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SHEAR TESTING OF COMPOSITES

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Introduction

Modern composite materials, incorporating fibers of glass, graphite, boron, etc., in a polymeric or metallic matrix, are finding increasing applications especially where high strength-to-weight and stiffness-to-weight ratios are required. The elastic constants and the strengths of composite materials have to be determined for designing structures utilizing these materials. For an orthotropic composite, there are five in-plane elastic constants and five values of strength that need to be determined. Referring to the in-plane material symmetry axes L and T, the elastic constants are the two Young's moduli E_L, E_T, the shear modulus G_{LT} and the Poisson's ratios ν_{LT} and ν_{TL}. The strength properties are the tensile strengths $S_{Lt} S_{Tt}$, the compressive strengths S_{Lc}, S_{Tc} and the shear strength S_{LT}.

The stiffness and strength properties of orthotropic composites along the material symmetry axes can easily be measured using standard tension or compression specimens. While the procedure is very similar to that of measuring the stiffness and strength of a metal, the following precautions must be observed: (1) The electrical resistance foil strain gage should be large enough to cover several fibers and thus indicate the over-all response of the composite; (2) As the composite can be highly orthotropic, the gages must be aligned very accurately, in order to minimize misalignment errors; (3) While the transverse sensitivity of the strain gages is usually small, sometimes it must be corrected for, as in the measurement of ν_{TL}.

The determination of the shear properties of composite materials has proved to be much more difficult than that of longitudinal and transverse properties. So many methods and variations of each method have been developed that there is now much confusion as to which technique is applicable in a specific application. In this paper, some of the more widely used methods are briefly described and the Iosipescu shear test is considered in detail.

Shear Testing of Composites

An ideal test method must satisfy all or most of the following requirements: (1) The method must be simple and should not require special equipment; (2) The method should use small specimens with simple geometry; (3) The test results should be reproducible;

(4) The data reduction procedure must be simple; (5) A uniform shear stress state accompanied by negligible normal stresses must be produced in the test section.

The block shear test was originally developed for wood and it was applied to glass fiber reinforced composites in the 1950's. In order to overcome the difficulty due to the overturning moment, the symmetric block shear test was developed. But in both versions of the test, a state of pure shear is not produced. Stress concentrations are also present. In the mid-1960's, when the use of composite materials was rapidly increasing, the short beam shear test was developed for quality control. The test is simple but the shear stress is non-uniform and is accompanied by significant normal stresses. Crushing at the loading and support points is also a problem.

The torsional shear of a circular thin-walled tube is the ideal test method to determine the shear modulus and the shear strength of any material. But from the practical point of view there are problems: (1) The cost of composite tubular specimens is very high; (2) The test apparatus tends to become more complex than at first it appears because bending must be avoided and the tube must be free to move axially; (3) Precautions must be taken to avoid crushing the regions where torques are introduced and also buckling.

The rail shear test is one of the more popular methods and it provides a good measurement for the shear modulus. In this method, a composite specimen is gripped along each side of a long narrow central region and the grips are loaded in opposite directions. The central region is assumed to be in pure shear. But the grips introduce normal stresses [1]. The picture-frame shear test is also commonly used. In this test, a uniaxial tensile or compressive load is applied at two diagonally opposite corners of a rigid frame which is attached to the edges of a composite plate specimen. The biaxial picture-frame test, in which equal tensile and compressive forces are simultaneously applied along the frame diagonals, provides a more uniform shear stress in the specimen. But both versions require expensive test fixtures and significant amounts of test material.

The off-axis tensile test utilizes a tensile specimen with the reinforcement oriented at a suitable angle to the specimen axis. An angle of 10 degrees has been strongly recommended [2]. While this test has the merit of being very simple, care must be taken in machining the specimen and in mounting the strain gages as small misalignments can lead to very large errors. Unlike conventional tensile tests, a large aspect ratio is required. A ratio of fifteen or greater has been suggested. Due to the presence of the normal stresses, this test gives the shear modulus and not the shear strength.

The slotted-tension shear test is based on the principle that a uniform shear stress exists in a region if equal orthogonal tensile and compressive stresses are imposed on the element's edges. Planes of pure shear will exist at 45 degrees to the load axes. A slotted tensile specimen has been suggested [3]; the slots machined parallel to the longitudinal axis of the specimen ensure that the transverse compressive stresses are transmitted only to the test section. This shear test provides both the shear modulus and shear strength. The major disadvantage of this method is the complexity of the test apparatus which must ensure that the two orthogonal stresses must be equal at all times.

The Iosipescu shear test and one of its modifications are described in the following sections.

Iosipescu Shear Test

The Iosipescu shear test was originally developed [4] in the 1960's for determining the shear properties of metals and has recently been adapted for composite materials. In an isotropic material, the Iosipescu shear test induces a state of pure shear at the specimen mid-section by applying two counteracting moments. Ninety-degree notches are machined in the specimen, as shown in Fig. 1. The parabolic shear stress distribution found in beams of constant cross-section is changed to a constant shear stress distribution in the region between the notches. As shown in Fig. 2, the specimen midsection (between the notches) is free of any bending stress.

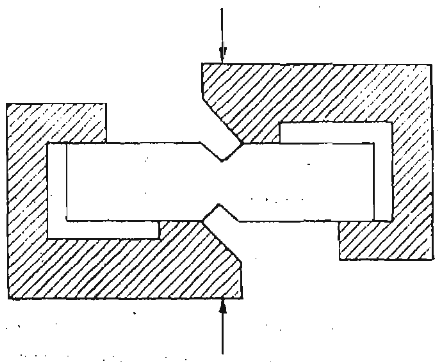

Fig. 1. Iosipescu shear specimen

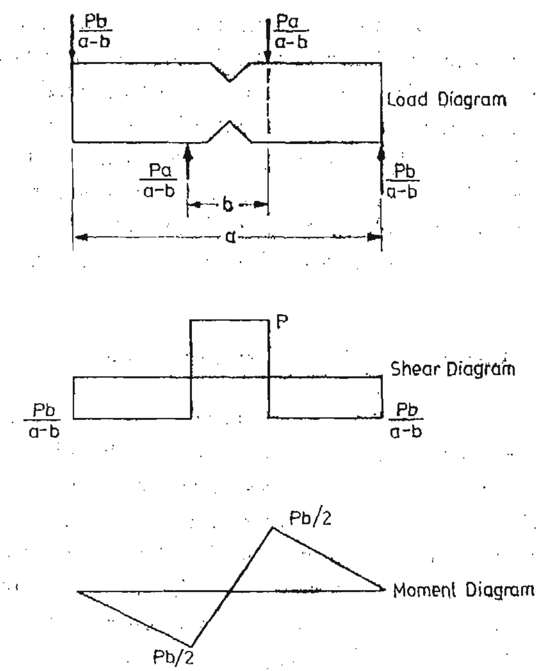

Fig. 2. Loading, shear and moment diagrams for Iosipescu specimen

An extensive finite element analysis of the Iosipescu specimen has been performed [5]. It has been shown that while the longitudinal stress due to bending is small over the test section, significant transverse compressive stresses are present due to the applied loads. The normalized reaction force profile for the upper loading point [5] is shown in Fig. 3. The compressive stresses rise rapidly towards the edge of the notch and the influence of these loading-induced compressive stresses extends into the test section of the specimen.

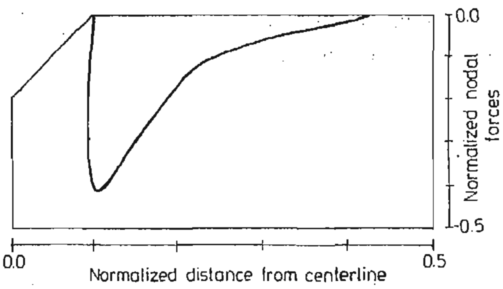

Fig. 3. Normalized compressive force distribution for Iosipescu specimen

This indicates that the loading surfaces need to be shifted away from the notches in the specimen.

Normalized shear stress contours indicate a shear stress concentration factor of 1.3 for isotropic materials and a shear stress concentration factor of 2.0 for orthotropic materials with an orthotropy ratio of 13. These results show that the notch geometry needs to be modified in order to minimize the shear stress concentration. In reference [5], the effect of notch depth, notch angle and notch tip radius on the shear stress concentration has been studied by finite elements. The notch depth does not appear to have any significant influence. In the case of isotropic as well as orthotropic materials, as the notch angle is increased from 90° to 120°, the shear stress concentration decreases while the average shear stress across the test section tends to be more uniform. The notch tip radius has a very similar influence. From a sharp notch, as the radius at the notch tip is increased to 0.100 in., the shear stress distribution becomes more uniform and the shear stress concentration drops, especially for materials with a high degree of orthotropy.

Asymmetrical Four Point Bend Shear Test

This test is an outgrowth of the Iosipescu shear test and the specimen mid-section is again subjected to a shear force without an accompanying bending moment [6]. The test, as shown in Fig. 4, applies concentrated forces to the specimen through cylindrical rods which can cause local crushing on the edges of the specimen. Doublers must be glued on to the faces of the specimen to prevent this crushing. The specimen need not be machined to the same close tolerances as in the Iosipescu test. This test appears good but there are still uncertainties in the test results because of the influence of the notch parameters. An extensive analytical and experimental investigation of this test has been performed [7]. It has been shown that when an attempt is made to optimize the notch parameters to obtain favourable stress distributions, the failure mode changes unexpectedly. The result is that the test section does not fail in a pure shear mode. Free edge effects have been proposed as the cause of this phenomenon. For a quasi-isotropic graphite-epoxy laminate, the 90°-sharp notch appears to give the best result in terms of a pure shear failure. Further work needs to be done to optimize the notch parameters for orthotropic materials.

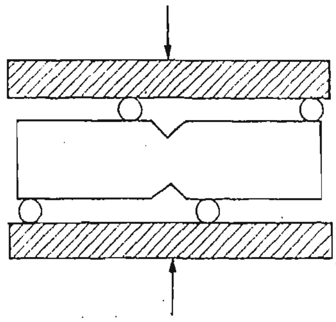

Fig. 4. Asymmetrical four point bend shear specimen

Photoelastic Calibration of Birefringent Orthotropic Materials

In recent years, the extension of transmission photoelastic techniques to transparent birefringent orthotropic composites has received considerable attention from researchers. Such materials are characterized by three fundamental photoelastic constants. The stress fringe values are f_L, f_T, and f_{LT}, corresponding to the two normal stress components parallel and perpendicular to the major material symmetry axis and to the shear stress component. While these three photoelastic properties can be calculated from simple stress-strain models [8], they can also be obtained from the photoelastic calibration of tensile, compressive or bending coupons. If the fiber orientation (or the direction of the major material symmetry axis) is parallel or perpendicular to the specimen axis, then f_L and f_T are obtained, respectively. As the application of a pure shear stress is not straightforward, a third specimen with an angle of 45 degrees between the major material symmetry axis and the specimen axis is calibrated in tension. The resulting stress-fringe value $f_{\pi/4}$ is used to calculate f_{LT} by the following equation:

$$f_{LT} = \left[\frac{1}{f_{\pi/4}^2} - \frac{1}{4}\left(\frac{1}{f_L} - \frac{1}{f_T}\right)^2\right]^{-1/2}. \qquad (1)$$

The circular disk specimen that is commonly used to calibrate isotropic model materials has not been used in the calibration of orthotropic model materials because a closed-form theoretical solution is not available. The fringe values f_L and f_T can be obtained by testing a circular disk with strain gages but f_{LT} cannot be determined.

A half-plane specimen with photoelastic coating has been utilized [9] in measuring the in-plane elastic constants of orthotropic composites. The half-plane specimen has also been used for simultaneous measurement of orthotropic elastic and photoelastic constants [10]. One half of the specimen is utilized for the measurement of elastic constants and the other half is useful for photoelastic observations. A sketch of the specimen, with the locations of the strain gages, is shown in Fig. 5. Composite laminates are heterogeneous materials which are assumed to be homogeneous for engineering applications. Usually average properties of the laminates are required. A least squares procedure that uses over-determined experimental data is ideally suited for this type of measurement [11].

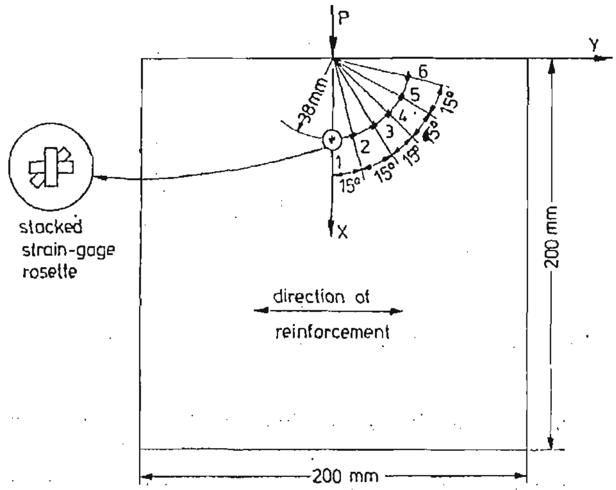

Fig. 5. Half-plane specimen with strain gages

The governing equation is written in terms of the required parameters in the general form

$$g_k = (A, B, C, D) = 0. \tag{2}$$

where $k = 1, 2, \ldots, M$ ($M > 4$) refers to particular points in the data field. The parameters to be evaluated are A, B, C and D. Expanding Eq. (2) in a Taylor's series,

$$(gk)_{i+1} = (gk)_i + \left[\frac{\partial g_k}{\partial A}\right]_i \Delta A + \left[\frac{\partial g_k}{\partial B}\right]_i \Delta B + \left[\frac{\partial g_k}{\partial C}\right]_i \Delta C + \left[\frac{\partial g_k}{\partial D}\right]_i \Delta D \tag{3}$$

where i refers to the iteration-step number i and ΔA, ΔB, ΔC, ΔD are the corrections to the previous estimates of the corresponding parameters. Since the desired result is $(gk)_{i+1} = 0$,

$$\left[\frac{\partial g_k}{\partial A}\right]_i \Delta A + \left[\frac{\partial g_k}{\partial B}\right]_i \Delta B + \left[\frac{\partial g_k}{\partial C}\right]_i \Delta C + \left[\frac{\partial g_k}{\partial D}\right]_i \Delta D = -(g_k)_i . \tag{4}$$

Rewriting the above equation in matrix notation,

$$[g] = [b][\Delta E] \tag{5}$$

where

$$[g] = \begin{bmatrix} -g_1 \\ -g_2 \\ - \\ - \\ -g_M \end{bmatrix}, \tag{6}$$

$$[b] = \begin{bmatrix} \frac{\partial g_1}{\partial A} & \frac{\partial g_1}{\partial B} & \frac{\partial g_1}{\partial C} & \frac{\partial g_1}{\partial D} \\ - & - & - & - \\ - & - & - & - \\ \frac{\partial g_M}{\partial A} & \frac{\partial g_M}{\partial B} & \frac{\partial g_M}{\partial C} & \frac{\partial g_M}{\partial D} \end{bmatrix}, \tag{7}$$

$$[\Delta E] = \begin{bmatrix} \Delta A \\ \Delta B \\ \Delta C \\ \Delta D \end{bmatrix}. \tag{8}$$

Solving Eq. (5),

$$[\Delta E] = [d]^{-1}[b]^{T}[g] \tag{9}$$

where

$$[d] = [b]^{T}[b]. \tag{10}$$

In implementing the above procedure, initial values of A, B, C, D are assumed and the matrices $[g]$ and $[b]$ are computed. Then the error vector $[\Delta E]$ is calculated and the estimates of A, B, C and D are revised. The steps are repeated until the convergence is satisfactory.

Considering a load P applied perpendicular to the edge of an orthotropic half-plane, with the major material-symmetry axis parallel to the loaded edge of the half-plane, the stress components in polar coordinates are given [12] by

$$\sigma_r = \frac{2P\sin\theta}{\pi r t(\alpha_1^{1/2}-\alpha_2^{1/2})}\left[\frac{\alpha_2-1}{\alpha_2+1+(\alpha_2-1)\text{Cos}2\theta} - \frac{\alpha_1-1}{\alpha_1+1+(\alpha_1-1)\cos 2\theta}\right] \tag{11}$$

$$\sigma_\theta,\ \tau_{r\theta} = 0 \tag{12}$$

where t is the thickness of the half-plane, θ is the angle from the loaded edge and α_1 and α_2 are derived elastic constants given by

$$\alpha_1\alpha_2 = E_T/E_L, \tag{13}$$

$$\alpha_1+\alpha_2 = E_T/G_{LT}-2\tau_{TL}. \tag{14}$$

The radial strain, ϵ_r at any point is given by

$$\varepsilon_r = \sigma_r/E_r \tag{15}$$

where

$$E_r = \left[\frac{1}{E_L}\cos^4\theta + \left(\frac{1}{G_{LT}} - \frac{2\nu_{LT}}{E_L}\right)\sin^2\theta\cos^2\theta + \frac{1}{E_T}\sin^4\theta\right]^{-1}. \tag{16}$$

For the elastic calibration, Eq. (15) together with Eq. (16) is the governing equation. It can be written as

$$g_k(\alpha_1, \alpha_2, E_T) = 0. \tag{17}$$

The least-squares method is employed to determine. The strain readings from the gages at location 1 can be directly used to compute ν_{TL}.

For the photoelastic calibration, the isochromatic fringe order per unit thickness, N, can be expressed as

$$N = \sigma_r \left[\left(\frac{\cos^2\theta}{f_T} - \frac{\sin^2\theta}{f_L} \right)^2 + \frac{\sin^2 2\theta}{f_{LT}^2} \right]^{1/2} + Ar + B \tag{18}$$

where the term $Ar+B$ accounts for the residual birefringence due to the matrix shrinkage during the fabrication process. The governing equation can be written as

$$g_k(f_L, f_T, f_{LT}, A, B) = 0. \tag{19}$$

The least-squares procedure gives f_L, f_T, f_{LT}, A and B.

Conclusions

To measure the shear modulus and the shear strength of composite materials, the Iosipescu and the Asymmetric Four Point Bend tests are very promising. But analytical and experimental work needs to be performed to establish optimum specimen geometry and loading. To measure the in-plane elastic and photoelastic constants of birefringent composites, the half-plane specimen appears very promising. The least-squares procedure gives the average properties of the model material by employing over-determined experimental data.

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Р е з ю м е

ИСПЫТАНИЯ КОМПОЗИТОВ НА СДВИГ

Исследованы распределения напряжений в сечениях образцов на сдвиг в зависимости от вида подкрепления и радиуса нарезок. Исследования проведены на образцах Йосипеску, их модификации, а также методом асметричного испытания на сдвиг.

S t r e s z c z e n i e

PRÓBY NA ŚCINANIE KOMPOZYTÓW

Zbadane zostały rozkłady naprężeń, w przekrojach próbek z karbami w zależności od sposobu podparcia i promienia karbu. Badania przeprowadzono na próbkach Josipescu i ich modyfikacji oraz metodą asymetrycznej próby zginania.

Praca została złożona w Redakcji dnia 20 kwietnia 1985 roku