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INDUCING ‘PURE’ MODE II SHEAR FAILURES IN LAMINATED COMPOSITES

S. R. Short, Ph.D., P.E.[1] and C.P. Sastry[1]

[1] Department of Mechanical Engineering, Northern Illinois University,
DeKalb, IL 60115, USA

ABSTRACT

A thorough knowledge of the resistance to delamination of laminated composite materials requires a test method capable of inducing Mode II fractures. However, pure Mode II (interlaminar shear) failure can be difficult to produce in a test coupon. Several researchers have documented the propensity of the typical flexure-type interlaminar shear test specimen to be adversely affected by a complex stress state near the region of loading and hence exhibit mixed-mode fracture characteristics. In the effort to induce a pure state of shear on the failure plane, a sandwich-coupon, flexure-test specimen has been suggested by the lead author. Such a specimen is capable of producing nearly pure interlaminar shear failures in graphite/epoxy laminates. The current research presents closed-form and finite element analysis results characterizing the stress state within the region of fracture initiation. The resulting shear failures are characterized with respect to fracture pattern, mode of failure, and stress state on the failure plane.

KEYWORDS

Mode II, interlaminar shear, fracture, composites, graphite-epoxy

INTRODUCTION

Strength theories based on failure criteria are essential to composite materials designers to enable prediction of the behavior of structural elements under complex loading. Subsequent to formulation, these strength theories must be verified by comparison with measured strengths. This verification process involves the development of test methods capable of producing a prescribed state of stress and failure mode within a test specimen.

In the past, engineers have relied upon the short-beam shear (SBS) test, as described in ASTM D2344 [1], to interrogate interlaminar shear failures and to provide an estimate of the interlaminar shear strength of composite materials. However, despite its popularity, the short-beam shear test is affected by complications that are not incorporated into the elementary Euler-Bernoulli beam theory upon which interpretation of the test method is based. According to the assumptions associated with this theory, the interlaminar shear stress is parabolically distributed across the face of the specimen with a maximum occurring at the midthickness plane. Unfortunately, the short-beam shear test configuration is deliberately chosen so that the interlaminar shear stress in the beam dominates the stress distribution.

Clearly, the behavior of a short beam deviates from that predicted by the elementary theory [2]. Numerous investigations have indicated the presence of high shear stresses near the concentrated load and supports as depicted in Figure 1 [3,4]. That such complex stress states exist within SBS specimens is corroborated by their typical fracture pattern as shown in Figure 2.

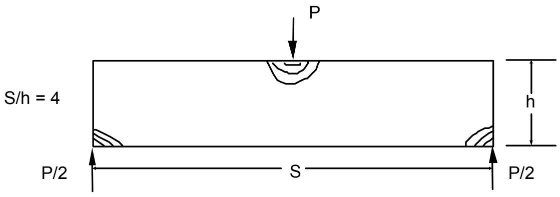

Figure 1: Stress concentrations affecting the short-beam shear (SBS) test

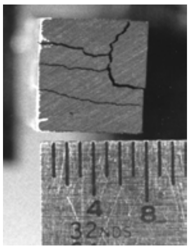

Figure 2: End view of a typical graphite/epoxy SBS test specimen

Analysis shows that the short-beam shear test configuration yields stress concentration effects which are never fully dissipated as St Venant's principle is not satisfied in a highly orthotropic beam of low span-to-depth ratio. While stress concentration effects are reasonably well localized in a standard flexural beam test, the dimensions of the short-beam shear test specimens used to test high-performance composites, such as graphite/epoxy, preclude the dissipation of stress concentration effects. Closer inspection of short-beam shear test specimen failures indicates the presence of microbuckling and microcracking in the region near the load roller. It has been theorized that initial damage in the form of vertical cracks may be necessary to induce the horizontal interlaminar failures observed. Thus, despite its simplicity and popularity, the short-beam shear test method is not appropriate for a general study of interlaminar shear failures of composite materials.

In an attempt to produce true interlaminar shear failure in laminated composite materials, alternatives to the standard short-beam test have been suggested. Some experimenters have proposed the use of thicker short beams; e.g. 50 plies, or the use of a four-point flexure test [5]. Thicker short-beam specimens, however, are still prone to vertical cracking in the load roller region, precluding true interlaminar shear failure. And, investigations have verified that the four-point flexure test is also adversely affected by stress concentrations in the regions of loading resulting in microbuckling and vertical cracking.

The ideal interlaminar shear test method should provide a region of pure, uniform shear stress within the test section of the specimen. Test results should not be affected by the presence of a complex stress state in the region of eventual specimen failure. Toward this goal, a simple test method capable of producing a state of pure interlaminar shear stress within a specified region of a flexure test specimen was developed by the lead author [6]. The test method employed an adhesively bonded test specimen referred to as the steel/composite/steel (SCS) test sample tested in four-point flexure (see Figure 3).

In that research, an SCS test sample was constructed of a coupon of Hercules AS4/3501-6, unidirectional, graphite/epoxy material, bonded between two thin strips of heat-treated steel using an epoxy adhesive. The design of the SCS test sample confined the composite material to the midthickness region of the beam where the stress state approached that of uniform shear. The steel face strips dissipated the stress concentration effects in the vicinity of the load and support points. Interlaminar shear failures along the midplane of the composite test coupon were achieved (see Figure 4). The propagation of the interlaminar shear failures produced by the SCS test sample was monitored using a crack detection device developed by Camping and Short [7]. The interlaminar shear failures of the specimens tested (5 replicates) were all found to follow the same general pattern of propagation, i.e., once the shear failure initiated in the region of pure shear stress between a load and support, it propagated in both directions along the length of the beam, first reaching the end of the specimen closest to the failure initiation site. The shear failure propagated through the zone of compressive stress corresponding to the support region, into the beam overhang region, and out to the end of the specimen.

The failure then propagated in the opposite direction, back into the flexure specimen, through the zone of compressive stress corresponding to the load region, terminating under the load roller farthest away from the failed end. The final interlaminar shear failure appeared as shown in Figure 5.

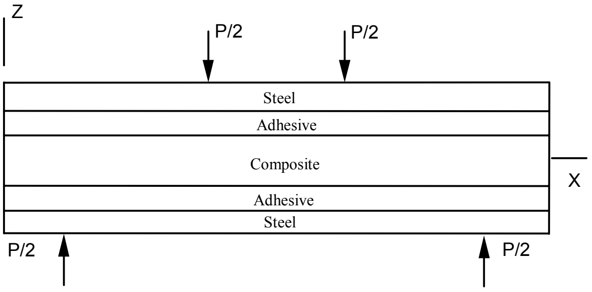

Figure 3: SCS test sample

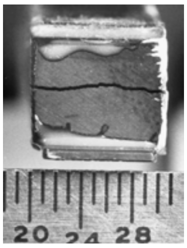

Figure 4: End view of a typical graphite/epoxy SCS test specimen (markings on scale shown are 1/32 in.)

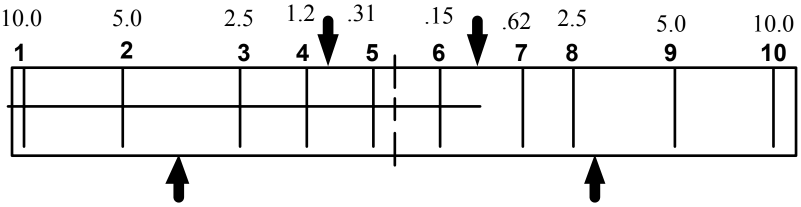

Figure 5: Final location of shear failure in SCS test sample (numbers refer to location of sensors of crack detection device [7]).

Short [6] reasoned that from the results of using the crack detection device, the scanning electron photomicrographs of the fracture surfaces presented for the region between the load and support correspond to that of pure interlaminar shear failure of unidirectional graphite/epoxy material. It was also noted that the fracture surface appearance was somewhat different from that usually reported in the literature as being representative of the pure shear failure of unidirectional graphite/epoxy composites. However, it is noted that in much of the work presented in the literature, the test methods used to produce the shear failures are not reported. Therefore, the question still remained as to whether the interlaminar shear failures produced by the SCS test sample do indeed represent 'pure' Mode II shear failures. Citing the work by Filon [8], Short reasoned that the magnitude of the through-thickness normal stress, σ_z , in the region between the load and supports damps out to such a degree that it can be considered to be fairly negligible on the failure plane (midplane). To answer this question, a more accurate estimate of the stress state on the failure plane between the load and support regions was required.

FINITE ELEMENT STRESS ANALYSIS

The three stress components σ_y , τ_{xy} , τ_{yz} , have little direct effect on the interlaminar shear failure due to the design of the SCS test sample and the nature of the flexure test. Furthermore, since previous research using the crack detection device verified that the shear failures initiate approximately on the midthickness plane of the SCS test sample, between a load and support region, it was assumed that the bending stress, σ_x , also has negligible effect on the failure. Hence, the through-thickness normal stress, σ_z , and the interlaminar shear stress, τ_{xz} , are the only stress components that significantly affect the interlaminar shear failure.

The finite element analysis (FEA) was performed using the software program ANSYS$^{©}$. A plane stress analysis was performed modeling only half of the SCS test sample due to symmetry. A total of five areas each representing one of the component layers was created. These areas were subsequently merged.

The composite region was modeled using a "lumped parameter" model based on the work by Post et. al. [9]. This model uses finite elements to represent resin-rich regions within the unidirectional graphite-epoxy laminate. This is consistent with the materialographic inspection of the composite laminate and also with the load-deflection results of the flexural testing. Contact stress elements were used to model the load and support regions.

DISCUSSION OF RESULTS

Excellent agreement was obtained between the FEA and experimental beam deflection and beam strain results as determined via strain gages. Five replicate SCS test samples were tested. Such agreement among the kinematic results supports the position that the corresponding FEA stress analysis results are fairly accurate. The distribution of the interlaminar shear stress, τ_{xz} , along a vertical line midway between the load and support rollers is shown in Figure 6. The abscissa represents the thickness of the SCS test sample with DIST = 0 representing the supported surface of the beam. The maximum value of interlaminar shear stress corresponding to the fracture load experienced by the SCS test sample at the midplane is 101.42 MPa. This compares favorably with the value 99.94 MPa reported by Short [6] using a closed-form analysis.

Figure 7 shows the distribution of the through-thickness normal stress, σ_z , on the midthickness plane between the load and support rollers. The minimum value of the abscissa is representative of a point on the midthickness plane, which lies on a vertical line drawn upward from the center of the support roller. The maximum value indicates a similar point with respect to the load roller. The distance between the two rollers is 15.24 mm. At the midpoint between the load and support rollers, the through-thickness normal (compressive) stress, σ_z , is 1.8 MPa, approximately 5% of the maximum interlaminar shear stress.

Figure 8 shows the distribution of the through-thickness normal stress, σ_z , beneath the load. The abscissa is representative of the beam thickness with the minimum value corresponding to the supported face. The results show that the compressive through-thickness normal stress, σ_z , is mostly dissipated by the top steel strip. The magnitude of this stress at the composite/adhesive interface is approximately 15% of the maximum compressive stress at the top face of the steel strip.

Previous research [6] showed that the SCS interlaminar shear failures initiated within a region of the beam approximately 5-mm wide, located symmetrically about a plane midway between the load and support. The results of the finite element analysis show that the average through-thickness normal stress acting in this region is approximately 5% of the maximum interlaminar shear stress. Therefore, it can be concluded that the crack initiation zone was subjected to a state of relatively pure Mode II interlaminar shear stress. The steel plates in the SCS test sample design proved effective in damping the stress concentration effects of the normal stress due to the load and supports. These stress concentration effects are known to promote failures in standard short-beam shear specimens.

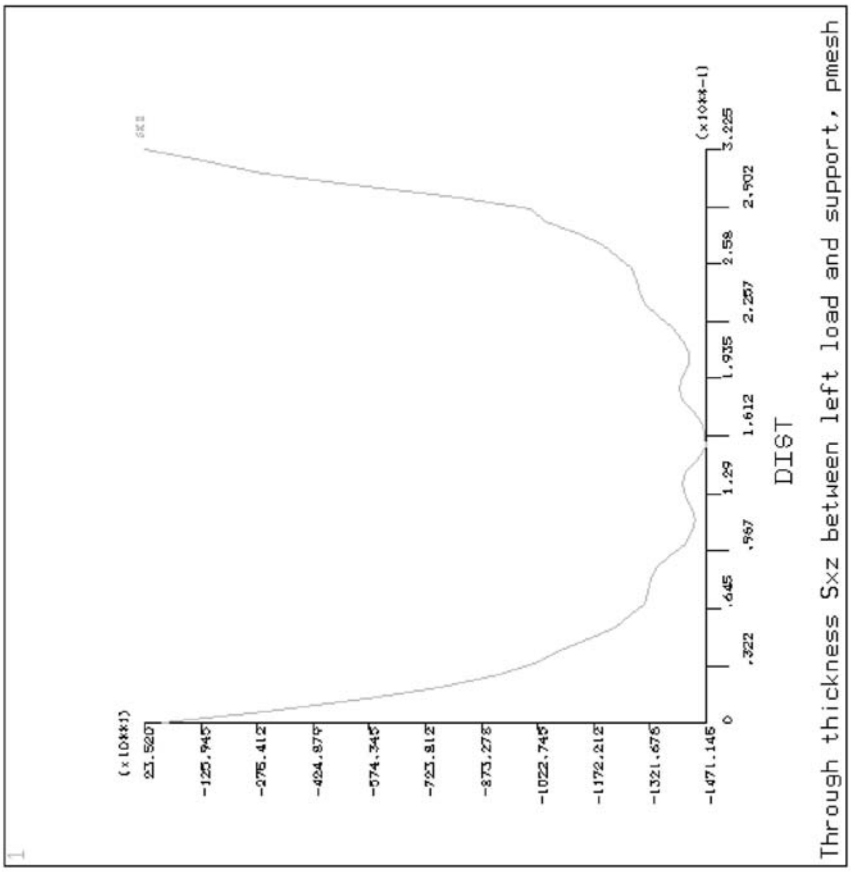

Figure 6: Interlaminar shear stress, τ_{xz} , midway between the load and support

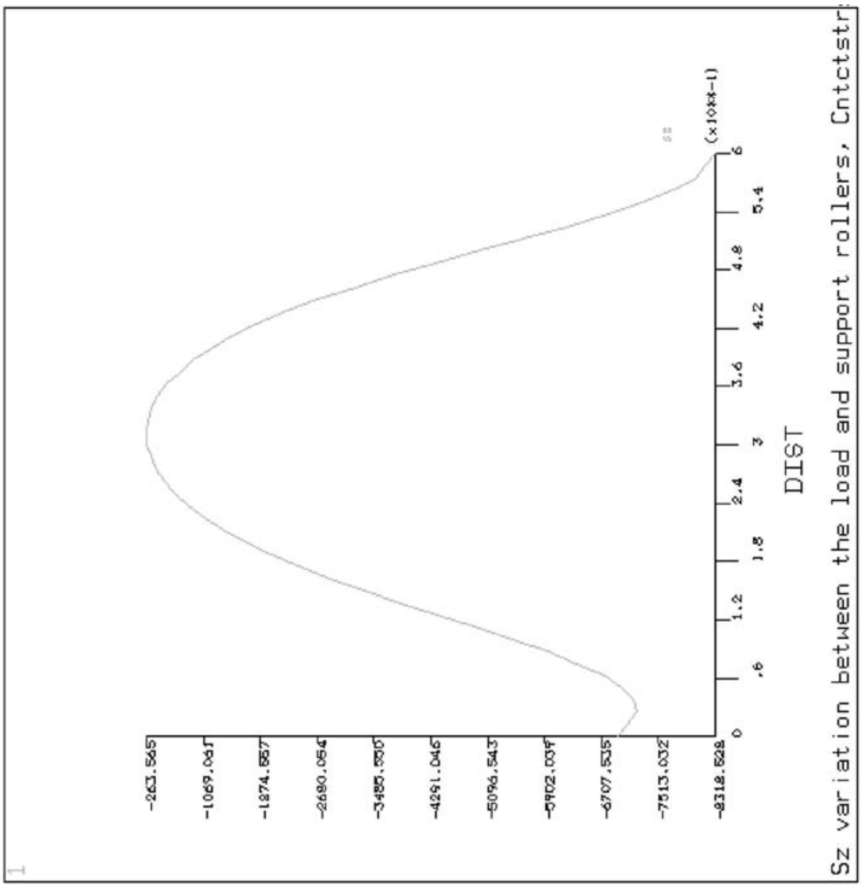

Figure 7: Through-thickness normal stress, σ_z , on midthickness plane between the load and support

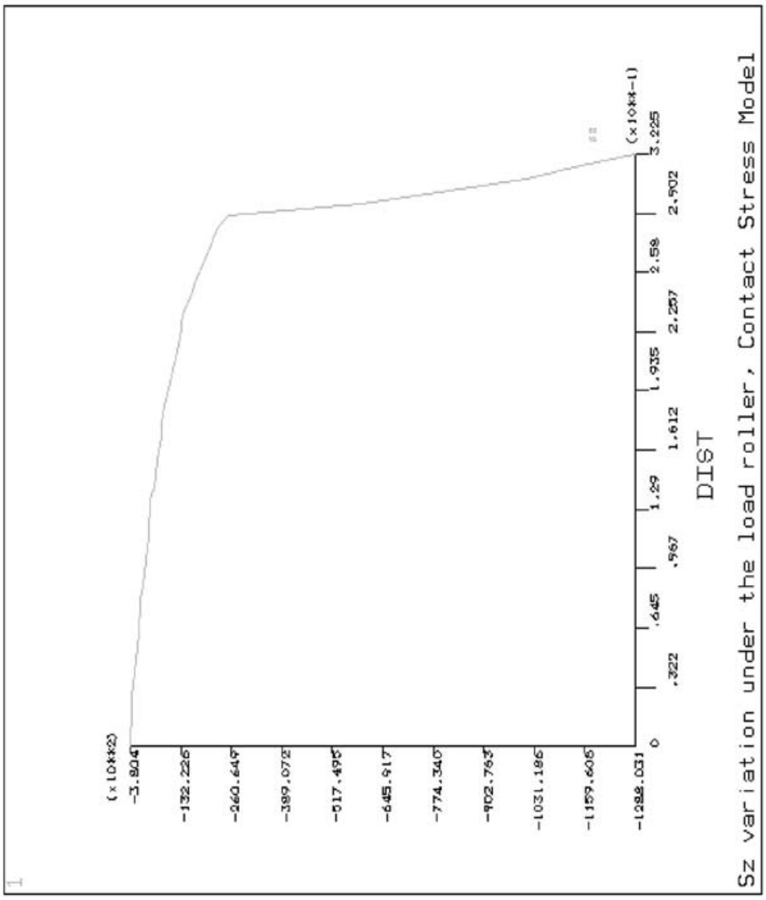

Figure 8: Through-thickness normal stress, σ_z , beneath the load

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