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TEST METHODS FOR CHARACTERIZATION OF FIBER REINFORCED COMPOSITES

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ABSTRACT

Because of their nonisotropic and inhomogeneous nature, the testing of composites is more extensive than that of metals and is still evolving. Sample preparation and test methods are not fully developed or standardized for the industry. Test data depend upon the test method, specimen design and the composite void content. The work reported in this paper is in the direction of standardizing test methods for the industry and reviews the present status of test methods for characterization of fiber reinforced composites. Test methods available for tension, compression and shear are summarized and advantages and disadvantages of each are discussed. Recommendations have been made as to which test methods are acceptable for determining design allowables and which test methods are suitable only for comparative purposes and quality control. Where available, test data obtained from different test methods and/or different specimen designs have been discussed.

"Key Words": Test Methods, Composite, Characterization, Standardization, Tension, Compression, Shear

INTRODUCTION

Composites offer advantages over metals in terms of lower weight, higher specific strength and modulus, higher fatigue resistance, better oxidation and corrosion resistance, and better control of thermal and electrical properties. For composites to be used efficiently, these must be characterized completely. Because of their inhomogeneous nature, the testing of the composites is more extensive than that of metals and is still evolving. Sample preparation and test methods are not fully developed or standardized for the industry. Test data depend upon the test method, specimen design and composite void content. Resin dominated properties like shear, compression and transverse tension are greatly affected by void content. In absence of standard test methods, the data reported by the individual companies cannot be used by the industry for accurate analysis or design allowables. This prohibits extensive use of the composites by individual companies without spending large amounts of money in characterization testing. Recently a significant amount of composite testing has been done in the industry to compare the various test methods (1-10). However, we are still far away from having standard test methods for the industry such that the test data obtained from different sources can be compared on a one to one basis. Efforts are being made by various agencies such as JANNAF, MIL-HDBK-17 and ASTM Committee on D-30 High Modulus Fiber to standardize the test methods.

This paper is in the direction of standardizing test methods for the industry and reviews the present status of the test methods for characterization of fiber-reinforced composites.

OBJECTIVES

- To review the present status of test methods for characterization of fiber reinforced composites.
- To summarize the test methods available for tension, compression and shear and discuss advantages and disadvantages of each.
- To recommend which test methods are suitable for determination of the design allowables and which are good just for quality control comparison purposes.
- Where available, discuss and compare test data obtained from different test methods or using different specimen designs.

SPECIMEN FABRICATION AND PREPARATION

Specimen design and fabrication should parallel that for the end product in order to obtain the most meaningful data. Where possible, a correlation factor should be established between the

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subscale and the large scale specimens or parts to account for the processing parameters. All mechanical data should be correlated with the specimen fiber volume, resin content, void content, density, glass transition temperature, etc. Though machining of glass and graphite composite specimens poses no problems, machining of Kevlar* specimens is not recommended by conventional methods using carbide blades or high speed carbide end mills. Because of the induced delaminations and fuzzing at the edges, laser machining may be required for Kevlar specimens. Machining of Kevlar specimens by a water jet cutting technique may be acceptable if there is no pickup of moisture during cutting and the specimen edges are clean and true.

Bonding of end tabs or strain gages generally does not give any problems with graphite, glass or regular Kevlar composites. However, composites using Kevlar 49 coated with release agents to give higher fiber pressure vessel performance (11) may give bonding problems. Generally the strain gage adhesive should be cured at test temperature. All finished specimens should be examined visually for any defects. Nondestructive inspection techniques can be included if quantitative data on the nature of the defects present in the specimens are needed.

TEST METHODS

PHYSICAL PROPERTY TESTING

Physical properties including fiber volume, resin content, void content and density should be determined on all representative composite specimens for correlation with the mechanical properties. All fiber dominated properties including longitudinal tensile strength and modulus are affected by fiber volume.

Resin dominated properties like shear, compression and transverse tension are affected by the void content, resin content and fiber volume. For every one percent increase in the void content, resin dominated properties generally decrease in the range of 5 to 10 percent. Hence, to get any meaningful test data fiber volume resin content and void content should be representative of the part for which design allowables or acceptance testing is being done.

Fiber dominated mechanical properties should always be normalized to the design fiber volume. Resin dominated properties cannot be normalized and should be rerun in case the fiber volume, resin content and void content of the specimens taken from the panel are outside the design limits.

Testing for glass transition temperature (Tg) should be done to determine the extent of the cure and detect any minute changes in resin formulation. Recommended test method for glass transition temperature is Dynamic Mechanical Analysis (DMA) which gives a plot of real and complex shear moduli versus temperature. Table I lists the various physical properties and the test methods used for determining them. Reference 12 gives the alternate test method for determining fiber volume for Kevlar composites. To get accurate data, extreme care should be taken to make sure that only the resin and not the fiber is digested by the solvent.

TENSION TESTING

The various tension test methods for composites are summarized in Table II. This table describes the available test methods, type of specimens needed and the test setup. It gives advantages and disadvantages of various methods with the recommendation if the test data are good for use in design or only for quality control.

Recommended test method for getting design allowables for tensile strength and modulus is ASTM D-3039. Alignment of the specimen is very critical and the test fixture shown in Fig. 1 is recommended. This method can be used for testing coupon specimens in direction 1, 2 and crossply layups. In testing of neat resins or direction 2 for composites, end tabs are not necessary. Direction 2 tension testing for composites can also be done using 90 deg hoop wound tube specimens in the test fixture shown in Fig. 2 (Ref. 13). Generally data obtained from hoop wound tubes are higher than those obtained from coupons because of minimal edge effects and also lower void content (better compaction in tubes). Alignment of the specimen is very critical.

For tension testing of direction 3 (through thickness) specimens, the test fixture shown in Fig. 3 is recommended. Here the bond strength between the composite and steel disc should be greater than the direction 3 tensile strength (interlaminar tension) of the composite. Kevlar and glass composites which generally have relatively low interlaminar tensile strength (direction 3 tensile strength) do not give any problem. For graphite composites which have relatively high value of 3 direction tension, selection of the appropriate bonding adhesive is important to make sure the failure occurs in the composite and not at the composite and steel interface.

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*Kevlar is a registered trademark of DuPont for aramid fiber.

Tensile strength and modulus values can also be determined using ring specimens. Rings are more representative of the cylindrical filament wound part and give more representative specimens than the coupons. It was found in Reference 1, 2 that after normalizing for fiber volume, data obtained were equivalent for rings and coupons. Absolute values for the rings were slightly higher because of the higher fiber volume for the rings as compared to that for the coupons, probably because of higher winding tension for the rings. With this in view, coupon testing is recommended as the ring testing is time consuming and costly. Test setup for hydrostatic testing of rings is shown in Fig. 4.

NOL ring split disk method gives the apparent rather than the true tensile strength because of the bending moment imposed during the test. Test data obtained from this method are recommended only for material evaluation and quality control. These data are not recommended for design purposes.

Elongated ring split disk (shown in Fig. 5) minimizes bending stresses during the test, but the fiber and void volume may not be uniform in the specimen due to difference in winding tension between the ring section and the straight section. This method is also recommended only for material evaluation and comparative quality control and not for determining design allowables.

Testing the 5.75-in. pressure vessel to determine hoop fiber stress is good for material evaluation, screening and quality control acceptance testing. This bottle is not recommended for dome contour, dome reinforcement or attachment studies because of too small a size. Data obtained from this testing are the maximum possible available for the full-scale design. Hoop fiber stress obtained depends upon the stress ratio, layup and processing. Air Force Rocket Propulsion Laboratory (AFRPL) is working in the direction of developing a Standard Test Evaluation Bottle (STEB) for the industry. Tentative diameter for this bottle is 10 inches. This bottle is currently being evaluated by the industry to check if it can be used to get the design information not available from the present 5.75-in. bottle (ASTM D-2585).

Various modifications to the ASTM 5.75-in. pressure vessel are possible. The factors which affect the pressure vessel performance include the stress ratio, dome contour, dome reinforcements, composite layup, processing and size (diameter). Besides the material system, the single most important parameter which affects the pressure vessel performance is the processing.

COMPRESSION TESTING

Compressive strength data obtained for a particular material system depends upon the mode of failure. If the failure is not truly compressive, low value for the test data is obtained. In general, specimens giving high strength data fail in the fiber compression mode. The specimens failing either by flexure or delamination generally give medium strength data. The specimens which give low strength data generally fail by Euler buckling with large unsupported specimen length. If the specimen is designed so as not to fail by buckling, compressive strength values obtained by the fiber compressive failure mode is the upper bound limit. The strengths predicted by either the flexure or the delamination failure modes give the lower bound values. Comparison of the experimental and predicted compressive strengths for T-300/5208 material system for the three failure modes is shown in Fig. 6, Ref. 6. The values of compressive modulus is generally not dependent on the test method (2, 3, 7).

In ASTM D-695 and FTMS-406 compression test methods, the specimens are end loaded and compressive strength data obtained are on the low side due to improper failure modes including end brooming. Load transfer is not through shear and is very inefficient. Though the dog bone shape in ASTM D-695 helps to transfer the load to the center, machining problems generally result in stress concentration at the corners leading to low compressive strength. Basically both the ASTM D-695 and FTMS-406 used as such are suitable for neat resins or plastics rather than the fiber reinforced composites.

Modifications to the above test methods for use with composites include the use of the end caps and/or end tabs. Setup used by SoRI (Southern Research Institute) using a dog bone specimen with end cap modification is shown in Fig. 7. Morton Thiokol, Inc. modification (Fig. 8) of ASTM D-695 uses rectangular coupons with the end caps. These modifications give more efficient load transfer through shear. Though not the ideal test methods for getting design data, they are fast and adequate for quality control, material evaluation and product acceptance purposes. Specimen thickness can be varied with the proper fixture design.

An end caps test fixture (Fig. 9) used by Irion and Adams of the University of Wyoming (Ref. 5) gives relatively higher test data due to effective load transfer. As reported by the above authors, data obtained by this test fixture are comparable to those obtained from ASTM D-3410 type test methods where load transfer is very effective.

For compression testing of cylinders, modification to ASTM D-695 includes use of bonded end plugs to prevent end brooming. Upper surfaces of the cylindrical surfaces should be parallel to within 0.001 in. to get proper alignment and reliable data. This method is recommended for material evaluation and quality control only. The test setup is shown in Fig. 10. Hydrostatic compression test method using ASTM D-2586 is also good only for material evaluation and comparative quality control. Ring testing by compression (Fig. 11) is also recommended only for quality control material acceptance. It gives failure load, stiffness and deflection at failure. Test setup for testing direction 3 compressive strength is similar to that used for direction 3 tension and is shown in Fig. 3.

ASTM D-3410 (Celanese developed) test method gives high compressive strength numbers due to very effective load transfer through shear. It uses a conical type fixture. This method has specimen thickness limitations but gives test data comparable to those obtained from the sandwich beam test method. This method is very highly recommended for getting design allowables. The test setup is shown in Fig. 12. IITRI (Illinois Institute of Technology Research Institute) modification of ASTM D-3410 includes the use of a pyramidal wedge type fixture instead of the conical type in ASTM D-3410. Use of pyramidal wedges allows specimens of various thicknesses. It gives data similar to those obtained with D-3410 and is also highly recommended for the design allowables. The test setup is shown in Fig. 13.

Modification used by SoRI to ASTM D-3410 includes test fixtures shown in Fig. 14 and Fig. 15. The modification in Fig. 14 does not have end tabs and is not supported throughout the specimen length. This gives lower data and this method is not recommended for design but only for quality control comparative purposes. The modification in Fig. 15 uses end tabs and the specimen is supported through the specimen length. This method gives relatively higher test data and is recommended. Test data using the above two modifications are shown in Fig. 16. As reported in Ref. 2, test data for configuration 1 (Fig. 15) are higher than those for configuration 2 (Fig. 14) for the various material systems.

Another type of compression test fixture which was developed by the National Bureau of Standards (Ref. 14, 15) is shown in Fig. 17. This fixture combines certain features of the IITRI and Celanese test fixtures, while introducing a feature which allows tensile loading. The test setup consists of a test specimen contained in end fixtures which are constrained to move in a colinear fashion by rigid rods and an external housing. Specimen gripping is achieved by friction due to interference between end fixtures and cylindrical specimen buildup. This method utilizes both square cross section and round cross section specimens. The round cross section is recommended for 0 deg unidirectional composites only.

Load transfer in the Sandwich Beam test method is the most effective (3, 16, 17). Test data obtained by this method give compressive strength numbers which match or are higher (Ref. 3) than those obtained by ASTM D-3410 of both Celanese and IITRI designs. Where practical, this test method should be run. This is highly recommended for getting design allowables. Disadvantages of the sandwich beam test method include high cost and its general unsuitability for running environmental aging tests.

SHEAR TESTING

Shear testing consists of testing for interlaminar and inplane shear. Various test methods for testing of interlaminar and inplane shear for composites are outlined in Table IV.

Interlaminar Shear Testing

In interlaminar shear testing, short beam shear (SBS) using the specimens cut from the NOL ring or flat panels are tested as per ASTM D-2344. SBS is dependent upon the void content and generally NOL ring specimens give higher SBS strength (Ref. 1, 10) due to low void content and better fiber/resin interface bonding. This test is recommended only for material evaluation and quality control. It is not recommended for design allowables because of nonuniform stress distribution in the test specimens.

Iosipescu (double V-notch) shear specimen (Fig. 18) consists of a flat laminated composite coupon with symmetric V-notches (Ref. 8, 18) along the two free edges. The ends of the coupon are gripped by fixtures (bolted, bonded or clamped) and the load is introduced through tension or compression. This is a simple test and the data obtained can be used either for material evaluation, quality control or design.

Data from double notch shear(ASTM D-3846) are not recommended either for design or for quality control. The data are generally in error (Ref. 10) as these are dependent upon the notch depth which is difficult to control.

Testing for interlaminar tension is done as per the test fixture shown in Fig. 3. These data are good only if the interlaminar shear strength of the composite is lower than the bond strength of the composite to the steel disk. For glass and Kevlar composites, generally no problem arises as shear strength is on the low side, but for graphite composites, which have relatively high interlaminar strength, care should be taken in selecting the appropriate adhesive to make sure the failure occurs in the composite and not at the composite/steel interface.

Inplane Shear Testing

Tube torsion using 0 or 90 deg winding gives the most accurate inplane shear strength and modulus data (1, 2, 9, 10) and is highly recommended for design. Similar data can also be obtained using solid rod torsion. Coupon torsion also gives very accurate shear strength and modulus data which can be used for the design. Coupon torsion can also be used to determine shear modulus in other planes including G_{13}, G_{23} (Ref 1, 2) and is highly recommended.

Panel shear (picture frame) and plate twist testing described in Ref. 2, 9 give test data acceptable for material evaluation and design.

Ten degree tensile shear testing developed by NASA to determine shear strength and modulus is not recommended. It gives low shear strength and high shear modulus (Ref. 10) due to tensile shear coupling.

± 45 deg tensile shear testing is a standard ASTM test method designated ASTM D-3518 and gives minimal tensile-shear coupling (Ref. 1, 10). This test method is fast, needs no tab bonding, gives acceptable data and is highly recommended for determining the composite shear strength and the modulus.

Iosipescu shear test as described above (Fig. 18) gives excellent data for inplane shear and is recommended both for the material evaluation and design allowables.

Rail shear testing is used widely for determining composite shear strength. This test has been used for a variety of materials and laminate configurations at room and elevated temperatures. A number of variations (2 rail shear, 3 rail shear) of the rail shear specimen have been used. Tensile or compressive loads are introduced at the rail ends to displace them essentially parallel to one another. Testing setup for rail shear is shown in Fig. 19.

In four-point ring twist testing (Fig. 20, Ref. 19), the specimen is subjected to out of plane four point loading. Applied are four forces of equal magnitude, two upwards at 0 and 180 deg and two downward at 90 and 270 degree. This method is used to measure the shear moduli of isotropic and composite materials. This test is simple and fast with no requirement for elaborate instrumentation or setup. Using this method, accurate values of the shear moduli can be measured at room temperature, cryogenic temperature and elevated temperatures.

Double notch shear as described above gives unreliable test data due to problems with the notch depth and for that reason is not recommended either for design allowables or for quality control.

The crossbeam shear specimen (Fig. 21, Ref. 8) consists of a compressive top flange separated from the bottom flange by a honeycomb core. When the orthogonal legs of the beam are loaded in positive and negative bending, a state of equal magnitude tension and compression is produced in the top flange test section (neglecting core influence and stress concentrations). This test is not recommended either for design or quality control as the specimen is complicated to fabricate and requires a large amount of the material.

A variety of slotted coupon specimens has been used to obtain shear properties of metals and composites (Fig. 22, Ref. 8). Slotted coupon has the advantage of requiring little in the way of material, fabrication time, fixtures and test apparatus. However the specimen is typically characterized by undesirable normal stresses and high stress concentrations at the slot ends which lead to early failures, outside the test section, giving low values of shear strength.

Data for interlaminar and inplane shear strength as determined by various test methods for epoxy material system using Kevlar, glass and graphite fiber are shown in Fig. 23.

SUMMARY AND RECOMMENDATIONS

Sample preparation and test methods for composites are not fully developed or standardized for the industry. The test data depend upon the test method, specimen design and the composite void content. In order to obtain the most meaningful data, specimen design and fabrication should be parallel to that for the end product. All mechanical data should be correlated with the specimen fiber volume, resin content, void content and glass transition temperature. Adequate care should be taken in specimen machining and preparation.

In physical property testing, the recommended method for glass transition temperature testing is Dynamic Mechanical Analysis.

In tension testing, the recommended method for tension testing of flat laminates is ASTM D-3039. For testing of tube specimens, modified ASTM D-3039 using grips is recomended for design allowables. For Direction 3 testing, tensile adhesion disk testing is recommended. For testing of rings or cylinders, hydrostatic testing is recommended. For biaxial tension of pressure vessels, ASTM D-2585 or its modifications are recommended. In compression testing, recommended methods for design allowables are ASTM D-3410 type test methods and sandwich beam testing. Using of test methods where specimens are end loaded or are not supported through the specimen length is not recommended for design allowables, though they may be acceptable for material acceptance or quality control.

In shear testing, recommended method for interlaminar shear is Iosipescu (double V-notch) testing. Short beam shear, because of nonuniform stress distribution should be used only for quality control. Double notch shear testing is not recommended either for design or for quality control because of the problem in controlling the notch depth.

In inplane shear testing, recommended methods are torsion of the tube, rod or coupon. Though 10 deg tensile shear gives lower shear strength and higher shear modulus because of tensile shear coupling, the date obtained from ±45 deg coupon or tube testing are acceptable for design. Whereas rail shear gives only acceptable shear strength data, Isopescu testing gives acceptable data for both the strength and the modulus.

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TABLE 1

PHYSICAL PROPERTY TESTING OF COMPOSITES

Property Evaluated	Test Method	Comments
Density	ASTM D-792	Liquid displacement
Fiber Volume	ASTM D 2584	Resin burn off for glass
Resin Content	ASTM D-3171	Solvent digestion for Kevlar and graphite
Void Content	ASTM D-2734	Void content calculation
Glass Transition Temperature (Tg,	Heat Distortion Temperature (ASTM D-648)	Gives softening temperature, Tg
	Thermal Mechanical Analysis (TMA)	Gives coefficient of thermal expansions, Tg
	Differential Scanning Calorimetry (DSC)	Gives extent of cure, Tg
	Dynamic Mechanical Analysis (DMA)	Gives Tg. Minute changes in resin formulation can be detected

TABLE 2

TENSION TESTING OF COMPOSITES

Test Method	Specimen Type	Test Set-up	Comments
ASTM D-638	Dog Bone Coupon	ASTM D-638	Test good only for neat resins. Machining and load transfer problems for fiber reinforced composite specimens.
ASTM D-3039	Coupon	Figure 1	Industry standard for composites. No end tabs needed for transverse tension and neat resin specimens. Recommended for design allowables.
ASTM D-3039 (Mod)	Tubes	Figure 2	Need grips for tubes. Especially good for direction 2 or cross ply testing. Minimizes edge effects encountered in coupon specimens. Recommended for design.
MTI/SoRI	Disk	Figure 3	3-direction tensile strength (tensile adhesion). Method good only for composites where bond strength of the composite and the steel disk is greater than direction 3 tensile strength.
Hydrostatic Ring SoRI/MTI	Ring/Cylinder	Figure 4	Costs more but gives data comparable to that obtained with coupons. Not recommended for routine testing.
ASTM D-2290	NOL Ring Split Disk	ASTM D-2290	Gives apparent rather than the true tensile strength. Bending moment imposed during the test. Data good only for material evaluation in Quality Control. Not good for design.
ASTM D-2290 (Mod)	Elongated Ring Split Disk	Figure 5	Minimizes bending stresses during testing. Fiber and void content in the specimen may be nonuniform due to difference in winding tension between the ring section and the straight section. Good for Quality Control.
ASTM D-2585	5 .-In. Pressure Vessels	ASTM D-2585	Biaxial tension. Method good for Material Evaluation and screening. Not recommended for dome contour, reinforcement or attachment studies.
ASTM D-2585 (Mod)	Larger Pressure Vessels at Different Designs		Can give design information including dome contour, dome reinforcements, wind angle, process variables, etc.

SoRI - Southern Research Institute

TABLE 3

COMPRESSION TESTING OF COMPOSITES

Test Method	Specimen Type	Test Set-up	Comments
ASTM D-695	Dog Bone Coupon	ASTM D-695	Specimen end loading. End Brooming - Improper failure modes. Gives low strength due to inefficient load transfer. Probable stress concentraton in dog bone machining. Good for plastics (neat resins). Not good for composites. Not recommended for design allowables.
FTMS-406	Rectangular Coupon	FTMS-406	Same as above. Gives low strengths due to inefficient load transfer. Good for plastics (neat resins) not for fibrous composites.
ASTM D-695 End Cap, (Mod) SoRI	Dog Bone Coupon	Figure 7	Efficient load transfer. Gives higher strength. Probable stress concentration in dog bone specimen machining. Specimen thickness can be varied with proper fixture design. Good for Quality Control material acceptance, not for design allowables.
ASTM D-695 End Cap, (Mod) MTI	Rectangular Coupon	Figure 8	Efficient load transfer. Gives high strength numbers. Specimen width constant, thickness can be varied. Good for Quality Control, comparative purposes, not for design allowables.
ASTM D-695 (Mod) End Cap, Univ of Wy	Coupon	Figure 9	Gives relatively higher data due to effective load transfer. Data obtained comparable to ASTM D-3410 type test methods. Can be used for quality control and design allowables.
ASTM D-695 (Mod) End Plug, MTI	Cylinder	Figure 10	End plugs for effective load transfer and to prevent improper failure modes at the specimen ends.
ASTM D-2586	Cylinder	ASTM D-2586	Hydrostatic compression, good for material evaluation, comparative quality control.
ASTM D-695 MTI (Mod)	Ring	Figure 11	For quality control material acceptance. Comparison of different materials. Gives failure load, stiffness and deflection at failure.
ASTM D-695 MTI/SoRI (Mod)	Disc	Figure 3	Similar to test fixture used for 3 direction tension. Minimizes end brooming.
ASTM D-3410 (Celanese)	Coupon	Figure 12	Very effective load transfer. Gives compressive strength numbers comparable to sandwich beam. Uses conical type fixture. Very highly recommended for getting design allowables.
ASTM D-3410 IITRI (Mod)	Coupon	Figure 13	Same as above except for modification that it uses pyramidal, wedge type fixtures. Highly recommended for design allowables.
ASTM D-3410 SoRI (Mod)	Coupon	Figure 14	Modification of D-3410. Uses bearing to support the specimens. Specimen does not have end tabs and is not supported throughout the length. Gives lower data. Good for acceptance testing. Not recommended for design allowables.
ASTM D-3410 SoRI (Mod)	Coupon	Figure 15	Modification of D-3410. Specimen bonded with end tabs and is supported throughout the length. Gives higher strength data. Recommended for design.
ASTM D-3410 NBS (Mod)	Coupon or Cylindrical	Figure 17 Ref 14, 15	Modification of ASTM D-3410. Combines features of Celanese and IITRI designs. This test fixture also allows tensile loading. Recommended for both design and material evaluation.
Sandwich Beam	Coupon	4 pt Flexure Ref 3, 16, 17 ASTM C364-61	Very effective load transfer. If test properly conducted, gives ideal compressive strength numbers. Data equal or slightly higher than that obtained from ASTM D-3410 test method. Highly recommended for design allowables.

TABLE 4

INTERLAMINAR AND INPLANE SHEAR TESTING OF COMPOSITES

Test Type	Test Method	Specimen Type	Data Obtained		Test Setup	Comments
			Strength	Modulus		
Interlaminar Shear						
Short Beam Shear (SBS)	ASTM D-2344	Panel/NOL Ring	Yes	No	ASTM D-2344	Nonuniform stress distribution. Test data not good for design. Used only for comparison and quality control.
Double Notch Shear	ASTM D-3846	Coupon	Yes	No	ASTM D-3846	Notch depth critical. Data not reliable. Not recommended for design or quality control.
Iosipescu (Double V Notch)	Ref 8, 18	Coupon	Yes	Yes	Figure 18	Gives excellent data. Good for design.
Tensile Adhesion (Interlaminar Tension)	MTI/SoRI	Disk	Yes	No	Figure 3	Composite interlaminar shear should be less than bond strength of composite with steel disk.
Inplane Shear						
Tube Torsion (0,90 deg)	Torsion	Hollow Tube	Yes	Yes	--	Gives most accurate values of G_{12}, t_{12}. Recommended for design.
Rod Torsion	Torsion	Solid Rod	Yes	Yes	--	Same as above
Coupon Torsion	Torsion	Coupon	Yes	Yes	--	Same as above. Can also be used to determine G_{13} and G_{23}.
Panel Shear (Picture Frame)	Ref 2, 9	Coupon	No	Yes		Induces stress concentration at the specimen edges. Questionable shear strength data.
Plate Twist	Ref 2, 9	Coupon	No	Yes		Gives good modulus data.
10 Deg Tensile Shear	NASA-TN-D-8215	Coupon	Yes	Yes	ASTM D 3039	Gives low strength and high modulus due to tensile shear coupling. Not recommended for design.
±45 Deg Tensile Testing	ASTM D-3518 ASTM D-3518	Coupon Tube	Yes Yes	Yes Yes	ASTM D-3518	Minimal shear coupling. Gives acceptable data. Can be used for design allowables. Avoid edge effects.
Iosipescu	Ref 8, 18	Coupon	Yes	Yes	Figure 18	Gives excellent data. Can be used for design allowables.
Rail Shear	Ref 8, 15	Coupon	Yes	No	Figure 19	Gives good strength data if no stress concentration at the edges.
4 Point Ring Twist	Ref 19	Ring	No	Yes	Figure 20	Gives good data for modulus at all temperatures
Double Notch Shear	ASTM D-3846	Coupon	Yes	No	ASTM D-3846	Gives unreliable data Notch depth critical. Not recommended for design
Cross Sandwich Beam Shear	Ref 8	Beam	Yes	No	Figure 21	Induces stress concentration within the test section and at the corners. Specimen complicated to fabricate and requires large amount of material. Not recommended.
Slotted Tension Shear	Ref 8	Coupon	Yes	No	Figure 22	Stress concentration gives low values of stress. Not recommended for design.

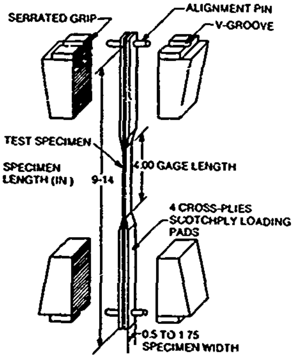

Figure 1. Alignment Test Fixture for Tension Testing (ASTM D-3039)

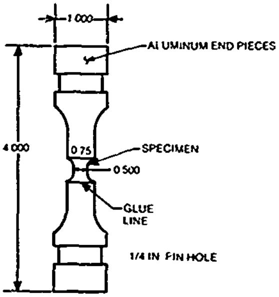

Figure 3b. SoRI Direction 3 Test Fixture

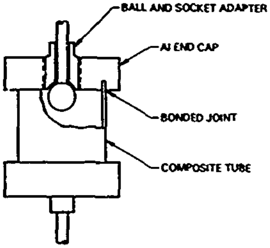

Figure 2. Transverse Tension Testing for Composite Tubes

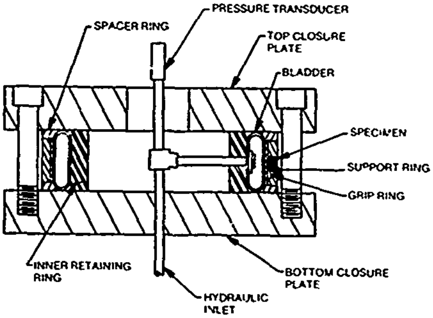

Figure 4. Hydrostatic Set-up For Tension Testing of Ring Specimens

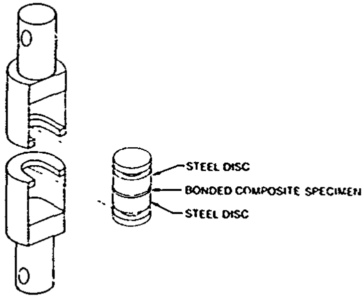

Figure 3a. Morton Thiokol Direction 3 Tension Testing Fixture

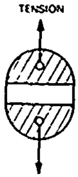

Figure 5. Elongated Ring Split Disk Testing

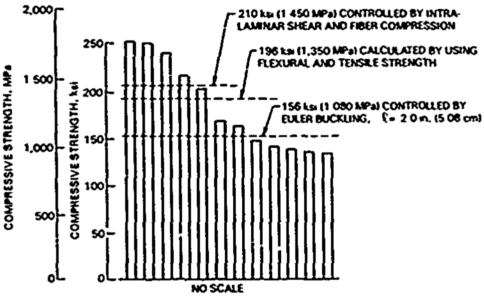

Figure 6. Experimental and Predicted Compressive Strength of T300/5208 for Different Failure Modes

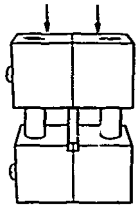

Figure 9. End Load Compression Fixture with Specimen

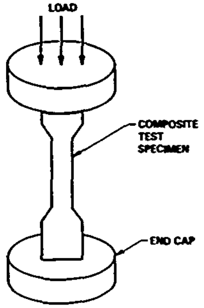

Figure 7. SoRI Compression End Cap Test Fixture

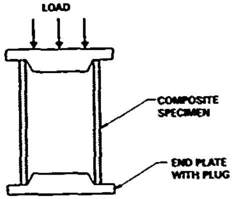

Figure 10. Compression Test Set-up for Cylinders

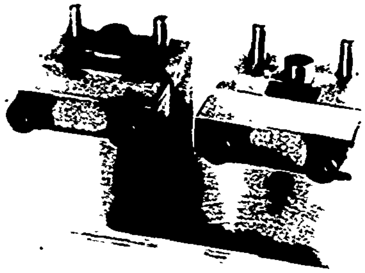

Figure 8. End Cap Test Fixture with Specimen

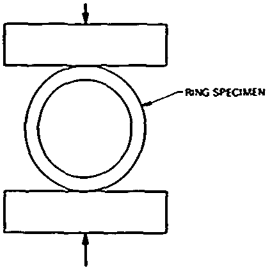

Figure 11. Compression Testing of Ring Specimens

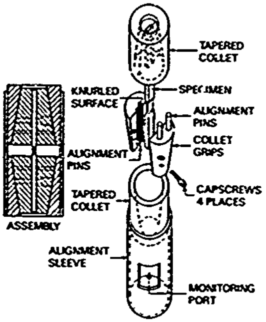

Figure 12. ASTM D-3410(Celanese) Compression Test Fixture Using Conical Wedges

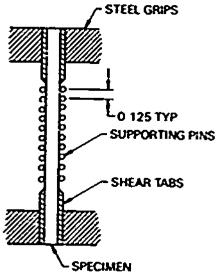

Figure 15. Compression Test Fixture-Loading Configuration 1

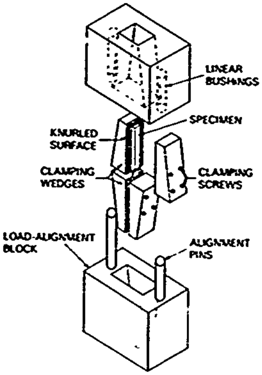

Figure 13. IITRI Compression Test Fixture Using Pyramidal Wedges

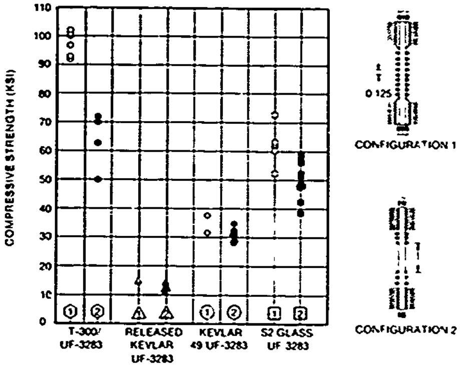

Figure 16. Compressive Strength Vs Specimen Free Length

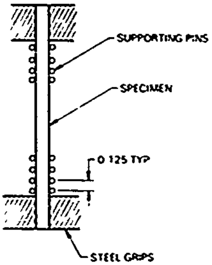

Figure 14. Compression Test Fixture-Loading Configuration 2

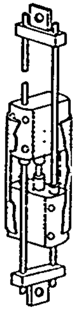

Figure 17. NBS Compression Test Fixture

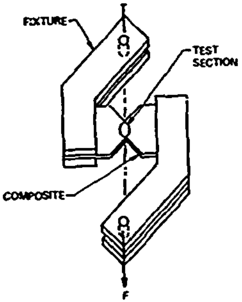

Figure 18. Double V-Notched (Iosipescu) Shear Testing

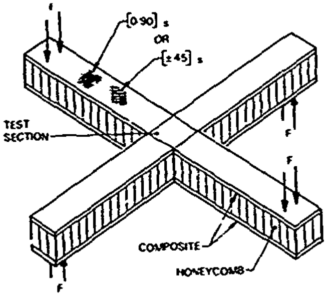

Figure 21. Cross-Beam Sandwich Testing

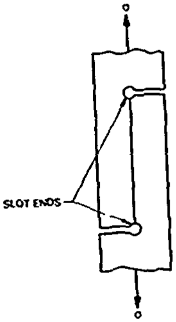

Figure 22. Slotted Coupon Testing

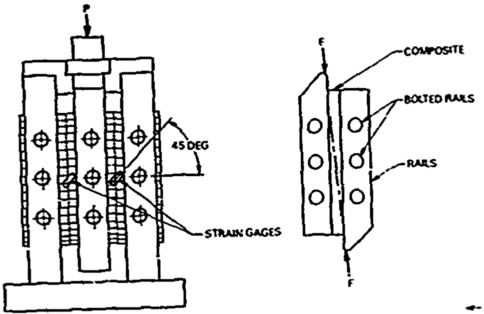

Figure 19. Rail Shear Testing

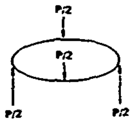

Figure 20. Four Point Loading of Ring Specimen

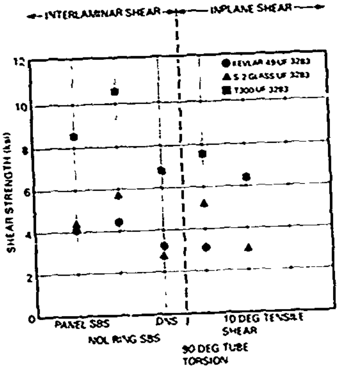

Figure 23. Shear Strength as Determined by Various Test Methods