Table 1 Ballistic limit determinations

Reference	Conical shell method, V_{50}, m/s	Lee–Sun method,[3] V_{50}, m/s
Lee–Sun,[3] specimen 1	46	42
Lee–Sun,[3] specimen 2	42	47
Lee–Sun,[3] specimen 3	81	67
Sun–Potti,[4] Fig. 3	72	68
Sun–Potti,[4] Figs. 4 and 14	100	89
Sun–Potti,[4] Fig. 5	119	107
Sun–Potti,[4] Fig. 6	No limit found	146
Silva et al.[5]	126	192
Jenq et al.[6]	No limit found	159
Goldsmith et al.[7]	No limit found	23

requires a significant number of tests for each target thickness and requires rigorous statistical analysis. The conical shell method, on the other hand, requires only enough tests to determine accurately the ultimate strain as a function of striking velocity, and the results can be easily manipulated to generate ballistic limit determinations for targets with differing thickness.

Conclusions

The conical shell model of a ballistic impact provides a relatively simple tool to determine 1) the ultimate strain as a function of striking velocity, 2) whether penetration of a structure will occur, 3) the residual velocity of the projectile if penetration occurs, and 4) the ballistic limit for that target and projectile combination. This process serves to enhance the work found in Ref. 2 by offering an updated and validated method.

Another conclusion is that for a given material system the relationship between striking velocity and ultimate shell strain is linear where the slope is constant across targets of the same material and stacking sequence with different thickness. When the thickness of a target increases, the strain function shifts vertically in a graphical sense. This is important because it permits target thickness to be a variable subject to interpolation and reduces required testing.

Finally, this method provides a valuable analytical tool for the design and analysis of fiber/matrix composite material systems subject to ballistic impact because very few experiments are needed to provide this predictive capability. The methods are useful in that only a very limited number of tests are needed to establish the failure strain as a function of the striking velocity for a given target structure. Then those methods can be used to predict whether any other blunt ballistic object of known mass, size, and striking velocity will penetrate that structure and, if it does, what the residual velocity will be. The methods also provide the ballistic limit for other projectile sizes and the given composite target.

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Modified Short Beam Shear Test for Measuring Interlaminar Shear Strength of Composites

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Introduction

INTERLAMINAR shear strength (ILSS) is an important material property for the design of laminated composite structures subjected to transverse loads. The American Society for Testing and Materials (ASTM)[1] proposed two test standards: three-point short beam shear (SBS) (D2344) and double-notched shear (D3846-99) tests to measure ILSS of composites. The four-point short beam shear (4P-SBS) test (ASTM D790) was also used in the literature. A number of analytical and experimental studies[2–7] have been conducted to determine the validity of these tests. Analytical studies include classical anisotropic beam and laminate analyses[2,6] and linear and nonlinear finite element analyses.[3–5] These studies concluded that the SBS test gives a qualitative estimate of ILSS and that many times failure is caused by indentation and/or flexure. A major problem of this test is the indentation deformation of the loading head. The waviness of textile fibers reduces the compression strength,[8] thus causing a compression failure on the loading side. Brittle matrix composites, like carbon-carbon composites, could also be crushed under the loading head. The 4P-SBS is an alternative test, but the loading heads arrangement restricts the specimen size.

Experimental study on the effect of indentation size[4,7] on failure of the SBS test showed that larger size indentation can increase the contact area and potentially reduce the indentation failure. Limitations of this hypothesis can be explained by the Hertzian contact analysis[9] of a steel cylinder pressing on a composite beam (insert in Fig. 1) resting on rigid support. Contact length c increased with increased cylinder radius and load q. Even with a 50-mm-radius cylinder the maximum half-contact length c that can be achieved is less than $\frac{1}{4}$ of the beam thickness, which is not enough to mitigate indentation failure.

Rahhal and Kotlesnsky[10] proposed a sandwiched specimen for carbon-carbon composite laminates and found some success. But sandwiching alters the material constraint and requires additional processing effort. Recently, Abali et al.[11] suggested a modification to the SBS test that alleviates the problems just mentioned. In this modified short beam shear (MSBS) test 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. This Note presents a summary of the analysis and test data for various textile fiber laminated polymer as well as carbon matrix composites.

Specimen Configuration and Loading

Figure 2 describes the specimen configuration and loading. The span is S, thickness t, width b, and the overhang length (or edge distance) t. The S/t ratio is proposed to be five for thin specimens

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Table 1 Material systems

Material system	System description
A	T300/5208 graphite/epoxy unidirectional
B	T300/vinyl ester plain weave
C	S2-glass/A.P.I. SC15 epoxy (woven roven plain weave)
D	E-glass BGF 2532/Derakane 411350 vinyl ester
E	T300/PT30 cyanate ester (eight-harness woven)
F	T300 carbon/carbon (eight-harness woven)
G	Three-layer engineered glass fabric with Reichhold Atlac 580-05 vinyl ester
H	Three-layer engineered glass fabric with A.P.I. SC15 epoxy
I	Two-layer engineered glass fabric with A.P.I SC15 epoxy

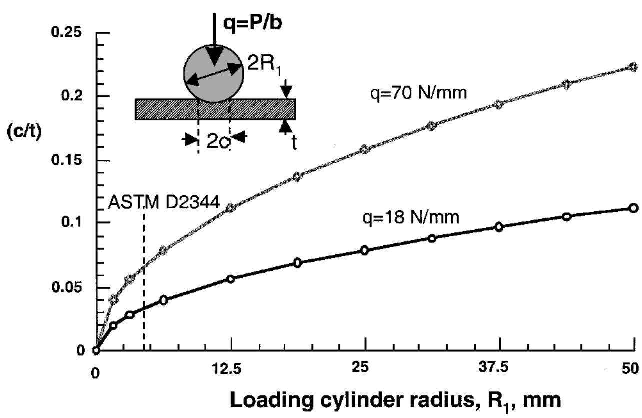

Fig. 1 Variation of contact length vs loading cylinder radius.

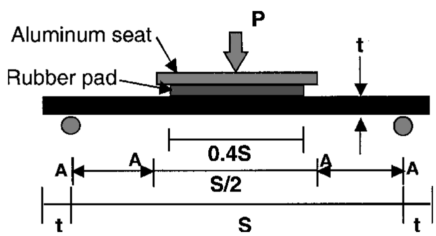

Fig. 2 Modified short beam shear test.

but could be four for thick specimens. These dimensions are 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 function of aluminum or any stiff plate is to distribute the load, and the function of the rubber pad is to maintain contact between the aluminum pad and the specimen. Lengths of aluminum and rubber were 0.5 and 0.4S, respectively. Both pads have the same width as the specimen. The thickness of the aluminum seat and the rubber pad were 1.3 and 2.5 mm, respectively. However their thickness can be selected based on no-yielding and no-punching criteria. The potential sites for the interlaminar shear failure are in the region A–A. The maximum interlaminar shear stress, based on the beam theory[12] is $\tau_b = 3P/4bt$. The beam theory is not exactly valid for beams made of shear flexible composites materials; therefore, the equation is rewritten with a correction factor κ: $\tau_b = \kappa(3P/4bt)$. The value will be established for different materials through contact finite elements.

Material Systems

Nine material systems listed in Table 1 were used in this study. They are carbon and glass (S2 and E) fibers from unidirectional to eight-harness satin weaves and engineered layered fabrics with through-the-thickness interlock. The resin system included brittle aerospace grade 5208 epoxy and marine grade vinyl ester to toughened SC-15 epoxy and carbon matrix. Materials A, B, and C were used in the finite element analysis to establish the κ factor. Two-dimensional (x-z) elastic properties of these materials are listed in Table 2. Through-the-thickness interlocking of preform layers can improve the interlaminar strength; materials G, H, and I represent such construction. For low-density interlocks interlaminar stitches can break under transverse shear.

Table 2 Two-dimensional elastic properties

Parameter	Materials A	B	C
E_x, GPa	131.0	50.0	33.4
E_z, GPa	13.0	6.3	17.6
ν_{xz}	0.34	0.26	0.34
G_{xz}, GPa	6.41	0.41	5.45
Factor κ	0.95	0.95	1.00

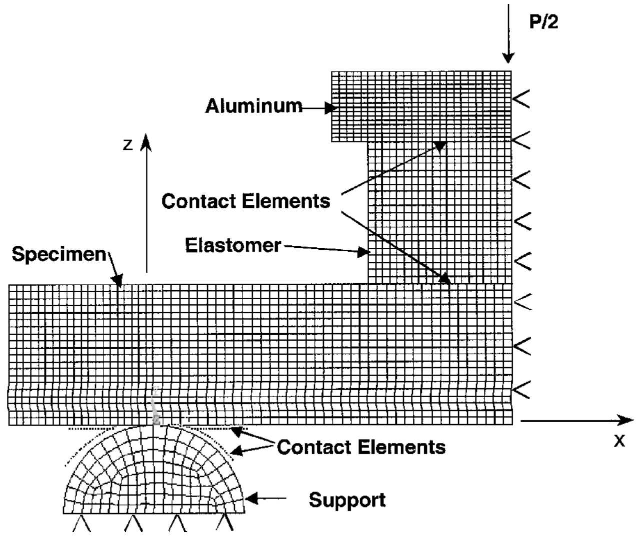

Fig. 3 Finite element modeling of the MSBS test.

Finite Element Analysis and Results

Nonlinear contact finite element analyses of the MSBS test were conducted. Finite element results of standard SBS tests are reported in Ref. 11. Critical stresses and the associated failure modes in test samples were examined to demonstrate the viability of the MSBS test. The maximum shear stress was compared with beam solution for a range of materials.

Figure 3 shows the finite element model of the MSBS setup. Boundary conditions and the loading are shown. Nonlinear contact elements were used between the aluminum and rubber pads and the specimen. The material A was used for the specimen. The model had 2120 Plane-42 elements and 240 contact elements. A geometric nonlinear finite element analysis was conducted using the ANSYS code. The stress distribution within the specimen remained linear with the applied load. Examination of pressure distribution between the specimen and the rubber pad was almost constant; the variation was between 1.15 (at $x/S = 0.25$) to 0.96 (at midsection) of the average pressure. This result validates the uniform pressure assumption made in the design of test setup to mitigate flexural failure.

Figure 4 shows the transverse shear-stress distribution across the thickness for x/S values of 0.125, 0.4, and 0.5. As expected, shear stress 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 (A and B) and carbon–carbon composites. No concentration of outer fiber bending stresses was found throughout the length of the beam except at the two ends of the support, which can be easily addressed.

Figure 5 shows the variation of normalized shear stress along the midplane of the beam for three different materials (A, B, and C). Two are carbon fiber systems, and the third is a glass fiber. The shear stress is nearly constant and largest in the region $0.1 \le x/S < 0.2$.

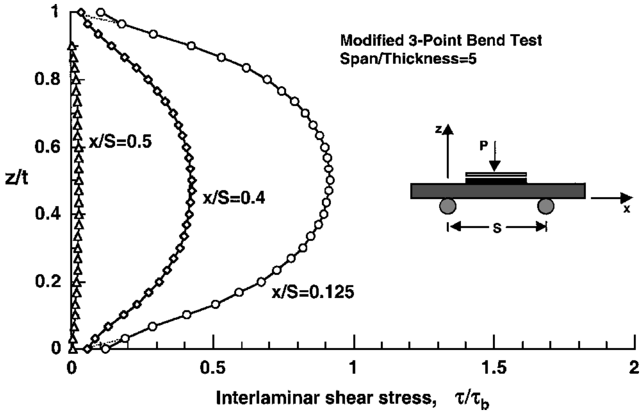

Fig. 4 Shear-stress distribution through the thickness of the MSBS test specimen.

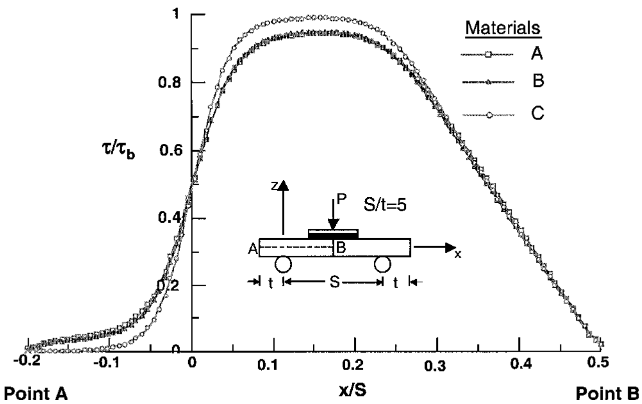

Fig. 5 Variation of shear stress at the midplane for the three different materials.

The normalized maximum shear-stress factor κ is nearly 1 for glass composites and isotropic materials ($G_{xz}/E_x \geq \frac{1}{6}$) and 0.95 for the carbon composites ($G_{xz}/E_x \approx \frac{1}{17}$). Therefore, the value of κ for shear flexible materials like carbon composites is 0.95, whereas for the stiff materials (isotropic and glass composites) the value is 1 (see Table 2).

Test

Test Procedure

Specimens were machined to the size described in Fig. 2 and tested as soon as the panels were made so that no moisture was absorbed. Panel thicknesses were measured, and test spans ($S = 5t$) were chosen accordingly. Most of the specimens thicknesses were about 2.5 mm, whereas materials D, C, G, and H had 5.0, 17.0, 7.6, and 5.0 mm, respectively. The specimens were tested by displacing the loading head at 1.25 mm per minute. The failure initiation and progression were monitored using a travelling microscope attached to the test frame. Typically, failure initiated as a delamination near the midplane of the specimen and progressed through the thickness as multiple delaminations. The maximum load recorded was used in ILSS computation using the beam equation with appropriate κ. At least five specimens were tested.

Test Results and Discussion

Table 3 summarizes all of the ILSS data generated by the standard SBS, 4P-SBS, and MSBS tests. Average values and the standard deviation (STD) are given. The SBS test consistently gave lower strength with large data scatter than the MSBS test. Although the 4P-SBS test gave nearly same strength as the MSBS, the data scatter was larger. Overall the MSBS test consistently caused by interlaminar shear near the midplane of the specimen gave small data scatter.

The materials G, H, and I were made by through-the-thickness interlocked woven fiber system. Specimens of G and H failed by breaking the interlocked fibers. Because the midplane of G and H did not match with the perform layers, the ILSS was calculated at the failure location. These values were lower than the midplane values. Although the resin system (SC-15) is the same for materials C and H, the ILSS were different (48.95 vs 42.13 MPa) because of fiber architecture.

Table 3 ILSS comparison of different tests and material systems

	Interlaminar shear strength, MPa					
	SBS		4P-SBS		MSBS	
Material system	Average	STD	Average	STD	Average	STD
C	——	——	47.78	1.86	48.95	0.41
D	——	——	32.34	2.34	46.20	0.83
E	——	——	——	——	22.55	0.28
F	——	——	——	——	20.48	0.55
G	47.92	3.03	55.85	6.41	50.68	1.45
H	——	——	——	——	47.37	1.79
I	——	——	——	——	28.48	1.93
G @ failure location	——	——	——	——	45.09	1.24
H @ failure location	——	——	——	——	42.13	1.72

Summary

A simple modified short beam shear test was proposed to measure interlaminar shear strength of laminated composite materials. The nonlinear contact finite element analysis and experiments showed that the proposed test is a viable approach. The ILSS for resin and carbon matrix composites were presented. Fiber architecture does influence the ILSS of the composite materials.

Acknowledgments

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