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AN EXPERIMENTAL PROCEDURE FOR THE IOSIPESCU COMPOSITE SPECIMEN TESTED IN THE MODIFIED WYOMING FIXTURE

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H. Ho, M.Y. Tsai, J. Morton
Department of Engineering Science and Mechanics
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0219

and

G.L. Farley
US Army Aerostructures Directorate
NASA Langley Research Center
Hampton, VA 23665-5225

ABSTRACT

A detailed description of the experimental procedure for testing composite Iosipescu specimens in the modified Wyoming fixture is presented. Specimen preparation and strain gage instrumentation are addressed. Interpretation of the experimental results is discussed. With the proper experimental setup and procedure, consistent and repeatable shear properties are obtained.

INTRODUCTION

Characterization of the in-plane shear properties is essential to the understanding of the mechanical behavior of a laminated composite structures. Since the late 1960's, numerous shear test methods [1-6] have been developed to perform shear stiffness and strength measurements for composite materials. Among these many shear test methods, the Iosipescu shear test, ±45° tension test, and 10° off-axis tension test were highly ranked by Lee & Munro based on a decision analysis [7]. However, none of these test methods produced pure and uniform shear stress fields in the test section and the shear strengths obtained from these test methods were also questionable because no specimen failed under pure shear [8-10]. For the 10° off-axis tension specimen, an after-test correction for the apparent shear modulus is needed [9] in order to account for the shear-extension coupling effect caused by the end constraints. The 10° off-axis tension test also produced lower

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failure stresses due to the bi-axial stress state in the specimen. In the ±45° tension test, the shear strain distribution in the surface layers contained local fluctuations associated with the neighboring sub-layer [8]. In addition, the ±45° tension specimen is a laminate rather than a lamina; therefore, it is subject to free edge effects [8]. For strength measurement, the ±45° tension specimens are susceptible to a specimen scaling effect [11,12]; that is, the measured in-plane shear strength is dependent on the specimen thickness and the stacking sequence (sublaminate and ply-level scaling). The usefulness of the 10° off-axis and ±45° tension tests is limited because the tests can only be applied to measure the in-plane shear properties of unidirectional composites. For multi-directional composites, short fiber composites, and woven fabric composites, other shear test methods must be used.

In the past decade, the Iosipescu shear test for shear property measurement of composite materials has been widely investigated and used. The popularity of the Iosipescu shear test is attributed to its capability of testing a wide range of material systems and ease of handling and simple instrumentation. However, without careful experimental procedure and interpretation of the experimental results, inaccurate and inconsistent shear modulus data can be obtained. For example, the shear modulus for unidirectional AS4/3501-6 graphite-epoxy composites measured by a number of investigators [13-15] using the Iosipescu specimen geometry, Fig.1, and modified Wyoming test fixture, Fig.2, are shown in Fig.3. The variations of the measured shear moduli between different investigators may be caused by different fiber volume fractions between their specimens. Nevertheless, a very large degree of data scatter was found in the measured shear modulus from either 0° or 90° specimens from the same investigator. In recent studies [10,16-19], both 0° and 90° specimens cut from the same panel were tested and the results showed that, in addition to the large scatter in the measured shear modulus data for either fiber orientation, the shear moduli obtained from the 0° and 90° specimens were inconsistent.

The main problems associated with the Iosipescu shear test method are: (1) the inability to obtain a pure shear state in the test section of the 0° specimens [10,16], (2) the different shear moduli between the 0° and 90° specimens [10,16-19], and (3) the large difference in shear stress-strain response that occurs for both 0° and 90° specimens [14-19]. The lack of a pure shear in the 0° specimen [10,16] is caused by the specimen's low transverse and large longitudinal stiffness. The measured shear moduli for the 0° and 90° specimens are different [10,16-19] because the shear strain distributions in the test section of the 0° and

90° specimens are nonuniform and are of different forms. The large load distribution area in the specimen/fixture contact region of the 0° specimen [17] and possible local hardness along the specimen/fixture contact region of the 0° specimen's long edges result in inconsistent load points between specimens. The variation in the measured shear moduli for the 0° specimen is attributed to the effect of the uncertainty of load points [10,17]. Due to the high transverse stiffness of the 90° specimen, twisting can occur when load is applied [10]. Specimen twisting causes different shear stress-strain responses in the front and back faces of the specimen. The variation in the measured shear moduli for the 90° specimen is caused by specimen twisting, which is material property and specimen dependent.

In this paper, general guidelines, as currently practiced by the authors, for testing the Iosipescu composite specimen in the modified Wyoming fixture are presented. The above mentioned problems are addressed in the guidelines in terms of specimen preparation, experimental setup, experimental procedure, and proper interpretation of experimental data.

TEST PROCEDURE

Specimen

Both unidirectional (0° or 90°) and cross-ply (0°/90°) specimens can be used to determine the in-plane elastic shear modulus (G_{12}) of a composite material. Unidirectional and cross-ply composite panels are laid up and cured according to the manufacturer's specifications. The in-plane dimensions of the specimen are 76.2mm x 19.1mm (3" x .75") with two V-notches at the opposite ends of the transverse center axis, Fig.1. The notch depth is 3.8mm (0.15") with a notch tip radius 1.3mm (0.05"). Specimen thickness ranging from 2.5mm (0.1") to 6.3mm (0.25") is recommended to facilitate handling. Specimens with fiber directions parallel and perpendicular to the longitudinal axis are designated as the 0° and 90° specimens, respectively, Fig.1. To avoid possible variations in the resin content and poor fiber alignment in the specimens, the edges of the panels are trimmed. Unidirectional 0° and 90° specimens are machined from the same panel to render direct comparison of the effect of fiber orientation on shear modulus measurement [10,16-19]. Due to the effect of the uncertainty of how load is transferred into the 0° specimens, variation of the measured shear modulus is inevitable [10]. The uncertainty of load transfer for the 0° specimen is an inherent property and the effect varies between specimens. Therefore, the 90° specimen is recommended for accurate shear modulus measurement.

Specimens were cut using a diamond impregnated wheel saw. The long edges of the specimen were ground flat and parallel to a tolerance of 0.0254mm (0.001"). Several specimens with backing material were held in a vise on a grinding machine to facilitate cutting the notch. A 150mm (6") diameter abrasive grinding wheel with a tip radius of 1.3mm was positioned at the center of the specimens held in the vise. The rotational speed and the feed rate of the grinding wheel were 2,950 RPM and 0.4m/min, respectively. The feed rate of the grinding wheel should be kept low to prevent delamination and splitting near the notches. It has also been determined that a variation in measured shear modulus can occur if the notches are not located at the center of the specimen.

Before attachment of the strain gage rosettes to the specimen, the test section of the specimen (the region between the top and bottom notches) is sanded flat with fine grade sand paper (600 grit). The specimen thickness, **t**, in the test section is then measured along with the notch width, **w**. Usually, three thickness and width measurements are taken and the average value is used to calculate the test section cross-section area (**A=tw**).

For each fiber orientation, at least five specimens are prepared. Because the thickness of the panel may not be uniform across the panel and the edges of the panel may have irregularities, such as wavy fibers, the specimen location on the panel and specimen thickness are recorded for further reference. Any variation in specimen thickness results in local changes in fiber volume fraction which could result in changes in mechanical response. The authors recommend the panels should have no more than a 3 percent variation in thickness.

Specimen twisting has been shown to be a significant problem when testing material with a 90° ply (i.e. 90° or 0°/90° laminates). To reduce the twisting induced strains a compliant layer (masking tape) is applied along the edges of the specimen, see Fig.1. The front and back shear responses of a 90° AS4/BMIPES (bismaleimide thermoset matrix with polysulfone thermoplastic additive) Iosipescu specimen before and after the application of the masking tapes are shown in Fig.4. The amount of specimen twisting decreases after the application of the tape. In general, the degree of twisting depends on the transverse stiffness of the specimen. For material with low transverse stiffness, the distance between the distributed forces [10] along the load introduction region of the specimen and the specimen mid-plane decreases as the applied load increases. Thus for AS4/3501-6 graphite-epoxy composite materials, the 90° specimen (E_y=138 GPa) twists while the 0° specimen (E_y=8.96 GPa) does not [20]. For isotropic materials, an aluminum alloy specimen (E_y=E=70 GPa) twists while an aluminum particulate filled epoxy composite specimen (E_y=E=7.75 GPa) does not [20]. Typical shear stress-strain data on the front and back faces of the 90° graphite-epoxy and aluminum specimens are shown in Figs.5 and 6. In Fig.5a, the shear stress-strain curves are obtained from the front and back faces of the same specimen when tested four different times in the fixture. That is, the specimen was loaded with one rosette facing the front of the fixture and the other facing the back of the fixture. The specimen was then unloaded and rotated 180° about a horizontal or vertical axis, and loaded again. The wide separation of the shear stress-strain curves indicates that the specimen twisting is sensitive to how the specimen contacts the test fixture. By taking the average of the front and back shear strains, the variability of the shear stress-strain data corresponding to the four specimen-to-fixture contact positions of the same specimen is greatly reduced, Fig. 5b. The response of an aluminum alloy specimen is shown in Fig.6a. The significant twisting, which is observed in Fig.6a, is eliminated by the averaging technique, see Fig.6b. Thus the twisting effect is not a result of material anisotropy.

Instrumentation

Measuring shear strain in the test section of the specimen requires at least two gages oriented at ±45° relative to the longitudinal axis of the specimen. The shear strain is expressed as

$$\gamma_{xy} = \varepsilon_{+45} - \varepsilon_{-45} \qquad (1)$$

where ε_{+45} and ε_{-45} are the extensional strains in the ±45° strain gages. The authors recommend that for each panel, at least one specimen be instrumented with stacked three-gage rosettes on the front and back surfaces. The three gages are orientated at ±45° and 0° directions relative to the longitudinal axis of the specimen. For general practice, less expensive unstacked two-gage rosettes oriented at ±45° to the specimens longitudinal axis can be used. The recommended gage length of the strain gages is 1.5mm. The advantage of using the stacked three-gage rosettes relative to the unstacked two-gage rosettes is that the 0° gage provides a means of measuring specimen out-of-plane bending. Furthermore, the stacked three gage rosette measures the strains over a common region in the test section whereas the unstacked two gages measure the strains at two different locations [17].

For 0° Iosipescu composite specimens, the strains recorded by the two gages in the ±45° directions are not equal in magnitude and opposite in sign as is the case for the 90° specimens, Fig. 7. The lack of symmetry in the ±45° gage readings is attributed to the presence of transverse normal strain ε_y in the test section [16]. The transverse normal strain field is found to be uniform in the test section for all the material systems studied in reference 20 (orthotropic ratio ranging from 1.0 to 15.4), thus, the shear strain still can be calculated using equation (1) [17]. However, if a single gage is attached at the 45° or -45° direction and the shear strain calculated by doubling the value of the single gage strain, an erroneous shear response will be obtained.

To identify and quantify specimen twisting and its influence on the shear response it is necessary to have back-to-back strain gages. Specimen twisting has been shown to cause variations in the measured shear moduli for 90° specimens [10] by producing unequal strains on the front and back surfaces of the specimen. The twisting effect is attributed to rigid body rotation of the test fixture and high transverse stiffness of specimens having 90° plies. The movable portion of the fixture slides along a guide post via roller bearing, Fig. 2. When the load is applied, the eccentricity of the load application point to the guide post will produce a moment about the horizontal axis. If the bearing is worn or if the tolerance between the bearing and the guide post is large, the movable portion of the fixture will rotate forward. The rotation of the movable portion of the fixture induces an eccentric load which can cause the specimen to slip in the fixture. On the front surface of the specimen, the twisting induced strains reduce the in-plane shear induced strains whereas on the back surface the converse occurs. The magnitude of the effect of twisting is different between specimens. If only one rosette is applied to one surface of the specimen, large variations of the shear modulus would be obtained. However, by averaging the front and back shear strains, consistent shear stress-strain responses can be obtained between successive specimens.

Strain gages may be inadequate for accurate shear modulus determination of coarse weave fabric composites. Based upon u- and v-field moire fringe patterns for a plain-weave, cross-ply ($[0/90]_{2s}$) woven fabric composite [20] with 12k AS4 fiber, shown in Figs.8a-8b, moire fringe bands occur which correspond to undulating shear strain distribution across the test section, see Fig.9. This variation in strain is associated with the architecture of the woven fabric. The shear stress-strain responses of six plain-weave, cross-ply ($[0°/90°]_{2s}$) woven fabric composite specimens were obtained using back-to-back unstacked two gage rosettes. Even after averaging the front and back shear strains, the shear stress-strain responses are also inconsistent, see Fig.10.

Experimental setup

The modified Wyoming fixture, Fig.2, is attached to the testing machine using a cross head adapter. Strain gages are connected to a Wheatstone bridge with a half bridge configuration which provides temperature compensation of the strain gages. The Wheatstone bridge is connected to a signal conditioning amplifier and the amplified analog signal is converted to digital signal through a circuit completion box. The circuit completion box is connected to a micro-computer controlled data acquisition system.

After the composite specimen is inserted into the fixture openings, the specimen is placed against the fixture wall. The movable and stationary parts of the fixtures should be adjusted to be in the same plane to prevent any rotation of the movable portion of the fixture about the guide rod after load is applied. The specimen is centered using an alignment pin. The alignment pin is lifted to engage the lower notch in the specimen, and the specimen is secured in the fixture with the adjustable wedge clamps. Load is applied to the movable portion of the fixture which is constrained to move vertically downward along a guide rod.

Experimental procedure

An aluminum alloy specimen with stacked three-gage rosettes on the front and back surfaces of the specimen is tested within the linear elastic response region to ensure that the test setup produces consistent results each time the test apparatus is placed in the test machine. Agreement between subsequent tests of the aluminum alloy specimen minimize any test setup errors.

The reaction force from the specimen, which is also the equivalent applied shear force, **P**, in the test section, is obtained from the load cell connected to the fixture. The shear stress is calculated by dividing the shear force **P** by the cross-sectional area **A** (A=tw) in the test section. A crosshead loading rate of 0.5mm/minute (0.02in/minute) is used.

Data interpretation

The shear stress-strain responses, in Figs.4-6, are the average shear stresses developed on the minimum cross-section plotted as a function of the average shear strains over the equivalent area covered by the strain gage rosettes. Problems arise when the shear fields are nonuniform. Due to the nonuniform shear fields in the test section for either 0° or 90° specimens, correction factors should be applied in calculation of shear modulus [10,17-19]. The difference in the apparent shear moduli obtained from the 0° and 90° specimens is largely due to the different forms of the shear stress/strain distributions in the test section. The correction factors depend on the material orthotropy and are defined by a finite element analysis for the material in question. It has been shown to be expressed approximately [17] as

$$CF = 1.036 - 0.125 \times \log(E_x/E_y). \tag{2}$$

where E_x and E_y are the longitudinal and transverse stiffnesses of the specimen, respectively. The corrected shear modulus G_{xy} is expressed as

$$G_{xy} = CF \times G^* \tag{3}$$

where G^* is the apparent shear modulus, τ_{ave}/γ_{gage}, with $\tau_{ave} = P/A$ and γ_{gage} = average of front and back shear strains. The distribution of the measured shear modulus for several 0° and 90° graphite-epoxy Iosipescu specimens is shown in Fig.11. The shear modulus for the 90° specimens is obtained using the averaged shear strain of the front and back surfaces of the specimen. The measured shear moduli for several 90° specimens are consistent. However, the measured shear moduli for several 0° specimens show a range of values due to uncertainty of load points between specimens. After application of correction factors, the shear modulus of the 0° specimen reduced while the shear modulus of the 90° specimen increased and the difference between the measured shear moduli of 0° and 90° specimens is reduced greatly, see Fig.11.

Twisting has been identified as playing an important roles for specimens with high transverse stiffness, (i.e., 90° and 0°/90° specimens). In addition to different front and back shear stress-strain responses, twisting also causes low failure stresses.

Iosipescu specimens (isotropic, 0° or 90° unidirectional composite materials) do not fail at the notch axis where the cross-section area is a minimum. The mixed mode failure is attributed to the presence of the tensile normal strains, ε_x, and ε_y, at the intersections of the notch roots and notch flanks for 90° and 0° specimens, respectively [16,17], and is an inherent problem due to the notch design of the specimen.

The effect of strain gage transverse sensitivity has been found to be negligible, about 2% for 90° and 2.6%, for 0° graphite-epoxy specimens instrumented with strain gages with a transverse sensitivity coefficient $k_t = 2\%$ [21].

CONCLUSIONS

For 0° and 90° graphite-epoxy specimens, significant variations in the shear modulus measurement could occur if a proper experimental procedure is not followed. In summary, the experimental guidelines for shear testing of the Iosipescu composite specimens are as follows.

1. The thickness of the composite panel should have less than 3% variation.
2. The edges of the panel from which the specimens are cut should be trimmed to ensure constant fiber volume fraction and straight fibers.
3. Use slow feed rate in the cutting of the notches.
4. Apply masking tape at specimen long edges to reduce specimen twisting.
5. For accurate shear modulus measurement, 90° specimens are recommended. Back-to-back rosettes should be applied.
6. Apply a correction factor to the measured shear modulus to obtain the corrected shear modulus of the composite material.

Following the proposed guidelines and by proper interpretation of experimental results, extremely consistent in-plane shear modulus data using the Iosipescu specimen tested in the modified Wyoming fixture can be obtained.

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FIGURE CAPTIONS

Fig.1 Modified Iosipescu shear specimen.

Fig.2 Modified Wyoming fixture.

Fig.3 Normalized values of in-plane shear moduli obtained from Iosipescu shear test on AS4/3501-6. Values are normalized with respect to G^*_{12} =5.12 GPa, the average obtained from ± 45° tension and 10° off-axis tests [8]. The ranges shown in the figure are moduli of repeatability [15] or denote one standard deviation.

Fig.4 Typical shear stress-strain data (a) before (b) after application of masking tapes to the specimen along load introduction region of a 90° AS4/BMIPES Iosipescu specimen.

Fig.5 (a) Front and back surface shear stress-strain data for a single 90° graphite-epoxy specimen. Specimen was loaded in different orientations by rotating the specimen about the x, y and z axes. (b) Average of front and back surface shear strains as a function of shear stress for 90° graphite-epoxy specimen.

Fig.6 (a) Front and back surface shear stress-strain data for a single aluminum specimen. Specimen was loaded in different orientations by rotating the specimen about the x, y and z axes. (b) Average of front and back surface shear strains as a function of shear stress for aluminum specimen.

Fig.7 Strain vs. stress for typical (a) 0° and (b) 90° graphite-epoxy specimen. Gages are aligned at ±45° and 0° directions.

Figs. 8a&b Typical moire fringe patterns of the plain weave $[0/90]_{2s}$ specimen at an applied shear stress of 14.2 MPa. (a) u-field, (b) v-field. Carrier rotation is applied such that the deformation information is equally contained in the u- and v-fields.

Fig. 9 Shear strains across the notches, normalized with respect to the average shear strain, for plain weave $[0/90]_{2s}$ specimens.

Fig. 10 (a) Shear stress-strain data from front and back faces, (b) average of front and back shear stress-strain data of six plain weave $[0/90]_{2s}$ specimens.

Fig.11 Calculated G_{12} for three graphite-epoxy 0° and 90° specimens, before and after application of correction factors.

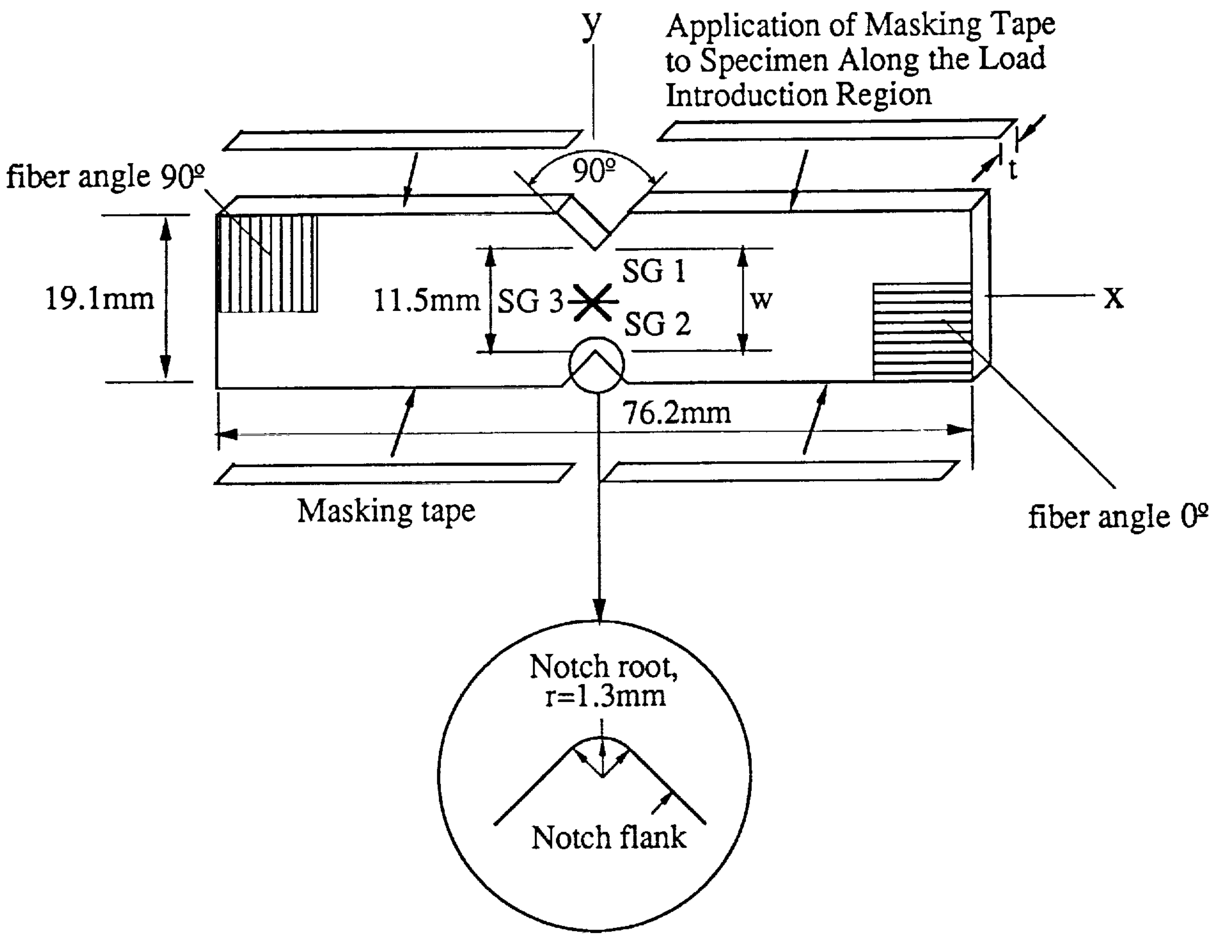


Fig.1. Modified Iosipescu shear specimen.

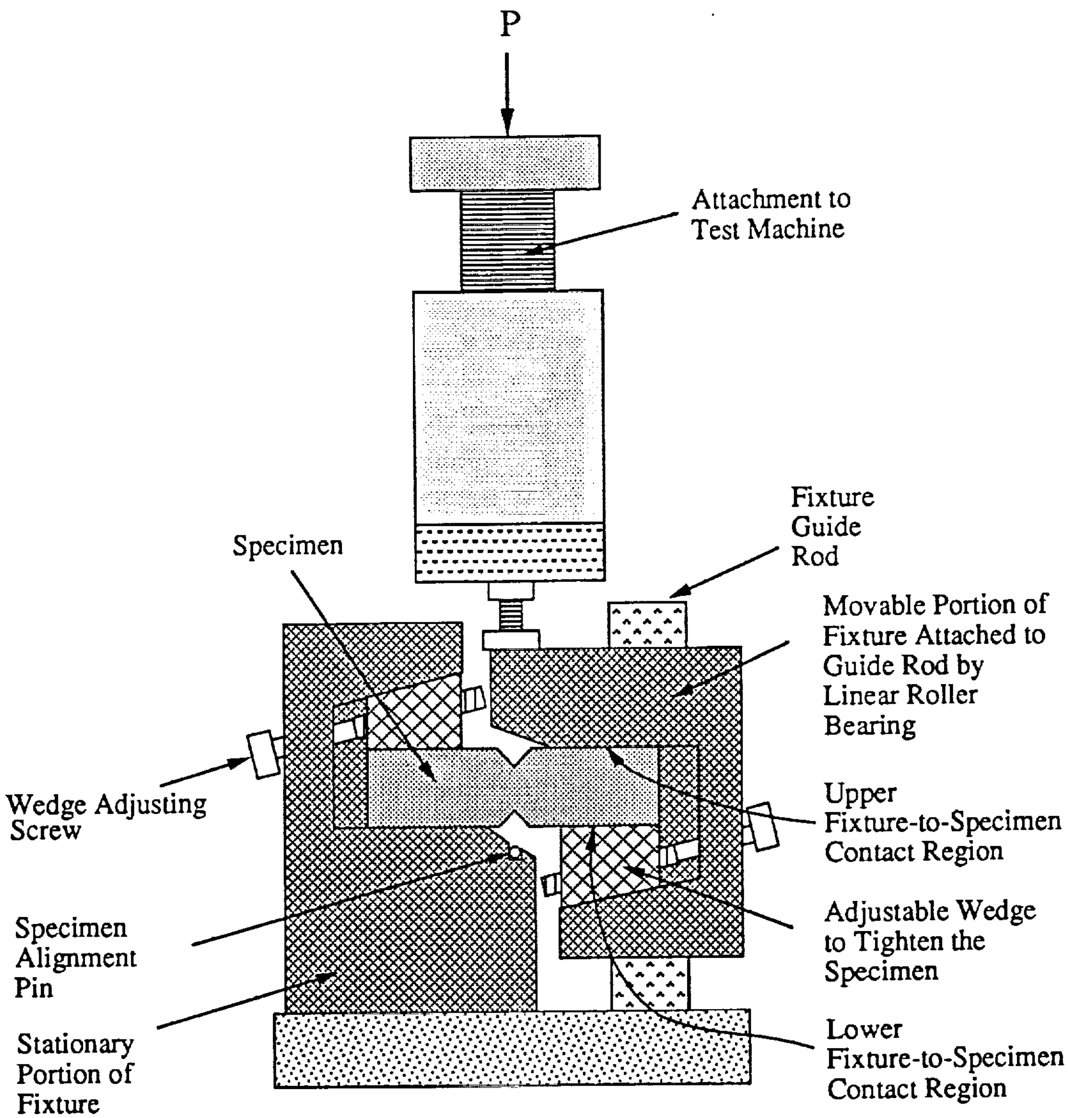


Fig. 2. Modified Wyoming fixture

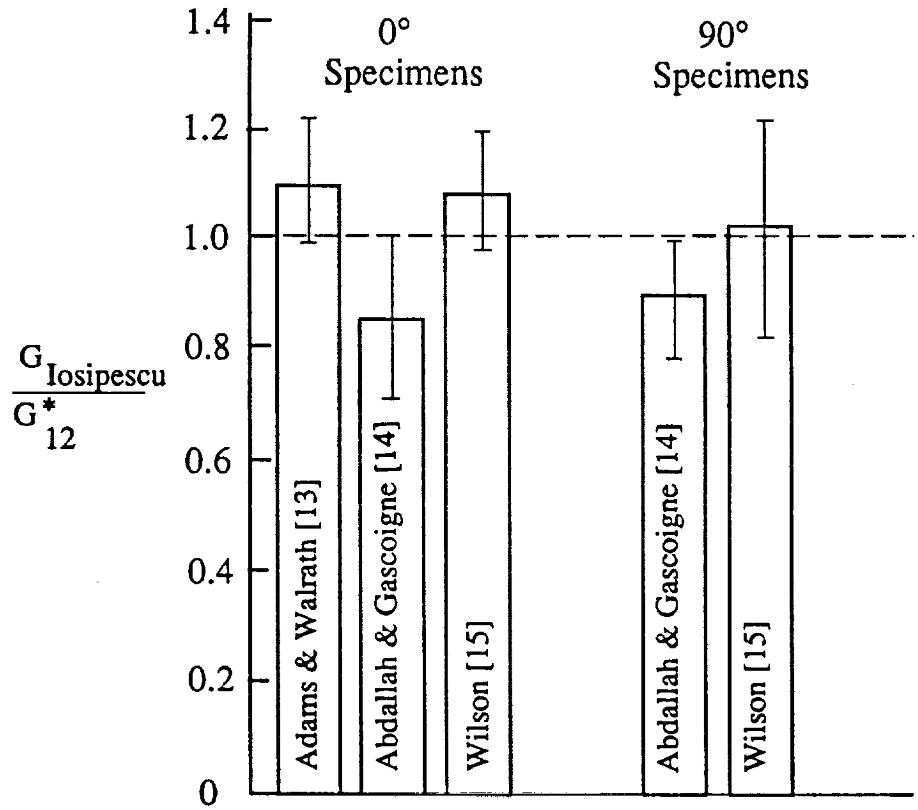


Fig.3 Normalized values of in-plane shear moduli obtained from Iosipescu shear test on AS4/3501-6. Values are normalized with respect to G^*_{12} =5.12 GPa, the average obtained from ± 45° tension and 10° off-axis tests [8]. The ranges shown in the figure are moduli of repeatability [15] or denote one standard deviation.

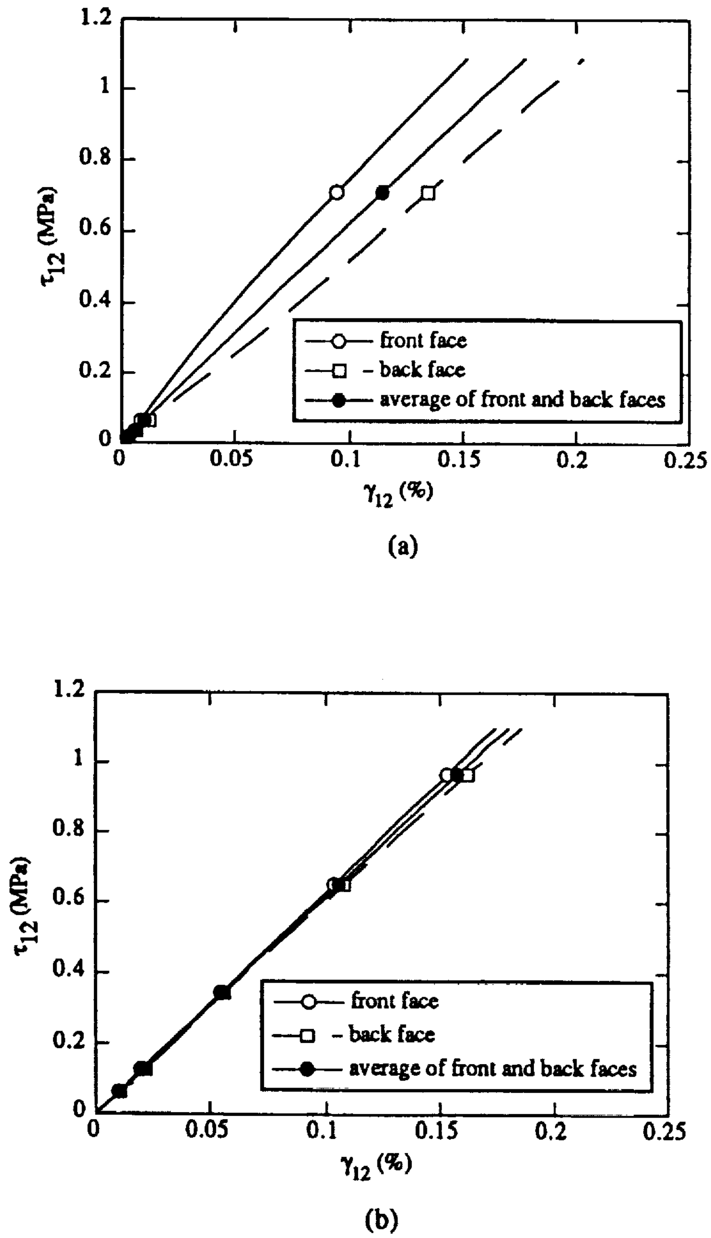
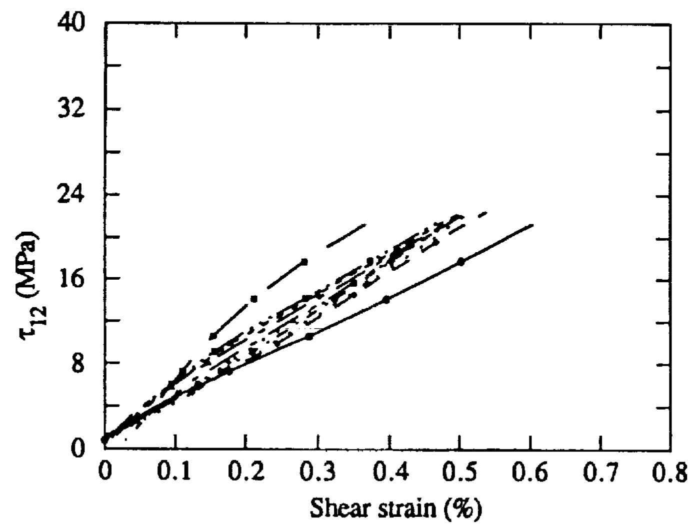


Fig.4 Typical shear stress-strain data (a) before (b) after application of masking tapes to the specimen along load introduction region of a 90° AS4/BMIPES Iosipescu specimen.



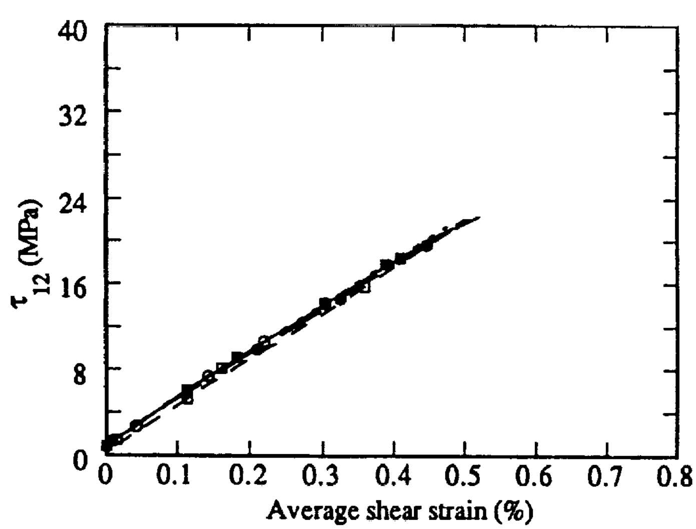
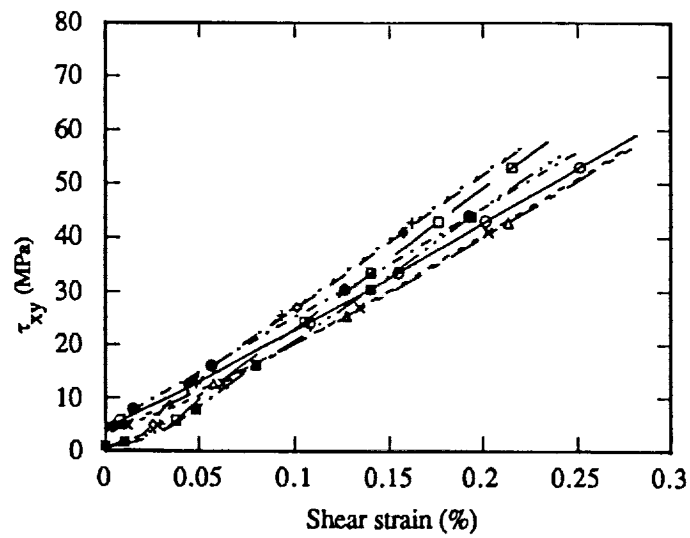


Fig.5 (a) Front and back surface shear stress-strain data for a single 90° graphite-epoxy specimen. Specimen was loaded in different orientations by rotating the specimen about the x, y and z axes. (b) Average of front and back surface shear strains as a function of shear stress for 90° graphite-epoxy specimen.



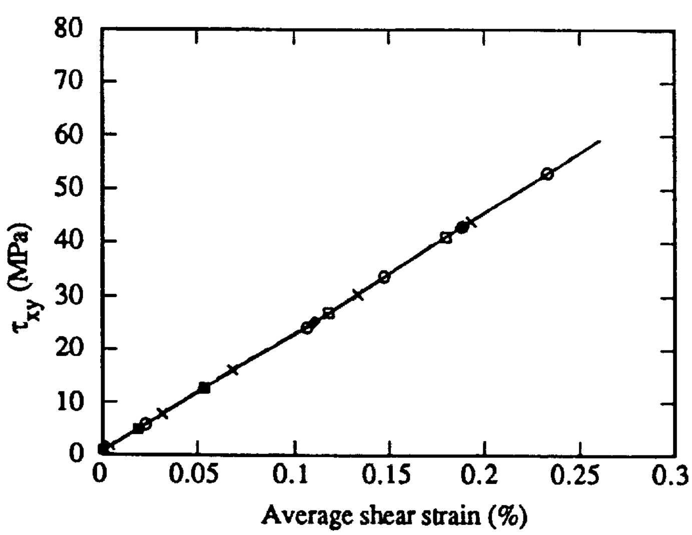
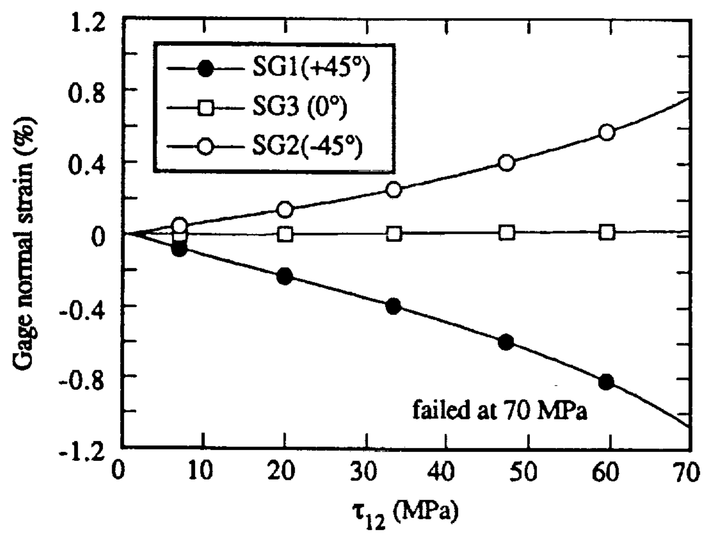
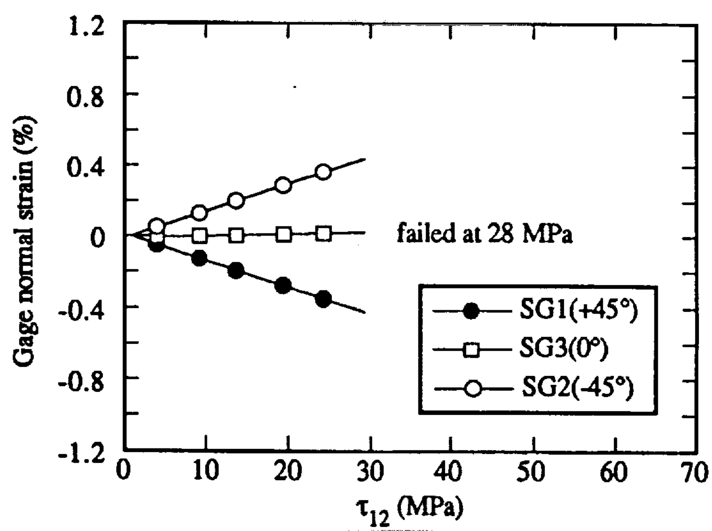


Fig.6 (a) Front and back surface shear stress-strain data for a single aluminum specimen. Specimen was loaded in different orientations by rotating the specimen about the x, y and z axes. (b) Average of front and back surface shear strains as a function of shear stress for aluminum specimen.

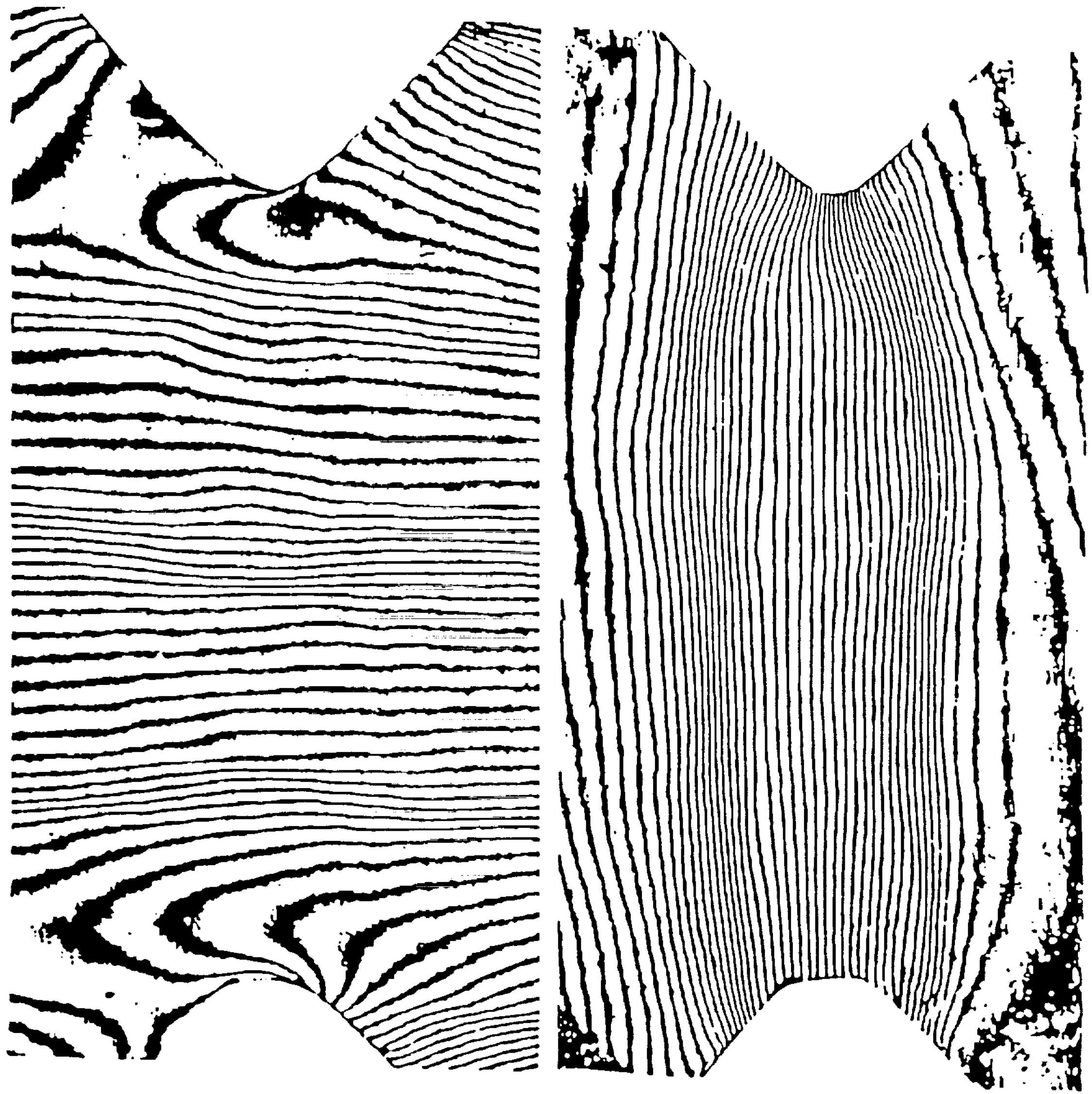


(a)



(b)

Fig.7 Strain vs. stress for typical (a) 0° and (b) 90° graphite-epoxy specimen. Gages are aligned at ±45° and 0° directions.



(a) (b)

Figs. 8a&b Typical moire fringe patterns of the plain weave $[0/90]_{2S}$ specimen at an applied shear stress of 14.2 MPa. (a) u-field, (b) v-field. Carrier rotation is applied such that the deformation information is equally contained in the u- and v-fields.

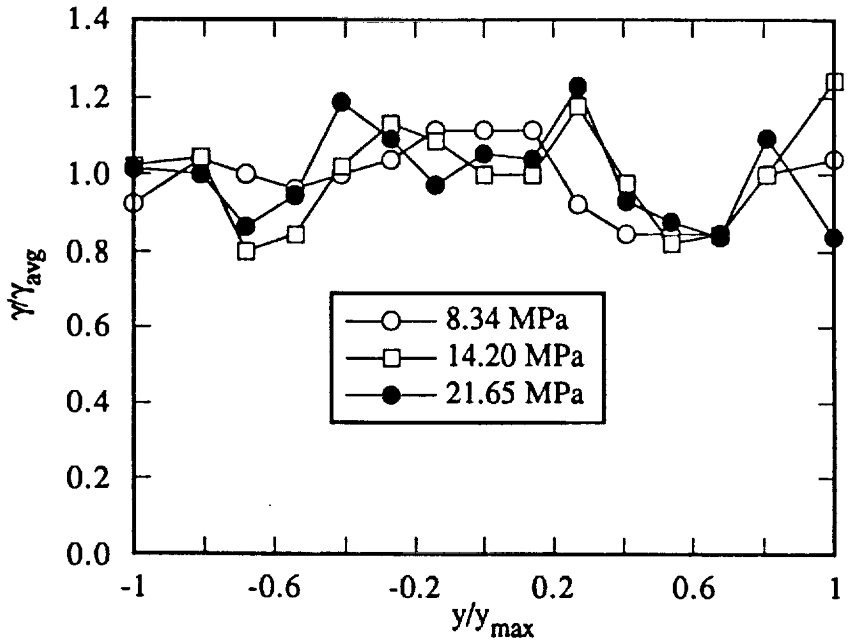


Fig. 9 Shear strains across the notches, normalized with respect to the average shear strain, for plain weave $[0/90]_{2s}$ specimen.

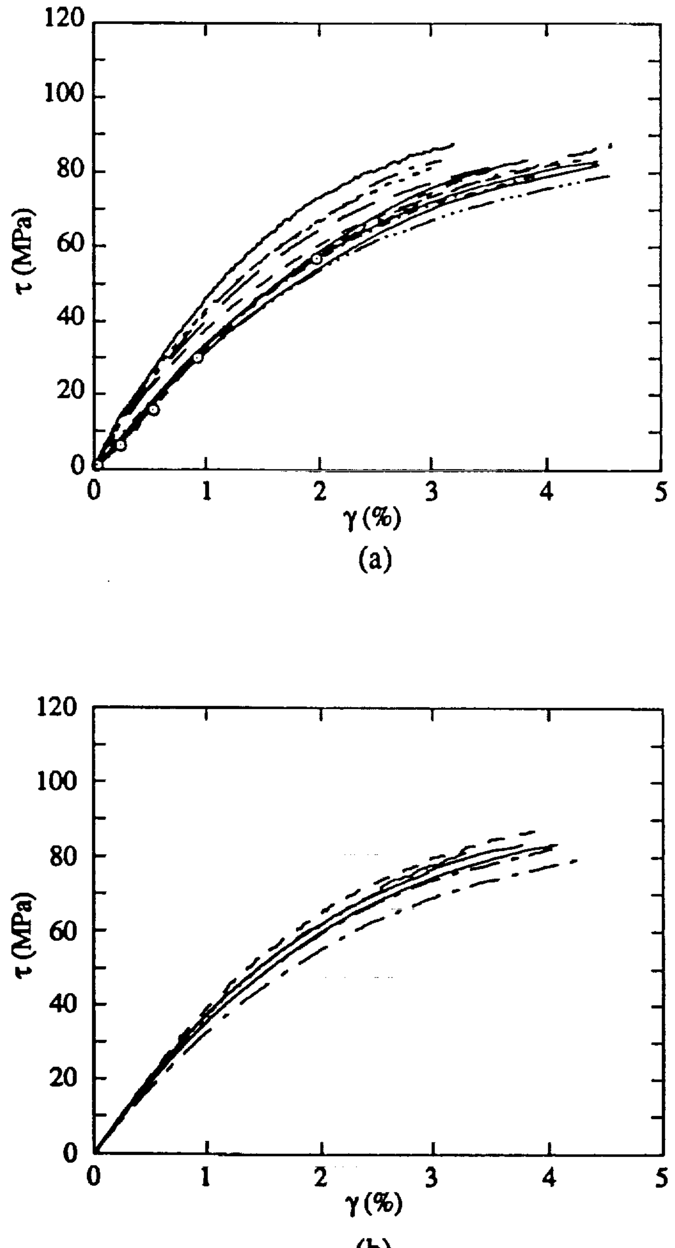


Fig. 10 (a) Shear stress-strain data from front and back faces, (b) average of front and back shear stress-strain data of six plain weave $[0/90]_{2s}$ specimens.

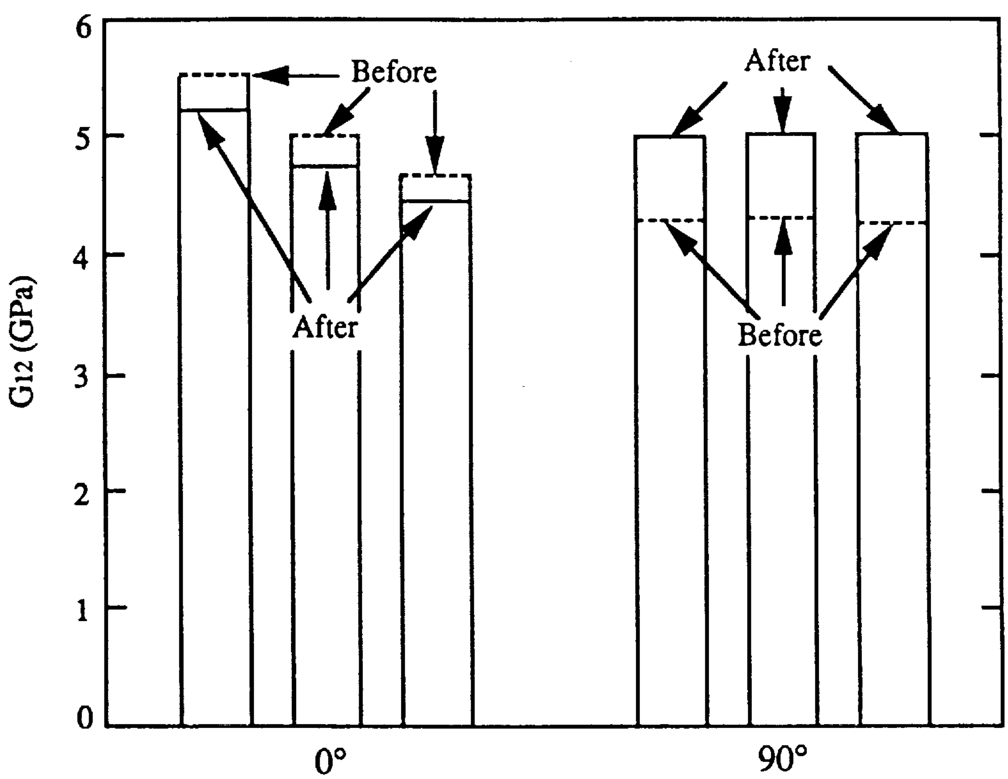


Fig. 11 Calculated G12 for three graphite-epoxy 0° and 90° specimens, before and after application of correction factors.