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INTERLAMINAR SHEAR TEST FOR LAMINATED TEXTILE FABRIC COMPOSITES

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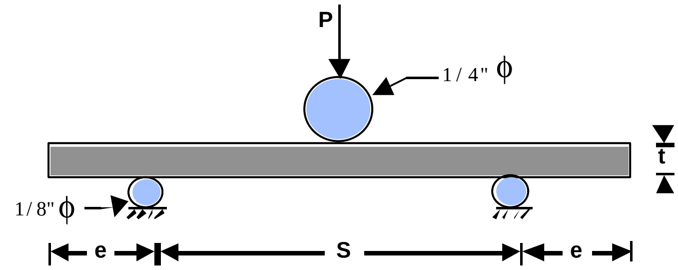
SUMMARY: Modified short beam shear (MSBS) test was used to measure interlaminar shear strength (ILSS) of nine different textile fabric composites. This includes carbon and glass fibers from unidirectional to 8-harness satin weaves and engineered layered fabrics with through-the-thickness interlocks. The resin system varied from brittle 5208 epoxy to marine grade vinyl ester, toughened SC-15 epoxy and carbon matrix. Test results from MSBS were very consistent with failure modes and small data scatter (standard deviation <3%) compared to standard and 4-point short beam shear tests. Therefore MSBS is simple and accurate test to measure ILSS of laminated composites. A detailed nonlinear finite element stress analysis of the test specimen with different composites having different transverse shear to flexural moduli showed that the beam theory shear stress equation requires a correction. The correction factor κ is 1 for isotropic and relatively high G_{xz}/E_x whereas it is 0.95 for shear flexible composites (G_{xz}/E_x>10) carbon/epoxy.

KEYWORDS: Laminated Composites, Interlaminar Shear Strength, and Modified Short Beam Shear Test

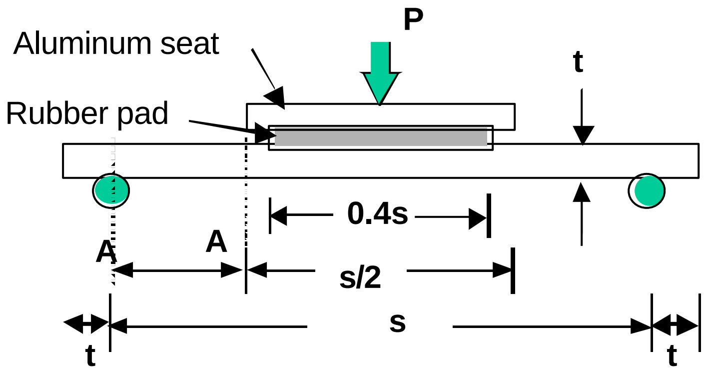
INTRODUCTION

Interlaminar Shear Strength (ILSS) is an important material property for design of laminated composite structures subjected to transverse loads. American Society for Testing and Materials (ASTM) [1] proposes two test standards: short beam shear (D2344) and double-notched shear (D3846-99) to measure ILSS of laminated polymeric composites. The four-point short beam shear test (ASTM D790) was also used in the literature. Both standard short beam shear (SBS) and 4-point shear (4P-SBS) tests have limitations. A number of analytical and experimental studies [2-6] have been conducted to determine the validity of these tests. The analytical studies include classical anisotropic beam and laminate analyses [2,6], and linear and non-linear finite element analyses [3-5]. A review of these studies conclude that SBS test, at best, gives a qualitative value of ILSS, and many times failure was not interlaminar shear, instead by indentation and/or flexure. A major problem of this test is the indentation deformation and concentration of compressive and transverse shear stresses at the loading head. Furthermore, in textile fabric composites the waviness of fiber reduces the compression strength [7] and causes the compression failure on the loading side. The brittle matrix composites, like carbon/carbon composites are crushed under the loading head. Although, the 4P-SBS is a better test for ILSS measurements, loading heads restricts the specimen size. Thin specimens cannot be tested by the standard (1/4" dia.) loading heads. Smaller diameter loading heads will aggravate the indentation failure. Therefore, a larger diameter loading head [4] and tabbed (sandwich) specimen [8] are the alternate methods suggested in the literature.

Recently, Abali et al. [9] suggested a modification to SBS test to alleviate the problems mentioned above. In this modified short beam shear test (MSBS), the central point loading is distributed uniformly over the middle half-span of the beam. This was achieved by the use of two pads (one stiff and the other soft) between the loading head and the specimen. Figure 1 shows the standard and modified short beam shear specimen configurations and loading. The pads can also be used (with reduced length) at the two supports, however the test results show no such need. Abali et al., also showed through simple beam and nonlinear contact finite element analysis that the maximum interlaminar stress is at least three times the material ILSS when the flexural failure occurs for a range of composites considered.



a. Standard short beam shear test.



b. Modified short beam shear test.

Figure 1. Standard and modified short beam shear tests.

The objective of this paper is to use MSBS test to measure interlaminar shear strength of various textile fiber laminated composites. This includes 2-D and 3-D woven glass as well as carbon fibers and various matrix systems. The second objective is to provide a correction factor for the ILSS beam equation through a detailed nonlinear contact finite element analysis.

SPECIMEN CONFIGURATION AND LOADING

Figure 1(b) describes the specimen configuration and loading. The span is s, thickness is t, width is b, and the over-hang length (or edge distance) is t. The s/t ratio proposed to be 5, for thin specimens and it could be 4 for thick specimens. These dimensions are the same as those in the ASTM D-2344 standard [1]. Aluminum and silicon rubber pads were placed between the loading head and the specimen. The aluminum (or any stiff plate) distributes the load over the rubber pad, which in turn transfers the load nearly uniformly on the specimen. Lengths of aluminum and rubber were 0.5S and 0.4S, respectively. Both pads have the same width as the specimen (0.5 inches). Thickness of the aluminum seat and the rubber pad were 0.05-in and 0.1-in, respectively. However they were selected based on yielding and no-punching criteria. The rubber pad length is slightly smaller than aluminum pad because under the load the rubber pad undergoes large deformation and fully covers the aluminum seat. Therefore, the potential sites for the interlaminar shear failure is the region A-A (Figure 1.b). The maximum interlaminar shear stress, based on the beam theory [10] is:

$$t_{max} = \frac{3P}{4bt} \qquad (1)$$

The beam theory is not exactly valid for short beams made of shear flexible composite materials, therefore the equation (1) is rewritten with a correction factor Kappa (κ).

$$t_{max} = k\frac{3P}{4bt} \tag{2}$$

The value of κ is established for different material system through nonlinear contact element analysis.

MATERIAL SYSTEMS

Nine material systems were considered. This includes carbon and glass (S2 and E) fibers from unidirectional to 8-harness satin weaves and engineered layered fabrics with through-the-thickness interlock fiber preforms. The resin system varied from brittle 5208 epoxy to marine grade vinyl ester, toughened SC-15 epoxy and carbon matrix. The carbon/carbon composite material was manufactured at the Center for Composites Materials Research of North Carolina A&T using its patented technology

Table 1. Materials system

Material A	T300/5208 graphite/epoxy unidirectional
Material B	T300/vinyl ester plain weave
Material C	S2-Glass/A.P.I. SC15 epoxy (woven roven plain weave)
Material D	E-Glass BGF 2532/Derakane 411350 vinyl ester
Material E	T300/PT30 cyanate ester (8-harness woven)
Material F	T300 Carbon/Carbon (8-harness woven)
Material G	3 layer engineered Glass fabric with Reichhold Atlac 580-05 vinyl ester
Material H	3 layer engineered Glass fabric with A.P.I. SC15 epoxy
Material I	2 layer engineered Glass fabric with A.P.I. SC15 epoxy

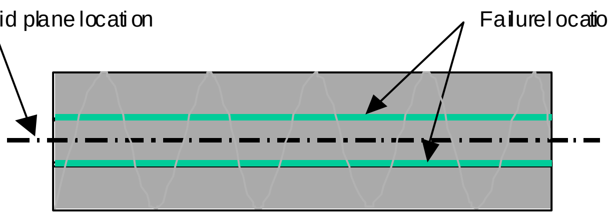


Figure 2. Schematic of engineered woven fabric composites.

Table 2. Three-dimensional elastic properties

Parameter	Material A	Material B	Material C
E_x, (Msi)	19.00	7.25	4.84
E_y, (Msi)	1.89	7.25	4.84
E_z, (Msi)	1.89	0.92	2.55
n_{xy}	0.34	0.02	0.14
n_{xz}	0.34	0.26	0.34
n_{yz}	0.35	0.26	0.34
G_{xy}, (Msi)	0.93	0.43	0.68
G_{yz}, (Msi)	0.70	0.41	0.79
G_{xz}, (Msi)	0.93	0.41	0.79
Factor κ	0.95	0.95	1.00

[11,12]. All composite materials considered are listed in table 1. The material systems A to C were used in the finite element analysis to establish the κ factor. Three-dimensional elastic properties of A, B and C materials are listed in table 2. Table 1 includes three engineered

preforms made by glass fiber. These were made by knitting through-the-thickness of heavy tow plain weave fabrics to improve through-the-thickness properties. Materials G and H had three layers and the material I had two layers. A schematic of interlock concepts and layers is shown in figure 2. Note that the layered planes are the potential sites for interlaminar failure. The mid-plane is also the separation plane for the two, (I), or even number of layered materials.

FINITE ELEMENT ANALYSIS AND RESULTS

Non-linear contact finite element analyses of standard and modified short beam shear tests (MSBS) were conducted. Critical stresses and the associated failure modes were examined to demonstrate the viability of the MSBS test. The maximum shear stress region was examined and its magnitude was compared with beam solution.

Standard Short Beam Shear Specimen

Figure 3 shows the finite element model of one-half of the test configuration. Because of symmetry, only one-half of the specimen was modeled. The specimen was idealized by 4-noded orthotropic elements (Plane-42). The loading and support were modeled by

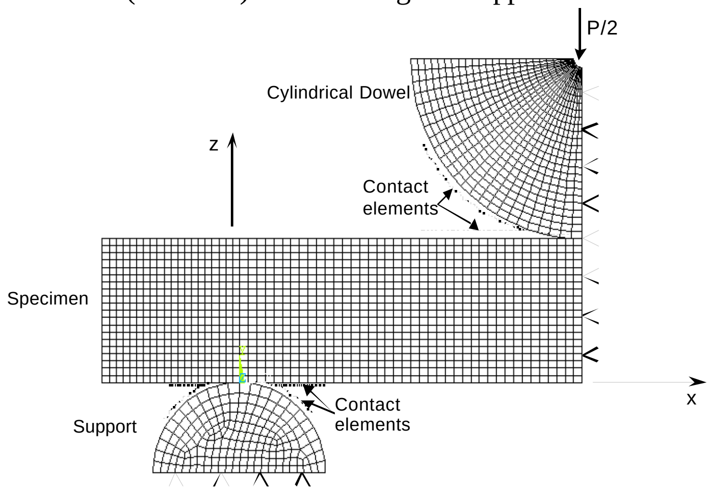


Figure 3. Finite element model of the short beam shear test.

hardened steel elements to simulate realistic load transfer mechanism. Line contact elements were used between the support cylindrical rods and the specimen. The boundary conditions and loading are shown. The model had 1792 Plane-42 elements and 200 contact elements. The material properties used in the analysis were for T300/5208 unidirectional composite (A) A geometric non-linear contact analysis was conducted using the ANSYS finite element code for an applied load of 100 lbs. Although the

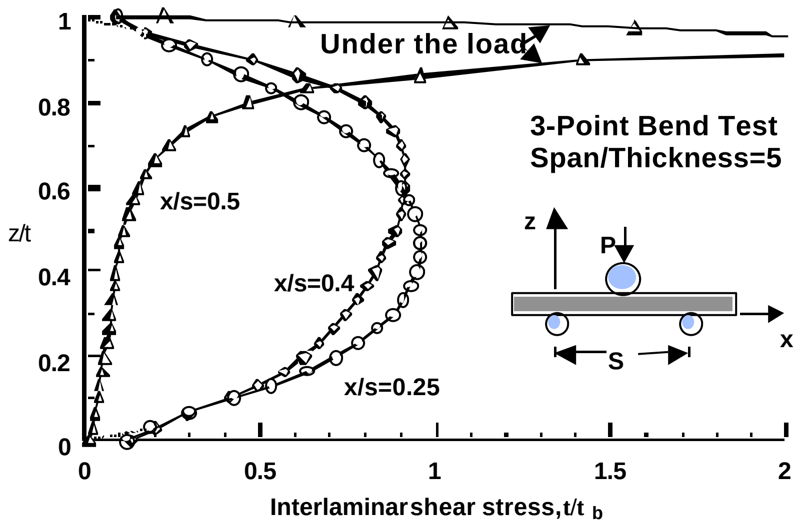


Figure 4. Transverse shear stress (t_{xz}) distribution through the thickness.

contact region varied with load, the deformation and stress distribution in the region of interest (outside the contact) remained linear with load. Figure 4 shows transverse shear (t_{xz}) distribution through the thickness of the beam at various sections along the half-span. For simplicity the transverse shear stress is referred to as shear stress with the symbol t . The shear stresses were normalized by maximum shear stress from beam theory ($t_b = \frac{3P}{4bt}$). The shear stress distribution at quarter-span remained almost parabolic as in the elementary beam theory [10]. At sections near the loading, shear stress peaks towards the loading surface (see figure 4 for x/s = 0.5). The shear stress becomes very large right under the load at a location slightly below the top surface. Outside the contact area (x/s = 0.25), the maximum shear stress occurred at the mid-plane and it is about 95% of the beam theory value. Figure 5 shows the outer fiber bending stress (s_x) distribution along the span. All stresses were normalized by the maximum bending stress ($s_b = \frac{3PS^2}{2bh^2}$) from the beam solution. The bending stress is compressive and tensile at the top and bottom surfaces of the specimen. Material under the loading head is subjected to very high compressive stresses. These high stresses can cause outer layer to delaminate and become unstable before an interlaminar shear failure could occur [13].

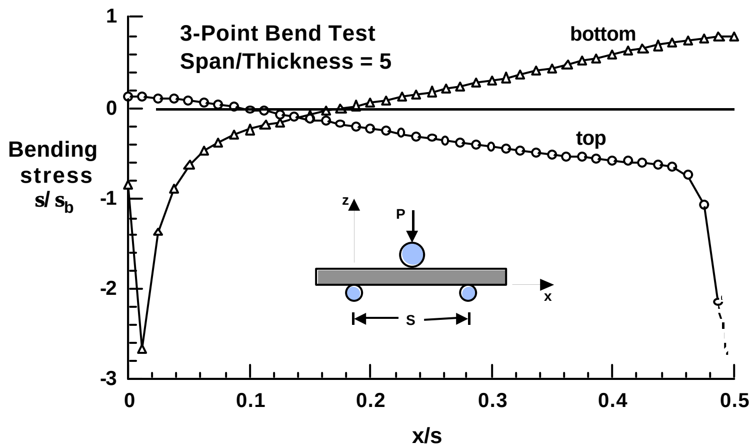


Figure 5. Outer fiber flexural stress distribution.

Modified Short Beam Shear Specimen

Figure 6 shows the finite element model of the modified short beam shear specimen, support, and the loading system. The figure also includes the boundary conditions and the

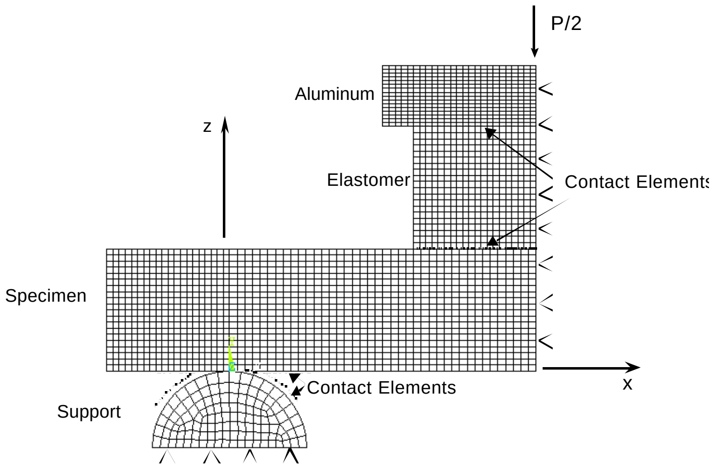


Figure 6. Finite element model of the modified short beam shear test.

coordinate system used. Non-linear contact elements were used between the aluminum and rubber pads, and the specimen. The model had 2120 Plane-42 elements and 240 contact elements. A geometric non-linear finite element analysis was conducted using ANSYS code. As stated previously, the stress distribution within the specimen remained linear with the applied load. A plot of pressure distribution between the specimen and the rubber pad is shown in figure 7. All pressure values were normalized by the average pressure $\{\frac{2P}{Sb}\}$, and the pressure distribution under the loading pad is nearly uniform. The normalized pressure varied from 1.15 at x/S=0.25 to 0.96 at the mid-section. This result validates the uniform pressure assumption made in the beam analysis. The bottom fiber bending stress is supposed to be zero at the left support according to the beam theory but a large value was recorded because of the indentation deformation. This stress can be reduced by inserting a rubber pad between the specimen and the support.

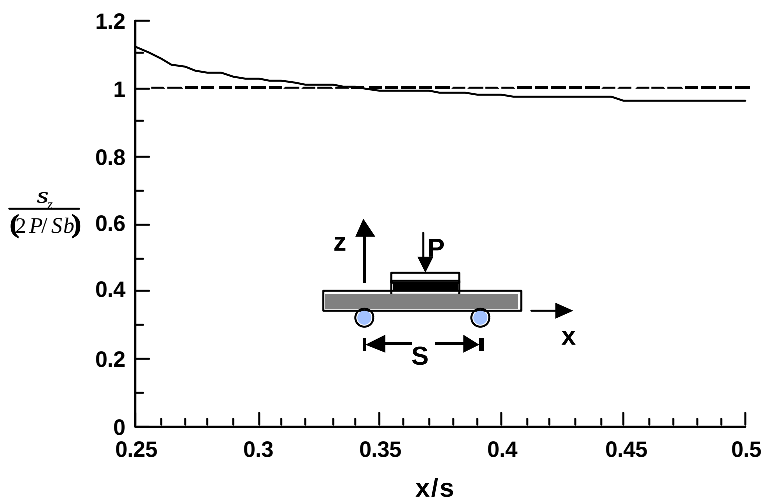


Figure 7. Contact pressure distribution between the rubber pad and the specimen.

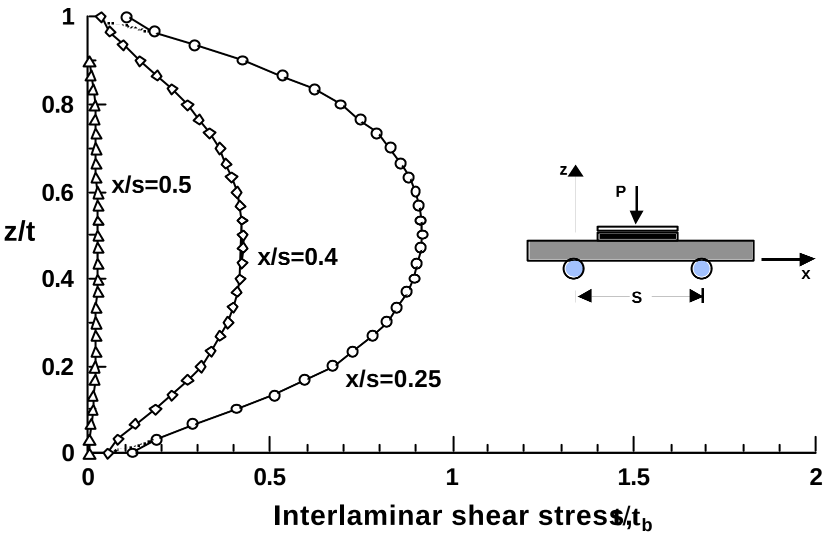


Figure 8. Shear stress distribution in the modified short beam shear specimen.

Figure 8 shows the transverse shear stress distribution across the thickness for x/s values of 0.125, 0.25, 0.4, and 0.5. As expected shear is nearly zero at x/s = 0.5 and largest at 0.125. The maximum value of shear stress is about 95% of the beam theory. This factor was same for both graphite/epoxy and carbon/carbon composites. The outer fiber bending stress distribution is shown in figure 9. Because of redistribution of applied load over the one-half span of the beam, the compressive bending stress is significantly reduced. It is less than 1/4 of the SBS test specimen. Because of reduced compressive stress and no change in shear stress, the material is likely to fail by interlaminar shear.

Figure 10 shows the variation of normalized shear stress along mid-plane of the beam for three different materials (A, B, and C). Two are carbon fiber systems and the third is glass fiber. The shear stress is nearly constant and largest in the region $0.1 \le x/S < 0.2$. The normalized maximum shear stress is nearly 1 for glass composites (G_{xz}/E_x~1/6) and it is 0.95 for the carbon composites (G_{xz}/E_x~1/17). Therefore the value of κ for shear flexible materials like carbon composites is 0.95 and for high stiff materials (isotropic and glass composites) it is 1.

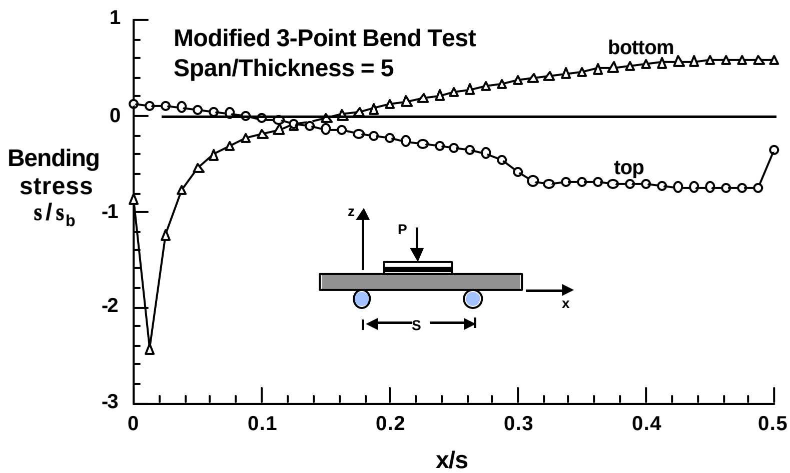


Figure 9. Outer fiber flexure stress distribution in the MSBS specimen.

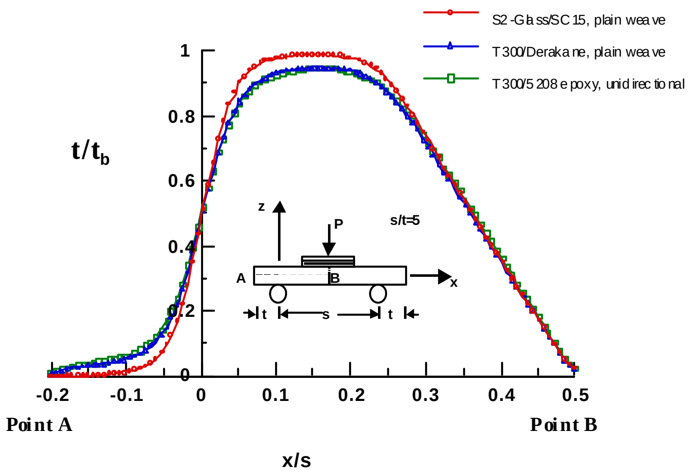


Figure 10. Variation of shear stress at the mid-plane for three different material systems.

TEST

Test Procedure

Specimens were machined to the size described in figure 1(b) and tested as soon as the panels were made at CCMR. A short environmental exposure reduces the moisture absorption. Panels thickness were measured and test spans (S=5t) were chosen accordingly. The aluminum and silicone rubber pad thickness was chosen from the no yielding and punching criteria at the maximum load. Most often specimens were about 0.1 in. thick, except materials D, C, G and H. Thicknesses of D, C, G and H were 0.2, 0.7, 0.3, and 0.2 in. respectively. The specimens were tested by displacing the loading head at 0.05 inches per minute. The failure initiation and progression were monitored using a travelling microscope attached to the test frame. Typically failure initiated as a delamination as in figure 11 (a) and propagated as in figure 11 (b). Failure load was the maximum load followed by 5% load drop. Figure 11 (c) shows a micrograph of failed specimen. The maximum load was recorded and the ILSS was calculated by equation (2) with appropriate κ. Whenever possible, at least five specimens were tested.

Test Results and Discussions

Table 3 compares the ILSS of material G measured by the standard SBS, 4P-SBS, and MSBS test. The average values from these tests were 6.95, 8.10, and 7.35 ksi respectively. The 4P-SBS test gave the largest value, however the standard deviation (STD) is about 11.5% in contrast to about 3% of MSBS test. SBS test gave a lower ILSS and larger scatter than the MSBS test. Therefore, MSBS is a preferred test compared to SBS or 4P-SBS.

a. Initiation of interlaminar failure

b. Final failure

c. Optical micrograph of a typical failure specimen.

Figure 11. Typical interlaminar failure in modified short beam shear test.

Table 3. Comparison of ILSS from the three test methods.

Specimen #	Interlaminar Shear Strength (ksi), Material G		
	Test methods		
	Short beam shear	4-Point short beam shear	Modified short beam shear
1	7.20	8.30	7.25
2	7.04	9.37	7.05
3	7.39	7.70	7.52
4	6.24	8.33	7.55
5	6.89	6.82	7.40
Average	6.95	8.10	7.35
Std. dev.	0.44	0.93	0.21

Table 4. Comparison of ILSS of woven glass laminated composites.

Specimen #	Interlaminar Shear Strength (ksi)			
	Material C		Material D	
	Test methods		Test methods	
	4-Point short beam shear	Modified short beam shear	Short beam shear	Modified short beam shear
1	6.66	7.06	4.93	6.59
2	6.93	7.07	4.45	6.63
3	7.20	7.17	~	6.86
4	~	~	~	6.72
Average	6.93	7.10	4.69	6.70
Std. Dev.	0.27	0.06	0.34	0.12

Table 4 compares 4P-SBS and MSBS test data for material C (very thick panel of 0.7 in.) and SBS and MSBS for material D. ILSS measured from MSBS test was the largest with the lowest data scatter. Table 5 summarizes the ILSS for materials C, D, E, and F. The carbon/carbon composite (F) had the lowest ILSS of 2.97 ksi and the glass/vinyl ester had the largest value about 7 ksi. Again, the data scatter in MSBS test for carbon was less than 3%.

Table 5. ILSS of laminated composites using modified short beam shear test method.

Specimen #	Interlaminar Shear Strength (ksi)			
	Material D	Material C	Material E	Material F
1	6.59	7.06	3.27	2.94
2	6.63	7.07	3.21	2.88
3	6.86	7.17	3.28	3.00
4	6.72	~	3.31	3.06
5	~	~	3.33	~
6	~	~	3.25	~
Average	6.70	7.10	3.27	2.97
Std. Dev.	0.12	0.06	0.04	0.08

The materials G, H, and I were through-the-thickness woven (interlocked) layered materials (see figure 2). Obviously, interlaminar failure occurred between the layers by breaking the interlocking fibers. Therefore, the ILSS was calculated at the interlaminar (failure) locations using the parabolic distribution of shear stress through the thickness. Accordingly, ILSS was reduced for materials G and H, because the material I had only two layers the value at the mid-plane and interlaminar location remain the same. Because the material I was thin, the specimen failed by flexure instead of interlaminar. Both materials D and G were made of same resin and fiber system and yielded nearly the same ILSS (see Table 4 and 6). The engineered fabric could also fail by breaking the interlocked fibers through the thickness, this may be the case for material H, which is same as material C, except the fabric architecture.

Table 6. ILSS based on the failure location (Modified short beam shear test).

Specimen #	Interlaminar Shear Strength (ksi)					
	Material G		Material H		Material I	
	3 layers laminate		3 layers laminate		2 layers laminate	
	Mid plane	Failure location	Mid plane	Failure location	Mid plane	Failure location
1	7.25	6.45	6.80	6.04	4.15	4.15
2	7.05	6.27	7.24	6.45	4.26	4.26
3	7.52	6.69	6.64	5.89	3.58	3.58
4	7.55	6.71	6.63	5.88	4.26	4.26
5	7.40	6.57	7.04	6.29	4.14	4.14
6	~	~	~	~	4.37	4.37
Average	7.35	6.54	6.87	6.11	4.13	4.13
Std. Dev.	0.21	0.18	0.26	0.25	0.28	0.28

CONCLUDING REMARKS

Modified short beam shear (MSBS) test was used to measure interlaminar shear strength (ILSS) of nine different textile fabric composites. This includes carbon and glass fibers from unidirectional to 8-harness satin weaves and engineered layered fabrics with through-the-thickness interlocks. The resin system varied from brittle 5208 epoxy to marine grade vinyl ester, toughened SC-15 epoxy and carbon matrix. Test results from MSBS were very consistent with failure modes and small data scatter (standard deviation <3%) compared to standard and 4-point short beam shear tests. Therefore MSBS is simple and accurate test to measure ILSS of laminated composites. A detailed nonlinear finite element stress analysis of the test specimen with different composites having different transverse shear to flexural moduli showed that the shear stress equation from the beam theory requires a correction. The correction factor κ is 1 for isotropic and relatively high G_{xz}/E_x whereas it is 0.95 for shear flexible composites (G_{xz}/E_x>10) carbon/epoxy.

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