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EFFECT OF FABRIC STRUCTURES ON MECHANICAL PROPERTIES OF 3-D TEXTILE COMPOSITES

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SUMMARY: An experimental study was conducted to evaluate the effect of fabric structures on the mechanical properties of 3-D textile composites reinforced with 3-D braid, 3-D woven fabric, and 3-D woven fabric with twisted yarns. The mechanical properties and macroscopic failure modes were evaluated in uniaxial tension, compression, three-point flexure and short beam shear. The 3-D braid composite has a higher level of shear resistance owing to the higher degree of stereo network in its internal structure, but it has relatively low in-plane properties such as moduli and strengths in tension, compression and flexure. In contrast, because of their layered fabric construction, the 3-D woven composites have good in-plane properties but a lower level of shear resistance.

KEYWORDS: Textile composites, textile preforms, 3D reinforcement, test, mechanical properties.

INTRODUCTION

Textile structural composites are reinforced with textile preforms for primary structural applications. The design capability together with other superior features such as light weight, strength, stiffness, toughness, integrity, and damage tolerance makes such composites very suitable for many high performance uses [1]. An understanding of the effect of fabric structures on the mechanical properties in such composites is useful for product development and applications.

Textile preforms consist of various reinforcing fabrics. 2-D fabrics have been relatively well developed in terms of production, analysis, and application, and some of them have long been used in structural composite fields [2-10]. However, most of 2-D textile composites retain the inherent weakness of laminated composites in interlaminar properties.

3-D fabrics are introduced to respond to the needs of the structural composites which are capable of withstanding multidirectional stresses [11-15]. They are often made into near net shape so the overall manufacturing cost can be very low for certain applications. The investigation reported here aimed at evaluating the effect of fabric structures on the mechanical properties of 3-D textile structural composites by means of an experimental analysis. Three types of composites were studied which were reinforced with three styles of E-glass textile preforms: 3-D braid, 3-D woven, and 3-D woven with twisted yarns. They are consolidated with epoxy resin using the resin transfer molding (RTM) process. The mechanical properties were evaluated in uniaxial tension, compression, three-point flexure and short beam shear.

EXPERIMENTAL PROCEDURE

Three styles of E-glass fabrics, 3-D braid, 3-D woven, and 3-D woven with twisted yarns, were used as reinforcing preforms. Information about these fabrics is given in Table 1, in which the fiber volume fractions of the composite samples are also indicated. Figure 1 shows photographs of the fabrics.

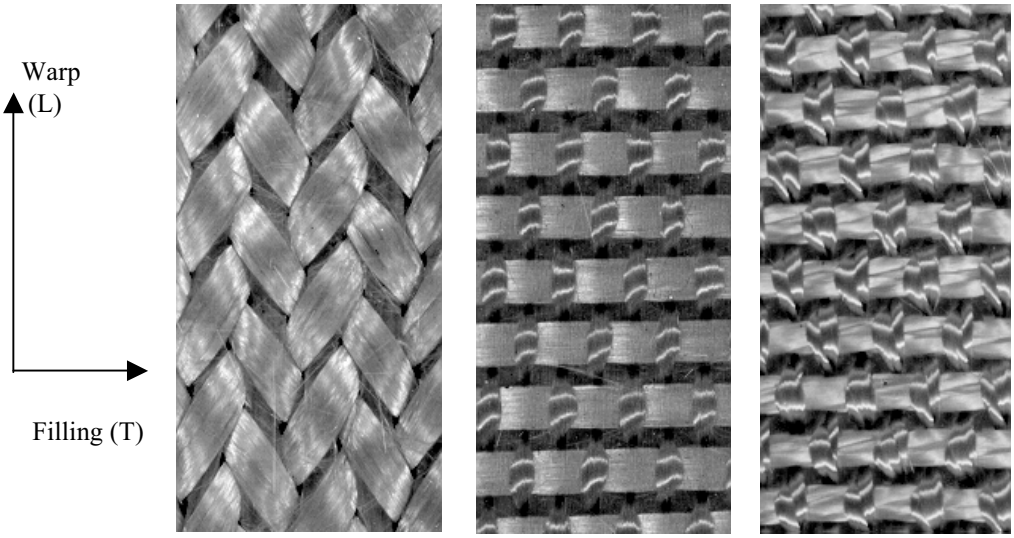

Fig. 1. Fabrics (left to right): BR-braided; WV-woven, TY-woven with twisted yarns

Table 1. Fabrics used as reinforcement in the 3-D textile composites.

Fabric Structure Style	*Textile Type*	*Weight (g/m^2)*	*Yarn Linear density (g/m)*	*Construction No. of layers*	*Volume Fraction*
3-D Braid	Braided	4187	Both A and B:2.0		45%
3-D Woven	Woven	4870	W:2.03, F:2.21, Z:0.55	W: 2, F: 3	53%
3-D Woven w/TY	Woven	4944	W:2.0, F:2.0, Z:0.6	W: 3, F: 4	47%

A: axial yarn, B: braider yarn. W: warp, F: filling, Z: through-thickness. TY: twisted yarn.

An epoxy system consisting of EPON DPL-862 resin and Curing Agent W (mix ratio = 100:26.4 by weight) supplied by the Shell Chemical Co., was used as the matrix material.

Composite panels were fabricated using a resin transfer molding (RTM) device, which consists of a metering, mixing and dispensing machine (MMDM) manufactured by Liquid Control Corp, a steel mold, and a vacuum pump, as illustrated schematically in Figure 2. The procedure is briefly described below.

The 3-D fabrics were first cut into pieces of 280 mm long and up to 230 mm wide (depending on the original width of the fabrics). A fabric preform was put into the steel mold which has interior dimensions of about 330 x 254 x 3.2 mm. Uniform thickness of the composite panels being fabricated was maintained when the mold was tightly closed. The resin was mixed with the curing agent and injected to the mold by the MMDM until the resin flowing out from the outlet was bubble free. The mold containing the impregnated preform was removed from the RTM connections with the inlet and outlet holes sealed. It was then placed in an electric convection oven for consolidation. After curing at 120°C for about eight hours and cooling down afterwards, the composite panel was removed from the mold and ready for cutting into test specimens.

Each composite panel was cut into several test specimens in both the longitudinal (*L*) and the transverse (*T*) directions using a diamond tipped abrasive saw. The specimens for different tests had the following typical dimensions: 200 x 25.4 mm for tension (152 x 25.4 mm was

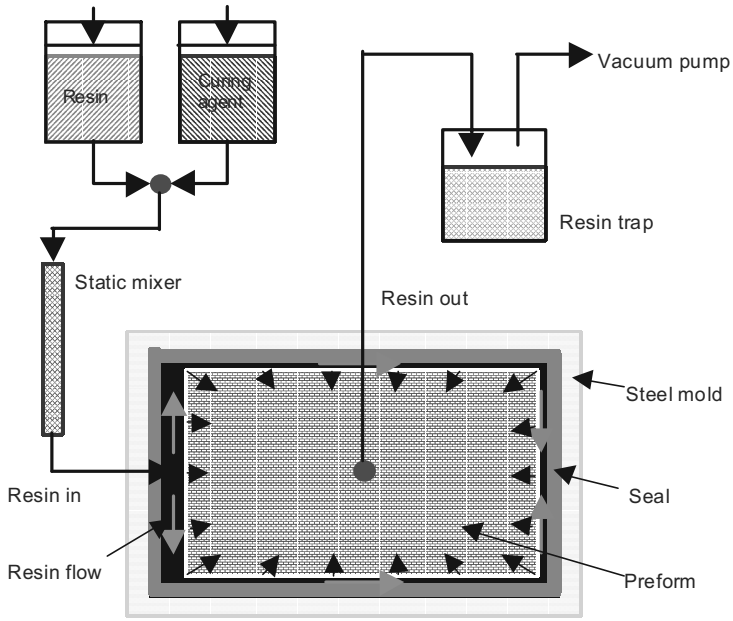

Fig. 2. Schematic of the RTM setup

used for 3-D woven composites in transverse direction), 100 x 25.4 mm for compression, 76 x 25.4 mm for three-point flexure and 25.4 x 25.4 mm for short beam shear (SBS). The thickness of the samples was measured using a digital caliper, ranging from 3.3 to 4.2 mm, depending on the preforms used in the panels.

Four types of mechanical tests including uniaxial tensile, compressive, three-point flexural and short beam shear test (Figure 3), were conducted on a computer controlled Material Testing System tester (MTS-810) and a computerized INSTRON 5500 tester following the appropriate ASTM procedures. The final test results are averages values over six specimens in each group.

Uniaxial tensile test was conducted on the MTS 810 tester at a speed of 2.0 mm/min. Hydraulic grips with surfalloy faces were used for specimen loading. A biaxial extensometer was used to monitor the specimen deformation in both the longitudinal and transverse directions. Mechanical properties, such as tensile strength, modulus, and Poisson's ratio, were determined.

Compressive properties such as modulus and strength were measured on the MTS 810 tester with Hydraulic grips. A clip gage is used to monitor the displacement.

Three-point flexural test was performed on the INSTRON 5500 tester using a three-point bending fixture at a test speed of 2.0 mm/min. The span length L was selected based on the specimen thickness t, so as to maintain a 16:1 L/t ratio (span-to-depth ratio).

The short beam shear test was conducted on the INSTRON 5500 tester with a modified three-point bending fixture, shown in Figure 3d. The loading nose and supports here had a radius of 0.5 mm. The test speed was 2.0 mm/min. The span length L varied with the specimen thickness to keep the span-to-depth ratio to be about 4:1. From the maximum load, the apparent mid-plane interlaminar shear strength τ was calculated following ASTM D2344 1989. Since there is no guarantee that the specimens (especially those reinforced by the 3-D textile structures) will fail in shear in the short beam shear test, the calculated τ is therefore

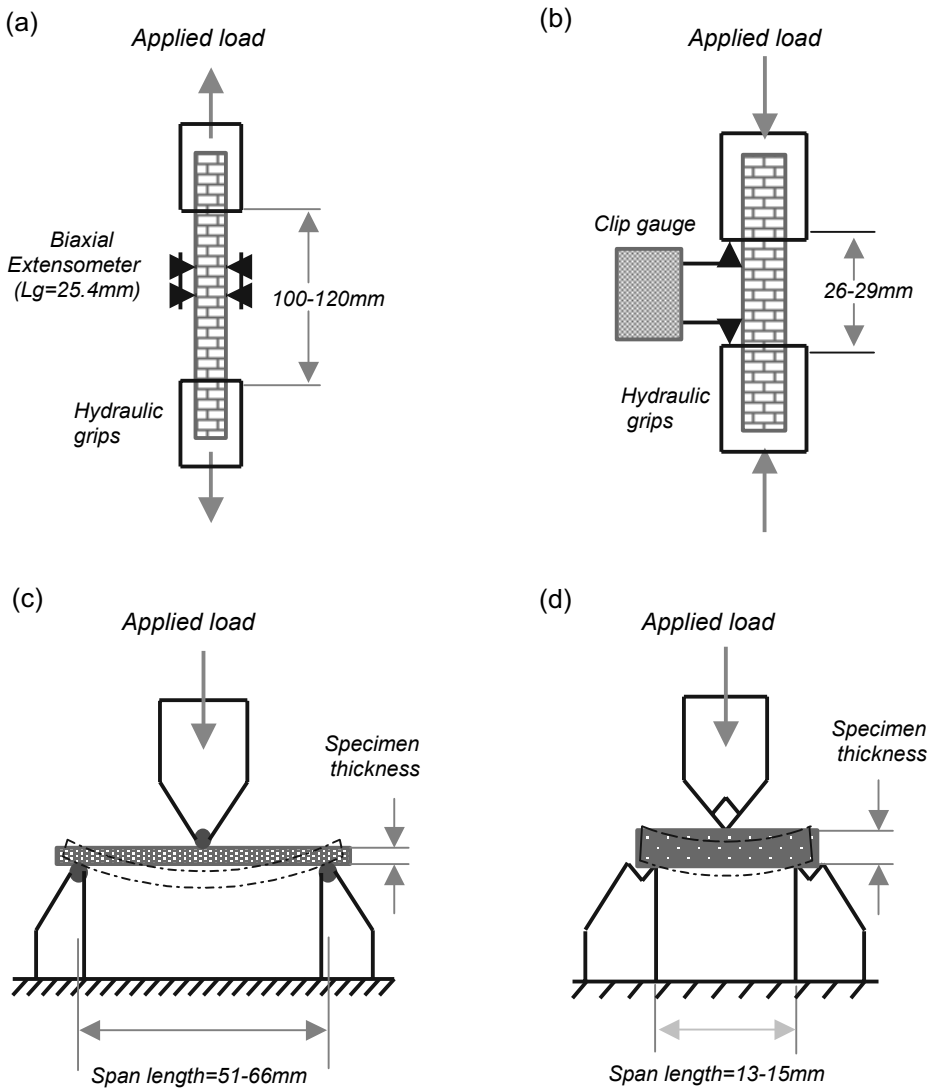

Fig. 3. Test configurations: (a) uniaxial tension, (b) compression, (c) three-point flexure, and (d) short beam shear (SBS)

referred to as the *apparent interlaminar shear strength* and it represents a lower bound for the shear strength. Generally the maximum bending stress σ_b under the short beam shear condition needs to be calculated to help identify the possible failure modes.

RESULTS AND DISCUSSION

The test results include load P versus displacement δ curves, elastic properties and strengths for all composites tested in both longitudinal and transverse directions under various test conditions. The experimental results are summarized in Table 2, including

(1) Sample ID, preform description along with fiber volume fraction V_f,
(2) Elastic modulus E, Poisson's ratio ν and strength σ_t from the uniaxial tensile test,
(3) Compressive modulus E and strength σ_c from the compressive test,
(4) Flexural modulus E and strength σ_f from the three-point flexural test, and
(5) Possible maximum bending stress σ_b and apparent interlaminar shear strength τ from the short beam shear test.

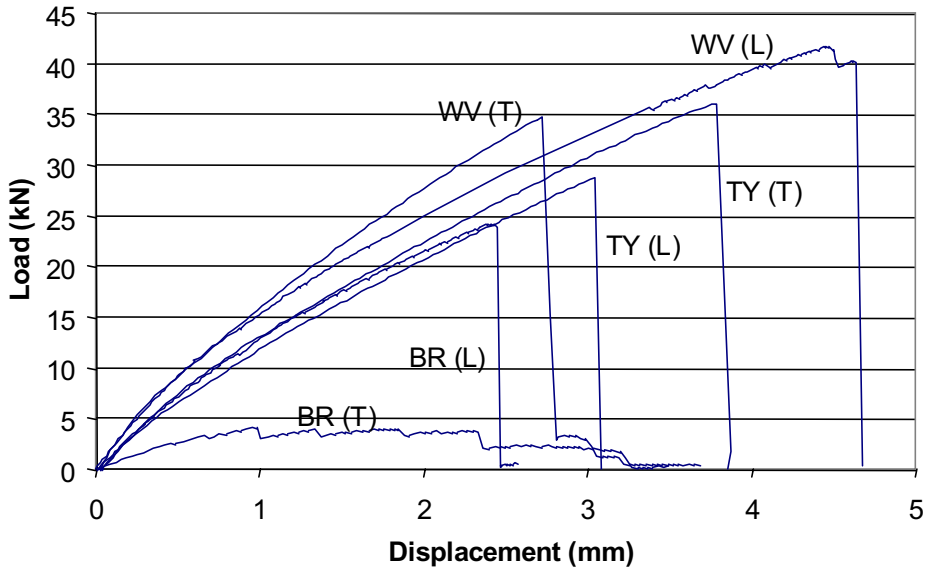

Fig. 4. Some typical tensile test curves

Table 2. Experimental results on mechanical properties of three 3-D textile composites.

Sample ID	*Preform Description*	*Tension*			*Compression*		*Flexure*		*SBS*	
		E (GPa)	σ_t (MPa)	ν	E (GPa)	σ_c (MPa)	E (GPa)	σ_f (MPa)	σ_b (MPa)	τ (MPa)
BR(L)	3-D Braid	18.8	236	.461	13.7	250	13.3	409	418	63.4
BR(T)	V_f=45%	8.81	43.6	.224	7.90	123	9.84	181	265	40.3
WV(L)	3-D Woven	25.4	399	.155	20.6	425	12.4	507	312	45.0
WV(T)	V_f=53%	24.0	357	.137	18.6	398	18.1	664	346	51.9
TY(L)	3D Woven: TY	19.9	340	.174	13.7	337	14.6	418	384	48.8
TY(T)	V_f=47%	18.6	290	.151	12.0	309	16.0	440	397	51.4

L: Longitudinal (warp), T: Transverse (filling). Matrix material: Epon epoxy

The behavior characteristics and mechanical properties are discussed below with respect to the test conditions.

Tensile Responses The typical tensile load-displacement (P-δ) responses of 3-D woven and braid composites tested in both the longitudinal (L) and transverse (T) directions are shown in Figure 4. It is first noted that the tensile strength and breaking elongation vary considerably depending on the reinforcement and test direction. The 3-D woven composite with twisted yarns exhibited similar behavior as that of the 3-D woven composite, though the strength and modulus are lower due to a lower fiber volume fraction, yarn twist, and fabric construction. The longitudinal tensile curve of braid composites, similar to those of WV and TY, has a single-peak response pattern, but its transverse curve is quite different which has a rough

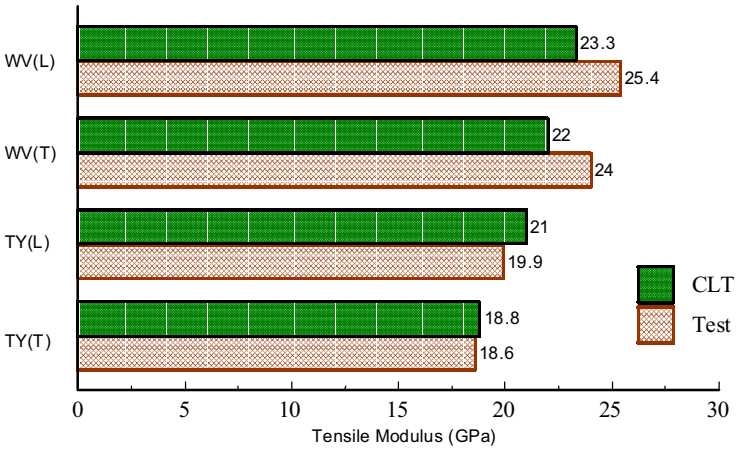

Fig. 5. Experimental results and theoretical predictions (CLT) on tensile modulus

plateau with multi-humps along with a larger extension. This multi-hump "plateau" response pattern is mainly due to the lack of axial yarns in the transverse direction.

From the property magnitude point of view, all three composites tested exhibited different levels of anisotropy (see Table 2), especially for the 3-D braid composite (BR). In BR the tensile moduli, strengths and Poisson's ratios between the longitudinal and transverse directions differ dramatically from each other. The largest discrepancy, appearing in tensile strengths, is more than 5-fold. The differences in Young's moduli and Poisson's ratios between both directions are noticeable too (more than 2-fold). Comparatively, the two 3-D woven composites (WV and TY) have much more balanced properties in both directions. It is of interest to note that the composites with more uniform properties between both directions have higher tensile moduli and strengths, and lower Poisson's ratios. For example, WV possesses the closest tensile properties between both directions (6-13% differences) and presents the highest tensile moduli (25.4 and 24.0 GPa in the longitudinal and transverse directions, respectively) and strengths (399 and 357 MPa) and the lowest Poisson's ratios (0.155 and 0.137), while BR having the most uneven properties (up to 5-fold difference) holds the lowest moduli (18.8 and 8.81 GPa) and strengths (236 and 43.6 MPa) and the highest Poisson's ratios (0.461 and 0.224). The corresponding properties of TY are in between.

A comparison of the experimental tensile modulus values with those predicted by the Classical Lamination Theory (CLT) [16] was made on the two 3-D woven composites, as shown in Figure 5, neglecting effects of fiber crimp and the through-thickness reinforcement. Good predictions was obtained for both composites, especially for TY, meaning that these effects on the tensile modulus are not significant. Better predictions could be achieved by CLT if proper treatment on the through-thickness reinforcement is made in the calculation.

Compressive Responses Figure 6 illustrates the typical compressive load-displacement (P-δ) responses of the 3-D fabric composites tested in both directions. The anisotropy of the compressive properties for these composites is less pronounced, particularly for the 3-D braid composite. It is noticed that the compressive moduli for all three composites are much lower than their respective tensile values, partly due to errors in measurement, as the very short gage length does not allow a transducer to be mounted on the specimen itself. The compressive strengths for these composites are generally close to the corresponding tensile strengths, except for BR whose transverse compressive strength is nearly 3-times as high as the corresponding tensile value.

Flexural Responses Some typical flexural load-displacement (P-δ) curves are shown in Figure 7. Because of the loading condition, the responses reflect both the tensile and compressive behavior of the composites. The response of the 3-D braid composite is similar to its tensile response, due to its strong anisotropic behavior in tension. The responses for the two 3-D woven composites are quite different from their tensile behavior. WV has the most

significant difference in flexural properties between the two test directions, with the values in the transverse direction being significantly higher than those in the longitudinal direction, up to 46% for modulus and 31% for strength, respectively. Unlike in tension, WV shows a lower elongation when tested in the transverse direction. In contrast, TY shows less direction dependence in flexure, with a less than 10% difference in properties in the two test directions. This clearly shows that the flexural properties are more structure-dependent. Figure 8 shows the cross sectional views of the three composites cut along the longitudinal direction. For the woven composites, the top and bottom layers of the structure contain filling yarns, which run in the transverse direction. This arrangement generally makes the composite stronger in the transverse direction under flexural loading. Under uniaxial tensile or compressive load, however, the location of the yarns plays a less important role. The difference between the behavior of WV and TY is mostly due to their different structures; in TY the filling yarns are distributed in five fiber layers in the transverse direction, as compared with three layers in WV.

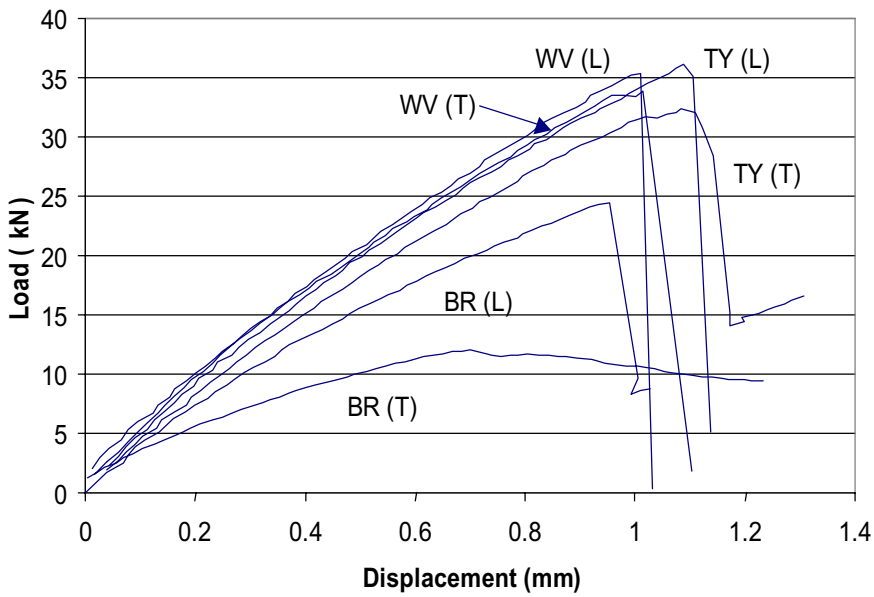

Fig. 6. Typical compressive test curves

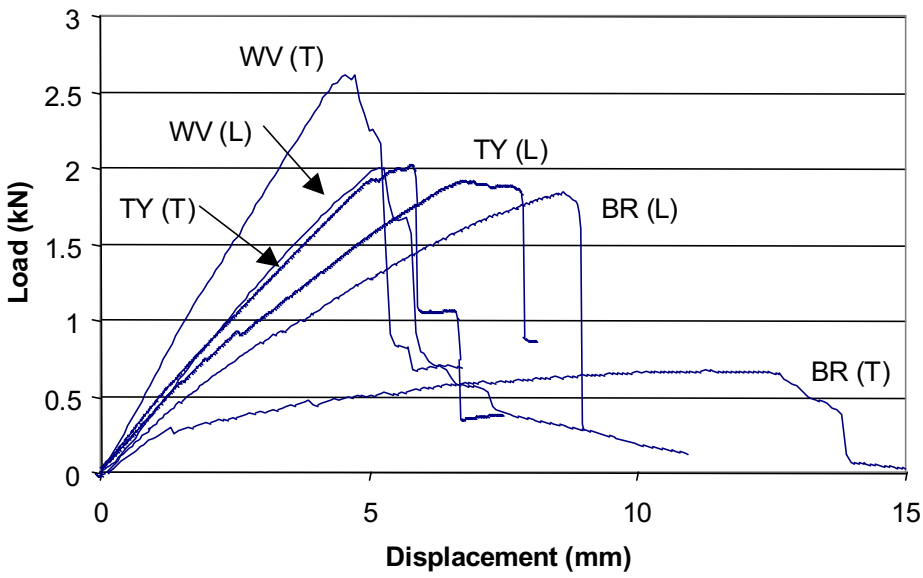

Fig. 7. Typical flexural test curves

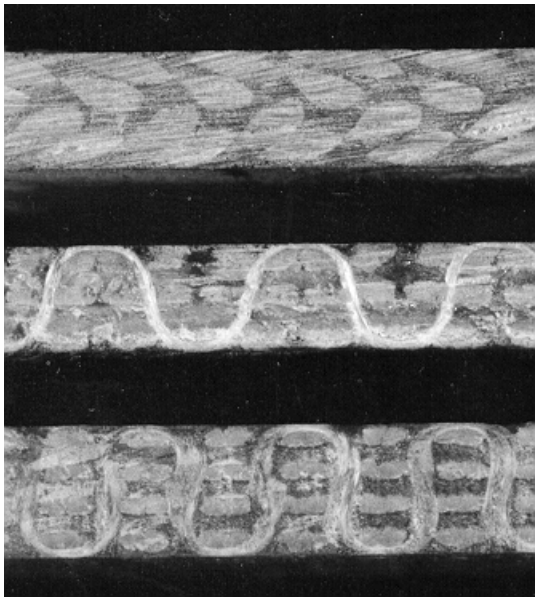

Fig. 8. Cross sectional views along the warp (longitudinal) direction.
Top: BR, Middle: WV; Bottom: TY

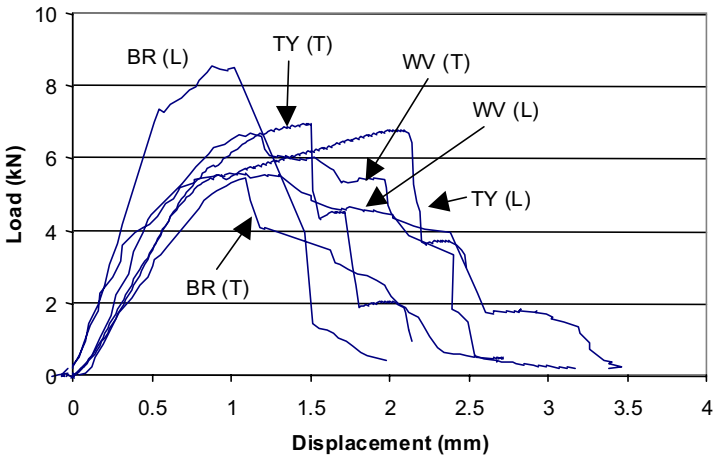

Fig. 9. Typical short beam shear test curves

Short Beam Shear Responses In a three-point bending test, the specimen is subjected to both bending stress and shear stress. While the shear stress remains unchanged, the bending stress decreases with the span length under a given load. When the span-to-depth ratio (L/t) is large, the specimen is more likely to fail in bending, whereas when L/t is small (short beam), the specimen is more likely to fail in shear. The ratio of the maximum shear stress (interlaminar shear stress) to the maximum bending stress, τ/σ_b), is related to the geometry by:

$$\tau/\sigma_b = 0.5/(L/t)$$

An isotropic material in bending will fail in shear if the ratio τ/σ_b exceeds 0.58, according to the von Mises criterion. Anisotropic materials like laminated composites, however, may fail in shear at a lower τ/σ_b ratio. The shear stress calculated from the maximum load is call the *apparent* interlaminar shear strength; it is equal to the actual interlaminar shear strength only

when the specimen actually fails in shear. If the specimen fails in bending before a shear failure, the calculated apparent interlaminar shear strength will be lower than the actual interlaminar shear strength of the material.

From the typical load-displacement responses (Figure 9), it is observed that the 3-D braid composite exhibited the highest resistance along its longitudinal direction, among all those tested. As indicated by data presented in Table 2, the bending stress for BR at failure in the short beam shear test is slightly higher than the corresponding flexural strength. Thus the failure in the short beam test is likely due to bending. Examination of the failed specimens also support this observation. Therefore, the actual interlaminar shear strength for the 3-D braid composite is higher than or equal to the apparent shear strength values reported in Table 2. The 3-D woven composites (WV) failed when the bending stress in the short beam test was significant lower than the corresponding flexural strengths. This suggests that the interlaminar shear stress is likely the cause of failure in these composites, and that the apparent interlaminar shear strengths (τ in Table 2) should be close to the actual interlaminar strength values. For the woven composites with twisted yarn (TY), however, the bending stress is close to the flexural strength, and the failure in the short beam test may be either bending-dominated or a combined bending and shear failure. The difference in behavior between the braid and woven composites may be attributed to the fabric structures. In the braid composites, a large number of yarns move up and down in the thickness direction, whereas in the 3-D woven composites, yarns are arranged in the x, y and z directions with only a small percentage of yarns are in the z-direction (about 7% for WV). For applications requiring a higher shear strength and stiffness, the improvement may be obtained for the woven composites by introducing bias yarns in the ±45° directions in the x-z and y-z planes [14].

SUMMARY AND CONCLUSIONS

Three types of 3-D textile structural composites were investigated by an experimental study to evaluate the effect of fabric structures on the mechanical properties of these composites. They were reinforced with three styles of E-glass textile preforms: 3-D braid, 3-D woven, and 3-D woven with twisted yarn, and consolidated with an epoxy resin system using the resin transfer molding (RTM) process. The mechanical properties and macroscopic failure modes were evaluated in uniaxial tension, compression, three-point flexure and short beam shear. Structure-property relationships and failure mechanisms were analyzed.

The composites tested behaved distinctively due to their different reinforcing preform architectures. The 3-D braid composite has a higher level of shear resistance owing to the higher degree of stereo network in their internal structures, but it has relatively low in-plane properties such as moduli and strengths in tension, compression and flexure. This is especially pronounced in the transverse direction because of the lack of straight yarns in that direction. In contrast, because of the basically layered, orthogonal yarn arrangement, the 3-D woven composite has higher values for the in-plane properties and a lower value for shear resistance.

Because of the flexibility in arranging the reinforcing yarns in composites, 3-D textile composites can be tailored for different loading situations. And their advantages can only be fully realized when the design of the reinforcement preform be matched with the end-use requirements.

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