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COMPOSITE SPECIMEN DESIGN ANALYSIS - VOLUME II: EXPERIMENTAL EFFORTS

January 1991

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COMPOSITE SPECIMEN DESIGN ANALYSIS

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ABSTRACT

This composite material test methods investigation involved the performance of seventeen different types of mechanical tests, all of which fell into one of five primary categories: axial tension, axial compression, in-plane shear, interlaminar shear, or combined stress. All test specimens were fabricated from Hercules AS4/3501-6 carbon/epoxy prepreg tape. In most cases, several different laminate configurations were tested using each method. The influence of potentially important test parameters such as specimen dimensions, ply angles, etc., on the results of a particular test method was determined by testing specimens of slightly different configurations while maintaining the same basic methodology. It was therefore possible to compare results from a basic test method with those from a slight variation of the same method, as well as with other basic methods from within the same primary category.

In general, five replicate specimens were tested for each basic method and variation, all testing being performed by the Composite Materials Research Group (CMRG) within the Department of Mechanical Engineering at the University of Wyoming.

The specimens were prepared by the CMRG from laminates fabricated by a vendor selected by MSC, and also from laminates fabricated by the CMRG. The test methods investigated are listed in Table 1.1, along with the laminates from which the specimens were prepared.

PREFACE

This final report presents the results of a wide-ranging composite material test methods evaluation performed by the Composite Materials Research Group (CMRG) at the University of Wyoming for the Materials Sciences Corporation (MSC) under MSC Subcontract No. 1705-1. The University of Wyoming internal account number assigned to the subcontract was 5-38290. The work presented is a part of Contract DAAL04-87-C-0064 between MSC and the U.S. Army Materials Technology Command, under the Small Business Innovative Research (SBIR) program. The Army Materials Technology Laboratory SBIR Monitor was Mr. R. Morrissey.

Mr. V. Ramnath was the MSC Program Monitor during the initial part of the effort while Dr. S.N. Chatterjee served in the same capacity for the major subsequent portions of the program. The Army Materials Technology Laboratory Technical Monitor was Mr. D.W. Oplinger.

All work described herein was performed by the CMRG, within the Mechanical Engineering Department at the University of Wyoming. Co-Principal Investigators were Jeff A. Kessler, Staff Engineer, and Donald F. Adams, Professor. Making contributions to the project were CMRG Staff Engineers Richard S. Zimmerman, Scott L. Coguill, and Hal D. Radloff, and the following CMRG undergraduate student members: S. Bartell, J.M. Bihr, W. Daughton, G. Innes, R. Powell, R. Schriner, D. Schroeder, T. Tygum, T. Weber, and K. Walcott.

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SECTION 1

SUMMARY

This composite material test methods investigation involved the performance of seventeen different types of mechanical tests, all of which fell into one of five primary categories: axial tension, axial compression, in-plane shear, interlaminar shear, or combined stress. All test specimens were fabricated from Hercules AS4/3501-6 carbon/epoxy prepreg tape. In most cases, several different laminate configurations were tested using each method. The influence of potentially important test parameters such as specimen dimensions, ply angles, etc., on the results of a particular test method was determined by testing specimens of slightly different configurations while maintaining the same basic methodology. It was therefore possible to compare results from a basic test method with those from a slight variation of the same method, as well as with other basic methods from within the same primary category.

In general, five replicate specimens were tested for each basic method and variation, all testing being performed by the Composite Materials Research Group (CMRG) within the Department of Mechanical Engineering at the University of Wyoming.

The specimens were prepared by the CMRG from laminates fabricated by a vendor selected by MSC, and also from laminates fabricated by the CMRG. The test methods investigated are listed in Table 1.1, along with the laminates from which the specimens were prepared. The remainder of this section is a brief summary of the test results. The specimen

Table 1.1

Composite Material Test Methods Studied

Test Category	Specific Method	Method Variation	Laminates Tested
Axial Tension	ASTM D-3039		$[0]_6$ $[0/90]_{3s}$
	Streamlined Profile	3 lengths	$[0]_6$
		1 length	$[0/90]_{3s}$
	Linear Tapered Profile		$[0]_6$ $[0/90]_{3s}$
	$[\pm\theta]_{ns}$ Tension		$[\pm 15]_s$ $[\pm 15]_{2s}$
			$[\pm 30]_s$ $[\pm 30]_{2s}$
			$[\pm 60]_s$ $[\pm 60]_{2s}$
			$[\pm 75]_s$ $[\pm 75]_{2s}$
Axial Compression	IITRI (ASTM D-3410)		$[0]_{16}$ $[0/90]_{4s}$
			$[0]_{24}$ $[0/90]_{6s}$
			$[0/\pm 45/90]_{2s}$
			$[0/\pm 45/90]_{3s}$
	Wyoming End-Loaded, Side-Supported		same as above
	Wyoming Modified Celanese		same as above
	Sandwich Beam Bending		$[0]_6$
Shear	Tension of $[\pm 45]_n$ Laminate (D-3518)	2 widths	$[\pm 45]_s$ $[\pm 45]_{2s}$
			$[\pm 45]_{4s}$
	Torsion of Rectangular Bar	2 widths	$[0]_{48}$
		1 width	$[0]_{24}$
	Torsion of Circular Bars	2 diameters	$[0]_{48}$ $[0]_{96}$

Table 1.1 (continued)

Composite Material Test Methods Studied

Test Category	Specific Method	Method Variation	Laminates Tested
Shear (continued)	Iosipescu Shear (in-plane)	2 notch angles	$[0]_8$ $[0/90]_{2s}$ $[0]_{16}$ $[0/90]_{4s}$ $[0/\pm45/90]_s$ $[0/\pm45/90]_{2s}$ $[\pm45]_{2s}$ $[\pm45]_{4s}$
	Tapered Rail Shear	Rectangular Specimen Shape and Parallelogram Specimen Shape	same as Iosipescu shear above
	Off-Axis Tension	2 aspect ratios and thicknesses	$[10]_8$ $[10]_{12}$ $[15]_8$ $[15]_{12}$ $[20]_8$ $[20]_{12}$ $[30]_8$
	Iosipescu Shear (interlaminar)		$[0]_{96}$ $[0/90]_{36s}$
	Short Beam Shear	2 span:depth ratios	$[0]_{48}$ $[0/90]_{6s}$

fabrication and test methods are presented in Section 2. Section 3 is a detailed presentation of the test results, while Sections 4, 5, and 6 contain the tabulated individual specimen results. In addition to ultimate strength, modulus, ultimate strain, and similar data presented in the tables in Sections 4, 5, and 6, the final table in each section lists the laminate source, breakload, and thickness data for each specimen.

For ease of discussion, the combined stress and interlaminar tests have been included with the other three test categories. The ±45° tension and off-axis tension tests are included in the shear group of test methods, and the $[\pm\Theta]_{ns}$ tension tests are included in the axial tension test group. In addition, the interlaminar shear test methods will be discussed with the in-plane shear methods.

The average results from the three axial tensile test methods investigated are presented in Figures 1 and 2 for the unidirectional material and Figures 3 and 4 for the cross-ply material. As can be seen, for the unidirectional composite, the tabbed ASTM D-3039 configuration yielded the highest tensile strengths and moduli. All three lengths of the streamline tapered tensile specimens yielded strengths and moduli lower than the ASTM method, but higher than the linear tapered specimens. On the other hand, the ASTM D-3039 cross-ply results were lower than those from the streamline and linear taper tests. The $[\pm\Theta]_{ns}$ tensile test results are presented in Figures 5 and 6.

The average results from three axial compressive test methods are presented in Figures 7 and 8 for the unidirectional material, Figures 9 and 10 for the cross-ply material, and Figures 11 and 12 for the

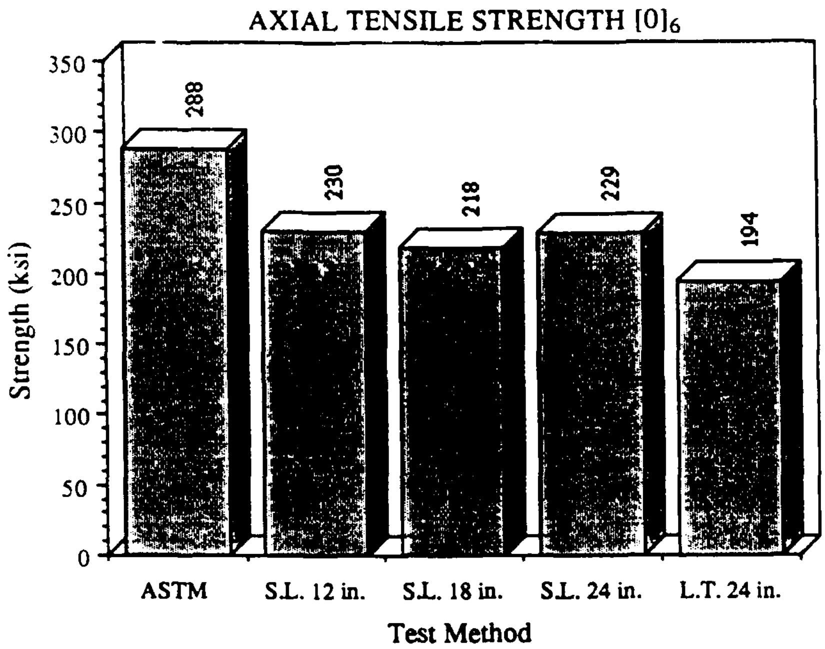


Figure 1. Uniaxial Tensile Strength Results

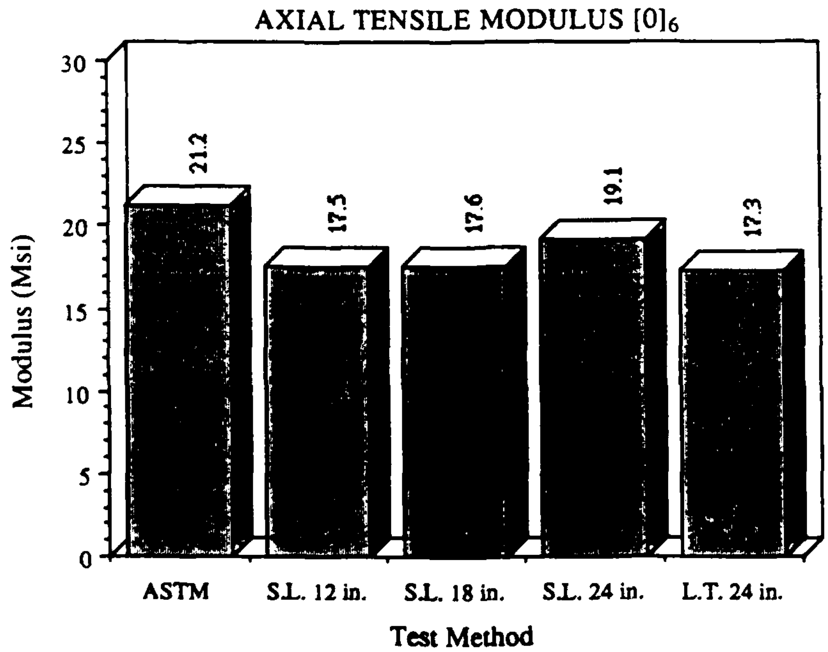


Figure 2. Uniaxial Tensile Modulus Results

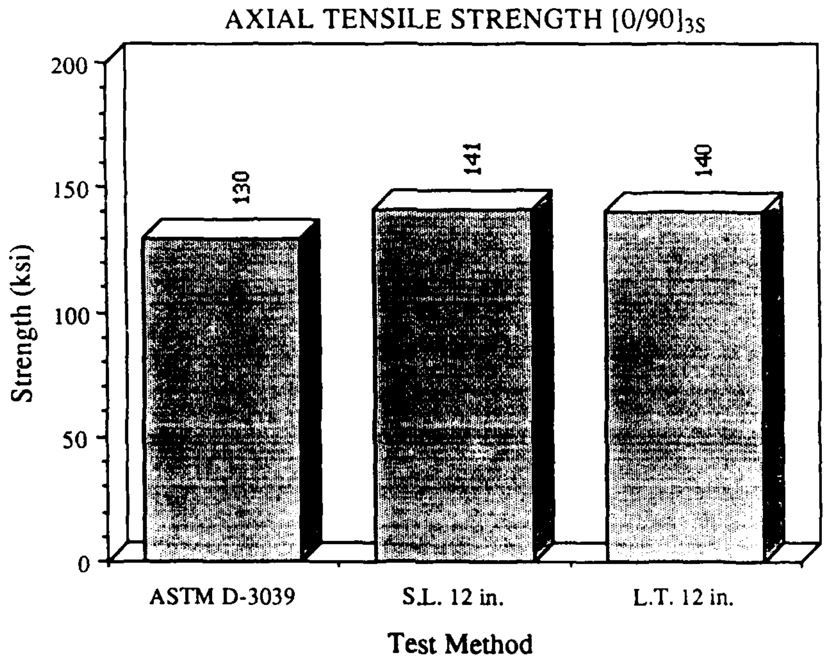
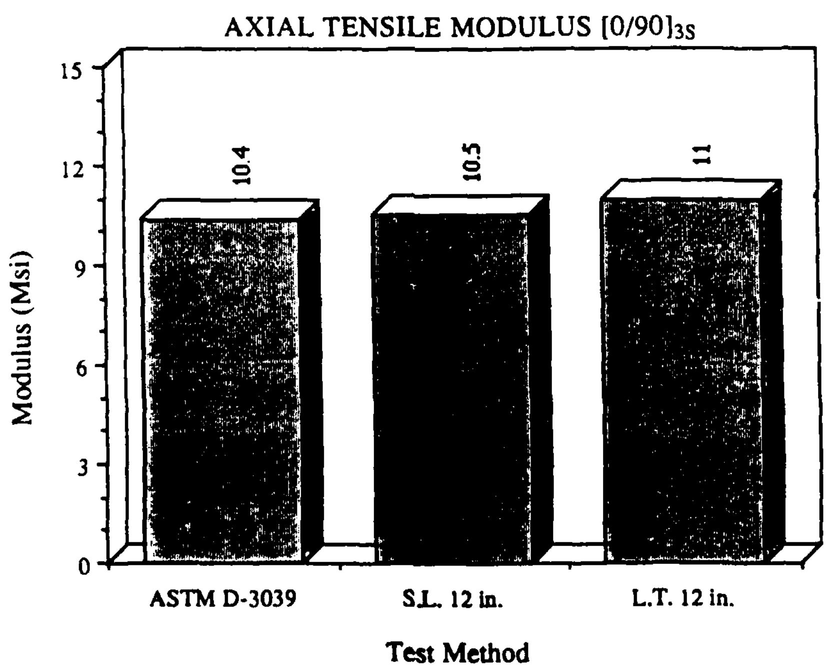


Figure 3. Cross-ply Tensile Strength Results



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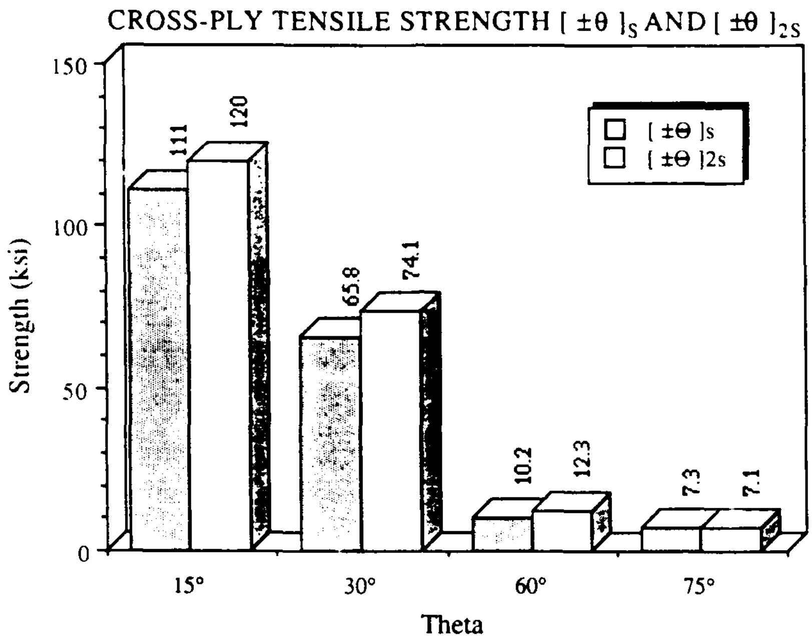


Figure 5. $[\pm\Theta]_{ns}$ Tensile Strength Results

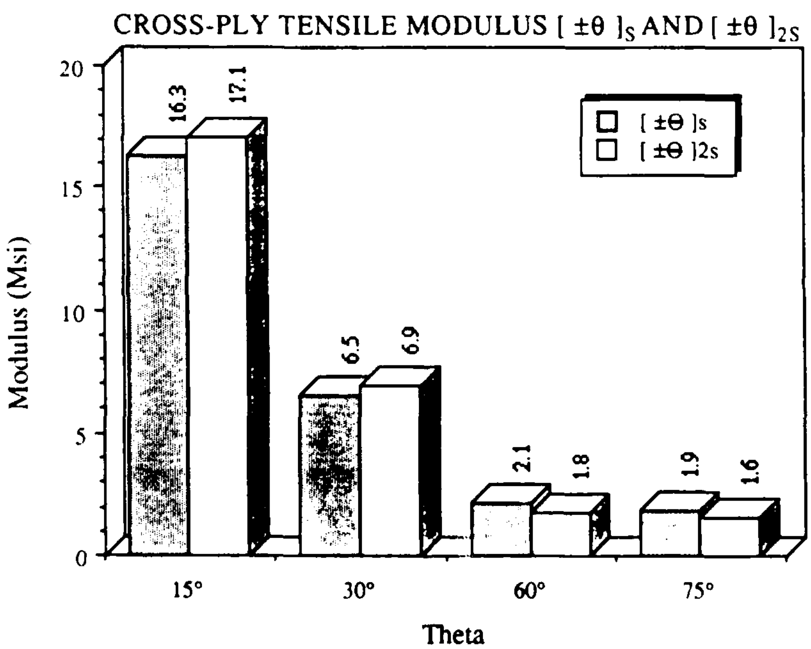
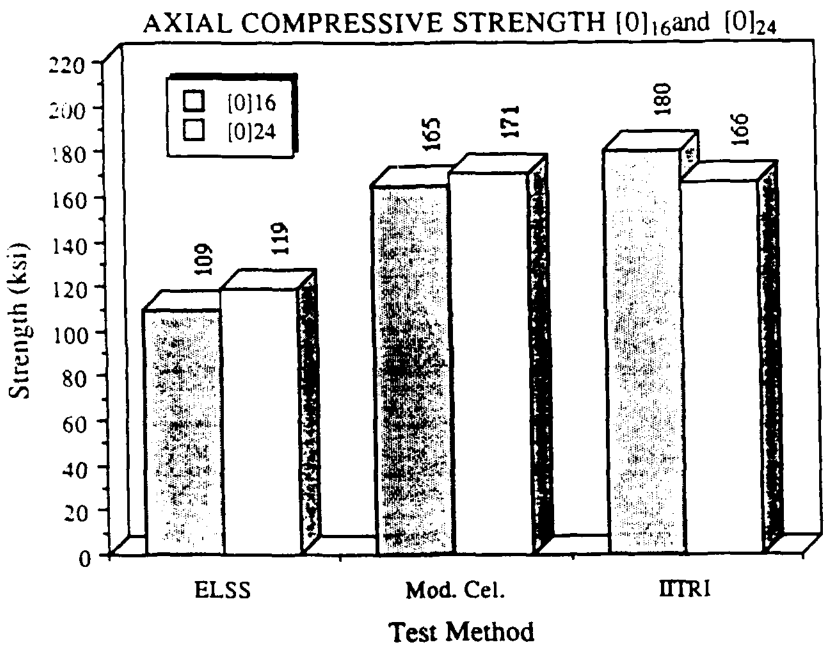


Figure 6. $[\pm\Theta]_{ns}$ Tensile Modulus Results



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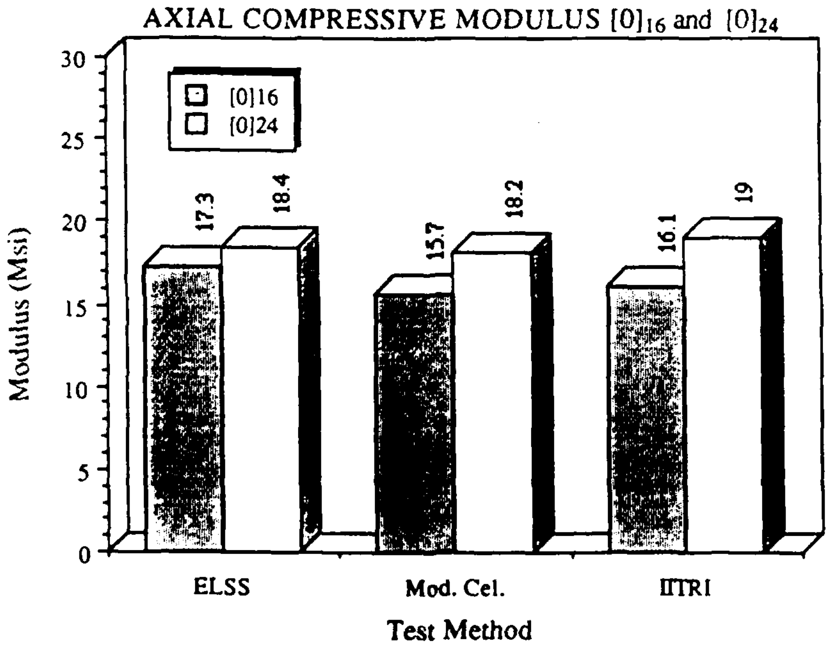

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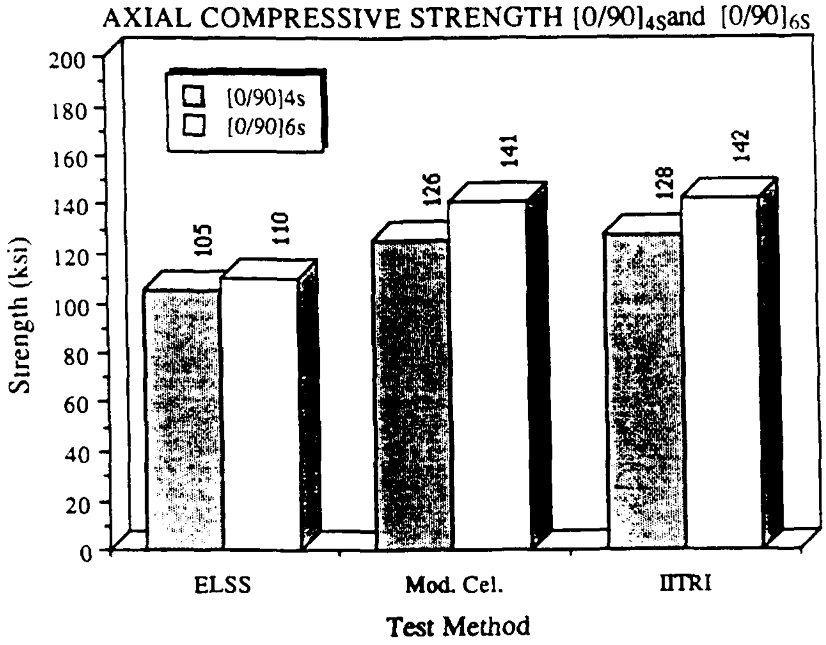

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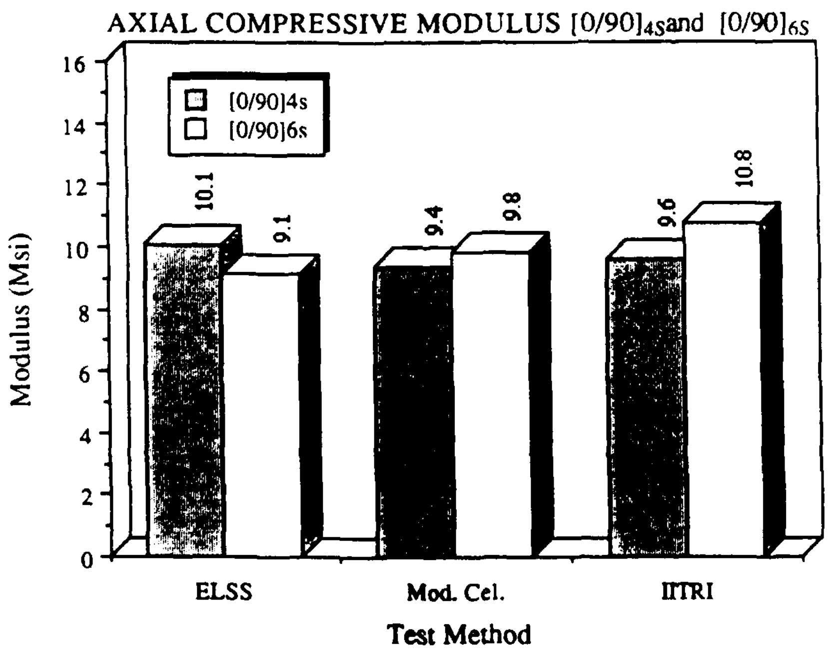

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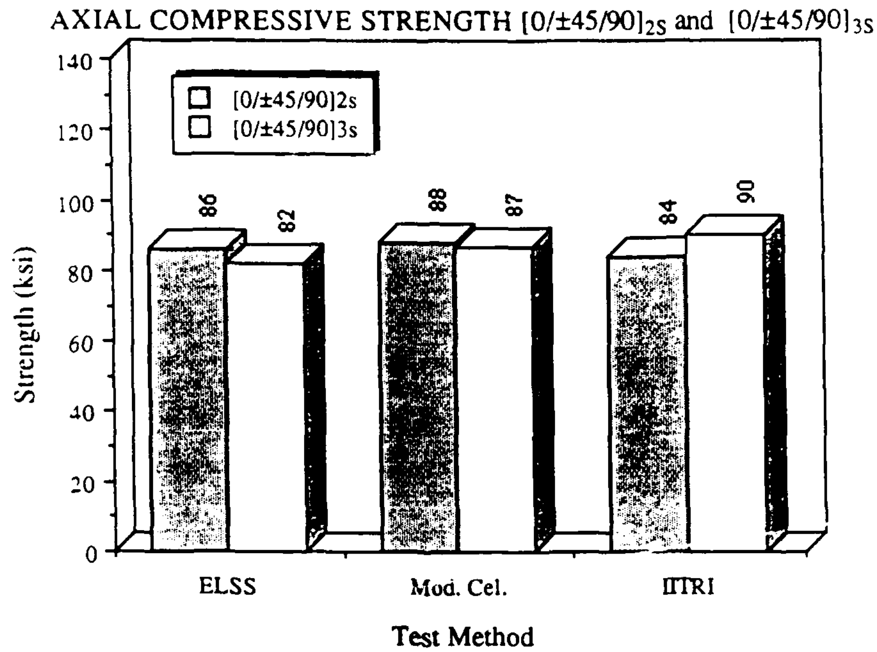

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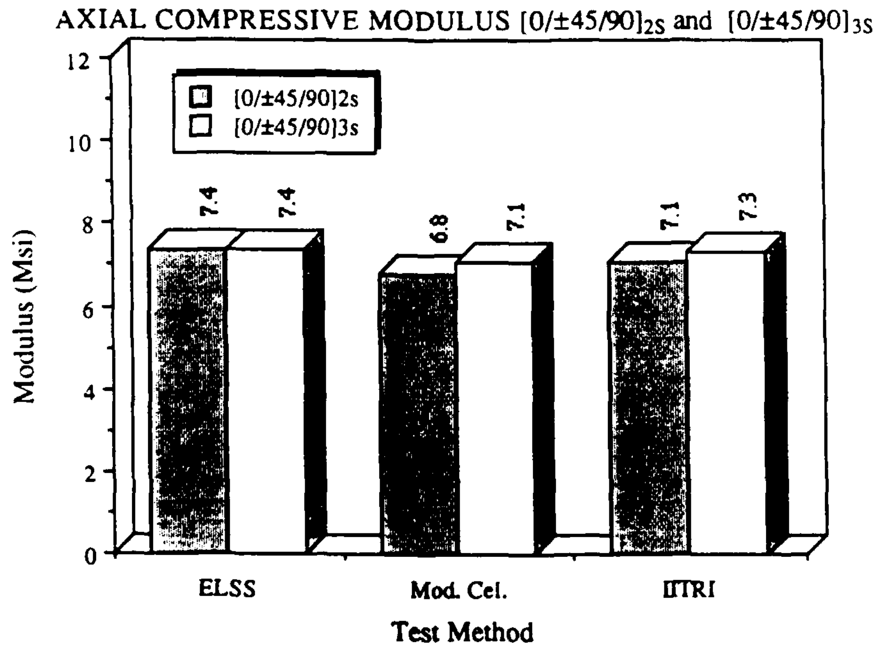

Figure 12. Quasi-isotropic Compressive Modulus Results

quasi-isotropic laminates. The Wyoming Modified Celanese and IITRI test methods yielded very similar compressive strengths, that were generally higher than for the End-Loaded, Side-Supported (ELSS) test method, for both the unidirectional and the cross-ply laminates. There were no clear differences in the moduli data using these three methods and these laminates. All three axial compression methods resulted in both strength and stiffness values in close agreement for the quasi-isotropic laminates. The sandwich beam bending compression tests were not successfully completed due to the problems noted in Section 2 of this report, and hence are not included in the figures.

The average shear test results from the ±45° tensile tests are presented in Figures 13 and 14, while those from the torsion of circular bars are presented in Figures 15 and 16. The average results from the Iosipescu shear and tapered-rail shear are presented together in Figures 17 and 18 for the unidirectional material, in Figures 19 and 20 for the cross-ply laminates, in Figures 21 and 22 for the quasi-isotropic laminates, and in Figures 23 and 24 for the $[\pm 45]_{ns}$ laminates. The off-axis tension test shear results are presented in Figures 25 and 26, and the interlaminar Iosipescu shear test results in Figures 27 and 28. Finally, the short beam shear test results are presented in Figure 29.

For the unidirectional and cross-ply materials, all of the shear test methods were in reasonable agreement for shear strength and shear modulus, with the exception of the ±45° tension test and the off-axis tension tests, which yielded lower shear strengths than the other methods. Short beam shear tests (which induce interlaminar shear stresses) were performed on the unidirectional material, but if the

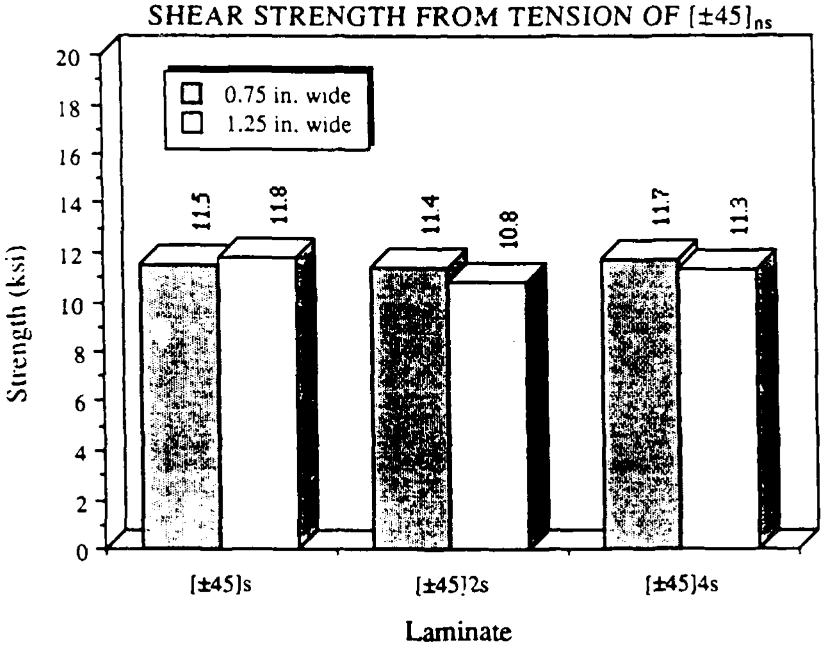

Figure 13. Shear Strength Results From Tension of $[\pm 45]_{ns}$ Laminates

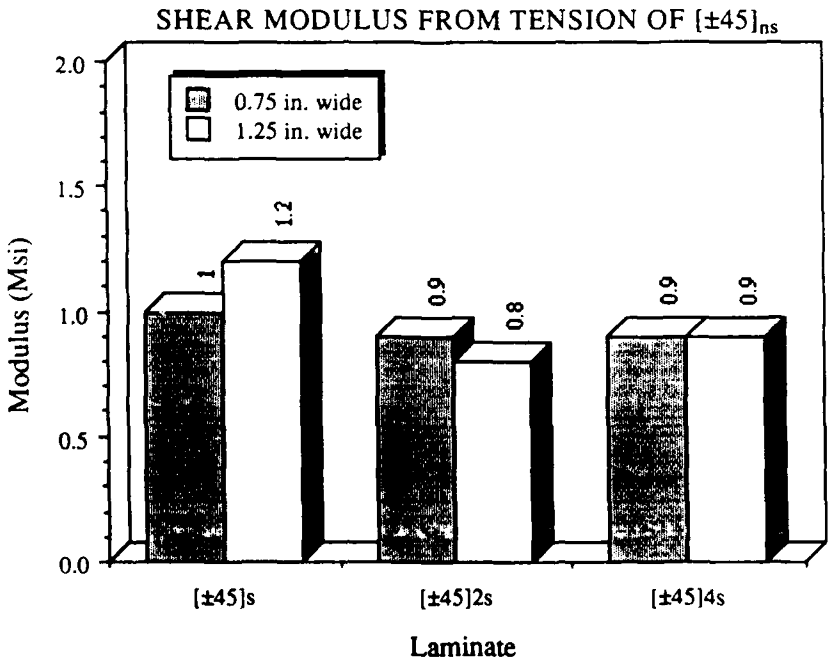

Figure 14. Shear Modulus Results From Tension of $[\pm 45]_{ns}$ Laminates

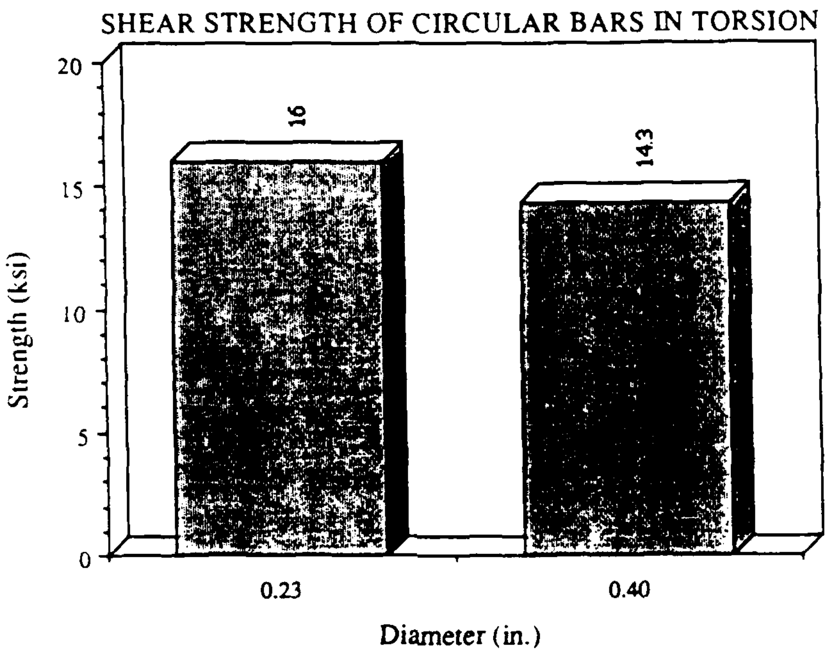

Figure 15. Circular Bar Torsional Shear Strength Results

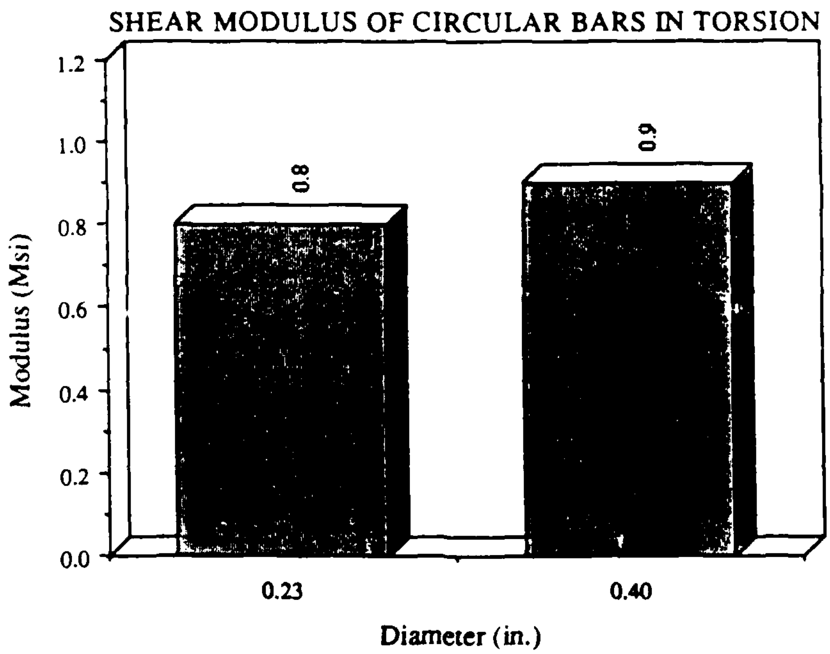

Figure 16. Circular Bar Torsional Shear Modulus Results

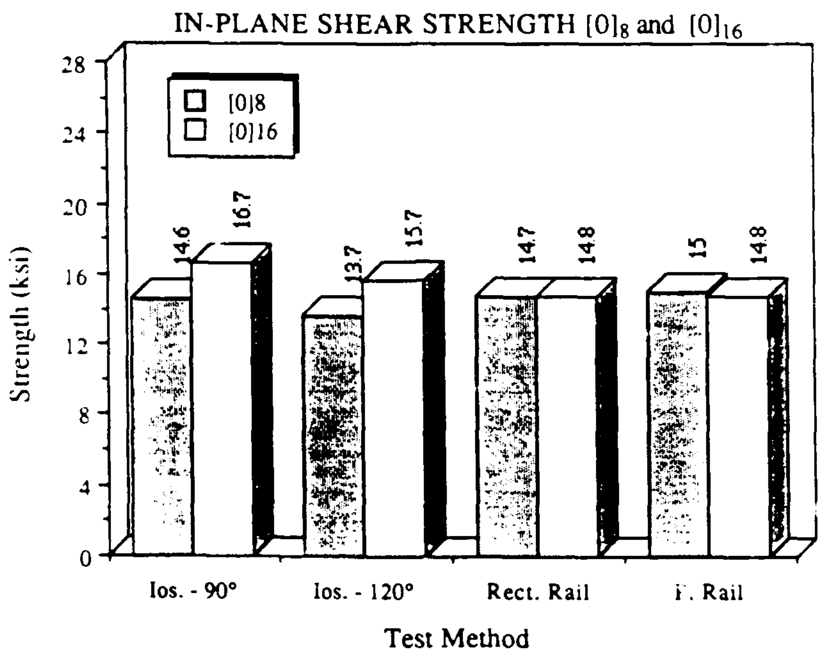

Figure 17. Unidirectional In-Plane Shear Strength Results

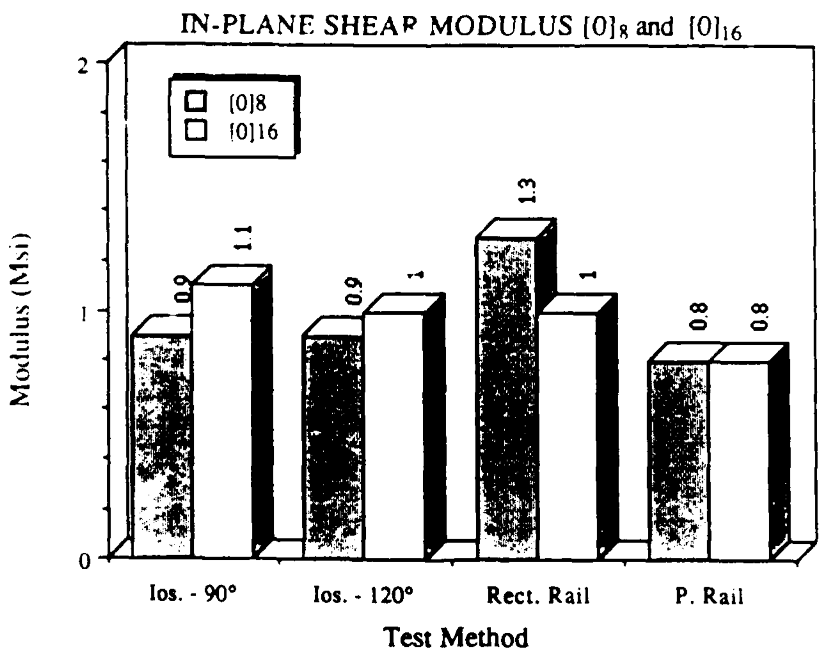

Figure 18. Unidirectional In-Plane Shear Modulus Results

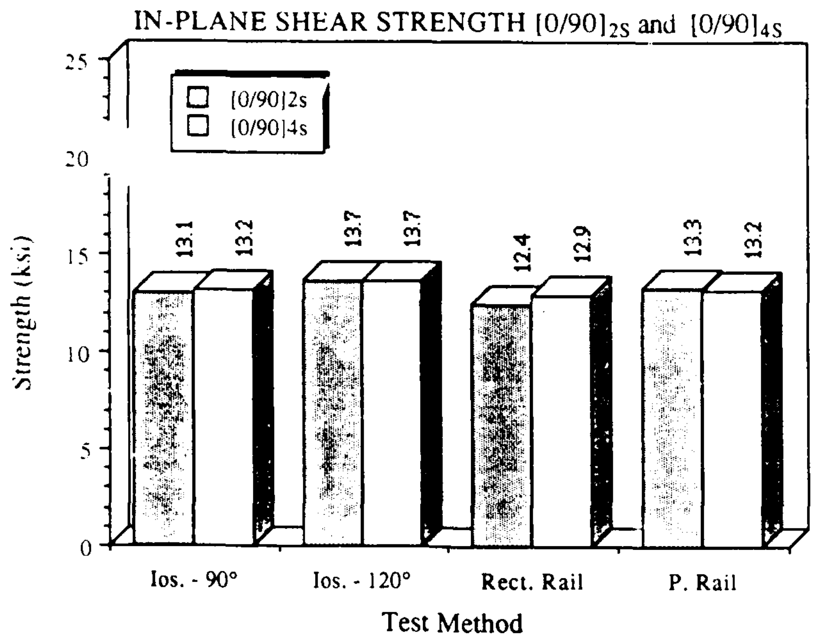

Figure 19. Cross-ply In-Plane Shear Strength Results

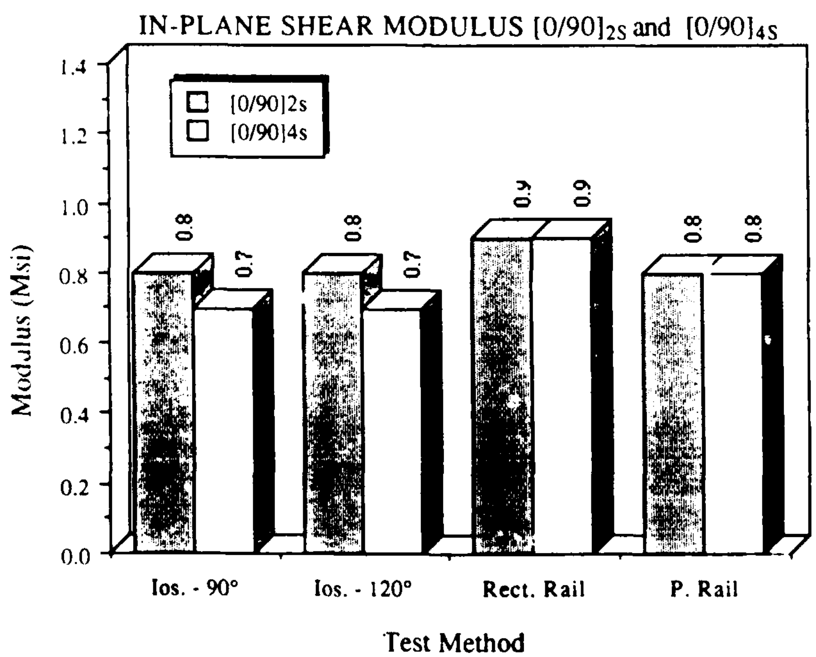

Figure 20. Cross-ply In-Plane Shear Modulus Results

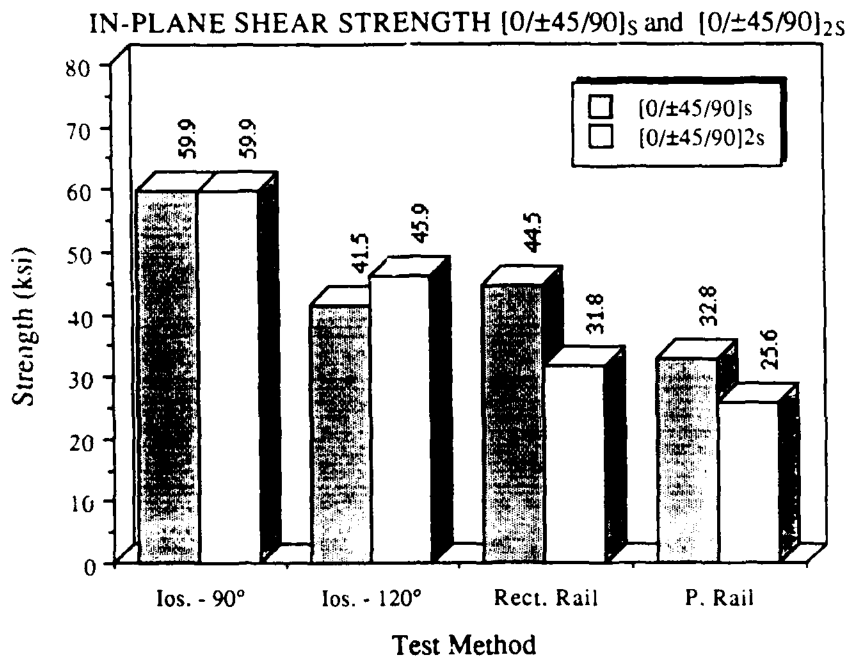

Figure 21. Quasi-isotropic In-Plane Shear Strength Results

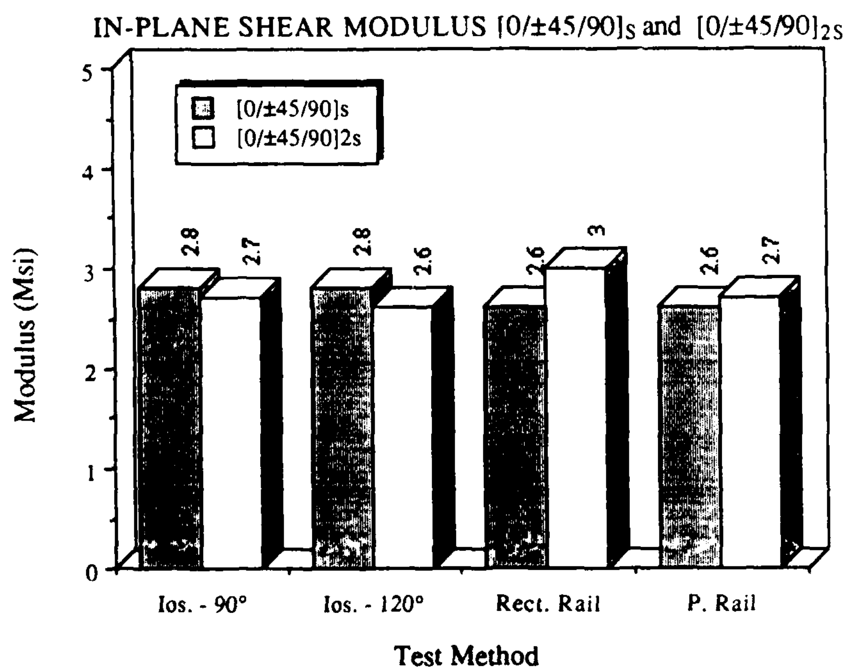

Figure 22. Quasi-isotropic In-Plane Shear Modulus Results

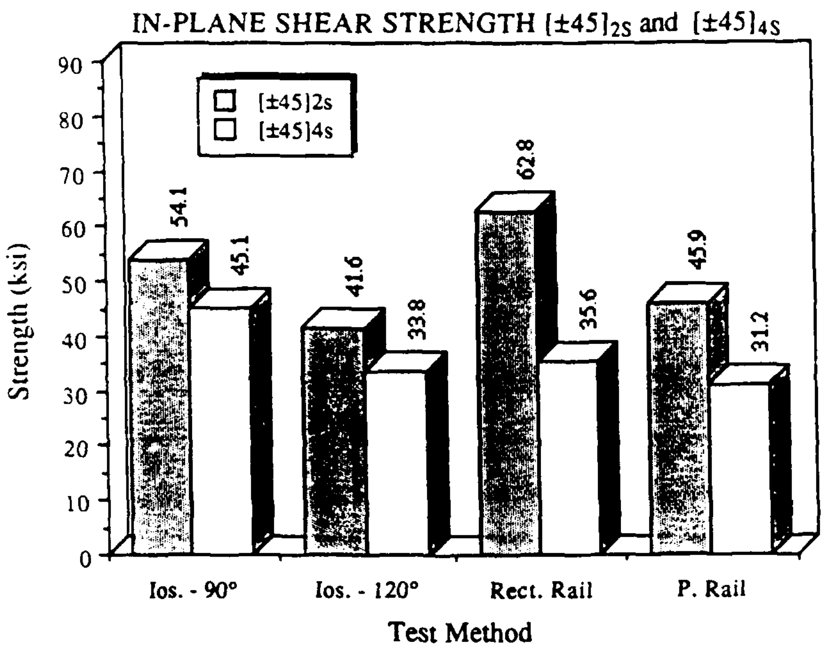

Figure 23. $[\pm 45]_{ns}$ In-Plane Shear Strength Results

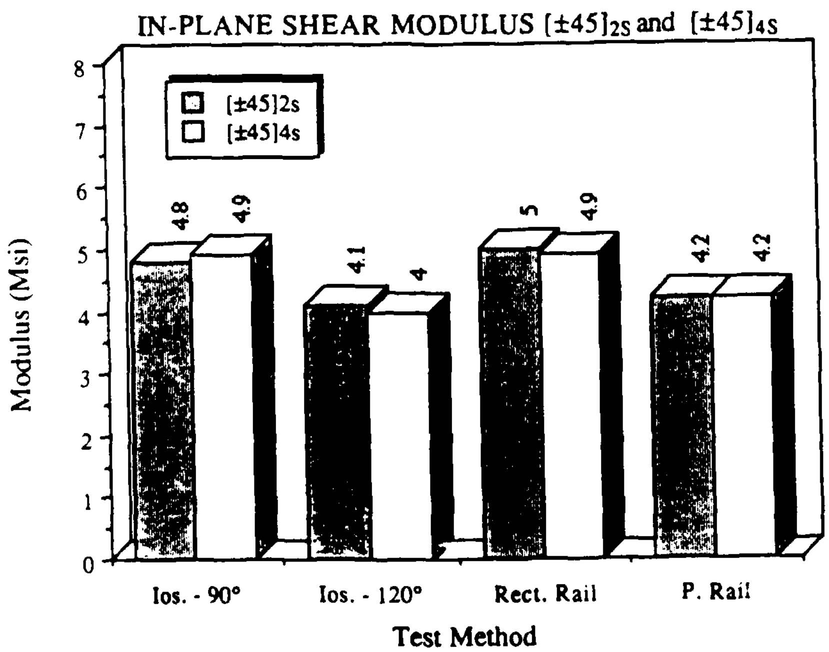

Figure 24. $[\pm 45]_{ns}$ In-Plane Shear Modulus Results

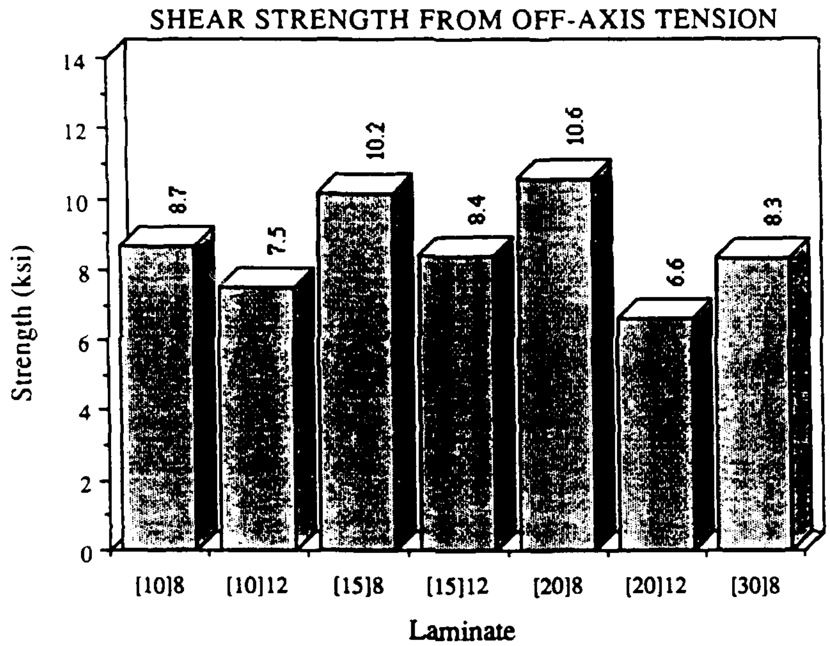

Figure 25. In-Plane Shear Strength Results From Off-Axis Tensile Tests

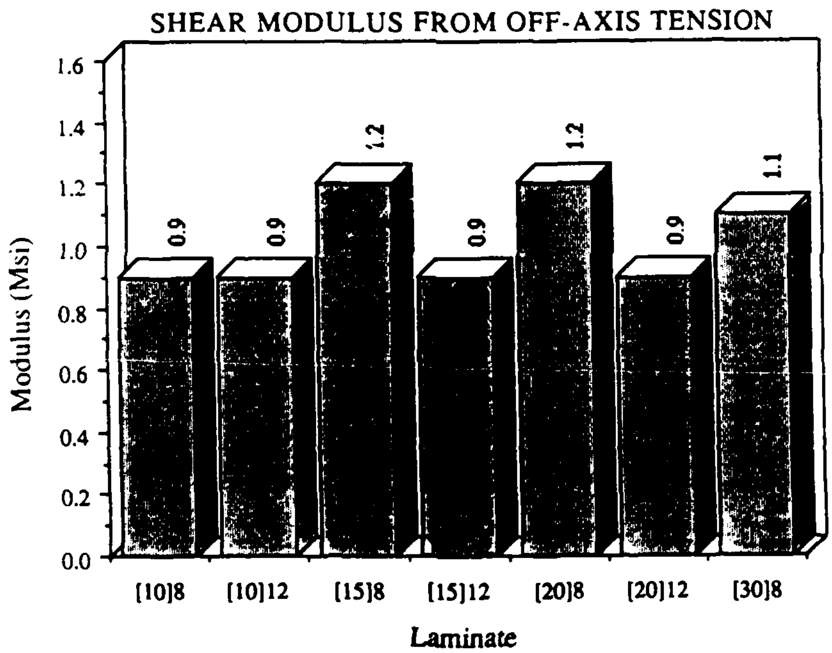

Figure 26. In-Plane Shear Modulus Results From Off-Axis Tensile Tests

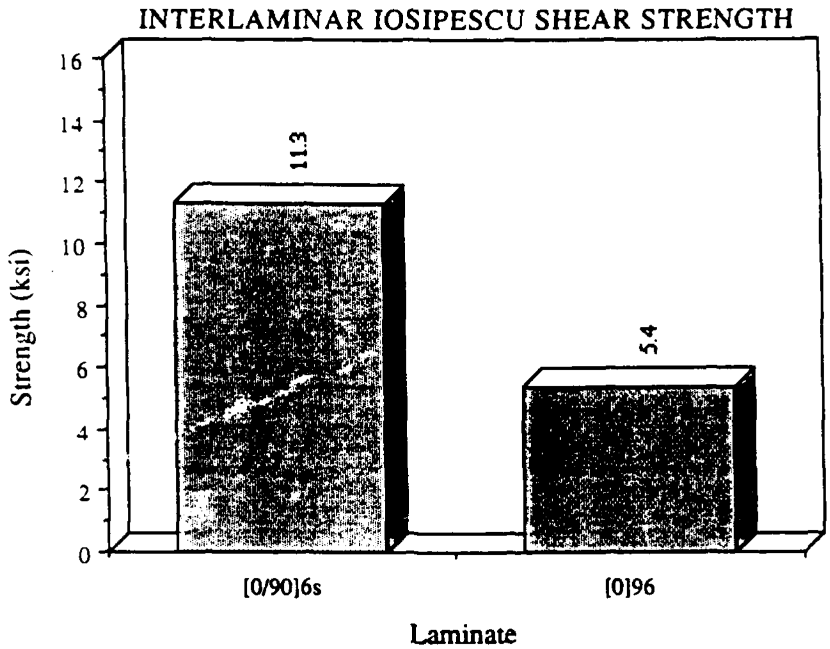

Figure 27. Interlaminar Iosipescu Shear Strength Results

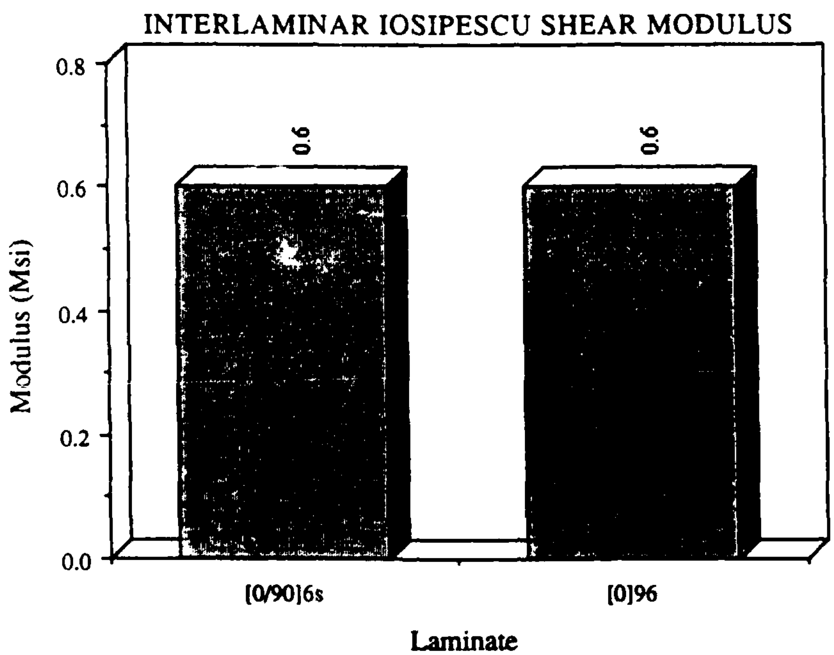

Figure 28. Interlaminar Iosipescu Shear Modulus Results

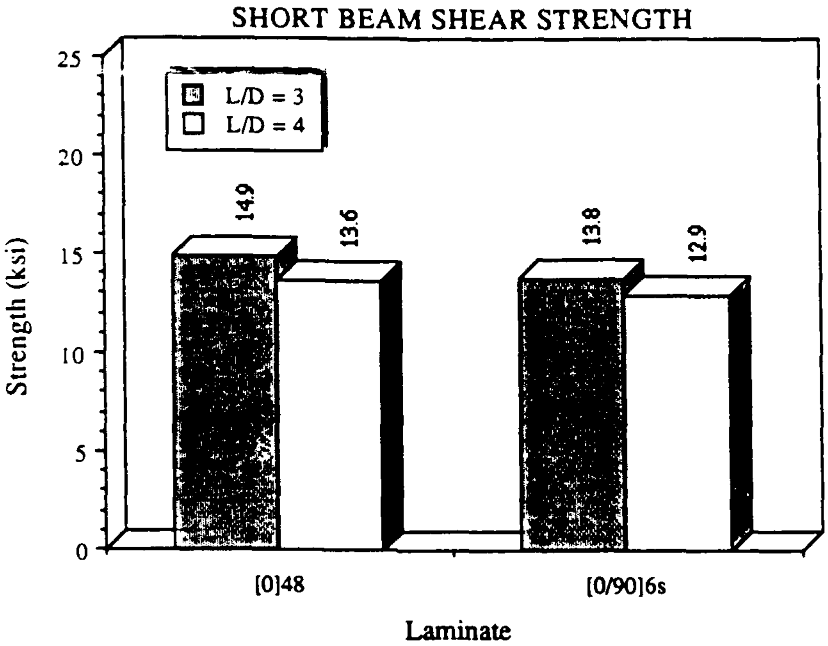

Figure 29. Short Beam Shear Strength Results

unidirectional material is assumed to be transversely isotropic, the interlaminar shear strength should be (and was) similar to the in-plane shear strength. It should be noted that all of the methods which were in mutual agreement utilized a direct shear loading of the specimen, while the other two methods used other schemes to induce shear loading, and are combined stress tests. Rectangular bars were also tested in torsion; the results of these tests are discussed in Section 3.

The Iosipescu and rail shear methods were also used to test quasi-isotropic and $[\pm45]_{ns}$ laminates. The Iosipescu tests yielded greater strengths than the rail shear tests for the quasi-isotropic laminates, although the moduli from the two methods were similar. Many of the quasi-isotropic rail shear specimens debonded from the rails prior to failure of the laminates, which precluded determination of the actual shear strengths. The $[\pm 45]_{ns}$ tests from both methods yielded mixed shear strength results yet the moduli were all within the same range.

The smaller diameter circular torsion specimens yielded slightly higher shear strengths than those with the larger diameter, while the moduli of the thicker specimens were just a bit higher. Similarly, the 16 ply unidirectional Iosipescu specimens exhibited uniformly higher strengths than the 8 ply specimens. However, unlike the torsion specimens, the moduli of the thicker Iosipescu specimens were also slightly higher.

The width of the $[\pm 45]_{ns}$ tension specimens did not appear to significantly affect the shear strengths or moduli determined with this test. Two specimens widths were tested, and the results were similar.

The influence of notch angle on the shear strengths and moduli of the Iosipescu specimens depended upon the laminate configuration. The unidirectional material with 90° notches exhibited slightly greater strength than that with the 120° notches. The moduli were approximately the same. The reverse was true for the cross-ply laminates, which yielded higher strengths with the 120° notches. Again, the moduli were similar. The quasi-isotropic specimens with the 90° notches were significantly stronger than those with the greater notch angle. However, all the quasi-isotropic specimens were tabbed to prevent crushing at the point of load introduction, and this in effect increased the unsupported length of the 120° specimens relative to the 90° specimens (because the tabs extended from the specimen ends to the outermost portion of the notches, and the 120° notches were wider). It is therefore difficult to determine if the difference in strengths was due to the difference in notch angle or the support provided by the tabs. Again, there was virtually no effect upon the moduli. The $[\pm45]_{ns}$ specimens exhibited the same strength trends as the quasi-isotropic laminates, and because they were also tabbed, the same questions exist regarding the influence of the tabs. There was a marked difference in the moduli, however, with the 90° notched specimens exhibiting higher stiffnesses than those with 120° notches.

The rectangular and parallelogram rail shear configurations yielded very similar shear strengths for the unidirectional material, for both thicknesses tested. However, the rectangular specimens exhibited consistently higher shear moduli than those with the parallelogram shape. No obvious reason for this phenomenon was evident. The cross-ply results, both shear strength and shear modulus, were very similar, with the parallelogram specimens exhibiting a slightly higher average strength and slightly lower modulus. The quasi-isotropic and $[\pm45]_{ns}$ laminate strengths and moduli of the rectangular specimens were greater than those of the parallelogram specimens.

Two different lengths and thicknesses of the off-axis tension tests were performed (for each angle), except for the $[30]_n$ specimens, for which only the 8-ply material was tested. The calculated shear strengths were much lower than expected, for all configurations, but the thinner specimens, which also had smaller length-to-thickness aspect ratios, appeared to produce higher shear strengths and moduli than the thinner specimens with the higher aspect ratios. This is discussed further in Section 3.

Interlaminar Iosipescu shear specimens were made from 6 layers of $[0/90]_{6s}$ material bonded together, and also from 3 layers of $[0]_{48}$ material bonded together. The shear strength and modulus of the cross-ply specimens was lower than for most of the other in-plane tests, although the shear strength was very similar to that of the $[\pm45]_{ns}$ tensile specimens. The modulus was lower than for the in-plane tests. The bonded unidirectional shear specimens were tested in the weakest (2-3) orientation, and they exhibited shear strengths less than one-half that of the in-plane specimens. The modulus in the 2-3 material direction was lower than the in-plane modulus, but very close to that of the bonded cross-ply specimens described above.

The average shear strength of the unidirectional short beam shear specimens was slightly higher than that of the cross-ply specimens, which were only half as thick. This was true at both span/depth ratios. In addition, the specimens tested with the span/depth ratio set at 3 were slightly stronger than those with the span/depth ratio set to 4, for both the 24-ply cross-ply and 48-ply unidirectional laminates.

SECTION 2

SPECIMEN FABRICATION AND TEST METHODS

2.1 Laminate Fabrication

The laminates from which the specimens tested in this study were prepared came from two sources due to the fact that this study was actually a combination of two distinct projects. The initial project consisted of the tests listed previously in Table 1.1, with the exception of the $[\pm\Theta]_{ns}$ and off-axis tension tests, which constituted the second project. MSC procured the laminates required for the first project from a third party and supplied them to the CMRG. After receipt of these laminates, the CMRG determined that many were of poor quality and inconsistent thickness, and that they should not be used for the study. After consultation with MSC and after consideration of the additional time and cost required to remake all of the laminates, it was agreed that the "best" laminates supplied from the vendor would indeed be used, but that the remainder would be remade by the CMRG. At this time, MSC also contracted with CMRG to conduct the $[\pm\Theta]_{ns}$ and off-axis tension testing; this second project included the fabrication of all four of the twelve-ply off-axis laminates, and a single eight-ply off-axis laminate. The other three eight-ply off-axis panels, as well as all of the $[\pm\Theta]_{ns}$ panels, were supplied by MSC (and presumably fabricated by the same vendor). The origins of the laminates used to prepare the specific test specimens, and the associated (possible) effects upon the test results, are discussed further in Section 3. The sources of the laminates are also presented in Tables 4.4, 5.4, and 6.15.

The fabrication procedure used by the supplier of the first set of laminates was not disclosed, and therefore is not included here. The laminates fabricated by the CMRG were manufactured with the procedure described below, using 12 inch wide AS4/3501-6 carbon fiber/epoxy resin prepreg tape purchased from Hercules, Inc.

The prepreg was cut to the required size and stacked in the appropriate sequence. The ply stack was then placed inside steel dams with the appropriate number of bleeder plies and a layer of Teflon-coated glass fabric peel-ply next to the outermost plies. A caul plate was then placed on top of the assembly, and the entire assembly was placed inside a blanket press for curing at the required temperatures and pressures. After curing, all laminates were post-cured for 2 hours at 200°C to ensure complete cure.

The $[0]_{48}$ laminate required for the rectangular torsion and short beam shear specimens was molded in a two-piece steel mold and cured in a heated platen press rather than the blanket press. The cure cycle and layup procedure was similar to that used for the laminates made in the blanket press.

After post-cure, density, fiber volume, and void volume determinations were made for each laminate. The target fiber volume for all panels was 62 volume percent, and this was generally achieved. Void volumes were generally in the 1 percent range.

Prior to completion of the project, the blanket press used to cure the laminates became disabled. Because it was the only device within the CMRG capable of curing laminates greater than 12 inches long, and because of time constraints, two laminates required for the program were not manufactured. These were the $[0/90]_{2s}$ panel needed for the sandwich beam bending compression tests, and the $[30]_{12}$ panel needed for the off-axis tension tests. Hence, these tests were not performed.

2.2 Specimen Fabrication

Straight-sided specimens, regardless of the test method, were cut from the laminates in a cutter-grinder with either an aluminum oxide abrasive blade or a diamond-coated abrasive blade. During machining, Cimcool 5K40B Pink/water cutting fluid served as a lubricant and coolant. Those specimens requiring ground surfaces, such as Iosipescu shear and off-axis tension specimens, were ground with an aluminum oxide abrasive wheel, using the same machine mentioned above, and the same coolant.

The streamlined profile and linear-tapered profile tensile specimens were rough cut with the abrasive blades noted above, and machined to final shape with a high-speed Tensilkut router and diamond grit coated abrasive bit. The router templates used to machine the linear-tapered profiles were machined with conventional shop techniques, while those for the streamlined-taper profiles were machined on a numerically controlled milling machine.

The specific tab geometries used for some of the tension, compression, and shear test methods are discussed below. Regardless of the test method, 0.062 inch thick G10 glass fabric/epoxy circuit board material was used for tabbing material. Tabs were bonded to the laminates using Techkits A-12 two-part epoxy adhesive.

The circular torsion specimens were machined from prismatic bars cut from flat laminates. The 0.23 inch diameter rods were machined with an aluminum oxide abrasive wheel in a tool post grinder mounted on a lathe. Excellent surface finish was achieved with this method. The 0.4 inch diameter rods were machined using conventional lathe cutting methods.

The notches in the Iosipescu shear specimens were cut on the cutter/grinder with specially dressed aluminum oxide abrasive wheels, with either 90° or 120° cutting faces. The coolant/lubricant mentioned above was used during notch cutting also.

The 0.5 inch diameter holes in the rail shear specimens were cut with two-fluted, solid carbide end mills on a conventional milling machine. The rail shear specimens were bonded to the rails with Hysol EA 9309NA epoxy adhesive, cured at a temperature below 100°C.

The interlaminar Iosipescu shear specimens were made by stacking and bonding several layers of material cut from the appropriate laminates. The unidirectional 2-3 shear specimens were made by bonding together 3 layers of the $[0]_{48}$ laminate, while the cross-ply specimens were made from 6 layers of the $[0/90]_{6s}$ material. Techkits A-12 epoxy adhesive was used to bond the layers together.

The strain instrumentation used for the specific specimen configurations of all test types is discussed in the following sections. In all cases, Measurements Group M-Bond 200 cyanoacrylate adhesive was used to bond strain gages to the specimens. Tests were conducted in Instron Model 1125, 1321, or 1334 universal testing machines. The Model 1125 is a 20,000 lb electromechanical screw-driven machine, and the latter two are 20,000 lb and 100,00 lb servohydraulic machines, respectively. Computerized data acquisition was used for all tests with either an Digital Equipment Corp. PDP 11/24 minicomputer or various personal computers adapted for such applications.

All of the strain gage signals were conditioned using Vishay 2120 amplifier/conditioner units.

2.3 Tensile Test Methods

Three different axial tensile test methods were performed on two different laminate configurations. In addition, the $[\pm\Theta]_{ns}$ tension tests were performed on laminates of four different angles and two thicknesses. The three axial tension methods were performed on both six ply unidirectional material and on $[0/90]_{3s}$ laminates. The axial strain in each specimen was measured with a Measurements Group EA-06-250BF-350 single grid strain gage mounted at specimen mid-length. All tensile specimens were tested using a crosshead rate of 0.079 inch/minute (2 mm/minute).

The ASTM D-3039 specimens of both layups were 10 inches long and had 2 inch long tapered tabs. The unidirectional specimens were 0.5 inch wide while the cross-ply specimens were 1.0 inch wide. Conventional mechanical wedge-action grips were used to apply loads to the specimens.

The unidirectional linear-tapered profile tensile specimens were 24 inches long, 0.75 inch wide at the ends, and 0.5 inch wide in the central two inches. The 12 inch long, cross-ply, linear-tapered specimens were 0.75 inch wide at the ends and 0.5 inch wide in the central two inches. The width decreased linearly from the specimen ends up to the central two inches, resulting in a taper angle of 89.35° for the unidirectional specimens and 88.57° for the cross-ply specimens (where a 90° taper angle would correspond to a straight-sided specimen). The general specimen configuration was as described in Reference [1]. Loads were applied to these specimens using MTS hydraulic grips. Emery cloth was placed between the grip faces and the specimens, with the grit in contact with the specimens, to reduce stress concentrations caused by the knurled grip faces and to provide more friction to prevent specimen slippage.

The streamline-tapered profile tensile specimens were modeled after the SL3 configuration in Reference [1], having a profile as specified by the author of that reference. Six-ply unidirectional specimens of 12 inch, 18 inch, and 24 inch length were prepared. The cross-ply specimens were 12 inches long. All specimens were 0.75 inch wide at the ends and 0.5 inch wide in the central 1.0 inch of length. The 12 inch specimens were tapered in the streamline shape as specified in Reference [1]. The longer specimens were tapered similarly, except the 12 inch profile was scaled to the specimen length. That is, the streamline shape was not regenerated for each length. Instead, the 12 inch streamline shape was spread-out axially to accommodate the greater lengths. Hydraulic grips and emery cloth as describe above were used to apply loads to the specimens.

The $[\pm\theta]_{ns}$ tensile specimens were 12 inches long , 1.0 inch wide, and had 2 inch long tapered tabs bonded to the ends. Each specimen was instrumented with a Measurements Group EA-06-062TT-350 two-gage biaxial rosette, to measure both axial and transverse strains. Two specimens of each configuration were loaded to approximately 60 percent of the failure load, unloaded, and retested to failure in order to determine the magnitude of the plastic strain response and to determine the reloading path (as requested by MSC for their constitutive modeling efforts). Conventional wedge-action mechanical grips were used to apply loads to the specimens.

2.4 Axial Compression Test Methods

Three different axial compression test methods were used in testing unidirectional, cross-ply, and quasi-isotropic laminates of two thicknesses each. The three test methods used were the IITRI compression test method (governed by ASTM Standard D 3410), the Wyoming-Modified Celanese compression test method (a modification of the Celanese compression test method also contained in ASTM Standard D 3410), and the Wyoming End-Loaded, Side-Supported (ELSS) compression test method (a modification of ASTM Standard D 695).

Axial strains were measured using Measurements Group EA-06-125AC-350 strain gages centered in the specimen gage section. A few specimens of each group were instrumented with two gages mounted on opposite sides of the specimen, to determine if column buckling was occurring. All compression tests were performed at a crosshead rate of 0.039 inch/minute (1 mm/min.).

2.4.1 IITRI Test Method

A schematic of the general configuration of the IITRI test fixture is shown in Figure 30. A disassembled view of the specific IITRI compression test fixture used in the present study is shown in the photograph of Figure 31. The base block incorporates two alignment rods, as can be seen, and rests directly on the base of the testing

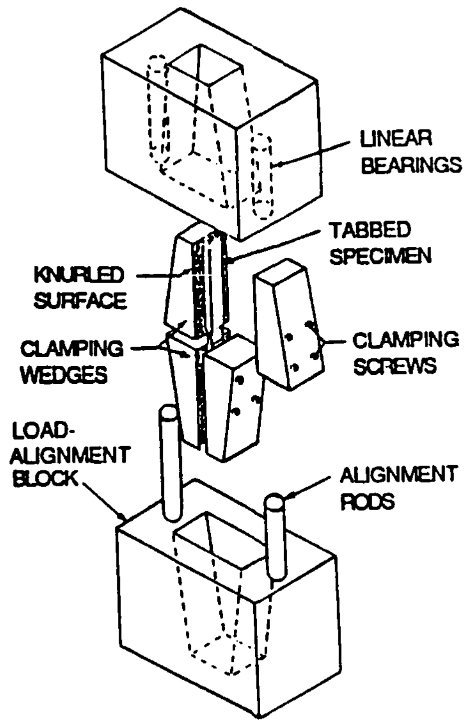

Figure 30. Schematic Diagram of IITRI Compression Fixture

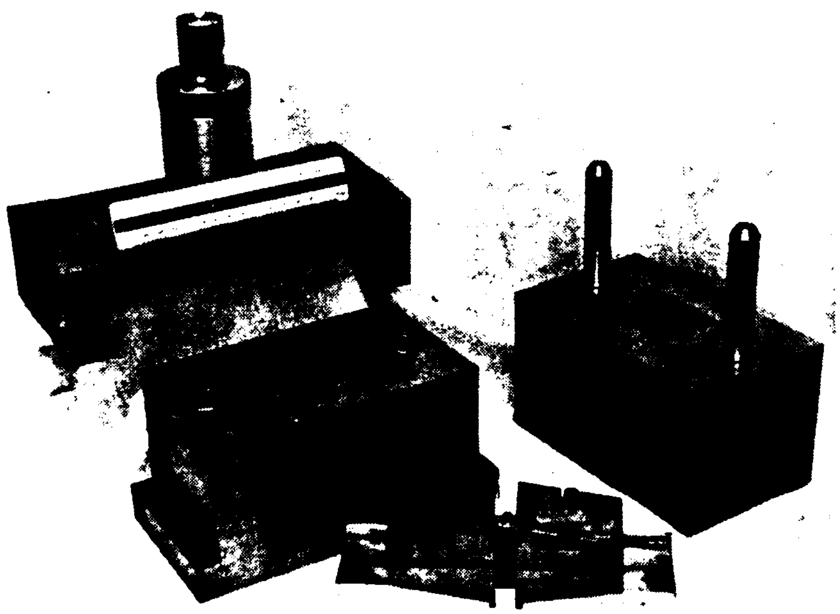

Figure 31. Disassembled View of IITRI Compression Fixture

machine. The upper block, shown positioned upside down in the photograph of Figure 31, contains linear ball bushings which mate with the alignment rods when the two halves of the fixture are assembled together. The C-shaped piece with the six-inch scale resting on it attaches directly to the crosshead of the testing machine, via the adaptor shown projecting upward. The flanges in the upper block slide into this channel, to support the weight of the upper block. The upper block can then easily be removed from the testing machine between tests, if desired, without having to detach the C-shaped piece from the crosshead. The wedge grips are shown resting on a specimen installation jig in the foreground of the photograph. The jig holds the flat, serrated grip faces parallel, for ease of specimen installation. The two halves of each pair of grips incorporate alignment pins, and are bolted together sufficiently tight after specimen installation to prevent movement of the specimen while the wedge grips are being inserted in the pockets of the upper and lower blocks. The fixture shown will accommodate a specimen of any width up to 38 mm (1.5 in), and of thickness at the tabbed ends ranging from 4.3 mm (0.17 in) to 15.2 mm (0.60 in). This wide range of specimen thicknesses is achieved via three sets of wedge-shaped spacers of different thicknesses, which can be interchangeably mounted in the pockets of the upper and lower blocks.

The complete IITRI fixture weighs approximately 90 lb, making it somewhat awkward to handle. Its large mass combined with the usual need for precision machining of any test fixture also makes it much more expensive that the other two test fixtures used in the present study. Nevertheless, it provides excellent test results [2,3].

The IITRI compression specimens used in the present study were 5.5 inches long and 0.25 inches wide, with 2.5 inch long tapered tabs of glass-fabric/epoxy bonded to each end, resulting in a gage length (distance between tabs) of 0.5 inch. This specimen overall length and gage length is as specified in ASTM D 3410.

2.4.2 Wyoming-Modified Celanese Compression Test Fixture

The Wyoming-Modified Celanese compression test fixture has been developed during the past ten years [2,3] in an attempt to incorporate the best features of both the ASTM Standard D 3410 Celanese and IITRI compression test fixtures, while minimizing their limitations. A sketch of the general configuration of the fixture is shown in Figure 32. A photograph of the specific fixture used in the present study is shown in Figure 33. The wedge grips are of constant radius along their tapered length so that they make full surface contact with the mating blocks independent of their relative axial position, unlike the standard Celanese fixture, which incorporates tapered cones. Thus, the thickness of the specimen at the tabbed ends can vary, just as for the IITRI fixture.

The range of tabbed specimen thickness for the fixture shown in Figure 33 is from 0.16 inch to 0.25 inch. The wedge grips are 0.5 inch wide, thus limiting the maximum specimen width to this value, which however is twice that of the standard Celanese fixture. Also, to facilitate machining, the wedge grips in the fixture shown are only 2 inches long, permitting the use of a specimen 4.5 inches long, with a standard 0.5 inch gage length. That is, the grips are each 0.5 inch shorter than for the standard Celanese and IITRI test fixtures. This

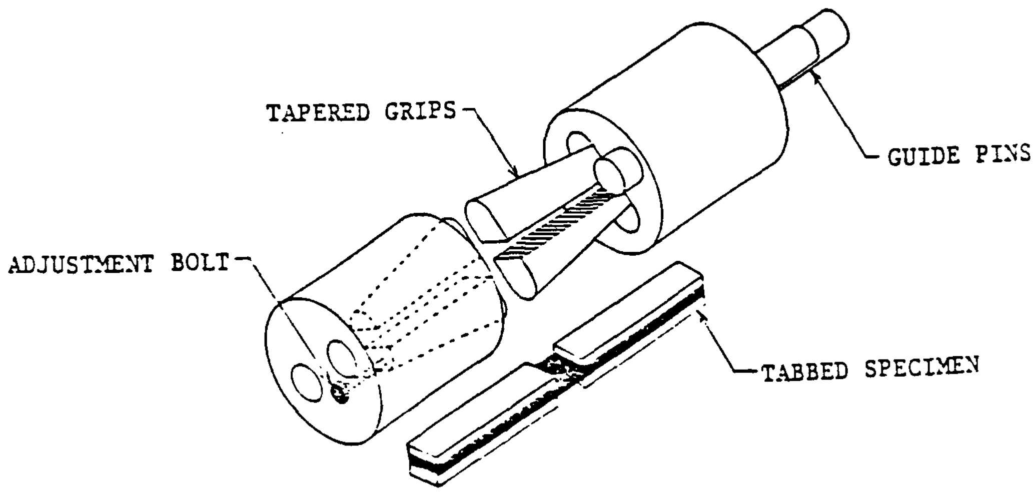

Figure 32. Schematic of Wyoming-Modified Celanese Compression Fixture

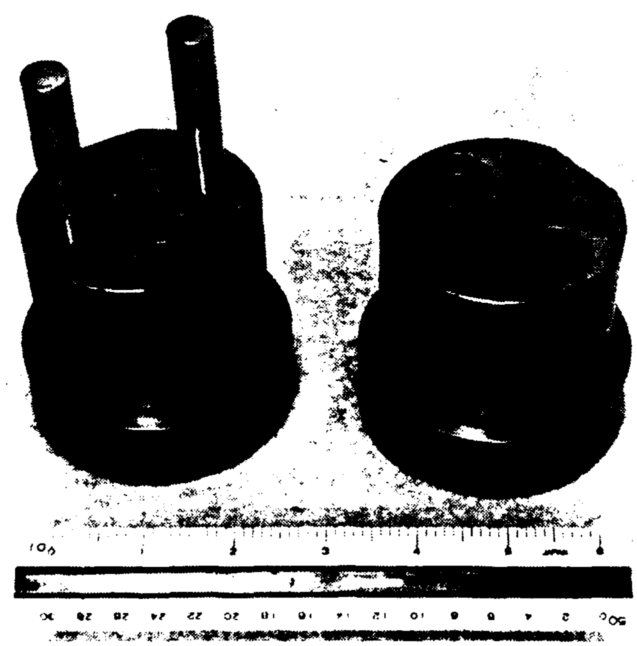

Figure 33. Photograph of Wyoming-Modified Celanese Compression Fixture

has not limited its performance to date. Of course the fixture could be readily lengthened, if desired, to accommodate a longer specimen, but at the expense of increased fixture fabrication cost.

As can be seen in Figure 33, the two halves of the fixture are aligned in a manner similar to the IITRI fixture, i.e., via alignment rods and linear bearings. However, the round shape of the standard Celanese test fixture has been retained, permitting the forces induced in the end blocks by the wedge grips to be efficiently carried as hoop stresses. Thus, the weight of the fixture, at approximately 10 lb, is comparable to that of the standard Celanese fixture, and only a small fraction that of the standard IITRI fixture, making it very easy to handle. Correspondingly, the cost of fabricating the Wyoming-Modified Celanese compression test fixture is also only a fraction that of the IITRI fixture. The penalty for this, however, is less specimen width and thickness capacity than for the IITRI fixture.

The Wyoming-Modified Celanese compression test specimens used in the present study were 4.5 inches long and 0.25 inch wide, with 2 inch long tapered tabs of glass-fabric/epoxy, which resulted in a standard gage length of 0.5 inch.

2.4.3 Wyoming End-Loaded, Side-Supported Compression Test Fixture

One disadvantage of using a shear-loaded test specimen, such as specified in ASTM D 3410, is the need for end tabs. The use of end tabs increases specimen preparation time and cost. Thus, methods have been developed for loading the specimen directly on its ends, rather than transferring the force via shear through tabs. The difficulty is preventing end crushing (brooming) in highly orthotropic, high strength materials such as unidirectional composites.

A sketch of the Wyoming End-Loaded, Side-Supported compression test fixture is shown in Figure 34. The actual fixture used in the present study is shown in the photograph of Figure 35. It follows the general principles of ASTM Standard D 695. The four blocks, bolted together in pairs, are intended to prevent specimen buckling, being only lightly clamped to the specimen [2]. The space between the upper and lower pairs of blocks established the gage length, which was 0.5 inch in the present study, and provides room for strain monitoring instrumentation.

This fixture has been found to work as well as any of the ASTM Standard D 3410 test fixtures for quasi-isotropic composite laminates and materials of similar or lesser strength [2]. However, end crushing is a problem for strong materials such as unidirectionally-reinforced composites. End tabs could be used, to increase the bearing area, but this would defeat the principal advantage of this test method. Attempts to date to dog-bone the test specimen in the width direction, thus increasing the bearing area at the specimen ends relative to the cross-sectional area in the gage section, have been relatively unsuccessful. If the specimen is dog-boned enough to prevent end crushing, the enlarged ends tend to shear off parallel to the fiber reinforcement, due to the relatively low shear strength of the unidirectional composite. In future work it is hoped to investigate face-waisting, i.e., reducing the thickness of the specimen in the gage section. The advantage over edge-waisting is that a much larger area must be sheared through if the enlarged ends are to fail prematurely. This was not attempted in the present study.

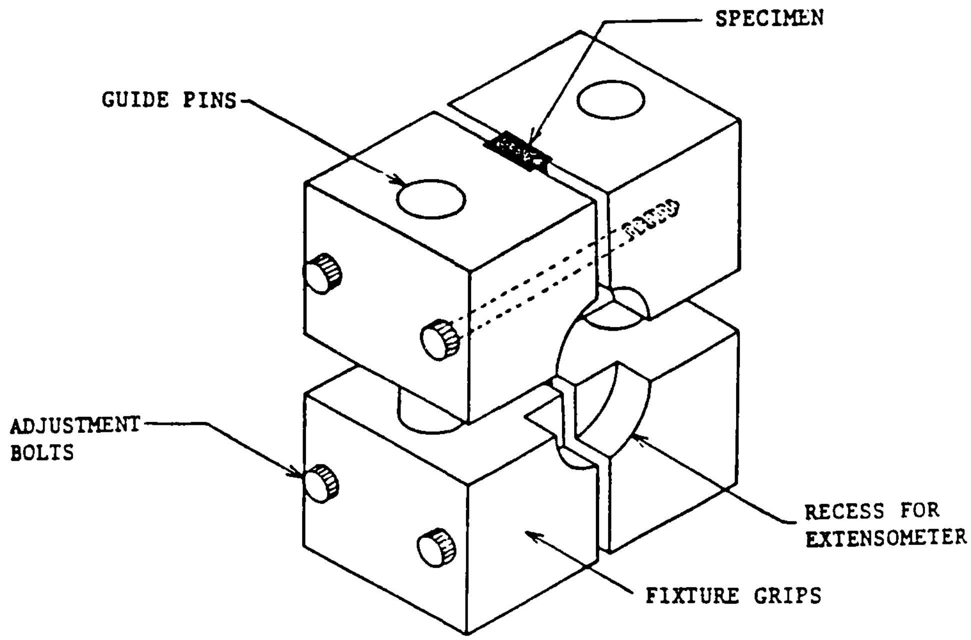

Figure 34. Schematic of Wyoming End-Loaded, Side-Supported Compression Fixture

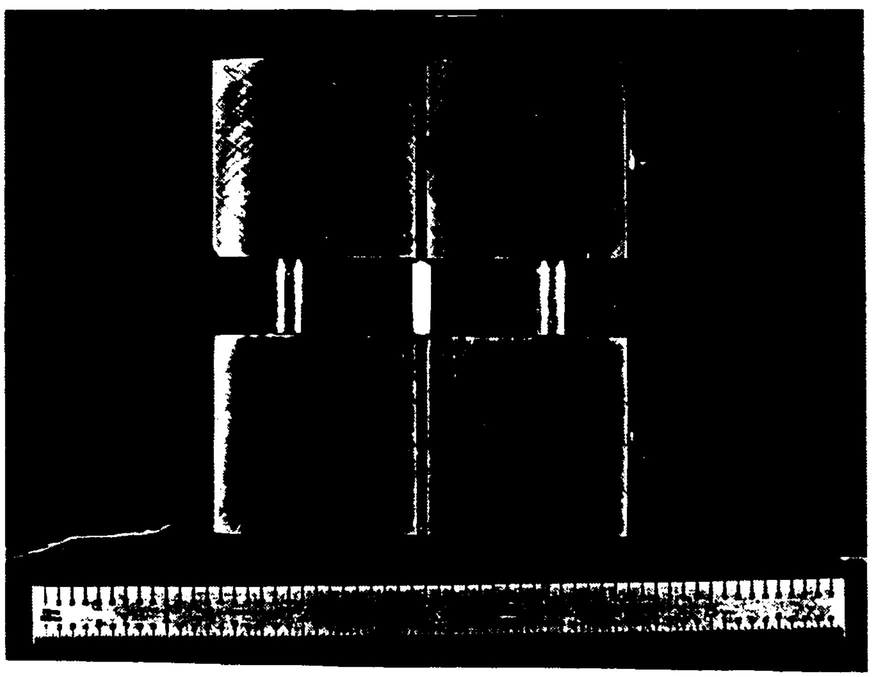

Figure 35. Photograph of Wyoming End-Loaded, Side-Supported Compression Fixture

The specimens used in the present study were 3.35 inches long, 0.5 inch wide, straight-sided, and untabbed. The gage length (distance between lateral support blocks) was 0.5 inch.

Because many of the laminates from which the ELSS specimens were prepared varied in thickness along the specimen axis, considerable binding between the fixture blocks and the fixture guide pins was observed. Therefore, many tests were conducted without the guide pins in the fixture.

2.4.4 Sandwich Beam Bending Compression Test Fixture

As mentioned previously, sandwich beam bending compression tests were also to have been performed, on six-ply unidirectional and $[0/90]_{2s}$ laminates. However, the cross-ply laminate was not fabricated, as previously discussed. In addition, it proved impossible to procure both the high density aluminum honeycomb and the titanium back sheets required by the method specified by MSC (which is described in Reference [4]). Instead, a lower density core material and 0.125 inch thick 6061-T6 aluminum were obtained and the unidirectional specimens were fabricated. They consisted of 22 inch long, 1 inch wide strips of composite bonded to a 22 inch long, 1 inch wide, 1.5 inch thick honeycomb. A 22 inch long, 1 inch wide aluminum strip was bonded to the opposite face of the honeycomb core. The specimens were loaded with a four-point bend fixture that had a 20 inch outer support span and a 4 inch inner loading span. The specimen axial strains were measured with a single Measurements Group EA-06-250BF-350 strain gage. The tests were not successfully completed, however; upon loading, the honeycomb core failed in shear prior to failure of the composite face sheets.

2.5 Shear Test Methods

Shear test methods investigated included those used for in-plane characterization as well as interlaminar (through-the-thickness) characterization. The tension of $[\pm 45]_{ns}$ laminates, torsion, Iosipescu, and tapered rail shear methods were of the former type, and the short beam shear and stacked-and-bonded-laminate Iosipescu shear methods were of the latter type. Because of the transverse isotropy of the unidirectional laminates, the circular torsion, Iosipescu shear of unidirectional laminates (not stacked and bonded), and interlaminar short beam shear of unidirectional laminates effectively measured the same quantities.

2.5.1 Tension of $[\pm 45]_{ns}$ Laminates

Tension of $[\pm 45]_{ns}$ laminates has been used for the determination of composite shear properties for some time [5], even though the specimens are placed in a state of combined stress rather than pure shear. The $[\pm 45]_{ns}$ tensile specimens tested in the present effort were 11 inches long and either 0.75 inch or 1.25 inch wide. All specimens had 1.5 inch long tapered tabs, which resulted in a gage section 8 inches long. Loads were applied to the specimens with conventional wedge-action mechanical grips at a crosshead rate of 0.1 inch/minute (2.54 mm/minute) until specimen rupture. Axial and transverse strains were measured with Measurements Group EA-06-125TQ-350 dual-element biaxial strain gages. The specimen axial loads and axial and transverse strains were used to calculate the in-plane shear stress-shear strain response as described in Reference [5].

2.5.2 Rectangular Torsion Specimen Tests

Three different rectangular torsion specimen configurations were tested. 48-ply specimens were 10 inches long, either 0.5 inch or 0.75 inch wide, and nominally 0.25 inch thick. The 24-ply specimens were 8 inches long, 0.5 inch wide, and nominally 0.125 inch thick. Torsional loads were applied to the specimens with special grips of the appropriate cross section, which gripped the specimen ends over a length of 1.75 inches. Hence, the 48-ply specimen gage section was 6.5 inches long, while the 24-ply specimen gage section was 4.5 inches long. The grips were mounted in an Instron Model 1125 testing machine using three-jaw Jacobs chucks. One of the chucks was not constrained axially, thereby reducing the stresses which occur as the specimen is twisted. The specimens themselves, however, were constrained axially by friction within the grips in the 1.75 inch long gripped sections. The specimens were loaded at 0.1 rev/minute, which is equivalent to 36 degrees/minute or 0.63 radian/minute. Strains were measured on the primary face of each rectangular torsion specimen with a Measurements Group EA-15-062RB-120 three-element (90-45-90) rectangular rosette. In addition, strains were measured on the minor faces with EA-06-062RF-350 three-element rectangular rosettes (for the 48-ply specimens) or EA-06-015RJ-120 three-element rectangular rosettes (for the 24-ply specimens). Several techniques exist for reducing rectangular torsion specimen test data (see, for example Reference [6]), but this reduction was not performed as part of the present effort. The as generated torque and strain data are presented in Appendix C.

2.5.3 Circular Torsion Specimen Tests

Circular torsion specimens were made from 48-ply and 96-ply unidirectional laminates. The specimens from the 48-ply laminates were 7 inches long and nominally 0.23 inch in diameter. The specimens from the 96-ply laminate were 7 inches long and 0.40 inch in diameter. Specimens of both diameters were tested at 0.1 rev/minute in the Instron Model 1125 testing machine using three-jaw Jacobs chucks to apply the torsional loads. Small flats were ground on the ends of the larger diameter specimens to aid in gripping after slippage in the grips occurred in specimens initially tested without the flats.

2.5.4 In-Plane Iosipescu Shear Specimen Tests

In-plane Iosipescu shear specimens were fabricated and tested from unidirectional, cross-ply, quasi-isotropic, and $[\pm 45]_{ns}$ laminates of two thicknesses. All specimens were 3 inches long and 0.75 inches wide, and had opposing 90° or 120° notches cut perpendicular to the long axis of the specimen at mid-length. The long axis was coincident with the fiber axis for the unidirectional specimens. The notches were cut to a nominal depth equal to 25 percent of the specimen width. This resulted in a notch depth of 0.188 inch. Because the notch depth was the same for the specimens of both notch configurations, the notch was wider in the specimens with 120° notches, i.e., more material was removed from the specimens with the 120° notches. Edge crushing at the load points was observed in the quasi-isotropic and $[\pm 45]_{ns}$ specimens of both thicknesses and both notch angles during preliminary testing. Thus, tabs were bonded to the faces of the remaining specimens, to prevent such crushing. The tabs extended from the specimen ends toward the specimen center to the point where the wide part of the notches intersected the specimen edges. This left an untabbed section on both major specimen faces equal to the width of the notches. The specimens with 120° notches therefore had wider untabbed regions than those with 90° notches.

The width of the abrasive wheel used to grind the 120° notches was not quite sufficient to allow the notch to extend to the specimen edge. Hence, the sides of the notches were vertical (perpendicular to the specimen long axis) nearest the loaded specimen edges for a few hundredths of an inch, and were then at the prescribed angle until intersecting at the notch root.

A Wyoming Iosipescu Shear test fixture was used to apply loads to the various specimens. A schematic of the loading method is indicated in Figure 36. A photograph of the actual fixture used in the present study is shown in Figure 37. Although the test fixture can be designed to be loaded in either tension or compression, researchers at the University of Wyoming have always used a compressively loaded fixture. The original Wyoming fixture configuration, used until late 1983, was designed for a 2 inch long, 0.50 inch wide specimen. This small size had originally been dictated by the need to conserve specimen materials when testing carbon-carbon composites of limited availability. However, the smaller the specimen, the smaller the region of uniform pure shear strain between notches, making the measurement of strain more difficult.

The original Wyoming fixture also was not adjustable to accommodate specimens deviating slightly from the specified 0.50 inch width. This had never been a problem for the CMRG, as the specimen edges are routinely precision ground to close tolerances. However, this is not

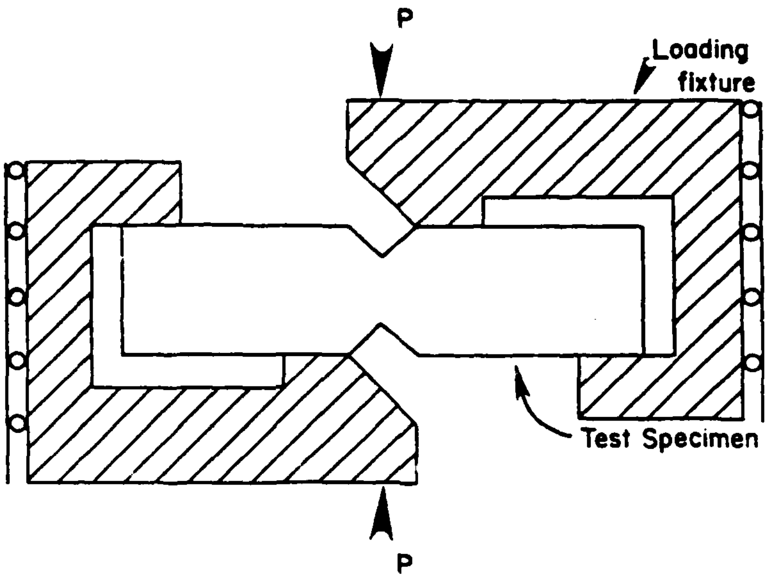

Figure 36. Schematic of Wyoming Iosipescu Shear Fixture

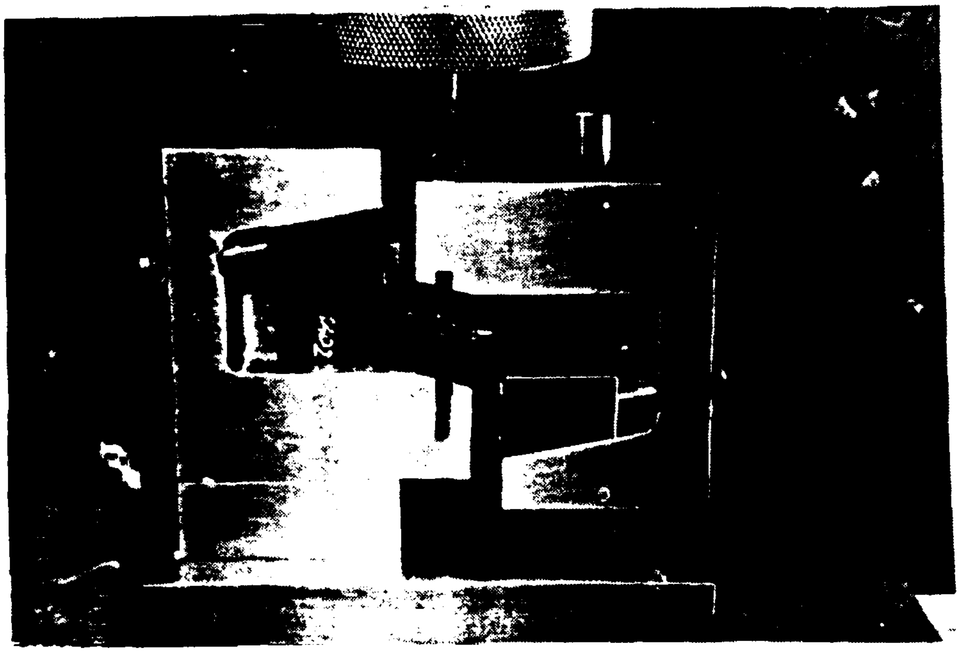

Figure 37. Photograph of Wyoming Iosipescu Shear Fixture

necessarily the procedure in other laboratories. During the 1983-84 time period, the fixture was redesigned to accommodate a specimen 50 percent larger, viz., 3 inches long and 0.75 inch wide. As noted, this facilitated mounting of the strain gages. The inner loading points were also moved outward from the notches, reducing the possibility of these concentrated loadings disrupting the pure shear stress state between the notches. The larger specimen is also easier to handle. On the other hand, it does consume more material.

The redesigned Wyoming fixture is the one shown in Figure 37. The movable wedges accommodate specimens of variable width. A centering tool is built directly into the base. It is simply lifted from its storage slot with one finger, and indexed into the lower notch of the specimen to center the specimen left to right. When released, it drops out of the way, back into the slot. Rather than having both fixture halves moving on shafts, the left half is now fixed to the base. to provide greater stability. Also, the moving half of the fixture is now directly attached to the moving crosshead of the testing machine via an adapter, rather than being loaded via a steel ball resting in a depression on its top surface. The combination of having both fixture halves pivoting, a loose centering tool, and a loose loading ball made it unnecessarily difficult to install a specimen in the original fixture. The current design is much easier to use. However, results obtained using the original fixture are still valid. A linear (recirculating ball) bearing is now used with the guide post, rather than the bronze bushing of the original design. This improvement further reduced friction, although friction did not appear to be a problem with the original design either.

The Wyoming Iosipescu shear fixture was used to apply loads to the specimens at a crosshead rate of either 0.039 inch/minute or 0.079 inch/minute. Strains were measured with Measurements Group EA-06-062TV-350 (±45°) dual-element rosette strain gages mounted between the specimen notches. It was assumed that the rosettes were measuring the (normal) principal strains, and therefore that the instantaneous shear strains were equal to the sum of the absolute values of the instantaneous principal strains measured by the rosette elements.

2.5.5 Tapered Rail Shear Tests

Tapered rail shear tests of two geometries were performed, on unidirectional, cross-ply, quasi-isotropic, and $[\pm 45]_{ns}$ laminates of two thicknesses. The specimen geometries were specified by MSC and are shown in Figure 38. As can be seen in the figure, one configuration utilizes a rectangular specimen and the other a parallelogram-shaped specimen. The latter is actually a rectangular specimen with two diagonally opposed corners removed. The specimen/rail combinations resulted in 0.5 inch wide gage sections that were nominally 4 inches long for the rectangular shape and 3.5 inch long for the parallelogram shape. Each specimen was both bonded and bolted to the rails. Hysol EA 9309NA high-strain epoxy adhesive was used to bond the rails to the specimens. Compressive loads were applied to the rails via 0.5 inch diameter steel rods which fit into corresponding grooves in the rails and V-notched platens mounted on the testing machine, at a crosshead rate of 0.039 inch/minute. Strains were measured with Measurements Group EA-06-062DY-120 single-element (45°) strain gages mounted in the center of the gage section. In addition, at least one specimen from

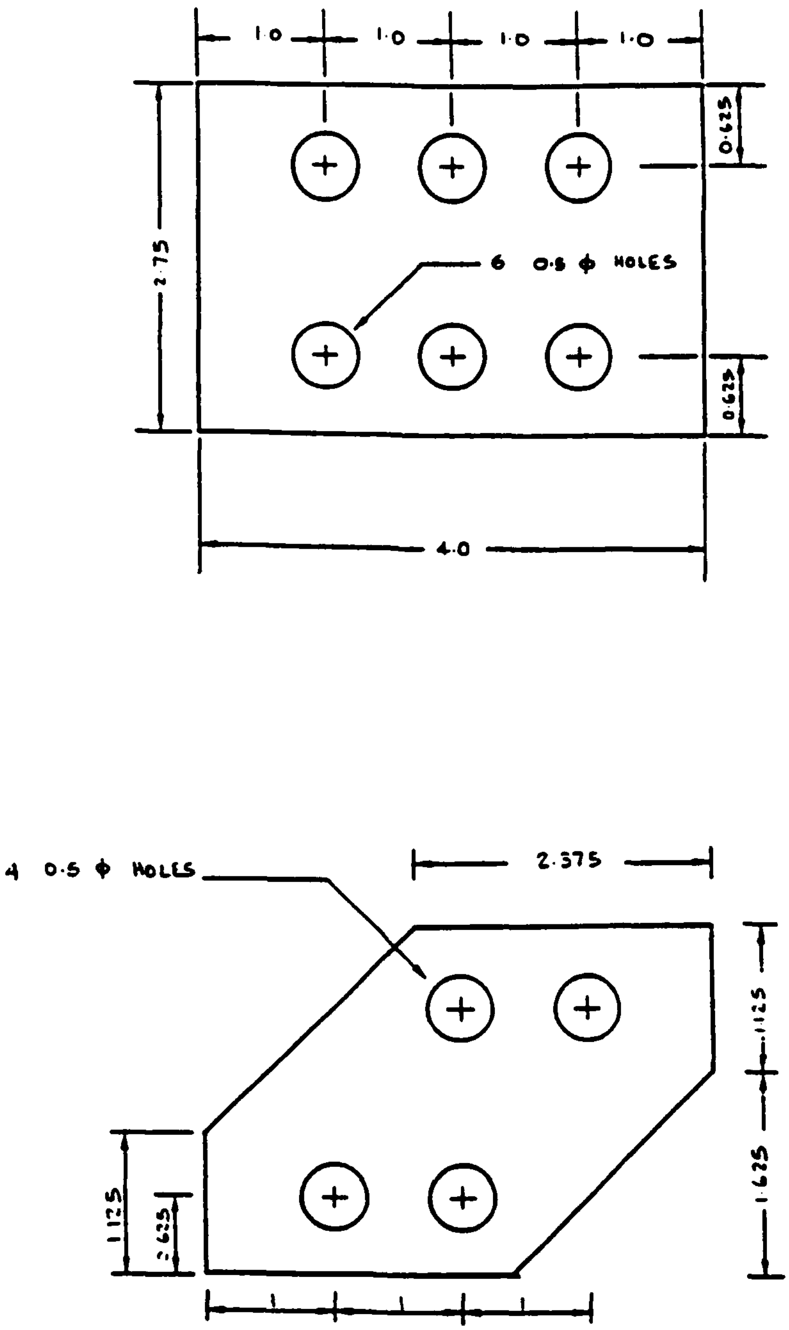

Figure 38. Rail Shear Specimen Geometries

each geometry and laminate family had a Measurements Group EA-15-062RB-120 three-element rectangular strain gage rosette mounted in the same location (but on the opposing specimen face). These rosettes were used to determine the validity of the assumption that the principal strains occur at 45° to the loading axis.

2.5.6 Off-Axis Tensile Shear Tests

The off-axis tension test, although not a pure shear test, has been recommended for determining the shear properties of composite materials [7]. Both 8-ply and 12-ply specimens were cut from unidirectional laminates at 10°, 15°, and 20° from the fiber axis. As mentioned in Section 2.1, only 8-ply specimens were prepared at 30°. Tapered tabs 2 inches in length were bonded to the specimen ends. Although it was originally intended that all specimens be of the same length, the 15°, 20°, and 30° 8-ply specimens were inadvertently cut 12 inches long while the 12-ply specimens were cut 16 inches long. The 10° specimens of both thicknesses were 16 inches long. All specimens were rough cut to approximately 1 inch in width and then ground to approximately 0.75 inch in width. Extra care was taken to assure good edge surface finish because tensile tests at these orientations appear to be very sensitive to flaws and frequently fail prematurely. Loads were applied to the specimens with special grips which allowed the specimen ends to rotate freely upon loading. The specimen tabs were placed in the grips 1.25 inches as recommended in Reference [8]. A crosshead rate of 0.039 inch/minute was used. Strains were measured at specimen mid-length with Measurements Group CEA-06-125UR-350 three-element rectangular strain gage rosettes. At least one specimen of each configuration had back-to-back three-element rosettes.

2.5.7 Interlaminar Iosipescu Shear Tests

Interlaminar Iosipescu shear specimens were prepared from two different laminates. These specimens were 3 inches long, 0.75 inch wide, and 0.25 inches thick. The first consisted of two layers of $[0]_{96}$ material bonded together (to make a specimen approximately two times the thickness of the laminate), with the fiber axis perpendicular to the specimen faces. This configuration is commonly referred to as a 2-3 shear specimen. The second consisted of six layers of the $[0/90]_{6s}$ laminate bonded together in a similar fashion, with the fibers in the outermost plies of the laminate perpendicular to the specimen faces. A Wyoming Iosipescu shear fixture was used to apply loads to the specimens. Strains were measured in the same manner as discussed above for the in-plane Iosipescu shear specimens.

2.5.8 Short Beam Shear Tests

Two different laminates were tested in interlaminar shear with the short beam shear method, each at span-to-depth (L/d) ratios of 3 and 4. Unidirectional 48-ply specimens 1.25 inch long were tested at the smaller span-to-depth ratio, while 1.5 inch long specimens were tested at the larger. Both specimen configurations were 0.25 inch wide. Specimens from a $[0/90]_{6s}$ laminate were 0.5 inch wide, 0.625 inch long for the L/d of 3 and 0.75 inch long for the L/d of 4. All of the short beam shear specimens were tested with a 3-point bend fixture with

0.25 inch diameter load and support noses, at a crosshead rate of 0.039 inch/minute.

SECTION 3

TEST RESULTS

3.1 Introduction

The following subsections discuss the individual test results from all of the tests performed for this study. Each of the three primary test types - tension, compression, and shear - is discussed separately but all of the specific methods within a particular primary test type are discussed together. Tables of the average test results are included here, but the individual test results are tabulated in Sections 4, 5, and 6, for tension, compression, and shear, respectively. Breakload, thickness, and laminate supplier data for all specimens of each primary test type are presented Tables 4.4, 5.4, and 6.15. Plots of the individual stress-strain results are presented in the Appendices to Volume II. Tensile test plots are in Appendix A, while compressive test plots are in Appendix B and shear test plots are in Appendix C.

The specific method utilized to determine the specimen moduli from individual stress-strain plots was dependent upon the linearity of the data, the ultimate strain of the material as determined by the particular test type, and the consistency or "smoothness" of the stress-strain curves. In general, the slope of the stress-strain curves was calculated between two discrete strain levels, which were the same for all replicates of a given test type. For example, all tensile test moduli were calculated by measuring the slope of the curve between 1000 microstrain and 5000 microstrain. However, on highly nonlinear stress-strain curves or those that did not exceed 5000 microstrain, other limits were used.

3.2 Tension

The average tensile test results for all three methods, for both the unidirectional and cross-ply laminates, are included in Table 3.1. Shown in Table 3.2 are the $[\pm\theta]_{ns}$ test results as well as predicted values. The test data are the same as previously presented graphically in Section 1, except the standard deviations of each data set are also included here.

As noted in Section 1, the ASTM D-3039 tensile test method yielded the highest tensile strength and modulus for the unidirectional material. It was expected that the strength of the tabbed ASTM specimens would be greater than that of the untabbed streamlined and linear tapered specimens because of the beneficial affects of the tabs. It was not expected, however, that the modulus of these specimens would be different from any of the others. All of the laminates from which the unidirectional specimens were fabricated had nearly identical fiber contents and void contents. In addition, the moduli were calculated similarly for all tests. No apparent reason for the higher moduli of the ASTM specimens was evident.

The tensile strengths and moduli of the unidirectional specimens were reasonably consistent, with standard deviations in the range of 2 to 7 percent of the averages, regardless of the test method. The data for the 18 inch long streamline tensile specimens were a bit less consistent than for the other specimens.

Table 3.1

Average Test Results for Three Axial Tensile Test Methods
(standard deviations shown in parentheses)

Laminate	Test Method	Axial Tensile Strength (ksi)	Axial Tensile Modulus (Msi)	Ultimate Tensile Strain (percent)
$[0]_6$	ASTM D-3039	288 (19)	21.2 (0.5)	1.31 (0.08)
	Streamlined Profile			
	L = 12 in.	230 (8)	17.5 (0.8)	1.22 (0.02)
	L = 18 in.	218 (30)	17.6 (1.1)	1.17 (0.12)
	L = 24 in.	229 (14)	19.1 (0.8)	1.17 (0.07)
	Linear Taper Profile			
	L = 24 in.	194 (13)	17.3 (0.6)	1.08 (0.08)
$[0/90]_{3s}$	ASTM D-3039	130 (9)	10.4 (0.5)	1.26 (0.06)
	Streamlined Profile			
	L = 12 in.	142 (11)	10.5 (0.4)	1.32 (0.07)
	Linear Taper Profile			
	L = 24 in.	140 (12)	11.0 (0.5)	1.26 (0.09)

Table 3.2

Average Axial Tensile Test Results for Six $[\pm\theta]_{ns}$ Laminates (standard deviations shown in parentheses)

Laminate	Axial Tensile Strength (ksi)		Axial Tensile Modulus (Msi)		Ultimate Tensile Strain (percent)
	Measured	Predicted*	Measured	Predicted**	
$[\pm 15]_s$	111 (11)	120	16.3 (1.3)	16.5	0.69 (0.02)
$[\pm 15]_{2s}$	120 (6)	120	17.1 (1.8)	16.5	0.73 (0.06)
$[\pm 30]_s$	65.8 (6.2)	70	6.5 (1.1)	8.1	1.45 (0.32)
$[\pm 30]_{2s}$	74.1 (8.7)	70	6.9 (0.7)	8.1	1.71 (0.17)
$[\pm 60]_s$	10.2 (0.7)	12	2.1 (0.2)	1.9	0.52 (0.06)
$[\pm 60]_{2s}$	12.3 (0.4)	12	1.8 (0.1)	1.9	0.71 (0.05)
$[\pm 75]_s$	7.3 (0.5)	5	1.9 (0.1)	1.4	0.39 (0.02)
$[\pm 75]_{2s}$	7.1 (0.6)	5	1.6 (0.1)	1.4	0.44 (0.05)

* Values supplied by MSC
** Predicted using classical laminated plate theory

The cross-ply tensile strengths were similar for all three methods investigated. The ASTM method yielded strengths about 10 percent lower than both of the tapered specimen configurations. However, the laminate from which the ASTM specimens were prepared was lower in fiber content by several volume percent than those from which the other specimens were made. Normalization of the strength data to a common fiber volume yielded very similar strength results for all three specimen shapes.

The moduli of the cross-ply specimens were also very similar. Interestingly, variations in the fiber content did not appear to produce the expected effect on the moduli.

The stress-strain curves for all unidirectional tests were slightly concave up, but reasonably close to linear. The ultimate strains were similar in magnitude, all near 1.2 percent, with the ASTM specimens exhibiting slightly higher values and the linear tapered specimens exhibiting slightly lower values. This was the same trend as for the strengths, and should be expected.

The cross-ply specimen stress-strain curves were also frequently slightly concave up. Some were virtually linear as well. The ultimate strains were nearly identical for the three test specimen configurations.

In general, the unidirectional specimen failure modes did not vary with specimen configuration except from the ASTM specimens to the tapered profile specimens. The ASTM specimens literally disintegrated upon failure; little or no contiguous laminate remained after specimen rupture. On the other hand, all of the tapered profile unidirectional specimens split longitudinally into many slender pieces. The amount of fiber breakage was much less in these specimens. Also, a brittle-type transverse fracture was evident on most of the tapered profile specimens. The fracture plane was perpendicular to the longitudinal specimen axis and was located within one inch of the gripped portion of the specimens. It was difficult to determine if this fracture was the result of the tensile load or if it was due to compressive recoil after the occurrence of primary specimen failure. It was noted that the portions of the tapered specimens which were of greater width than the gage sections split from the center portion of the specimens prior to catastrophic failure. This splitting generally occurred when the specimen loads were between 60 percent and 90 percent of the ultimate loads.

The cross-ply specimens tended to fracture into two distinct pieces by a single transverse crack perpendicular to the longitudinal specimen axis, regardless of specimen configuration. The ASTM specimens failed in the gage section generally, although on some specimens the fracture was close to the tabs. There was a considerable degree of delamination in the vicinity of the primary fracture, but little longitudinal splitting, evident on these specimens. Both the streamline taper and the linear taper cross-ply specimens also failed primarily by a single transverse crack, which divided the specimen into two distinct pieces. However, the fracture frequently occurred outside of the gage section. That is, the fractures sometimes appeared to have occurred at a location with a greater cross-sectional area than the gage section. This is not desirable, as it lends difficulty to the interpretation of the results. Longitudinal cracks were evident in these specimens, extending from the gage section, as were observed on the unidirectional tapered specimens. It was not determined if these splits occurred in the surface plies only, or if they existed in all of the longitudinally oriented plies. Cracks were not evident in the transversely oriented plies.

The strengths and moduli of the $[\pm\Theta]_{ns}$ tensile specimens were close to the predicted values. Both the predicted strengths (supplied by MSC) and predicted moduli (from the AC3P point stress analysis program) are presented in Table 3.2. Fairly good agreement between the experimental data and the predicted values was achieved, although the $[\pm30]_{ns}$ moduli were a bit lower than expected. With just a few exceptions, the results from the thicker laminates were closer to the predicted strengths and moduli than those from the thinner laminates. The data were fairly consistent within each data set; standard deviations were generally less than 10 percent of the averages.

The linearity of the $[\pm\Theta]_{ns}$ stress-strain curves varied with the off-axis angle. The $[\pm15]_{ns}$ specimens of both thicknesses exhibited nearly linear stress-strain response, with small upward concavity evident at the latter portion of some tests. The transverse strain-axial strain curves from the same material were linear. The stress-strain curves for the remaining three ply angles did exhibit some nonlinear response (the curves were concave down) to varying degrees. Most exhibited linear behavior up to strain levels of between 0.2 and 0.3 percent, beyond which some nonlinear behavior was evident.

Two specimens of each $[\pm\Theta]_{ns}$ laminate configuration were loaded to between 50 percent and 70 percent of their respective failure loads, unloaded, and then retested to failure. This was done at MSC's request, to determine the magnitude of the plastic strain response and to determine the reloading path. Those specimens tested in this manner are marked as such in the tables in Section 4. Both of the $[\pm15]_s$ specimens tested in this manner exhibited unloading and reloading along the same initial loading path. One of the $[\pm 15]_{2s}$ specimens also exhibited this behavior. The second specimen exhibited considerably less stiffness upon reloading, and hence reloaded along a path with lower slope; both the initial loading and the reloading were linear, however. All of the $[\pm 30]_{ns}$ specimens had small amounts of permanent strain (offset) after unloading, and hence reloaded along paths that were offset from the initial load paths. The slopes upon reloading were very close to the initial slopes. The $[\pm 60]_{ns}$ specimens exhibited virtually no offset upon reloading, and had similar moduli during the second load cycle as well. No offset was evident upon reloading of the $[\pm 75]_{ns}$ specimens, and the moduli were identical for all but one of the thicker specimens, which was slightly less stiff during the second load cycle.

The $[\pm 15]_{ns}$ specimen failures fell into three types. Some specimens failed along the fibers, all the way through the thickness of the laminate. These fractures were generally very clean breaks, although there tended to be slight fuzzing of the plies that were oriented opposite the surface plies on the thicker laminates. Other specimens failed by cleaving on a plane transverse to the specimen axis. Thirdly, some specimens failed along the fibers for a short distance, then transverse to the specimen axis for a few tenths of an inch, and the along the fibers again. This pattern was repeated several times until the fracture extended across the entire specimen width. The fractures on a few of the specimens that failed transversely or along the fibers extended into that part of the specimen that was tabbed. The strengths of these specimens were not noticeably different than the strengths of those that failed in the gage section. The $[\pm 30]_{ns}$

specimens failed much like the $[\pm15]_{ns}$ specimens. A mix of the fracture types described previously was observed for these specimens. The thinner specimens exhibited more fractures along the fibers than transverse to the specimen axis. Several of the specimens from the thicker laminates had both transverse fractures and fractures along the fiber axes. None of the $[\pm60]_{ns}$ specimens fractured into two pieces. The thinner specimens exhibited fractures in the surface plies along the fiber axes. Very little delamination was evident. It was not obvious if the inner plies fractured as well. Several of the thicker specimens of this laminate configuration failed like the thinner ones, although damage to the inner plies was indeed evident on the thicker specimens. Two of the thicker specimens had failure zones much like shear failures which traversed the width at an angle equal to the angle of the subsurface plies. These were characterized by locally delaminated surface plies, which also exhibited many cracks along the fiber axes within the delaminated zone. That is, a delaminated area about 0.2 inch wide extended from one edge to the other, on both specimen faces, at an angle equal to fiber angle of the plies directly below the surface. It is conceivable that the subsurface plies failed first, and that the delamination and many small cracks along the fiber axes (of the surface plies) were a result of the displacements that occurred when the subsurface plies failed. The $[\pm75]_{ns}$ tensile specimens failed by cleaving through the entire thickness along the fiber direction, most of or all of the way across the specimen width. The plies oriented opposite the surface plies appeared to have failed similarly, although their appearance was more jagged.

3.3 Compression

The average compressive test results for all methods and laminates are presented in Table 3.3. These data are the same as presented graphically in Section 1 except the standard deviations, as well as laminate fiber volumes, are included in the table.

All of the laminates from which the axial compression specimens were fabricated were provided to the CMRG by a third party selected by MSC (or the AMTL), and many were of less than desired quality. The unidirectional laminates varied in thickness and had considerable fiber wash-out. Both of these types of defects lead to specimens in which the fibers are not coincident with the loading or specimen axis, and consequently can lead to erroneous strengths and moduli. Considerable effort was put into generating high quality unidirectional compressive test data, given the constraints of the laminate quality. Fiber volume and void volume determinations were performed on virtually all laminates from which compressive specimens were prepared, in an attempt to aid in the interpretation of the results. In addition, a second set of compressive tests were performed, beyond the five replicates called for, using all three methods, from a single 16-ply unidirectional laminate. The second set of tests on the unidirectional materials did not change the indicated ranking of the test methods. That is, the second set of tests confirmed the results of the first set. The averages presented in Table 3.3 are for all tests conducted.

As can be seen in Table 3.3, the modified Celanese and IITRI compressive tests of the unidirectional specimens yielded compressive strengths that were similar to each other and significantly higher than those from the ELSS tests. The ELSS specimens failed by end-crushing,

Table 3.3

Average Test Results for Three Axial Compressive Test Methods
(standard deviations shown in parentheses)

Laminate	Test Method	Axial Compressive Strength (ksi)	Axial Compressive Modulus (Msi)	Ultimate Compressive Strain (percent)
$[0]_{16}$	ELSS	109 (10)	17.3 (2.1)	0.7 (0.1)
	Mod. Celanese	165 (17)	15.7 (2.0)	1.4 (0.4)
	IITRI	180 (20)	16.1 (1.3)	1.5 (0.5)
$[0]_{24}$	ELSS	119 (19)	18.4 (2.0)	0.6 (0.2)
	Mod. Celanese	171 (13)	18.2 (1.2)	1.0 (0.2)
	IITRI	166 (11)	19.0 (2.2)	>1.1 (0.3)
$[0/90]_{4s}$	ELSS	105 (10)	10.1 (0.3)	1.1 (0.2)
	Mod. Celanese	126 (12)	9.4 (1.0)	2.2 (0.9)
	IITRI	128 (7)	9.6 (1.2)	>1.7 (0.5)
$[0/90]_{6s}$	ELSS	110 (14)	9.1 (0.6)	1.4 (0.2)
	Mod. Celanese	141 (10)	9.8 (0.6)	1.5 (0.5)
	IITRI	142 (4)	10.8 (1.3)	1.8 (0.6)
$[0/\pm45/90]_{2s}$	ELSS	86 (4)	7.4 (0.2)	1.4 (0.1)
	Mod. Celanese	88 (5)	6.8 (0.9)	1.9 (0.2)
	IITRI	84 (7)	7.1 (0.8)	1.6 (0.2)
$[0/\pm45/90]_{3s}$	ELSS	82 (6)	7.4 (1.1)	1.3 (0.3)
	Mod. Celanese	87 (7)	7.1 (1.0)	1.5 (0.3)
	IITRI	90 (11)	7.3 (0.8)	1.4 (0.2)

which has been observed frequently in the testing of unidirectional composites with end loading. Of course, crushing at the point of load introduction is not the desired failure mode, and likely results in an apparent strength lower than the actual material strength.

The compressive moduli of the unidirectional specimens differed greatly between the methods for the thinner, 16-ply material, but were in reasonable agreement for the thicker, 24-ply specimens. The moduli of the thinner ELSS specimens were higher than those determined with the other two methods, as has been reported previously [2]. In Reference [2] the higher indicated moduli were attributed to binding of the fixture guide posts. However, the guide posts were not used for the tests reported herein (because the variations in thickness caused the fixture to bind when the specimens were mounted in the fixture and the bolts were tightened). Consideration of the fiber volumes of the laminates from which the specimens were prepared revealed that the ELSS specimens had greater fiber contents than the other two types of specimens. The "second" set of compressive tests performed on 16-ply unidirectional material, with the specimens from all three methods coming from a single panel, yielded moduli from the ELSS specimens that were lower, not higher, than from the modified Celanese and IITRI methods. The guide posts were used in the second set of ELSS tests. It is conceivable that specimen bending occurred during the first set of tests, because the posts were not present to restrain side deflections. Although not required by the original contract, the CMRG performed five replicate tests using a recently modified ELSS fixture which utilizes a 5.5 inch long, untabbed specimen, and incorporates ball bushings to reduce fixture post binding. The average strength measured with this modified fixture was 130 ksi, the average modulus was 17.8 Msi, and the average ultimate strain was greater than 0.8 percent. The guide posts were in place during these tests. Obviously, it is difficult to draw any conclusions from the thinner unidirectional compressive moduli test data.

The thicker, 24-ply compressive test data were in better agreement, and all three methods yielded similar results. All of the unidirectional specimens were prepared from laminates with very similar fiber contents, and this surely improved the quality of the results. Again, the ELSS method yielded the lowest strengths, while the other two methods were higher and of similar magnitude. The moduli were all within less than 1 Msi of each other. It was noted that the moduli of these thicker specimens were higher than the moduli of the thinner material. The thicker laminates did have higher fiber contents than the previously discussed 16-ply laminates, however, so a higher modulus was expected.

As mentioned in Section 2, the sandwich beam bending tests were not successfully completed. The cross-ply tests were not performed at all, and the unidirectional test specimens failed by shear in the honeycomb core, rather than by compressive failure of the laminate face sheet. However, it is important to note that the average compressive stress in the face sheets upon shear failure of the core was 212 ksi, which was greater than that from any of the other three methods.

The cross-ply compressive test results followed the same trends as the 24-ply unidirectional test results. The ELSS strengths were much lower than those from the IITRI and Wyoming Modified Celanese tests, which were about equal. The moduli results from all three methods were in reasonable agreement, although the thicker laminate IITRI average value was about 1 Msi greater than most of the others.

The quasi-isotropic compressive test results were essentially independent of the test method utilized. The strengths were between 82 ksi and 90 ksi and the moduli were between 6.8 Msi and 7.4 Msi, regardless of the laminate thickness or the test method.

The axial compressive stress-strain curves for most tests, for all laminates, were nearly linear or slightly concave downward for the initial portion of the tests. Most were concave down in the latter portions also, although some specimens instrumented with back-to-back strain gages appeared to have undergone bending or buckling prior to failure. The specimen curves which exhibited either a large degree of nonlinear deformation, or were concave up in the latter portions of the test, indicated gross bending, buckling, or significant disturbances of the surface plies to which the gages were bonded. It was not determined which of these phenomena was responsible for the nonlinear response, but considering the variations in specimen thickness, the bending and buckling modes appear likely to have occurred.

The unidirectional ELSS specimens failed primarily by end crushing, by delamination and fiber breakage at the fixture block-gage section intersection, or by splitting along the fiber axis. The latter mode was present primarily in the 24-ply specimens in which the fiber axis was not coincident with the specimen axis because of panel fabrication anomalies. There was no noticeable relationship between failure mode and strength or modulus. The unidirectional Modified Celanese specimens failed by fracturing transversely under the tapered portions of the tabs. The thinner specimens exhibited fractures that were perpendicular to the specimen axis, while the fractures on the thicker specimens were oriented approximately 30° from the specimen axis (but still parallel to the thickness direction). Some longitudinal splitting was evident in specimens of both thicknesses. The thinner IITRI specimens failed at the ends of the tabs, by delamination, longitudinal splitting, and fiber fracture, accompanied by brooming. Some of the fractures were angled through the thickness or across the width of the specimens. The thicker unidirectional IITRI specimens all fractured into two pieces under the tapered portion of the tabs. The fractures were oriented at approximately 30° from the width direction and parallel to the thickness direction. Some splitting and brooming was evident also.

The cross-ply ELSS compressive specimens failed primarily by end crushing. Very little or no damage was evident in the gage section. A few of the thicker specimens exhibited bending failures at the edge of the gage section, next to the edge of the fixture half, as well as by end crushing. None of the cross-ply ELSS specimens fractured into two pieces. The cross-ply Modified Celanese specimens fractured in or near the gage section. There was a large variation in the orientation of the fractures. Some were transverse to the specimen axis, while others were angled with respect to the width and thickness directions. Some of the thinner specimens exhibited V-notch shaped failures as well. There was a great deal of brooming and out-of-plane deflection of the surface plies due to the compaction of the fracture surfaces during failure. The IITRI cross-ply specimens exhibited failures similar to the Modified Celanese specimens.

The 16-ply ELSS quasi-isotropic compressive specimens all failed by end crushing, while two of the specimens also exhibited very coarse transverse fractures within the gage section. Three of the five thicker specimens failed as desired, with transverse fractures in the gage section. The reminder failed by end crushing. The strengths appeared to be independent of failure mode. The quasi-isotropic Modified Celanese compressive specimens failed in or very near the gage section, by transverse fracture parallel to both the thickness and width directions. Considerable brooming was evident, and likely occurred after primary failure. The 16-ply IITRI specimens all failed near the tab ends and appeared to have undergone bending to a certain degree. The thicker IITRI specimens failed in the gage section similar to the quasi-isotropic Modified Celanese specimens.

There is considerable evidence that the quality of the compressive test results was not as high as desired. The low compressive strengths relative to published experimental data, or theoretical values based upon fiber strengths, and the large variation in failure modes, the relative differences in strengths and moduli between laminates of a given family, particularly in the unidirectional and cross-ply composites, as well as the documented variation in plate thickness and fiber placement, all contribute to this conclusion. The relatively high strengths from the sandwich beam bending tests (even though the composite never failed) serve to reinforce this. It is believed that the relative results are indicative of the suitability of the test methods, but that the specific compressive strength and moduli results are not indicative of the "true" material properties except in the case of the quasi-isotropic laminates.

3.4 Shear

The average shear test results for all methods examined, except for the rectangular torsion tests, are presented in Table 3.4. As mentioned in Section 1, most of the shear methods were in reasonable agreement for the shear strength and moduli results, and the reader may refer to the earlier discussion for the general trends and comparisons.

As noted previously, the ±45° tensile strength results were lower than those from the other tests. Yet, among the three different laminate thicknesses and two different widths tested with the ±45° tensile method, there was excellent agreement. It appears this method leads to lower indicated strengths than the other methods. The shear moduli determined with the ±45° tensile tests were also in good agreement with each other, as well as with the other test methods. The only exception was the thin (4-ply), 1.25 inch wide specimens. The moduli from these tests were 20 percent to 50 percent higher than the moduli determined with the same method from specimens of different thicknesses or widths. The fiber volumes of the laminates from which all specimens were prepared were similar, so differences in fiber content cannot be used to account for the moduli difference. The other two thicknesses tested did not follow the trend of increasing stiffness with increasing width. Hence, no reason for the difference is evident.

The circular torsion specimen shear strengths were greater for the smaller diameter rods than for the those with the larger diameter. However, it was necessary to grind flats in the gripped portions of the larger rods to prevent slippage during testing, and it appears that the flats may have induced premature failure. The moduli from both methods were comparable. Both had similar fiber contents and void contents.

Table 3.4

Average Test Results for Six Shear Test Methods
(standard deviations shown in parentheses)

Laminate	Test Method	Shear Strength (Msi)	Shear Modulus (Msi)	Ultimate Strain (percent)
$[\pm 45]_s$	Laminate Tension			
	0.75 in. width	11.5 (0.4)	1.0 (0.1)	1.9 (0.3)
	1.25 in. width	11.8 (1.0)	1.2 (0.1)	1.4 (0.2)
$[\pm 45]_{2s}$	Laminate Tension			
	0.75 in. width	11.4 (1.2)	0.9 (0.2)	2.1 (0.3)
	1.25 in. width	10.8 (0.3)	0.8 (0.1)	2.3 (0.2)
$[\pm 45]_{4s}$	Laminate Tension			
	0.75 in. width	11.7 (0.5)	0.9 (0.1)	2.5 (0.4)
	1.25 in. width	11.3 (1.2)	0.9 (0.1)	2.5 (0.8)
$[0]_{48}$	Torsion of Circular Bar			
	0.23 in. dia.	16.0 (1.2)	0.8 (0.1)	3.0 (0.6)
$[0]_{96}$	Torsion of Circular Bar			
	0.4 in. dia.	14.3 (1.6)	0.9 (0.0)	2.0 (0.6)
$[0]_8$	Iosipescu			
	90° Notch	14.6 (1.3)	0.9 (0.1)	4.2 (1.9)
	120° Notch	13.7 (1.2)	0.9 (0.2)	2.8 (1.0)
	Rectangular Rail	14.7 (-)	1.3 (-)	2.1 (-)
	Parallelogram Rail	15.0 (-)	0.8 (-)	5.2 (-)

Table 3.4 (Continued)

Average Test Results for Six Shear Test Methods
(standard deviations shown in parentheses)

Laminate	Test Method	Shear Strength (ksi)	Shear Modulus (Msi)	Ultimate Strain (percent)
$[0]_{16}$	Iosipescu			
	90° Notch	16.7 (0.6)	1.1 (0.1)	4.3 (1.2)
	120° Notch	15.7 (1.0)	1.0 (0.1)	4.2 (1.4)
	Rectangular Rail	14.8 (0.2)	1.0 (0.1)	3.4 (0.1)
	Parallelogram Rail	14.8 (1.3)	0.8 (0.1)	4.5 (0.7)
$[0/90]_{2s}$	Iosipescu			
	90° Notch	13.1 (0.7)	0.8 (0.1)	4.1 (0.6)
	120° Notch	13.7 (0.5)	0.8 (0.1)	4.3 (0.2)
	Rectangular Rail	12.4 (1.0)	0.9 (0.1)	2.9 (0.7)
	Parallelogram Rail	13.3 (0.8)	0.8 (0.1)	3.9 (0.6)
$[0/90]_{4s}$	Iosipescu			
	90° Notch	13.2 (0.8)	0.7 (0.1)	4.6 (0.4)
	120° Notch	13.7 (0.3)	0.7 (0.1)	5.1 (0.7)
	Rectangular Rail	12.9 (1.3)	0.9 (0.1)	3.3 (0.7)
	Parallelogram Rail	13.2 (1.2)	0.8 (0.1)	3.3 (0.5)

Table 3.4 (Continued)

Average Test Results for Six Shear Test Methods
(standard deviations shown in parentheses)

Laminate	Test Method	Shear Strength (ksi)	Shear Modulus (Msi)	Ultimate Strain (percent)
$[0/\pm45/90]_s$	Iosipescu			
	90° Notch	59.9 (0.5)	2.8 (0.3)	2.4 (0.1)
	120° Notch	38.0 (5.6)	2.8 (0.4)	1.4 (0.4)
	Rectangular Rail	44.5 (3.1)	2.6 (0.3)	2.0 (0.3)
	Parallel. Rail	>32.8 (2.9)	2.6 (0.1)	>1.4 (0.1)
$[0/\pm45/90]_{2s}$	Iosipescu			
	90° Notch	>59.9 (1.5)	2.7 (0.4)	>2.2 (0.0)
	120° Notch	45.9 (3.4)	2.6 (0.2)	2.0 (0.2)
	Rectangular Rail	31.8 (5.7)	3.0 (0.2)	>1.1 (0.2)
	Parallelogram Rail	>25.6 (5.7)	2.7 (0.2)	>1.1 (0.2)
$[\pm45]_{2s}$	Iosipescu			
	90° Notch	>54.1 (8.1)	4.8 (0.5)	1.2 (0.4)
	120° Notch	41.6 (1.3)	4.1 (1.5)	1.2 (0.1)
	Rectangular Rail	62.8 (6.0)	5.0 (0.3)	1.2 (0.2)
	Parallelogram Rail	45.9 (4.7)	4.2 (0.4)	1.2 (0.3)

Table 3.4 (Continued)

Average Test Results for Six Shear Test Methods
(standard deviations shown in parentheses)

Laminate	Test Method	Shear Strength (ksi)	Shear Modulus (Msi)	Ultimate Strain (percent)
$[\pm45]_{4s}$	Iosipescu			
	90° Notch	45.1 (5.1)	4.9 (0.7)	0.8 (0.1)
	120° Notch	33.8 (2.3)	4.0 (0.3)	0.9 (0.1)
	Rectangular Rail	>35.6 (1.4)	4.9 (0.2)	>0.8 (0.1)
	Parallelogram Rail	>31.2 (3.7)	4.2 (0.3)	>0.7 (0.0)
$[10]_8$	Off-Axis Tension	8.7 (0.8)	0.9 (0.1)	1.2 (0.1)
$[10]_{12}$	Off-Axis Tension	7.5 (0.5)	0.9 (0.1)	1.0 (0.1)
$[15]_8$	Off-Axis Tension	10.2 (1.5)	1.2 (0.0)	1.2 (0.3)
$[15]_{12}$	Off-Axis Tension	8.4 (0.3)	0.9 (0.1)	1.2 (0.1)
$[20]_8$	Off-Axis Tension	10.6 (0.8)	1.2 (0.1)	1.3 (0.1)
$[20]_{12}$	Off-Axis Tension	6.6 (0.4)	0.9 (0.1)	0.9 (0.1)
$[30]_8$	Off-Axis Tension	8.3 (0.3)	1.1 (0.0)	0.9 (0.1)
$[0]_{48}$	Short Beam Shear			
	L/D = 3	14.9 (0.5)		
	L/D = 4	13.6 (0.9)		
$[0/90]_{6s}$	Short Beam Shear			
	L/D = 3	13.8 (0.6)		
	L/D = 4	12.9 (0.7)		

Table 3.4 (Concluded)

Average Test Results for Six Shear Test Methods
(standard deviations shown in parentheses)

Laminate	Test Method	Shear Strength (ksi)	Shear Modulus (Msi)	Ultimate Strain (percent)
$[0/90]_{36s}$	Iosipescu Shear Bonded 6 Layers	11.3 (0.4)	0.6 (0.1)	3.2 (0.4)
$[0]_{96}$	Iosipescu Shear 2-3 Interlaminar Bonded 3 Layers	5.4 (0.7)	0.6 (0.1)	1.0 (0.1)

Because the data reduction for the rectangular torsion specimens was not performed, no data are reported herein for these tests. Included in Section 6 are the ultimate torque and specimen dimension data.

As noted in Section 1, the unidirectional, in-plane Iosipescu shear strengths and moduli were greater for the 16-ply laminate than for the 8-ply laminate. Fiber volume determinations on the laminates (which were manufactured by the third party) revealed that the 8-ply laminate consisted of only 50 percent fiber, as opposed to over 64 percent fiber in the 16-ply laminate. Even though shear properties are not generally considered to be strongly influenced by fiber content, it is likely that the differences between the thin and thick unidirectional properties was due at least in part to the very large differences in fiber content.

There is no obvious explanation for the difference in moduli between the rectangular rail shear specimens and the parallelogram shear specimens, even though the moduli of the rectangular specimens were consistently greater than those of the parallelogram specimens, regardless of laminate configuration. The laminates from which the specimens were prepared were very similar in fiber content and other physical properties.

The cross-ply rail shear and Iosipescu shear stress - shear strain curves were nearly linear at low strains, and then very nonlinear as the stresses neared the ultimate strength of the material. This was as expected. However, rather than fracturing after considerable nonlinear strain, the specimens exhibited a large increase in stiffness and corresponding cessation of plastic behavior. An example of this phenomenon is presented in Figure 39. The shear stress-crosshead displacement plot of the same specimen is also shown in Figure 39. It is obvious that a different mode of loading is occurring after the large plastic deformation. It is likely that the rotation of the reinforcing fibers into the principal stress directions is responsible for the observed behavior. The shear strengths reported in Table 3.4 correspond to the peak stresses in or before the zone of plastic response, not the maximum stress to which the specimen was subjected after the zone of plastic response was exceeded.

Although the cross-ply laminate shear strength and modulus test results were about the same regardless of test method or laminate thickness, this was not the case for the quasi-isotropic or $[\pm 45]_{ns}$ laminates. The shear strength of the quasi-isotropic laminates was much greater when tested with the tabbed Iosipescu method, and the Iosipescu

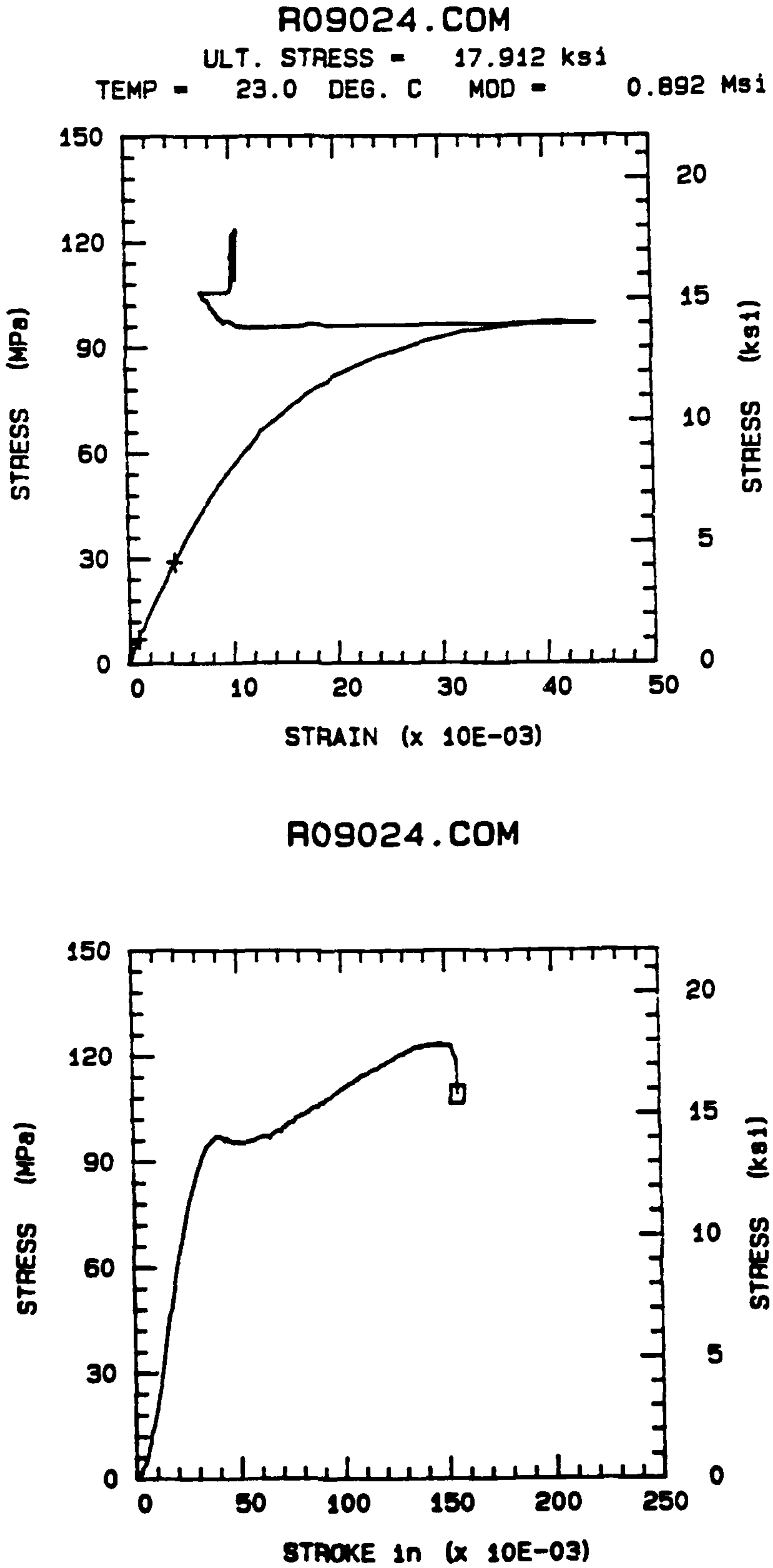

Figure 39. Typical In-Plane Shear Stress-Shear Strain (a) and Shear Stress-Crosshead Displacement Plots for Cross-ply Laminates

specimens with 90° notch angles were stronger than those with 120° notch angles. The thinner $[\pm45]_{2s}$ rectangular rail shear specimens exhibited much higher shear strengths than either the parallelogram rail shear or the two Iosipescu shear specimen configurations. All of the thicker, and about one-half of the thinner, quasi-isotropic rail shear specimens debonded prior to failure of the composite laminate itself, as did all of the thicker $[\pm45]_{4s}$ rail shear specimens. Hence, the strength results from these tests are not indicative of the material behavior. Interestingly, the thinner $[\pm45]_{2s}$ rail shear specimens did not debond, and appeared to have failed in the desired mode. The moduli of the quasi-isotropic and $[\pm45]_{ns}$ laminates were essentially independent of thickness or test method, with the few exceptions evident in Table 3.4.

The shear strength results from the off-axis tensile tests presented in Table 3.4 are much lower than from other in-plane methods, except for the $[\pm45]_{ns}$ tensile method, but the moduli are similar to values generated with other methods. It is believed by the authors that flaws in the edges of the off-axis tensile specimens were responsible for premature failures, and hence the low strength values, even though great care was taken to prevent the occurrence of such flaws.

There is an obvious difference between the strengths and moduli of the thin laminates and those of the thick laminates, at all angles except 10°. This is due, however, not to the difference in specimen thickness, but rather to the different length:width aspect ratios (ratio of specimen length to specimen width) of the particular specimens tested. Both thicknesses of the 10° specimens were the same nominal length and width, and the indicated calculated shear strengths and moduli are similar. However, the 8-ply specimens with greater off-axis angles, which were 12 inches in length, exhibited greater strengths and moduli than the 12-ply specimens with the same off-axis angles, but which were 16 inches in length. Both sets of specimens were of the same nominal width. Therefore, the aspect ratio of the thinner, shorter specimens was approximately 11, and that of the thicker, longer specimens was approximately 16. The indicated shear strengths and moduli of the specimens with the smaller aspect ratio were greater than those of the specimens with the larger aspect ratio. This is as predicted in Reference [9], which includes a fairly rigorous discussion of the end constraint and aspect ratio effects on a similar composite. That reference indicates that the results for the specimens with the higher aspect ratio are the more valid.

The majority of the unidirectional and cross-ply in-plane shear stress-shear strain curves, including those from the torsion, Iosipescu, and rail shear test methods, were nearly linear up to shear strains of approximately 0.5 percent. Above this level, plastic response became evident to varying degrees, until with many specimens almost pure plastic deformation occurred prior to fracture. Although most of the specimens did exhibit initial stress-strain response that was close to linear, it was evident that there was a small degree of nonlinearity present, even at low stress and strain levels.

The off-axis tensile test shear stress-shear strain response was less linear than that of the pure shear methods, with approximately linear response up to strain levels of about 0.3 percent. On the other hand, the unidirectional interlaminar Iosipescu shear specimens exhibited linear response to failure. The cross-ply specimens of the same type were linear up to approximately 0.7 percent shear strain.

The quasi-isotropic Iosipescu shear and rail shear stress - shear strain response was nearly linear up to shear strains of between 0.5 percent and 1.0 percent, depending on the particular specimen. There were variations among replicates of a specific configuration of a test method as well as among the various test methods.

The $[\pm 45]_{ns}$ Iosipescu and rail shear stress-strain response was difficult to categorize. Some curves were concave up, others concave down, and still others almost linear.

The short beam shear strength test does not allow measurement of strains directly, so no stress-strain response was determined.

The unidirectional Iosipescu shear specimen failures were characterized by longitudinal cracks, parallel to the fiber (specimen) axis, which originated at the notch roots. That is, the cracks observed are typical and have been reported elsewhere (see, for example, Reference [10]). There was little or no evidence of shear failures in the region between the notches, especially in the 8-ply specimens. It is possible that the longitudinal cracks observed were due to out-of-plane bending failures caused by specimen edges (the edges which are loaded by the fixture) which were not perfectly flat. The notch angle and specimen thickness did not appear to affect the failure mode for these specimens.

The unidirectional rail shear specimens failed by cracking along the transverse specimen axis, which was parallel to the fiber axis. Each specimen generally exhibited several parallel cracks. Some were in the regions between the bolt holes, and others went from holes on one side of the gage section to holes on the opposite side of the gage section. Shear deformations and shear failures were not evident in these specimens. The thickness and geometry did not appear to affect the failure mode for these specimens either.

The cross-ply Iosipescu shear specimens did exhibit shear failures consisting of many cracks along the fiber axes in the region between the notches. Notch cracks as described above were also present in some specimens. Delaminations were also present in the shear zone. About one-half of the specimens exhibited shear failures that were offset in relation to each other, so that one sheared zone occurred directly between the notches, while the shear zone that occurred on the other specimen face was offset in the fiber direction a few hundredths of an inch. Visual inspection of the specimen edges revealed failure zones tilted with respect to the thickness direction. As with the unidirectional specimens, there was very little visual difference between the specimens of different notch angles and thicknesses.

The cross-ply rail shear specimens exhibited failures consisting of many cracks along the fiber direction throughout the entire gage section, as desired. A delamination zone was visible in the gage section and parallel to the long gage section axis. This delamination zone was centered in the width direction of the gage section but was only about half as wide as the gage section. All of the thin, rectangular specimens also failed by compression or crushing at the diagonally opposed corners of the gage section that were subjected to compressive forces when loaded (rather than the two opposite corners which were subjected to tensile forces upon loading). The thicker rectangular specimens exhibited fewer transverse cracks than the thin specimens, and in addition some appeared to have failed in tension in the diagonally opposed corners of the gage section subjected to tensile forces when loaded. The thin parallelogram-shaped specimens generally exhibited a single compressive failure in one gage section corner, rather than in two. Only one of the thicker parallelogram-shaped specimens failed prior to failure of the rail-specimen bond, so discussion of the failure modes of this specimen configuration is not possible.

The quasi-isotropic Iosipescu shear specimen failures were difficult to characterize. Longitudinal cracks were evident on some specimens near the notch roots. Others were delaminated in the region between the notches, while still others exhibited failure of surface or sub-surface plies. These ply failures were often oriented at 45° to the long specimen axis and were frequently transverse to the ply fiber axis.

Only a few of the quasi-isotropic rail shear specimens appeared to have failed prior to failure of the rail-specimen bond. Damage was visible on two of the thin, rectangular specimens and two of the thin parallelogram-shaped specimens. On both of the rectangular specimens and one of the parallelogram specimens, the damage consisted of delamination at a single corner of the gage section and was accompanied by some compressive crushing of the plies in that location. The other thin, parallelogram-shaped specimen failed by fracturing along a line connecting the center portions of the edges formed by the removal of the diagonally opposed corners of the specimen. The fracture passed through the center of the gage section. None of the specimens broke into two or more pieces.

The $[\pm 45]_{ns}$ Iosipescu shear specimens with 90° notches failed along the fiber axes of either the surface or subsurface plies; each failure extended from the notch root along a fiber (and hence at 45° to the long specimen axis) and extended into the tabbed region away from the gage section. One possible failure mode that fits the specimen appearance is that the region near the notch root that is in compression when loaded failed locally by crushing and delamination. This failure then propagated along the fiber axis into the tabbed region. One of the specimens with 120° notch angles also failed as above. The others failed by compressive buckling and crushing of the plies at the corner formed by the vertical portion of the notch and the angled portion of the notch (see Section 2). The specimens of both thicknesses failed similarly.

The $[\pm 45]_{2s}$ rectangular shear specimens failed by cracking along the fiber axis in the gage section or near the bolt holes out of the gage section. Some of the cracks extended to the free ends of the gage section (the short ends not bonded to the rails). The parallelogram-shaped specimens either debonded prior to failure, or failed as described above for the thin, parallelogram-shaped quasi-isotropic specimen. A fracture zone extended from near the center of one angled edge of the parallelogram, diagonally through the gage section to the center of the other angled edge. There was evidence of shear failure of the rail-specimen bond in the triangular region bounded by the fracture, the angled specimen edge, and the gage section. It was not possible to ascertain whether the fracture or debond occurred first. None of the failed specimens fractured into two pieces, and all of the thicker specimens of both geometries debonded prior to failure.

The circular torsion specimens all failed by axial cracks in the gripped section. The larger diameter specimen failures all originated at the flats that were ground into the specimens to facilitate gripping.

The cracks in the larger specimens extended radially inward, and it is likely that those in the thinner specimens did also, although this was not visible. None of the circular torsion specimens failed in the gage section, or separated into two or more pieces.

The $[\pm45]_{ns}$ tensile specimens cracked along fibers in the outer plies and delaminated in the same region. The subsurface plies exhibited transverse (perpendicular to the fiber axis in the subsurface plies) tensile failures. A few specimens exhibited similar failures, but with the transverse tensile failures in the outer plies, and the cracks along the fiber axes on the subsurface plies. The $[\pm45]_s$ and $[\pm45]_{2s}$ specimens of both widths appeared to have failed in every ply, but the thickest specimens only failed in some of the plies. Those specimens with some intact plies also appeared to have delaminated near the midplane. There was little difference between the failure modes of the 0.75 inch wide and 1.25 inch wide specimens.

All of the off-axis tensile specimens, of all configurations tested, failed by a single fracture parallel to the fiber direction. The fractures extended from one specimen edge along a fiber to the other specimen edge. The fractures in all of the $[10]_{12}$ and $[20]_{12}$ specimens, and approximately half of the other specimens of all configurations, extended into, or originated in, the tabbed region. Generally, only a very small portion of a given fracture was in the tabs.

The unidirectional interlaminar Iosipescu shear specimens typically failed by the formation of two distinct cracks, each initiating at the root of a notch. Each crack then propagated across the width of the specimen at approximately a 45° angle away from the centerline between notches (the 45° plane being the plane of maximum tensile stress), eventually terminating at the inner loading point on the opposite edge of the specimen (a region of high local contact stresses). This is a typical failure for a brittle material, as has been reported previously [11]. There was no visible damage to the cross-ply interlaminar Iosipescu shear specimens, although the load did drop off abruptly during testing. Any cracks which formed apparently closed upon removal of the applied load.

The unidirectional short beam shear specimens exhibited two types of failures simultaneously. Each specimen of both lengths crushed or failed via through-the-thickness compression directly under the center loading nose. The damaged zone extended from the surface in contact with the loading nose to approximately one-third the way through the thickness. There was material visibly displaced in the width direction on the specimen surfaces under the loading nose after unloading. Several interlaminar cracks parallel to the loaded specimen faces were also present in each specimen. In some specimens these cracks extended from the specimen midpoint to one end. On others, the cracks extended the full specimen length. The location of the cracks varied considerably in the thickness direction. Some were in the center (midplane) and others were near either the top or bottom surface.

All of the rectangular torsion specimens failed by splitting longitudinally. The cracks extended from the gripped region at one end towards the middle of the specimens, lengthwise. None of the specimens fractured into multiple pieces. The cracks in the 24-ply specimens, which were cut from a laminate supplied by the third party, were not parallel to the specimen axis because the fibers were washed-out considerably in the laminate. The cracks started near the specimen edge in the gripped region, and extended towards the center of the width of the specimen, as well as axially. The cracks did not extend the entire specimen length, for any specimen configuration.

SECTION 4

TABULATED INDIVIDUAL TENSILE TEST RESULTS

This section consists of four tables. Tables 4.1, 4.2, and 4.3 list the strength, modulus, Poisson's Ratio, and ultimate strain data for each specimen of each laminate family tested (unidirectional laminates, cross-ply laminates, and $[\pm\theta]_{ns}$ laminates, respectively). The fourth table, 4.4, lists the specific laminate, the laminate supplier, breakload, and thickness for each specimen. All laminate families are included in the fourth table.

Table 4.1

Individual Test Results for Three Axial Tensile Test Methods (unidirectional material)

Test Method	Specimen Number	Axial Tensile Strength (ksi)	Axial Tensile Modulus (Msi)	Ultimate Tensile Strain (percent)
ASTM D-3039	M77011	281	21.0	1.29
(L = 10 in.)	3	271	20.7	1.27
	4	310	22.0	1.32
	5	308	20.9	1.43
	6	272	21.2	1.23
	Average	288	21.2	1.31
	Std. Dev.	19	0.5	0.08
Streamlined Profile				
L = 12 in.	MST001	-	18.2	-
	2	238	18.1	1.24
	3	-	16.7	-
	4	-	17.2	-
	5	-	16.5	-
	6	233	18.5	1.21
	7	230	-	-
	8	219	-	-
	Average	230	17.5	1.22
	Std. Dev.	8	0.8	0.02
L = 18 in.	MST301	255	19.2	1.25
	2	174	16.5	0.97
	3	206	17.0	1.13
	4	232	17.3	1.25
	5	225	18.2	1.24
	Average	218	17.6	1.17
	Std. Dev.	30	1.1	0.12

Table 4.1 (Concluded)

Individual Test Results for Three Axial Tensile Test Methods (unidirectional material)

Test Method	Specimen Number	Axial Tensile Strength (ksi)	Axial Tensile Modulus (Msi)	Ultimate Tensile Strain (percent)
L = 24 in.	MST201	222	18.5	1.15
	2	225	18.0	1.13
	3	238	20.0	1.18
	4	239	18.9	1.27
	5	242	19.7	1.16
	6	206	19.5	1.05
	Average	229	19.1	1.16
	Std. Dev.	14	0.8	0.07
Linear Taper Profile (L = 24 in.)	MLT001	185	17.7	1.00
	2	182	16.7	1.06
	3	209	16.8	1.20
	4	207	18.0	1.11
	5	188	17.2	1.02
	Average	194	17.3	1.08
	Std. Dev.	13	0.6	0.08

Table 4.2

Individual Test Results for Three Axial Tensile Test Methods
(cross-ply material)

Test Method	Specimen Number	Axial Tensile Strength (ksi)	Axial Tensile Modulus (Msi)	Ultimate Tensile Strain (percent)
ASTM D-3039	M81011	139	10.6	1.31
(L = 10 in.)	2	132	10.0	1.32
	3	124	9.8	1.28
	4	127	10.0	1.26
	5	130	10.2	1.28
	6	139	10.9	1.27
	7	131	10.5	1.25
	8	127	9.6	1.31
	9	136	10.6	1.28
	0	122	10.0	1.21
	M81021	125	10.7	1.16
	2	153	11.3	1.36
	3	139	10.2	1.35
	4	114	10.3	1.14
	5	119	9.7	1.21
	6	121	10.0	1.25
	7	136	10.4	1.32
	8	128	10.0	1.25
	9	132	11.8	1.14
	0	126	10.5	1.21
	Average	130	10.4	1.26
	Std. Dev.	9	0.5	0.06

Table 4.2 (Continued)

Individual Test Results for Three Axial Tensile Test Methods
(cross-ply material)

Test Method	Specimen Number	Axial Tensile Strength (ksi)	Axial Tensile Modulus (Msi)	Ultimate Tensile Strain (percent)
Streamlined Profile (L = 12 in)	MST100	144	10.8	1.32
	1	143	10.2	1.34
	2	152	10.9	1.34
	3	141	10.8	1.28
	4	163	10.9	1.42
	5	126	10.6	1.16
	6	142	10.7	1.29
	7	149	10.6	1.40
	8	127	10.4	1.21
	9	127	10.1	1.26
	MST110	126	9.8	1.28
	1	143	10.4	1.33
	2	152	11.0	1.35
	3	136	9.9	1.33
	4	158	10.7	1.42
	5	138	10.4	1.30
	6	149	10.3	1.40
	7	128	10.5	1.21
	8	149	11.1	1.34
	9	140	10.7	1.39
	Average	142	10.5	1.32
	Std. Dev.	11	0.4	0.07

Table 4.2 (Concluded)

Individual Test Results for Three Axial Tensile Test Methods
(cross-ply material)

Test Method	Specimen Number	Axial Tensile Strength (ksi)	Axial Tensile Modulus (Msi)	Ultimate Tensile Strain (percent)
Linear Taper	MLT101	129	10.5	1.19
Profile	2	141	10.7	1.39
(L = 24 in.)	3	145	11.5	1.28
	4	137	10.6	1.25
	5	155	11.8	1.31
	6	144	10.8	1.30
	7	150	11.1	1.30
	8	144	11.2	1.29
	9	132	10.5	1.23
	MLT110	150	11.4	1.30
	1	133	11.6	1.12
	2	135	10.3	1.29
	3	111	10.9	1.02
	4	153	11.5	1.31
	5	143	11.5	1.22
	6	147	11.0	1.31
	7	133	10.8	1.22
	8	130	10.9	1.18
	9	159	11.1	1.39
	MLT100	148	10.5	1.40
	Average	141	11.0	1.26
	Std. Dev.	11	0.4	0.09

Table 4.3

Individual Axial Tensile Test Results For Six $[\pm\theta]_{ns}$ Laminates

Laminate	Specimen Number	Axial Tensile Strength (ksi)	Axial Tensile Modulus (Msi)	Ultimate Tensile Strain (percent)	Poisson's Ratio (percent)
$[\pm15]_s$	M15S01	120	16.2	0.73	1.12
	2	[illegible]	13.8	0.68	1.22
	3	115	17.9	0.67	0.80
	4	59*	15.7	-	0.89
	5	111	16.1	0.69	0.89
	6	57*	17.1	-	0.88
	7	116	17.2	0.67	0.89
	Average	111	16.3	0.69	0.96
	Std. Dev.	11	1.3	0.02	0.15
$[\pm15]_{2s}$	M152S9	80*	19.9	-	1.16
	8	128	17.5	0.74	0.75
	2	117	18.0	0.64	0.80
	3	121	7.0**	1.71**	0.85**
	4	113	14.7	0.78	1.00
	5	123	16.5	0.76	0.92
	6	74*	16.2	-	1.10
	Average	120	17.1	0.73	0.96
	Std. Dev.	6	1.8	0.06	0.16
$[\pm30]_s$	M30S01	72.1	7.2	1.34	1.13
	2	56.6	4.9	1.89	0.93
	3	65.9	7.7	1.03	1.17
	4	36.9*	6.3	-	0.89
	5	63.7	6.4	1.40	0.91
	6	38.2*	6.4	-	-
	7	70.8	6.4	1.58	1.24
	Average	65.8	6.5	1.45	1.04
	Std. Dev.	6.2	1.1	0.32	0.15

Table 4.3 (Continued)

Individual Axial Tensile Test Results For Six $[\pm\theta]_{ns}$ Laminates

Laminate	Specimen Number	Axial Tensile Strength (ksi)	Axial Tensile Modulus (Msi)	Ultimate Tensile Strain (percent)	Poisson's Ratio (percent)
$[\pm 30]_{2s}$	M302S1	82.1	7.9	1.44	1.35
	2	74.9	6.6	1.72	1.36
	3	78.3	6.3	1.82	1.30
	4	53.0*	6.4	-	1.24
	5	59.3	6.4	1.70	1.27
	6	39.1*	7.1	-	1.22
	7	75.8	7.2	1.89	1.25
	Average	74.1	6.9	1.71	1.28
	Std. Dev.	8.7	0.7	0.17	0.05
$[\pm 60]_{s}$	M60S01	9.7	2.2	0.47	0.31
	2	9.8	2.1	0.48	0.29
	3	10.4	2.2	0.48	0.31
	4	5.9*	2.1	-	0.35
	5	11.4	2.1	0.58	0.35
	6	5.3*	1.8	-	0.29
	7	9.8	1.8	0.59	0.30
	Average	10.2	2.0	0.52	0.31
	Std. Dev.	0.7	0.2	0.06	0.03
$[\pm 60]_{2s}$	M602S1	12.7	1.7	0.73	0.26
	2	12.1	1.8	0.65	0.31
	3	12.8	1.8	0.74	0.25
	4	6.7*	1.7	-	0.29
	5	12.0	1.7	0.76	0.29
	6	6.6*	1.9	-	0.30
	7	11.8	1.8	0.67	0.28
	Average	12.3	1.8	0.71	0.28
	Std. Dev.	0.4	0.1	0.05	0.02

Table 4.3 (Concluded)

Individual Axial Tensile Test Results For Six $[\pm\theta]_{ns}$ Laminates

Laminate	Specimen Number	Axial Tensile Strength (ksi)	Axial Tensile Modulus (Msi)	Ultimate Tensile Strain (percent)	Poisson's Ratio (percent)
$[\pm75]_s$	M75S01	6.8	1.8	0.38	0.11
	2	7.7	2.1	0.38	0.07
	3	7.7	1.9	0.39	0.11
	4	5.3*	1.8	-	0.10
	5	7.4	1.9	0.42	0.09
	6	4.3*	1.8	-	0.08
	7	6.8	1.8	0.38	0.08
	Average	7.3	1.9	0.39	0.09
	Std. Dev.	0.5	0.1	0.02	0.02
$[\pm75]_{2s}$	M752S1	6.5	1.8	0.36	0.08
	2	7.9	1.7	0.46	0.08
	3	6.8	1.5	0.46	0.07
	4	4.2*	1.6	-	0.07
	5	7.6	1.6	0.49	0.06
	6	4.1*	1.6	-	0.08
	7	6.7	1.5	0.45	0.09
	Average	7.1	1.6	0.44	0.08
	Std. Dev.	0.6	0.1	0.05	0.01

* Maximum stress applied to specimen prior to unloading; not a failure stress and therefore not included in average

** Not included in average

Table 4.4

Individual Tensile Test Specimen Breakload and Thickness Values

Laminate	Test Type	Laminate Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[0]_6$	D3039	WYO	M77011	4496	0.032
			3	4516	0.033
			4	4960	0.032
			5	4938	0.032
			6	4216	0.031
	S.L. 12	WYO	MST001	-	0.037
			2	4073	0.035
			3	-	0.036
			4	-	0.036
			5	-	0.038
			6	4427	0.038
			7	4318	0.038
			8	4211	0.039
	S.L. 18	WYO	MST301	4413	0.034
			2	3328	0.037
			3	3880	0.037
			4	4558	0.038
			5	4304	0.037
	S.L. 24	WYO	MST201	4226	0.038
			2	3938	0.035
			3	4182	0.035
			4	4311	0.036
			5	4009	0.033
			6	3826	0.037
	L.T. 24	WYO	MLT001	3550	0.038
			2	3486	0.038
			3	4026	0.038
			4	3883	0.037
			5	3601	0.038

Table 4.4 (Continued)

Individual Tensile Test Specimen Breakload and Thickness Values

Laminate	Test Type	Laminate Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[0/90]_{3s}$	D3039	WYO	M81011	9053	0.065
			2	9286	0.070
			3	8590	0.069
			4	8807	0.069
			5	8320	0.064
			6	9035	0.065
			7	8786	0.067
			8	8990	0.071
			9	8875	0.065
			0	8566	0.070
			21	8759	0.070
			2	9524	0.062
			3	9869	0.071
			4	7410	0.069
			5	8457	0.071
			6	8107	0.067
			7	9375	0.069
			8	8841	0.069
			9	8729	0.066
			0	8476	0.067
	S.L. 12	WYO	MST100	4636	0.064
			1	4800	0.067
			2	5102	0.067
			3	4601	0.065
			4	5033	0.062
			5	4267	0.068
			6	4626	0.064
			7	5012	0.067
			8	4216	0.066
			9	4263	0.067
			10	4301	0.068
			1	4604	0.064
			2	4970	0.065
			3	4515	0.066
			4	5036	0.064
			5	4458	0.065
			6	4833	0.065
			7	4088	0.064
			8	4758	0.064
			9	4384	0.063

Table 4.4 (Continued)

Individual Tensile Test Specimen Breakload and Thickness Values

Laminate	Test Type	Laminate Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[0/90]_{3s}$	L.T. 24	WYO	MLT101	4072	0.063
			2	4468	0.063
			3	4133	0.057
			4	4290	0.063
			5	4622	0.060
			6	4509	0.063
			7	4706	0.063
			8	4303	0.060
			9	4067	0.062
			10	4678	0.062
			1	4164	0.063
			2	4311	0.064
			3	3552	0.064
			4	4705	0.062
			5	4415	0.062
			6	4758	0.065
			7	4148	0.062
			8	4160	0.064
			9	5029	0.063
			100	4745	0.064
$[+15]_s$	N/A	ALB	M15S01	2653	0.022
			2	1880	0.021
			3	2407	0.021
			5	2336	0.021
			7	2563	0.022
$[\pm 15]_{2s}$	N/A	ALB	M152S8	5392	0.042
			2	4919	0.042
			3	5440	0.045
			4	4398	0.039
			5	4437	0.036
$[\pm 30]_s$	N/A	ALB	M30S01	1510	0.021
			2	1098	0.020
			3	1319	0.020
			5	1319	0.021
			7	1413	0.020

Table 4.4 (Concluded)

Individual Tensile Test Specimen Breakload and Thickness Values

Laminate	Test Type	Laminate Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[\pm 30]_{2s}$	N/A	ALB	M302S1	3462	0.042
			2	2930	0.039
			3	3135	0.040
			5	2012	0.034
			7	3038	0.040
$[\pm 60]_{s}$	N/A	ALB	M60S01	194	0.020
			2	196	0.020
			3	208	0.020
			5	228	0.020
			7	216	0.022
$[\pm 60]_{2s}$	N/A	ALB	M602S1	510	0.040
			2	484	0.040
			3	514	0.040
			5	505	0.042
			7	507	0.043
$[\pm 75]_{s}$	N/A	ALB	M75S01	143	0.021
			2	170	0.022
			3	163	0.021
			5	155	0.021
			7	143	0.021
$[\pm 75]_{2s}$	N/A	ALB	M752S1	266	0.041
			2	332	0.042
			3	307	0.045
			5	328	0.043
			7	310	0.046

SECTION 5

TABULATED INDIVIDUAL COMPRESSIVE TEST RESULTS

This section consists of four tables. Tables 5.1, 5.2, and 5.3 list the strength, modulus, and ultimate strain data for each specimen of each laminate family tested (unidirectional laminates, cross-ply laminates, and quasi-isotropic laminates, respectively). The fourth table, 5.4, lists the specific laminate, the laminate supplier, breakload, and thickness for each specimen. All laminate families are included in the fourth table.

Table 5.1

Individual Test Results for Three Axial Compressive Test Methods
(unidirectional material)

Test Method and Laminate Configuration	Specimen Number	Axial Compressive Strength (ksi)	Axial Compressive Modulus (Msi)	Ultimate Compressive Strain (percent)
ELSS				
$[0]_{16}$	2ELSS0	104.6	18.3	0.6
	1	126.5	20.2	0.7
	2	111.5	17.6	-
	3	96.0	17.5	0.5
	6	111.0	18.2	-
	MEL001	110.8	16.3	0.7
	2	100.6	13.3	0.9
	Average	108.7	17.3	0.7
	Std. Dev.	9.8	2.1	0.1
$[0]_{24}$	22ELS1	107.5	17.7	0.8
	2	139.6	18.0	0.8
	3	138.9	19.0	0.8
	4	130.6	16.7	0.2
	5	121.2	16.8	0.8
	6	124.7	16.5	0.8
	7	93.9	18.4	0.6
	8	82.2	20.1	0.3
	22EL21	110.0	16.2	0.7
	2	139.1	20.4	0.7
	3	126.2	22.4	0.6
	Average	119.4	18.4	0.6
	Std. Dev.	19.1	1.9	0.2

Table 5.1 (Continued)

Individual Test Results for Three Axial Compressive Test Methods
(unidirectional material)

Test Method and Laminate Configuration	Specimen Number	Axial Compressive Strength (ksi)	Axial Compressive Modulus (Msi)	Ultimate Compressive Strain (percent)
Mod. Celanese				
$[0]_{16}$	2CEL00	146.4	14.8	>1.0
	1	178.7	15.6	>1.3
	2	-	13.7	-
	22	197.3	-	1.4
	04	148.5	15.7	1.0
	5	159.5	15.3	>0.8
	MMC001	167.3	19.9	-
	2	170.0	15.0	1.8
	3	156.9	14.6	1.9
	4	144.9	13.7	1.9
	5	181.1	18.4	>1.5
	Average	165.1	15.7	1.4
	Std. Dev.	17.1	2.0	0.4
$[0]_{24}$	22CEL0	177.5	18.6	1.2
	1	147.6	19.8	0.7
	4	179.6	18.9	1.1
	5	173.8	16.9	0.9
	6	178.1	17.0	1.1
	Average	171.3	18.2	1.0
	Std. Dev.	13.4	1.2	0.2
IITRI (ASTM D-3410)				
$[0]_{16}$	2IIT00	203.9	18.4	1.8
	1	180.8	14.6	1.4
	2	195.5	13.7	2.5
	3	135.6	16.4	0.9
	4	160.3	15.8	1.1
	MIIT01	196.3	16.0	1.6
	2	190.0	16.7	>1.[illegible]
	3	173.1	15.6	1.6
	4	186.2	16.4	1.3
	5	181.0	17.2	1.7
	Average	180.3	16.1	>1.5
	Std. Dev.	20.1	1.3	0.5

Table 5.1 (Concluded)

Individual Test Results for Three Axial Compressive Test Methods
(unidirectional material)

Test Method and Laminate Configuration	Specimen Number	Axial Compressive Strength (ksi)	Axial Compressive Modulus (Msi)	Ultimate Compressive Strain (percent)
$[0]_{24}$	22IIT0	-	18.2	1.1
	2	176.6	-	1.3
	3	156.4	15.2	>0.9
	4	176.5	19.7	1.6
	5	164.9	22.6	1.0
	6	154.3	19.2	0.9
	Average	165.7	19.0	>1.1
	Std. Dev.	10.6	2.7	0.3

Table 5.2

Individual Test Results for Three Axial Compressive Test Methods ($[0/90]_{ns}$ cross-ply material)

Test Method and Laminate Configuration	Specimen Number	Axial Compressive Strength (ksi)	Axial Compressive Modulus (Msi)	Ultimate Compressive Strain (percent)
ELSS				
$[0/90]_{4s}$	6ELSS0	93.7	10.1	1.0
	1	107.9	10.3	1.1
	2	119.0	10.3	1.3
	3	107.9	10.3	1.3
	5	97.9	9.7	0.9
	Average	105.3	10.1	1.1
	Std. Dev.	9.9	0.3	0.2
$[0/90]_{6s}$	66ELS0	112.3	8.9	1.4
	1	97.3	10.0	1.0
	2	133.2	9.4	1.7
	3	97.8	8.1	1.3
	4	114.0	9.0	1.4
	5	103.3	9.2	1.3
	Average	109.6	9.1	1.4
	Std. Dev.	13.5	0.6	0.2
Mod. Celanese				
$[0/90]_{4s}$	CELL01	127.0	8.4	2.3
	2	-	9.4	-
	3	131.1	10.6	2.8
	4	119.2	8.4	2.9
	5	110.3	9.8	1.0
	7	141.5	10.0	1.8
	Average	125.8	9.4	2.2
	Std. Dev.	11.8	0.9	0.8

Table 5.2 (Concluded)

Individual Test Results for Three Axial Compressive Test Methods ($[0/90]_{ns}$ cross-ply material)

Test Method and Laminate Configuration	Specimen Number	Axial Compressive Strength (ksi)	Axial Compressive Modulus (Msi)	Ultimate Compressive Strain (percent)
$[0/90]_{6s}$	66CEL0	144.1	10.3	0.9
	1	126.0	9.1	2.3
	2	152.8	10.5	1.3
	3	141.6	9.6	1.2
	4	141.6	9.6	1.7
	Average	141.2	9.8	1.5
	Std. Dev.	9.7	0.6	0.5
IITRI (ASTM D-3410)				
$[0/90]_{4s}$	6IIT00	128.9	9.9	2.0
	1	116.4	7.6	>1.2
	2	133.5	10.6	2.1
	3	127.3	9.6	>2.1
	5	134.3	10.4	>1.1
	Average	128.1	9.6	>1.7
	Std. Dev.	7.2	1.2	0.5
$[0/90]_{6s}$	66IIT0	149.4	12.5	>1.4
	1	140.4	10.1	2.3
	2	140.0	10.1	>1.7
	3	140.8	11.9	1.4
	4	141.7	9.4	>0.6
	Average	142.5	10.8	>1.5
	Std. Dev.	3.9	1.3	0.6

Table 5.3

Individual Test Results for Three Axial Compressive Test Methods ($[0/\pm45/90]_{ns}$ quasi-isotropic material)

Test Method and Laminate Configuration	Specimen Number	Axial Compressive Strength (ksi)	Axial Compressive Modulus (Msi)	Ultimate Compressive Strain (percent)
ELSS				
$[0/\pm45/90]_{2s}$	8ELSS0	81.8	7.6	1.3
	2	86.8	7.4	1.5
	3	87.1	7.5	1.4
	4	91.6	7.4	1.5
	5	81.9	7.0	1.4
	Average	85.8	7.4	1.4
	Std. Dev.	4.1	0.2	0.1
$[0/\pm45/90]_{3s}$	9ELSS0	88.4	8.9	1.0
	1	89.0	6.4	1.6
	2	72.1	6.2	1.3
	3	87.2	7.2	1.5
	4	77.4	7.4	1.5
	5	80.0	8.6	1.0
	Average	82.4	7.4	1.3
	Std. Dev.	6.9	1.1	0.3
Mod. Celanese				
$[0/\pm45/90]_{2s}$	8CELL0	84.4	5.8	2.0
	1	81.3	6.0	2.1
	2	93.9	7.8	1.7
	3	90.7	6.8	2.1
	5	89.8	7.6	1.7
	Average	88.0	6.8	1.9
	Std. Dev.	5.1	0.9	0.2
$[0/\pm45/90]_{3s}$	9CELL0	85.7	8.5	1.0
	1	96.1	7.1	1.6
	2	80.4	7.1	1.4
	4	81.5	6.3	1.6
	6	91.8	5.9	1.7
	Average	87.1	7.1	1.5
	Std. Dev.	6.7	0.9	0.3

Table 5.3 (Concluded)

Individual Test Results for Three Axial Compressive Test Methods ($[0/\pm45/90]_{ns}$ quasi-isotropic material)

Test Method and Laminate Configuration	Specimen Number	Axial Compressive Strength (ksi)	Axial Compressive Modulus (Msi)	Ultimate Compressive Strain (percent)
IITRI (ASTM D-3410)				
$[0/\pm45/90]_{2s}$	8IIT01	80.9	6.8	1.4
	2	86.2	7.1	1.4
	3	78.9	7.9	1.8
	4	96.9	7.9	1.6
	5	84.4	5.8	1.8
	6	79.6	6.9	1.7
	Average	84.5	7.1	1.6
	Std. Dev.	6.7	0.8	0.2
$[0/\pm45/90]_{3s}$	9IIT01	101.3	8.3	1.4
	2	101.7	7.7	1.2
	3	83.8	7.0	1.6
	4	80.9	7.3	1.5
	5	80.4	6.2	1.3
	Average	89.6	7.3	1.4
	Std. Dev.	10.9	0.8	0.2

Table 5.4

Individual Compressive Test Specimen Breakload and Thickness Values

Laminate	Test Type	Laminate Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[0]_{16}$	ELSS	ALB	2ELSS0	4682	0.092
			1	4734	0.077
			2	4460	0.082
			3	4199	0.090
			6	4468	0.083
			MEL001	3885	0.070
			2	3795	0.075
	MOD. CEL.	ALB	2CEL00	3796	0.100
			1	4403	0.098
			22	5088	0.104
			04	3759	0.100
			5	4048	0.100
			MMC001	2417	0.090
			2	3868	0.091
			3	3557	0.091
			4	3335	0.092
			5	4101	0.091
	IITRI	ALB	2IIT00	4898	0.095
			1	4191	0.093
			2	4463	0.090
			3	3420	0.099
			4	4000	0.100
			MIIT01	4132	0.085
			2	4054	0.085
			3	3676	0.085
			4	3968	0.085
			5	3831	0.085
$[0]_{24}$	ELSS	ALB	22ELS1	6361	0.121
			2	8437	0.124
			3	8275	0.123
			4	8450	0.133
			5	8014	0.136
			6	8444	0.139
			7	5722	0.125
			8	4922	0.125

Table 5.4 (Continued)

Individual Compressive Test Specimen Breakload and Thickness Values

Laminate	Test Type	Laminate Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[0]_{24}$	ELSS	ALB	22EL21	7880	0.140
			2	8357	0.125
			3	7560	0.125
	MOD. CEL.	ALB	22CEL0	5109	0.115
			1	4440	0.120
			4	5175	0.115
			5	5177	0.119
			6	5429	0.122
	IITRI	ALB	22IIT2	5610	0.125
			3	4454	0.131
			4	5477	0.123
			5	5343	0.129
			6	5044	0.131
$[0/90]_{4s}$	ELSS	ALB	6ELSS0	3822	0.082
			1	3953	0.075
			2	4926	0.085
			3	3937	0.075
			5	3842	0.080
	Mod. Cel.	ALB	CELL01	3008	0.094
			2	-	0.090
			3	3006	0.090
			4	2808	0.094
			5	2492	0.091
			7	3248	0.090
	IITRI	ALB	6IIT00	3035	0.093
			1	2686	0.093
			2	3071	0.092
			3	3036	0.096
			5	2848	0.085
$[0/90]_{6s}$	ELSS	ALB	66ELS0	6311	0.115
			1	5953	0.125
			2	7999	0.124
			3	5080	0.100
			4	7038	0.130
			5	5859	0.116

Table 5.4 (Continued)

Individual Compressive Test Specimen Breakload and Thickness Values

Laminate	Test Type	Laminate Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[0/90]_{6s}$	Mod. Cel.	ALB	66CEL0	3960	0.110
			1	3938	0.125
			2	4399	0.115
			3	3621	0.100
			4	4083	0.115
	IITRI	ALB	66IIT0	4599	0.122
			1	4236	0.123
			2	4586	0.130
			3	4318	0.123
			4	4139	0.118
$[0/\pm45/90]_{2s}$	ELSS	ALB	8ELSS0	3195	0.079
			2	3517	0.083
			3	3063	0.072
			4	3561	0.080
			5	3019	0.076
	Mod. Cel.	ALB	8CELL0	1821	0.085
			1	1802	0.089
			2	2092	0.089
			3	1966	0.085
			5	1684	0.075
	IITRI	ALB	8IIT01	1730	0.076
			2	1636	0.074
			3	1541	0.078
			4	1867	0.077
			5	1672	0.079
			6	1440	0.072
$[0/\pm45/90]_{3s}$	ELSS	ALB	9ELSS0	4765	0.115
			1	4535	0.104
			2	3506	0.102
			3	4406	0.109
			4	4020	0.113
			5	4480	0.115

Table 5.4 (Concluded)

Individual Compressive Test Specimen Breakload and Thickness Values

Laminate	Test Type	Laminate Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[0/\pm45/90]_{3s}$	Mod. Cel.	ALB	9CELL0	2527	0.122
			1	2880	0.120
			2	2142	0.105
			4	2612	0.125
			6	2872	0.121
	IITRI	ALB	9IIT01	3068	0.123
			2	2987	0.120
			3	2288	0.113
			4	2490	0.122
			5	2289	0.114

SECTION 6

TABULATED INDIVIDUAL SHEAR TEST RESULTS

This section consists of fifteen tables. Tables 6.1 through 6.11, and Table 6.13 list the strength, modulus, and ultimate strain data for each specimen of each laminate family tested. Table 6.12, Individual Short Beam Shear Test Results, lists strength only because shear strains cannot be measured with the short beam shear test. Table 6.14 contains the specimen dimensions and ultimate torque and rotation data for the rectangular torsion shear tests. No additional calculations were performed on the rectangular torsion results as part of the present effort. The final table, 6.15, lists the specific laminate, the laminate supplier, breakload, and thickness data for each specimen. All laminate families are included in the fourth table.

Table 6.1

Individual In-Plane Shear Test Results From Axial Tension Of Three $[\pm 45]_{ns}$ Laminates

Laminate	Specimen Width (in.)	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[\pm 45]_s$	0.75	M45TS1	11.5	1.1	1.5
		2	11.7	0.9	2.2
		3	11.8	0.9	2.2
		4	10.9	1.0	1.7
		5	11.7	1.1	2.1
		Average	11.5	1.0	1.9
		Std. Dev.	0.4	0.1	0.3
	1.25	M45T01	12.0	1.2	1.4
		2	10.1	1.0	1.3
		3	12.0	1.2	1.6
		4	12.7	1.1	1.7
		5	12.3	1.4	1.2
		Average	11.8	1.2	1.4
		Std. Dev.	1.0	0.1	0.2
$[\pm 45]_{2s}$	0.75	MSC3S2	13.3	1.2	2.2
		3	11.1	0.9	1.8
		4	11.0	0.8	2.4
		5	11.7	0.8	2.4
		6	10.8	0.9	1.9
		Average	11.4	0.9	2.1
		Std. Dev.	1.2	0.2	0.3
	1.25	MSC301	11.1	0.9	2.1
		3	>11.6*	0.8	>3.1
		4	10.8	0.7	2.6
		5	11.0	0.8	2.4
		6	10.4	0.9	2.1
		Average	10.8	0.8	2.3
		Std. Dev.	0.3	0.1	0.2

Table 6.1 (Concluded)

Individual In-Plane Shear Test Results From Axial Tension Of Three $[\pm 45]_{ns}$ Laminates

Laminate	Specimen Width (in.)	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[\pm 45]_{4s}$	0.75	MSC4S1	12.1	0.9	2.8
		3	11.1	1.0	2.1
		4	12.4	0.9	3.0
		5	11.8	1.0	2.4
		6	11.3	0.9	2.3
		Average	11.7	0.9	2.5
		Std. Dev.	0.5	0.1	0.4
	1.25	MSC401	12.5	1.0	3.5
		2	12.5	0.9	2.8
		3	11.1	0.9	2.3
		4	9.2	0.9	1.3
		5	10.9	0.9	2.1
		6	11.8	0.8	2.8
		Average	11.3	0.9	2.5
		Std. Dev.	1.2	0.1	0.8

* Not included in average

Table 6.2

Individual Torsional Shear Test Results
(from torsion of unidirectional circular bars)

Specimen Diameter (in.)	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
0.23	MSTR14	16.0	0.9	2.9
	5	17.3	0.8	3.7
	6	14.3	0.9	2.2
	8	>7.2*	0.8	>1.0*
	9	16.3	0.8	3.1
	Average	16.0	0.8	3.0
	Std. Dev.	1.2	0.1	0.6
0.40	MSTR26	14.4	0.9	2.2
	7	13.3	0.9	2.0
	8	13.0	1.0	1.3
	9	16.5	0.9	2.7
	Average	14.3	0.9	2.0
	Std. Dev.	1.6	0.0	0.6

* Not included in average

Table 6.3

Individual Iosipescu Shear Test Results
(unidirectional material)

Laminate	Notch Angle (degrees)	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[0]_8$	90	MC9101	12.4	1.1	1.6
		2	14.5	0.8	4.5
		3	15.8	0.9	4.9
		4	15.3	0.8	>3.0*
		5	15.0	0.8	6.0
		Average	14.6	0.9	4.2
		Std. Dev.	1.3	0.1	1.9
	120	MC2101	14.8	0.7	>6.0*
		2	13.8	1.1	2.1
		3	11.8	1.0	1.9
		4	14.8	0.8	4.1
		5	13.2	0.8	3.2
		Average	13.7	0.9	2.8
		Std. Dev.	1.2	0.2	1.0
$[0]_{16}$	90	MC9201	17.5	1.1	6.0
		2	17.1	1.0	4.6
		3	16.2	1.0	3.4
		4	16.2	1.2	3.0
		5	16.4	1.1	4.5
		Average	16.7	1.1	4.3
		Std. Dev.	0.6	0.1	1.2
	120	MC2201	16.6	1.1	4.8
		2	16.6	1.0	6.0
		3	15.2	1.1	2.9
		4	14.5	0.9	3.3
		Average	15.7	1.0	4.2
		Std. Dev.	1.0	0.1	1.4

* Not included in average

Table 6.4

Individual Iosipescu Shear Test Results
($[0/90]_{ns}$ cross-ply material)

Laminate	Notch Angle (degrees)	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[0/90]_{2s}$	90	MC9301	13.2	0.7	4.1
		2	13.8	0.7	4.5
		3	13.5	0.8	3.2
		4	12.0	0.9	4.7
		5	13.0	0.7	3.9
		Average	13.1	0.8	4.1
		Std. Dev.	0.7	0.1	0.6
	120	MC2301	14.2	0.8	4.0
		2	13.5	0.7	4.5
		3	13.0	0.7	4.1
		4	14.2	0.8	4.2
		5	13.8	0.8	4.5
		Average	13.7	0.8	4.3
		Std. Dev.	0.5	0.1	0.2
$[0/90]_{4s}$	90	MC9401	13.5	0.8	4.5
		2	13.8	0.7	4.2
		3	13.6	0.7	4.8
		4	12.0	0.7	5.1
		Average	13.2	0.7	4.6
		Std. Dev.	0.8	0.1	0.4
	120	MC2401	13.5	0.6	5.8
		2	13.3	0.6	4.9
		3	13.8	0.8	-
		4	13.6	0.7	4.5
		5	14.1	0.7	-
		Average	13.7	0.7	5.1
		Std. Dev.	0.3	0.1	0.7

Table 6.5

Individual Iosipescu Shear Test Results
($[0/\pm45/90]_{ns}$ quasi-isotropic material)

Laminate	Notch Angle (degrees)	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[0/\pm45/90]_s$	90	MS9101	-	3.0	-
		2	-	2.4	-
		4	-	2.8	-
		MQIS91	61.8	3.0	2.4
		2	65.9	-	-
		3	61.9	-	-
		4	57.4	-	-
		5	52.7	2.6	2.3
		Average	59.9	2.8	2.4
		Std. Dev.	0.5	0.3	0.1
	120	MQIS11	42.0	2.7	1.6
		2	39.0	2.6	1.8
		3	43.2	-	-
		4	41.0	-	-
		5	42.5	-	-
		MC1201	-	2.8	-
		2	-	3.6	-
		3	-	2.6	-
		4	-	2.6	-
		Average	41.5	2.8	1.7
		Std. Dev.	1.6	0.4	0.1
$[0/\pm45/90]_{2s}$	90	MC9801	-	3.1	-
		2	-	2.8	-
		3	-	2.0	-
		MQ2S91	60.0	2.8	2.2
		2	62.0	3.0	2.2
		3	58.0	-	-
		4	60.5	-	-
		5	58.9	-	-
		Average	59.9	2.7	2.2
		Std. Dev.	1.5	0.4	0.0

Table 6.5 (Concluded)

Individual Iosipescu Shear Test Results
($[0/\pm45/90]_{ns}$ quasi-isotropic material)

Laminate	Notch Angle (degrees)	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[0/\pm45/90]_{2s}$	120	MS1201	-	2.5	-
		2	-	2.5	-
		3	-	2.3	-
		4	-	2.8	-
		5	-	2.8	-
		MQ2S11	47.9	-	-
		2	41.9	2.7	1.8
		3	49.0	-	-
		4	48.3	2.7	2.1
		5	42.5	-	-
		Average	45.9	2.6	2.0
		Std. Dev.	3.4	0.2	0.2

Table 6.6

Individual Iosipescu Shear Test Results
($[\pm 45]_{ns}$ material)

Laminate	Notch Angle (degrees)	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[\pm 45]_{2s}$	90	MC9501	-	4.3	-
		2	-	4.8	-
		3	-	4.2	-
		4	-	5.6	-
		5	-	5.2	-
		M45291	55.4	5.3	1.2
		2	51.5	4.5	1.2
		3	45.1	-	-
		4	64.4	-	-
		Average	54.1	4.8	1.2
		Std. Dev.	8.1	0.5	0.0
	120	MC2501	-	7.3	0.7
		2	-	3.6	0.7
		4	-	3.8	0.8
		5	-	3.6	0.6
		M45211	40.4	3.7	1.2
		2	43.4	4.2	1.1
		3	41.5	-	-
		4	41.3	-	-
		Average	41.6	4.1	1.2
		Std. Dev.	1.3	1.5	0.1
$[\pm 45]_{4s}$	90	MC9602	-	6.0	-
		3	-	4.4	-
		5	-	4.2	-
		M45491	38.9	5.0	0.9
		2	43.0	5.0	0.8
		3	48.7	-	-
		4	49.8	-	-
		Average	45.1	4.9	0.8
		Std. Dev.	5.1	0.7	0.1

Table 6.6 (Concluded)

Individual Iosipescu Shear Test Results
($[\pm 45]_{ns}$ material)

Laminate	Notch Angle (degrees)	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[\pm 45]_{4s}$	120	MC1601	-	4.3	-
		2	-	4.2	-
		3	-	3.7	-
		4	-	3.9	-
		5	-	3.5	-
		M45411	33.0	4.2	0.9
		2	37.3	4.2	0.9
		3	32.1	-	-
		4	33.0	-	-
		Average	33.8	4.0	0.9
		Std. Dev.	2.3	0.3	0.0

Table 6.7

Individual Rail Shear Test Results
(unidirectional material)

Laminate	Specimen Geometry	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[0]_8$	Rect.	R008R1	14.7	1.3	2.1
	Paral.	R008P1	15.0	0.8	5.2
$[0]_{16}$	Rect.	R016R1	14.7	0.9	3.4
		2	14.6	1.0	3.5
		3	15.0	1.1	>1.0*
		Average	14.8	1.0	3.4
		Std. Dev.	0.2	0.1	0.1
	Paral.	R016P1	13.0	0.7	3.8
		2	15.9	0.8	5.2
		3	14.4	0.9	5.0
		4	15.7	0.8	3.9
		Average	14.8	0.8	4.5
		Std. Dev.	1.3	0.1	0.7

* Not included in average

Table 6.8

Individual Rail Shear Test Results
($[0/90]_{ns}$ cross-ply material)

Laminate	Specimen Geometry	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[0/90]_{2s}$	Rect.	R09021	12.4	1.0	2.2
		2	12.1	0.8	3.1
		3	12.2	0.8	2.6
		4	14.0	0.9	4.1
		5	11.4	0.9	2.5
		Average	12.4	0.9	2.9
		Std. Dev.	1.0	0.1	0.7
	Paral.	R0902A	14.0	0.8	4.8
		B	14.2	0.8	4.1
		C	12.7	1.0	3.2
		D	13.2	0.8	3.8
		E	12.3	0.8	3.6
		Average	13.3	0.8	3.9
		Std. Dev.	0.8	0.1	0.6
$[0/90]_{4s}$	Rect.	RS0901	14.0	0.9	3.5
		2	11.4	0.9	2.8
		3	12.7	0.9	2.8
		4	11.4	0.8	2.9
		RS0911	14.5	1.0	4.3
		2	13.2	-	-
		Average	12.9	0.9	3.3
		Std. Dev.	1.3	0.1	0.7
	Paral.	RS0905	13.2	0.8	3.5
		6	11.5	0.8	2.6
		7	12.4	0.8	3.2
		8	13.0	0.9	3.1
		9	13.9	0.8	4.0
		10	15.0	-	-
		Average	13.2	0.8	3.3
		Std. Dev	1.2	0.1	0.5

Table 6.9

Individual Rail Shear Test Results
($[0/\pm45/90]_{ns}$ quasi-isotropic material)

Laminate	Specimen Geometry	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[0/\pm45/90]_s$	Rect.	RQA1R1	47.3	2.3	2.2
		2	40.9	2.5	1.6
		3	46.9	2.6	2.4
		4	41.3	2.5	2.1
		5	46.1	3.1	1.8
		Average	44.5	2.6	2.0
		Std. Dev.	3.1	0.3	0.3
	Paral.	RQA1P1	>34.9	2.8	>1.3
		2	32.1	2.6	1.4
		3	35.1	2.6	1.5
		4	>28.9	2.6	>1.2
		Average	>32.8	2.6	>1.4
		Std. Dev.	2.9	0.1	0.1
$[0/\pm45/90]_{2s}$	Rect.	RQA2R1	>24.8	2.7	>1.0
		2	>26.8	3.1	>0.9
		3	>34.3	3.0	>1.3
		4	>38.0	2.9	>1.3
		5	-	3.2	-
		Average	>31.8	3.0	>1.1
		Std. Dev.	5.7	0.2	0.2
	Paral.	RQA2P1	>17.7	2.4	>0.8
		2	>25.0	2.8	>1.0
		3	>23.0	2.9	>1.0
		4	>31.4	2.8	>1.4
		5	>30.7	2.7	>1.3
		Average	>25.6	2.7	>1.1
		Std. Dev.	5.7	0.2	0.2

Table 6.10

Individual Rail Shear Test Results
($[\pm45]_{ns}$ material)

Laminate	Specimen Geometry	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[\pm45]_{2s}$	Rect.	R452R1	69.0	5.3	1.2
		2	65.7	5.3	1.1
		3	>54.6	5.0	>1.1
		4	58.7	4.8	1.1
		5	66.2	4.8	1.6
		Average	62.8	5.0	1.2
		Std. Dev.	6.0	0.3	0.2
	Paral.	R452P1	>42.4	4.2	>1.2
		2	>42.6	4.8	>0.9
		3	>46.2	4.5	>1.2
		4	52.4	3.8	1.6
		5	>30.8*	3.8	>0.8*
		Average	>45.9	4.2	>1.2
		Std. Dev.	4.7	0.4	0.3
$[\pm45]_{4s}$	Rect.	R454R1	>34.5	4.9	>0.7
		2	>35.0	4.6	>0.8
		3	>35.1	4.9	>0.7
		4	>37.6	5.2	>1.0
		Average	>35.6	4.9	>0.8
		Std. Dev.	1.4	0.2	0.1
	Paral.	R454P1	>32.5	4.4	>0.7
		2	>32.1	4.5	>0.7
		3	>34.3	4.2	>0.8
		4	>25.9	3.8	>0.7
		Average	>31.2	4.2	>0.7
		Std. Dev.	3.7	0.3	0.0

Table 6.11

Individual Off-Axis Tension Shear Test Results

Laminate	Specimen L/W Ratio	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[10]_8$	16	MOT102	9.3	1.0	1.3
		3	8.6	0.9	1.2
		4	9.3	1.0	1.2
		5	7.6	0.9	1.0
		Average	8.7	0.9	1.2
		Std. Dev.	0.8	0.1	0.1
$[10]_{12}$	16	MO10B1	6.7	0.9	0.8
		2	7.6	0.8	1.1
		3	8.1	0.9	1.1
		4	7.8	0.8	1.1
		5	7.4	0.9	0.9
		Average	7.5	0.9	1.0
		Std. Dev.	0.5	0.1	0.1
$[15]_8$	11	MO15A1	12.1	1.2	1.6
		2	10.8	1.2	1.2
		3	10.7	1.3	1.2
		4	8.3	1.2	0.8
		5	9.2	1.2	0.8
		Average	10.2	1.2	1.2
		Std. Dev.	1.5	0.0	0.3
$[15]_{12}$	16	MO15B1	5.9*	0.9	0.7*
		2	8.5	0.9	1.2
		3	5.2*	1.0	0.6*
		4	8.0	0.9	1.1
		5	5.3*	0.9	0.7*
		6	8.6	0.8	1.3
		7	5.1*	1.0	0.6*
		8	8.5	0.9	1.2
		Average	8.4	0.9	1.2
		Std. Dev.	0.3	0.1	0.1

Table 6.11 (Concluded)

Individual Off-Axis Tension Shear Test Results

Laminate	Specimen L/W Ratio	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[20]_8$	11	M020A1	11.7	1.3	1.2
		2	11.1	1.2	1.3
		3	9.6	1.0	1.5
		5	10.2	1.2	1.3
		6	10.5	1.1	1.3
		Average	10.6	1.2	1.3
		Std. Dev.	0.8	0.1	0.1
$[20]_{12}$	16	M020B1	6.7	0.9	0.9
		2	6.9	0.9	0.8
		3	6.5	0.8	0.9
		4	6.9	0.9	0.9
		5	6.0	0.8	0.8
		Average	6.6	0.9	0.9
		Std. Dev.	0.4	0.1	0.1
$[30]_8$	11	M030A1	8.7	1.1	1.0
		2	8.2	1.1	0.9
		3	8.0	1.0	1.0
		4	8.2	1.1	0.9
		5	4.6*	1.1	0.5*
		Average	8.3	1.1	1.0
		Std. Dev.	0.3	0.0	0.1

* Not included in average because specimen edges not ground

Table 6.12

Individual Short Beam Shear Test Results

Laminate	Span to Depth Ratio	Specimen Number	Shear Strength (ksi)
$[0]_{48}$	3	SBS031	15.4
		2	14.6
		3	14.8
		4	15.4
		5	14.6
		6	15.2
		Average	14.9
		Std. Dev.	0.5
$[0]_{48}$	4	SBS041	14.4
		2	12.1
		3	13.7
		4	13.6
		5	14.2
		Average	13.6
		Std. Dev.	0.9
$[0/90]_{6s}$	3	SBS931	13.2
		2	14.6
		3	13.4
		4	14.4
		5	13.6
		Average	13.8
		Std. Dev.	0.6
	4	MSBL01	13.6
		2	12.5
		3	13.3
		4	13.2
		5	12.0
		Average	12.9
		Std. Dev.	0.7

Table 6.13

Individual Iosipescu Shear Test Results
(interlaminar)

Laminate	Specimen Number	Shear Strength (ksi)	Shear Modulus (Msi)	Shear Strain (percent)
$[0/90]_{6s}$	MIL961	11.8	-	-
	2	11.6	0.7	>2.0*
	3	10.9	0.6	3.1
	4	10.9	0.6	>2.7*
	5	11.4	0.7	2.8
	6	11.3	0.6	3.6
	Average	11.3	0.6	3.2
	Std. Dev.	0.4	0.1	0.4
$[0]_{96}$	M23001	5.6	0.6	1.0
	2	5.5	0.5	1.1
	3	5.8	0.6	1.0
	4	6.0	0.5	1.1
	5	4.1	0.6	0.8
	6	5.7	0.5	1.1
	Average	5.4	0.6	1.0
	Std. Dev.	0.7	0.1	0.1

* Not included in average

Table 6.14

Individual Rectangular Torsion Test Results

Laminate	Gage Length (in.)	Specimen No.	Width (in.)	Thickness (in.)	Ultimate Torque (in.lbs)	Ultimate Rotation (Radians)
[0]]$_{24}$	4.5	MSTS12	0.468	0.133	55.0	2.10
		3	0.465	0.131	54.9	1.47
		4	0.464	0.121	41.2	1.25
		5	0.462	0.124	55.7	1.63
[0]$_{48}$	6.5	MSTS21	0.475	0.256	150	0.97
		2	0.473	0.257	153	0.98
		3	0.476	0.256	149	0.94
		4	0.474	0.253	144	1.10
		5	0.471	0.257	148	1.08
		MSTS31	0.727	0.250	262	0.89
		2	0.742	0.249	252	0.75
		3	0.739	0.243	263	0.90
		4	0.740	0.242	250	0.82
		5	0.726	0.244	255	0.84

Table 6.15

Individual Shear Test Specimen Breakload and Thickness Values

Laminate	Test Type	Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[\pm45]_s$	Tension	ALB	M45TS1	329	0.019
	0.75 in.		2	341	0.019
	wide		3	339	0.019
			4	331	0.020
			5	340	0.019
	Tension	ALB	M45T01	540	0.018
	1.25 in.		2	407	0.016
	wide		3	546	0.018
			4	577	0.018
			5	556	0.018
$[\pm45]_{2s}$	Tension	ALB	MSC3S2	719	0.036
	0.75 in.		3	648	0.039
	wide		4	700	0.042
			5	742	0.042
			6	633	0.039
	Tension	ALB	MSC301	1228	0.044
	1.25 in.		3	1291	0.044
	wide		4	1220	0.045
			5	1266	0.046
			6	1089	0.042
$[\pm45]_{4s}$	Tension	ALB	MSC4S1	1525	0.084
	0.75 in.		3	1338	0.080
	wide		4	1550	0.083
			5	1410	0.080
			6	1403	0.083
	Tension	ALB	MSC401	2589	0.083
	1.25 in.		2	2387	0.077
	wide		3	2501	0.090
			4	1653	0.072
			5	2143	0.079
			6	2395	0.081

Table 6.15 (Continued)

Individual Shear Test Specimen Breakload and Thickness Values

Laminate	Test Type	Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[0]_8$	IOS 90° Notch	ALB	MC9101	184	0.036
			2	302	0.050
			3	296	0.045
			4	293	0.046
			5	321	0.051
	120° Notch	ALB	MC2101	320	0.054
			2	187	0.035
			3	189	0.041
			4	286	0.051
			5	239	0.048
$[0]_{16}$	IOS 90° Notch	ALB	MC9201	513	0.072
			2	579	0.083
			3	522	0.079
			4	493	0.074
			5	476	0.071
	120° Notch	ALB	MC2201	511	0.078
			2	451	0.069
			3	430	0.071
			4	468	0.081
$[0/90]_{2s}$	IOS	ALB	MC9301	267	0.050
			2	267	0.048
			3	245	0.046
			4	204	0.042
			5	258	0.048
	120° Notch	ALB	MC2301	236	0.042
			2	259	0.049
			3	260	0.050
			4	212	0.039
			5	249	0.046
$[0/90]_{4s}$	IOS 90° Notch	ALB	MC9401	500	0.089
			2	471	0.082
			3	491	0.087
			4	456	0.091

Table 6.15 (Continued)

Individual Shear Test Specimen Breakload and Thickness Values

Laminate	Test Type	Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[0/90]_{4s}$	120° Notch	ALB	MC2401	520	0.092
			2	476	0.086
			3	436	0.076
			4	507	0.090
			5	423	0.072
$[0/\pm45/90]_s$	IOS 90° Notch	ALB	MS9101	655	0.038
			2	671	0.038
			4	642	0.037
			MQIS91	1041	0.042
			2	1024	0.041
			3	1018	0.041
			4	955	0.044
			5	916	0.043
	120° Notch	ALB	MQIS11	637	0.041
			2	583	0.040
			3	646	0.040
			4	531	0.035
			5	660	0.042
			MC1201	558	0.037
			2	355	0.037
			3	617	0.039
			4	476	0.038
$[0/\pm45/90]_{2s}$	IOS 90° Notch	ALB	MC9801	860	0.071
			2	1096	0.074
			3	1300	0.074
			MQ2S91	1992	0.083
			2	1974	0.080
			3	1883	0.082
			4	1984	0.082
			5	1946	0.082

Table 6.15 (Continued)

Individual Shear Test Specimen Breakload and Thickness Values

Laminate	Test Type	Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[0/\pm45/90]_{2s}$	IOS 120° Notch	ALB	MS1201	1042	0.070
			2	974	0.070
			3	1149	0.069
			4	1087	0.069
			5	1132	0.073
			MQ2S11	1398	0.077
			2	1178	0.075
			3	1396	0.076
			4	1413	0.078
			5	1246	0.078
$[\pm45]_{2s}$	IOS 90° Notch	ALB	MC9501	442	0.042
			2	489	0.041
			3	416	0.036
			4	421	0.038
			5	354	0.035
			M45291	810	0.039
			2	714	0.038
			3	609	0.036
			4	927	0.039
	IOS 120° Notch	ALB	MC2501	845	0.042
			2	536	0.040
			4	461	0.041
			5	427	0.041
			M45211	606	0.040
			2	656	0.040
			3	607	0.039
			4	635	0.041
$[\pm45]_{4s}$	IOS 90° Notch	ALB	MC9602	1072	0.076
			3	976	0.083
			5	857	0.074
			M45491	1058	0.068
			2	1216	0.070
			3	1492	0.077
			4	1589	0.079

Table 6.15 (Continued)

Individual Shear Test Specimen Breakload and Thickness Values

Laminate	Test Type	Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[\pm45]_{4s}$	IOS 120° Notch	ALB	MC1601	815	0.075
			2	780	0.080
			3	737	0.069
			4	817	0.073
			5	816	0.079
			M45411	917	0.074
			2	1066	0.076
			3	908	0.075
			4	930	0.075
$[0]_8$	RECT. RAIL	ALB	R008R1	2058	0.035
	PAR. RAIL	ALB	R008P1	2202	0.042
$[0]_{16}$	RECT. RAIL	ALB	R016R1	4650	0.079
			2	4561	0.078
			3	4329	0.072
	PAR. RAIL	ALB	R016P1	4213	0.094
			2	4769	0.086
			3	4430	0.089
			4	4629	0.084
$[0/90]_{2s}$	RECT. RAIL	ALB	R09021	1950	0.039
			2	2084	0.043
			3	2201	0.045
			4	2523	0.045
			5	2055	0.045
	PAR. RAIL	ALB	R0902A	2237	0.047
			B	1988	0.040
			C	1900	0.044
			D	1975	0.044
			E	1796	0.042
$[0/90]_{4s}$	RECT. RAIL	ALB	RS0901	4704	0.084
			2	3830	0.084
			3	4267	0.084
			4	3830	0.084
			RS0911	4640	0.080
			2	3960	0.075

Table 6.15 (Continued)

Individual Shear Test Specimen Breakload and Thickness Values

Laminate	Test Type	Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[0/90]_{4s}$	PAR. RAIL	ALB	RS0905	4008	0.088
			6	3491	0.088
			7	4021	0.094
			8	3498	0.078
			9	3910	0.082
			10	3818	0.074
$[0/\pm45/90]_s$	RECT. RAIL	ALB	RQA1R1	8610	0.045
			2	7207	0.044
			3	8746	0.046
			4	6613	0.040
			5	6454	0.035
	PAR. RAIL	ALB	RQA1P1	4819	0.040
			2	4467	0.040
			3	4914	0.040
			4	4349	0.043
$[0/\pm45/90]_{2s}$	RECT. RAIL	ALB	RQA2R1	8635	0.087
			2	8362	0.078
			3	11127	0.081
			4	11391	0.075
			5	10585	0.075
	PAR. RAIL	ALB	RQA2P1	4766	0.078
			2	6640	0.076
			3	6941	0.087
			4	8281	0.076
			5	8571	0.080
$[\pm45]_{2s}$	RECT. RAIL	ALB	R452R1	10791	0.039
			2	10011	0.038
			3	8954	0.041
			4	9911	0.042
			5	10113	0.038
	PAR. RAIL	ALB	R452P1	5730	0.039
			2	6078	0.041
			3	6768	0.038
			4	7659	0.042
			5	4837	0.045

Table 6.15 (Continued)

Individual Shear Test Specimen Breakload and Thickness Values

Laminate	Test Type	Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[\pm 45]_{4s}$	RECT. RAIL	ALB	R454R1	11142	0.080
			2	11256	0.080
			3	11232	0.080
			4	12009	0.079
	PAR. RAIL	ALB	R454P1	9100	0.080
			2	8219	0.074
			3	8927	0.075
			4	7365	0.082
$[10]_8$	Tension	WYO	MOT102	1915	0.046
			3	1736	0.046
			4	1888	0.045
			5	1464	0.044
$[10]_{12}$	Tension	WYO	MO10B1	2132	0.067
			2	2453	0.068
			3	2599	0.068
			4	2553	0.069
			5	2394	0.069
$[15]_8$	Tension	ALB	MO15A1	1409	0.036
			2	1326	0.038
			3	1291	0.038
			4	1032	0.039
			5	1171	0.039
$[15]_{12}$	Tension	WYO	MO15B1	1521	0.064
			2	2197	0.065
			3	1318	0.063
			4	1988	0.062
			5	1024	0.064
			6	1672	0.065
			7	1001	0.065
			8	1627	0.064
$[20]_8$	Tension	ALB	MO20A1	1059	0.036
			2	1124	0.040
			3	1011	0.042
			5	1025	0.040
			6	1082	0.041

Table 6.15 (Continued)

Individual Shear Test Specimen Breakload and Thickness Values

Laminate	Test Type	Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[20]_{12}$	Tension	WYO	MO20B1	1143	0.068
			2	1178	0.069
			3	1115	0.069
			4	1175	0.069
			5	1040	0.069
$[30]_{8}$	Tension	ALB	MO30A1	485	0.030
			2	424	0.030
			3	417	0.030
			4	459	0.030
			5	267	0.031
$[0]_{48}$	Short Beam L/D = 3	WYO	SBS031	1272	0.245
			2	1209	0.248
			3	1202	0.243
			4	1287	0.248
			5	1198	0.244
			6	1253	0.245
	L/D = 4	WYO	SBS041	1166	0.240
			2	934	0.239
			3	1098	0.240
			4	1105	0.239
			5	1131	0.238
$[0/90]_{6s}$	Short Beam L/D = 3	ALB	SBS931	1023	0.113
			2	1102	0.112
			3	1012	0.112
			4	1102	0.114
			5	1012	0.111
	L/D = 4	ALB	MSBL01	1068	0.117
			2	1000	0.119
			3	1102	0.121
			4	1079	0.121
			5	978	0.121

Table 6.15 (Continued)

Individual Shear Test Specimen Breakload and Thickness Values

Laminate	Test Type	Supplier	Specimen Name	Breakload (lbs.)	Specimen Thick. (in.)
$[0/90]_{6s}$ 6 layers	Inter-laminar Iosipescu	ALB	MIL961	1077	0.250
			2	1058	0.250
			3	1019	0.254
			4	1001	0.251
			5	1050	0.251
			6	1048	0.254
$[0]_{96}$ 2 Layers	Inter-laminar Iosipescu	ALB	M23001	571	0.245
			2	580	0.248
			3	604	0.245
			4	637	0.252
			5	433	0.249
			6	603	0.250

Laminate	Test Type	Supplier	Specimen Name	Breakload (in. lbs)	Specimen Dia. (in.)
$[0]_{48}$	Torsion Circ. Bars	WYO	MSTR14	40	0.233
			5	43	0.233
			6	36	0.235
			8	18	0.232
			9	41	0.234
$[0]_{96}$	Torsion Circ. Bars	ALB	MSTR26	189	0.406
			7	195	0.421
			8	225	0.445
			9	207	0.400

Table 6.15 (Concluded)

Individual Shear Test Specimen Breakload and Thickness Values

Laminate	Test Type	Supplier	Specimen Name	Breakload (in. lbs)	Specimen Thick. (in.)
$[0]_{24}$	Torsion	ALB	MSTS12	55	0.133
	Rect. Bars		3	55	0.131
			4	41	0.121
			5	56	0.124
$[0]_{48}$	Torsion	WYO	MSTS21	150	0.256
	Rect. Bars		2	153	0.257
	0.5 in.		3	149	0.256
	Nominal		4	144	0.253
	Width		5	148	0.257
	0.75 in.	WYO	MSTS31	262	0.250
	Nominal		2	252	0.249
	Width		3	263	0.243
			4	250	0.242
			5	255	0.244

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