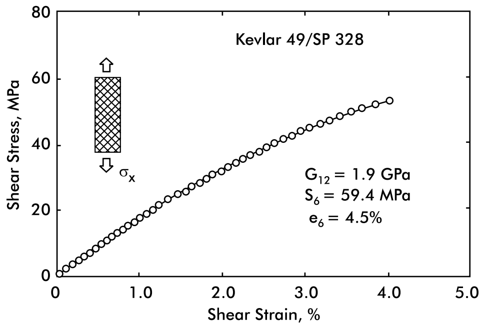

FIGURE 7.14
Shear stress–strain curve obtained from a tensile test of a $[\pm 45]_{2s}$ Kevlar/epoxy test specimen.

As an alternative to determining the shearing modulus using the method presented above, it is also possible to measure the axial stiffness and Poisson's ratio of the [±45] laminate, i.e., E_x and ν_{xy}, and then determine the shear modulus according to the following relationship:

$$G_{12} = \frac{E_x}{2\,(1+\nu_{xy})} \tag{7.6}$$

7.5 Short Beam Shear Test Method (ASTM D 2344)

This is an interlaminar shear test method. For a unidirectional composite the τ_{13} component is the shear stress applied, assuming the fibers to be oriented parallel to the beam axis. However, if the shear strengths in the 13 and 12 directions are equal, as is often assumed for a unidirectional composite, this test method can be, and often is, used to determine the in-plane shear strength of a unidirectional lamina. As for the $[\pm 45]_{ns}$ tension shear test method, it is in common use despite some serious limitations. This ASTM standard was titled "Apparent Interlaminar Shear Strength…" for many years, the word "apparent" acknowledging these limitations [6].

A specimen with a low support span length-to-specimen thickness ratio (typically a ratio of 4) is subjected to three-point loading. Both bending (flexural) and interlaminar shear stresses are induced in any beam loaded in this manner, as discussed in more detail in Chapter 8. The axial bending stresses are compressive on the surface of the beam where the load is applied, and tensile on the opposite surface, varying linearly through the beam thickness if the material response is elastic. By definition, the neutral axis (neutral plane) is where the bending stress passes through zero. It is on this neutral plane that the interlaminar shear stress is theoretically at maximum, varying parabolically from zero on each surface of the beam. Thus, although a combined stress state exists in general, the stress state should be pure shear on the neutral plane. For a shear test, by keeping the span length-to-specimen thickness ratio low, the bending stresses can be kept low, promoting shear failures on the neutral plane. Unfortunately, the concentrated loadings on the beam at the loading and support points create stress concentrations throughout much of the short beam [17,18], complicating the stress state. As the result, the assumption of a parabolic stress distribution with a maximum at the neutral plane becomes only an approximation. Nevertheless, the ASTM standard assumes a parabolic stress distribution, which for a beam of rectangular cross section results in a maximum shear stress of

$$\tau_{13} = 0.75\ P/A \tag{7.7}$$

where P is the applied load on the beam, and A is the cross-sectional area of the beam. This assumption is the reason for the use of "apparent" in the previous title of ASTM D 2344. Despite these limitations, the short beam shear test method usually produces reasonable values of shear strength [19].

The specimen can be very small, consuming a minimal amount of material. For example, when a span length-to-specimen thickness ratio of 4 and a 2.5-mm-thick composite are used, the span length is only 10 mm. If one specimen thickness of overhang is allowed on each end, the total specimen length is still only 15 mm. In addition, minimum specimen preparation time is required because the length and width dimensions, and the quality of the cut edges of the specimen, are not critical. The test fixturing can be relatively simple and a test can be performed quickly. A typical short beam shear test fixture is shown in Figure 7.15.

For the above-described reasons, the short beam shear test is used extensively as a materials screening and quality control test. It has definite advantages for these purposes. However, another reason the test is both quick and economical is that no strain or displacement measurements are made because the span length-to-specimen thickness ratio is too small. Unfortunately, this means that shear modulus cannot be determined, and a shear stress–strain curve is not obtained.

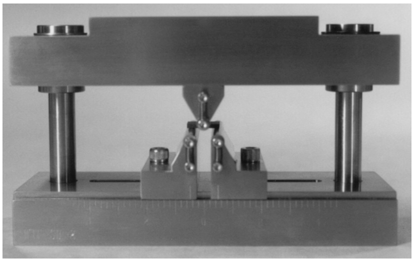

FIGURE 7.15
Short beam shear test fixture with adjustable support span. (Photograph courtesy of Wyoming Test Fixtures, Inc.)

7.6 Summary

Of the many shear test methods in existence, the Iosipescu shear test method is judged superior in meeting the various requirements of an ideal test. The two-rail shear test method is a viable alternative, and may become more prominent as it is further developed. The $[\pm 45]_{ns}$ tensile shear test utilizes a relatively simple specimen geometry and test configuration, but the influences of the biaxial stress state present can diminish shear strength measurements. Many of the other shear test methods have serious deficiencies, which limit their validity.

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