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Effects of Preform Architecture on Modulus and Strength of 2-D Triaxially Braided Textile Composites

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The following pages contain annotated copies of the figures presented at the Mechanics of Textile Composites Symposium held in December 1994 at NASA Langley Research Center. The figure presented at the meeting will be reproduced at the top of each page; comments on important points in the figure will be added at the bottom.

Outline of Presentation :

- Introduction

  Objective

  Materials

- Experimental Results
- Analytical Results
- Summary

Figure 1. Outline of Presentation.

Laminates formed using braided fibrous preforms have been extensively investigated during the course of the past few years as alternatives to unidirectional prepreg tape systems. This paper focused on one aspect of that work. It defined the role of the fibrous preform architecture in controlling a laminate's mechanical properties. The presentation was divided into four sections as the outline listed above illustrates. The presentation began with a brief introduction which defined the objectives of the study and detailed the materials studied. This was followed by a review of empirical test results. The materials' moduli and strengths were measured in both tension and compression. Their shear moduli were also experimentally determined. The review of the empirical data comprised the bulk of the presentation. A comparison of the experimental data to results predicted analytically was then presented. The presentation concluded with a few summary remarks.

TRIAXIAL BRAID PATTERN: DESCRIPTION OF MATERIAL TESTED

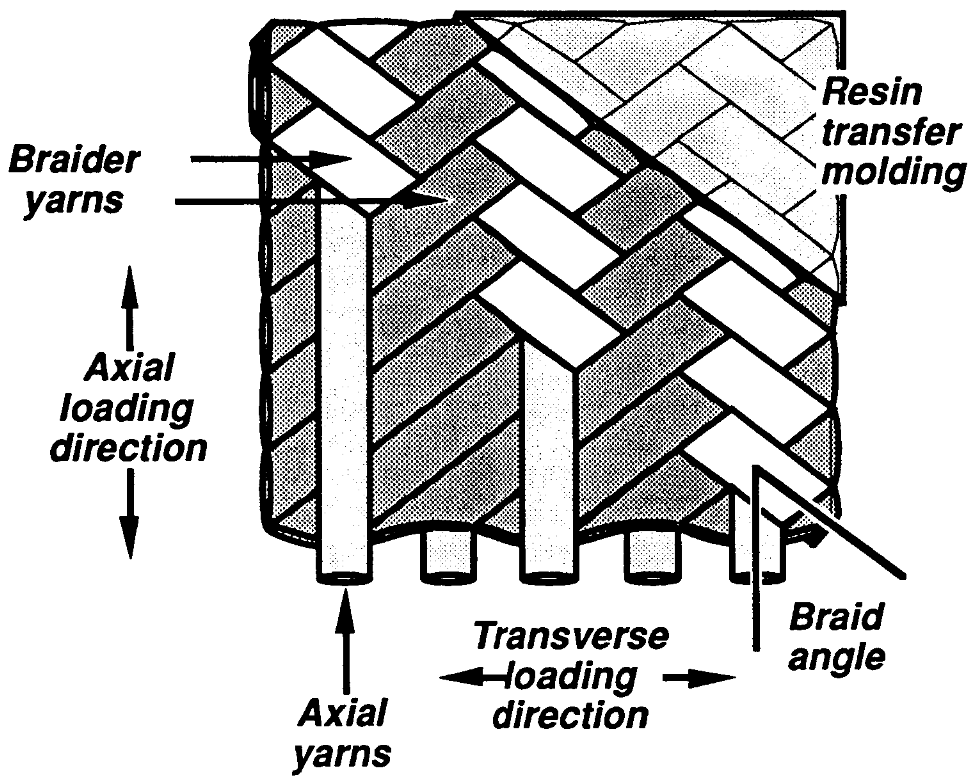


Figure 2. Triaxial Braid Pattern.

The specimens studied in this investigation featured 2-D triaxially braided AS4 graphite fiber preforms impregnated with Shell 1895 epoxy resin. In a triaxially braided preform three yarns are intertwined to form a single layer of 0°/ ± Θ° material. In this case, the braided yarns are intertwined in a 2 x 2 pattern. Each + Θ yarn crosses alternatively over and under two - Θ yarns and vice verse. The 0° yarns were inserted between the braided yarns. This yields a two dimensional material. The figure above schematically illustrates the fiber architecture and establishes the nomenclature used in the paper.

The yarns were braided over a cylindrical mandrel. The desired preform thickness was achieved by overbraiding layers; there are no through-the-thickness fibers. After braiding, the preforms were removed from the mandrel, slit along the 0° fiber direction, flattened, and border stitched to minimize fiber shifting. The resin was introduced via a resin transfer molding process.

Objective :

Measure the Effects of Primary and Secondary Braid Parameters on Laminate Response

Figure 3. Objective of Study.

Simply stated, the objective of this work was to define the role of the fibrous preform architecture in controlling laminate response. The results reviewed in this paper, as indicated above, measure the effects of a variety of primary and secondary braid parameters on laminate mechanical properties. The properties examined in this paper include the materials' Young's moduli and strength in both the longitudinal and the transverse directions and their shear moduli. The longitudinal and transverse properties were measured in both tension and compression.

BRAIDING PARAMETERS INVESTIGATED

Primary Braid Parameters :

- **Yarn Size**
- **Braid Angle**
- **Axial Yarn Content**

Secondary Braid Parameters :

- **Axial Yarn Spacing**
- **Braid Yarn Crimp Angle**
- **0° Yarn Crimp Angle**

Figure 4. Braiding Parameters Investigated.

An examination of the schematic of the preform architecture shown in an earlier figure suggests four parameters that can be altered to change the preform's properties. They are the axial yarn size, the braider yarn size, the braid angle, and the axial yarn spacing. Several braids were designed to isolate the effect of these individual parameters. The objective was to directly measure their effect on the materials' elastic properties and strength.

As the table above indicates, the parameters were divided into primary and secondary categories. The primary parameters were expected to have the greatest effect on the material. Based on experience with laminate prepreg tape composites, they are the parameters that would be considered first when a material is being designed for a particular application.

The three primary preform parameters listed are braid angle, yarn size, and 0° yarn content. As defined in an earlier figure, the braid angle is the angle the braider yarns make with the axial yarns. Braid angles typically range from 15° to 75°. Yarn size is expressed in terms of the number of filaments per yarn. The AS4 fibers used in these materials have a nominal diameter of 7 microns. The last parameter listed, axial yarn content, is typically expressed as a percentage of 0° yarns. It is the volumetric proportion of longitudinal yarns to total yarn content and is a function of braid angle and yarn size. Although it is not an independent parameter, the axial yarn content is typically defined for each preform because it provides valuable insight into the material response.

The table also lists three parameters as secondary braid parameters. The first two, axial yarn spacing and braider yarn crimp angle, are controlled by the specifics of the braiding machinery used. Axial yarn spacing is a function of the mandrel diameter and the number of yarn carriers used to make the braid. The braider yarn crimp angle in the angle that the braider yarns make out-of-the-plane of the preform as they pass over and under other braider and axial yarns. The braider yarn crimp angle is a function of the axial yarn size and spacing. The third parameter listed as a secondary braid parameter, 0° yarn crimp, may be thought of as a material defect. In theory, the axial yarns are not crimped when they are inserted between the braider yarns.

TEST METHODS AND PROCEDURES

Primary Braid Parameters. These test results were obtained as a part of a program to develop standard test methods for textile composites [1]. The program evaluated a number of straight-sided tensile test specimen geometries and concluded that width and length effects were minimal. The axial tension data presented in this paper are the average of the eighteen values in that study. Specimen widths ranged from 25.4 mm (1.0 in) to 63.5 mm (2.5 in) and their lengths ranged from 90 mm (3.5 in) to 220 mm (8.75 in). The specimens used to measure the braids' transverse tension properties measured 50.8 mm (2.0 in) by 180 mm (7.0 in). Three replicate test values were averaged to determine these data. All specimens featured 57 mm (2.25 in) long, 1.25 mm (0.05 in) thick beveled fiberglass tabs.

The tensile specimens were ramped to failure in displacement control at a loading rate of 1.25 mm/min (0.05 in/min). They were instrumented with 12.7 mm (0.500 in) square strain gages (Measurements Group Inc. gage EA-06-500AE-350) which were mounted in both the longitudinal and transverse directions. The specimens' moduli were calculated by performing a linear regression of stress versus axial strain. The axial strain range used in the calculation was 1000 to 3000 microstrain.

The compression data presented in this paper were obtained using a modified IITRI test specimen. Unbeveled fiberglass tabs were mounted to the straight-sided specimen. The baseline test section used was 6.35 mm (0.25 in) thick, 38 mm (1.5 in) wide, and 38 mm (1.5 in) long. Instead of using the special IITRI loading fixture, the specimen is gripped in the test machine with hydraulic grips. Special attention was taken in machining the tabs to insure that the tab surfaces are parallel. Strain gages were mounted on the front and back of the specimens to monitor specimen stability and to insure that bending did not occur.

Secondary Braid Parameters: Similar specimen geometries and test procedures were used to measure the tensile properties of these specimens. The longitudinal tension specimens were 40 mm

(1.5 in) wide and 255 mm (10.0 in) long in these tests. The transverse tension specimens measured 40 mm (1.5 in) by 175 mm (7.0 in). All specimens had 57 mm (2.25 in) long fiberglass tabs bonded to each end.

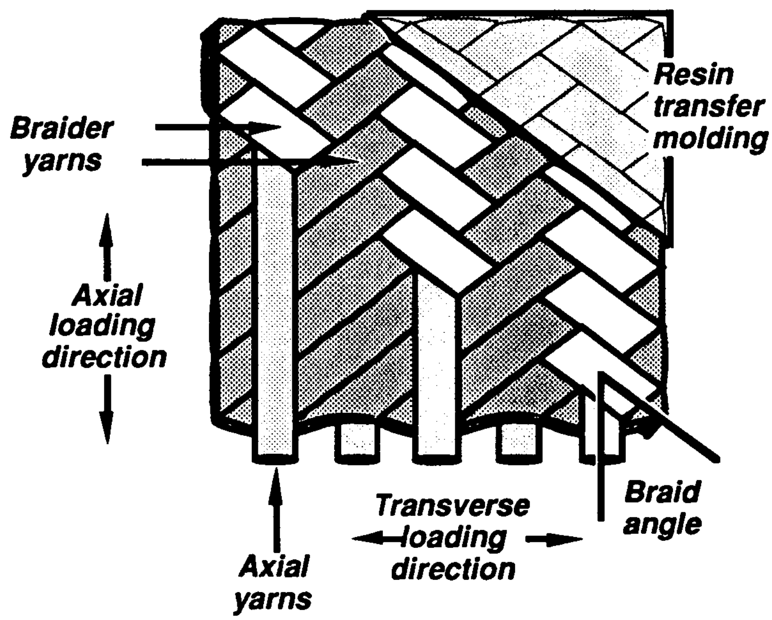
These tests were conducted in displacement control at a ramp rate of 0.254 mm/min (0.01 in/min). The longitudinal tension specimens used 12.7 mm (0.500 in) by 4.6 mm (0.180 in) wide strain gages (Measurements Group Inc. gage CEA-06-500UW-350) to measure both the axial and transverse strains. The transverse tension test specimens were instrumented with 2.54 mm (1.0 in) long gages (EA-13-10CBE-120) in the load direction; 12.7 mm (0.500 in) gages (CEA-06-500UW-350) were used to measure the specimens' Poisson's contraction. Moduli and Poisson's ratios were again computed via linear regression to the data gathered as the specimens were loaded from 1000 to 3000 microstrain.

Shear Testing: The Compact Shear Specimen developed by Ifju [2] was used to measure the shear moduli of all seven braids tested. This 40 mm (1.5 in) by 40 mm (1.5 in) square specimen features a 20 mm (0.750 in) test section. Strain gages (Measurements Group Inc. gage EA-06-500AE-350), developed specifically for these specimens, were mounted to the front and back of the specimens. The two strain measurements were averaged together and used to compute the shear moduli. Moduli were again computed over the 1000 to 3000 microstrain range.

Normalization: All the data presented in this paper were normalized to 60% fiber volume to facilitate comparison of results.

PROPOSED SHORTHAND NOTATION:

A shorthand notation, similar to the practice used to define the stacking sequence of laminates formed of uni-directional prepreg tape, was introduced to define the braid architecture. It is based on the nomenclature defined in the figure.



$$[0^\circ\ xk\ /\ \pm\ \Theta^\circ\ yk]\ N\%\ \text{Axial}$$

where: Θ indicates the braid angle,

x indicates the number of fibers in the axial yarn bundles,

y indicates the number of fibers in the braided yarn bundles,

k indicates thousands, and

N indicates the percentage by volume of axial yarns in the preform

Figure 5. Proposed Shorthand Notation for 2-D Triaxial Braids.

Table I. Braids Developed For Primary Braid Parameter Study

Braid	Comparison
[0 30k / ± 70 6k] 46% Axial [0 75k / ± 70 15k] 46% Axial	<u>Yarn Size Effect:</u> Yarns Scaled by Factor of 2.5
[0 75k / ± 70 15k] 46% Axial [0 36k / ± 45 15k] 46% Axial	<u>Braid Angle Effect:</u> Angle Changed from 70° to 45° *Axial Yarns Differ by Factor of 2*
[0 36k / ± 45 15k] 46% Axial [0 6k / ± 45 15k] 12% Axial	<u>Axial Yarn Content:</u> Content Changed from 46% to 12% *Axial Yarns Differ by Factor of 6* *Braider Yarn Crimp Angle Changes (11° to 6.5°)*

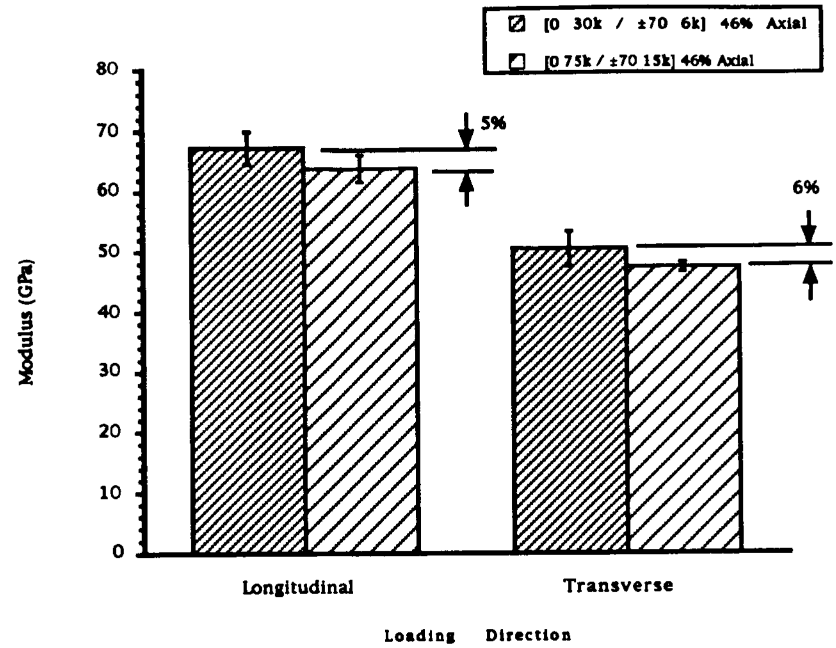
COMMENTS ON THE BRAID ARCHITECTURES: PRIMARY BRAID PARAMETER STUDY

Four braid architectures were designed to isolate the effects of the primary braid parameters on the laminate response. They are listed in Table I in the shorthand notation defined earlier.

The most straightforward way to analyze the data to be presented is to consider the four braids as three sets of pairs. The table groups the braids in this manner and compares their preforms. It lists the primary braid parameter to be considered when the data are compared. The first two architectures listed, for example, were designed to define the effects of yarn size on mechanical properties. In this case, both the axial and braider yarns have been scaled by a factor of 2.5; the braid angle and the axial yarn content were held constant. Unfortunately, it was not possible to vary only a single braid architecture parameter in the other two pairs of laminates. The comparisons given for these laminates identify the primary braid parameter that was varied by design (underlined and in regular text); the other parameters that were varied by necessity are shown in italics.

It should be noted that these architectures were chosen to define the extremes of the family of 2-D triaxial braids. Emphasis was given in their design to providing a wide range of mechanical properties to support analytical model development.

EFFECT OF YARN SIZE ON TENSILE PROPERTIES



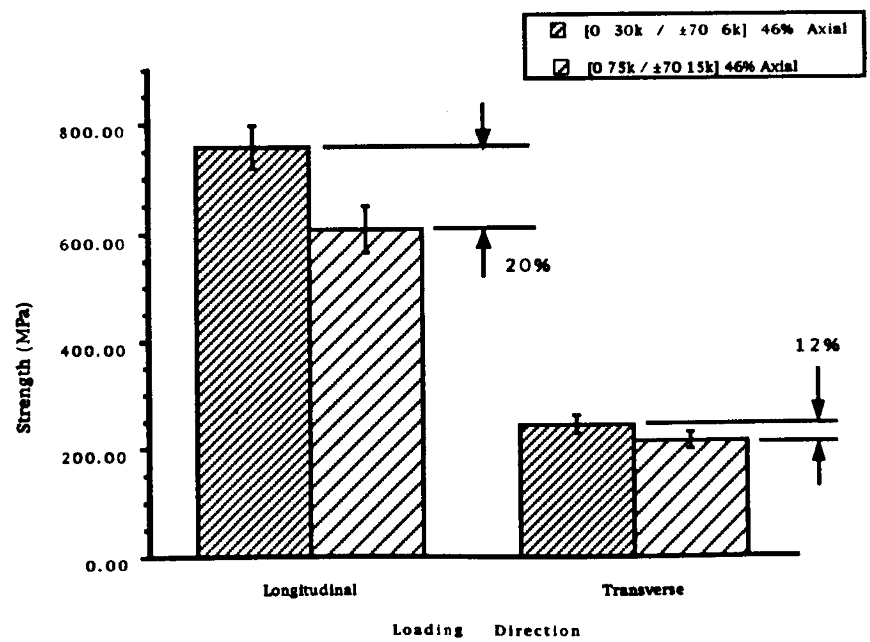
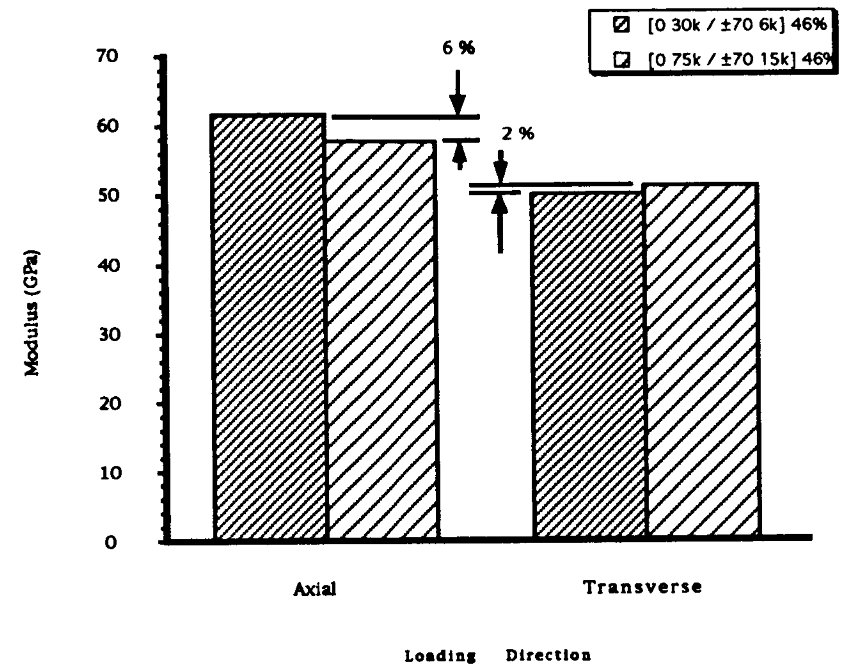


Figure 6. Effect of Yarn Size on Tensile Modulus and Strength.

EFFECT OF YARN SIZE ON COMPRESSION PROPERTIES



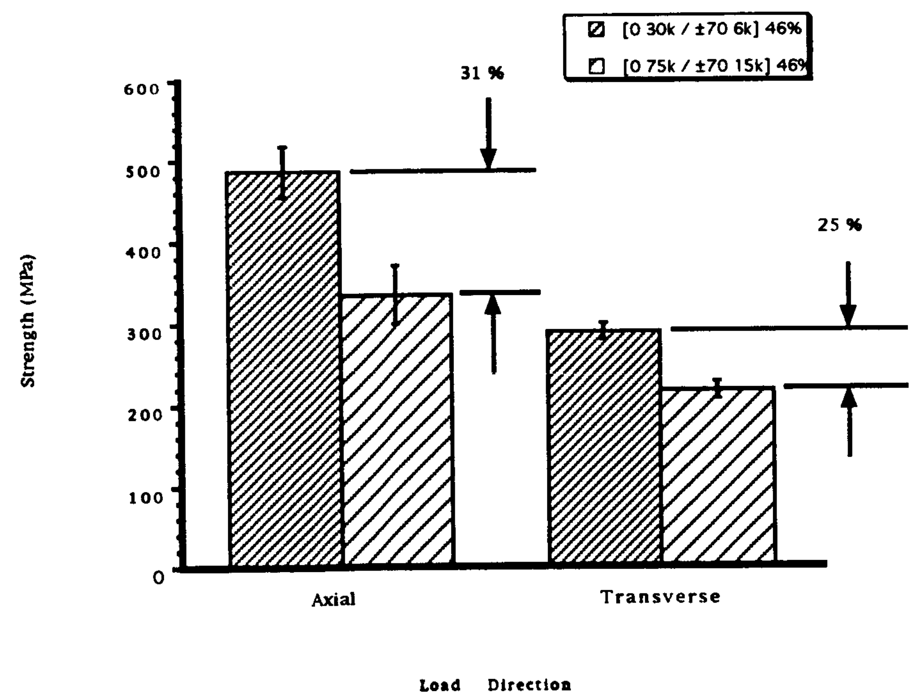
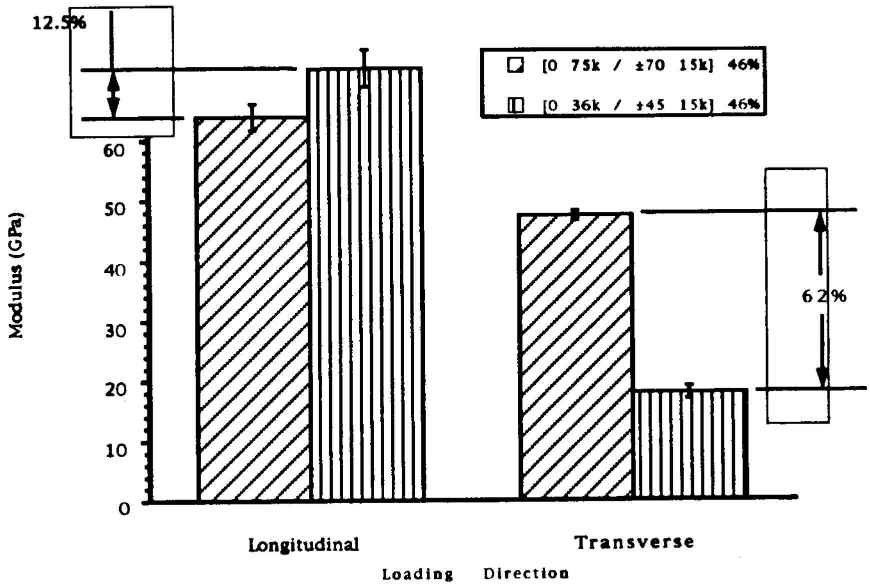


Figure 7. Effect of Yarn Size on Compression Modulus and Strength.

EFFECT OF BRAID ANGLE ON TENSILE PROPERTIES



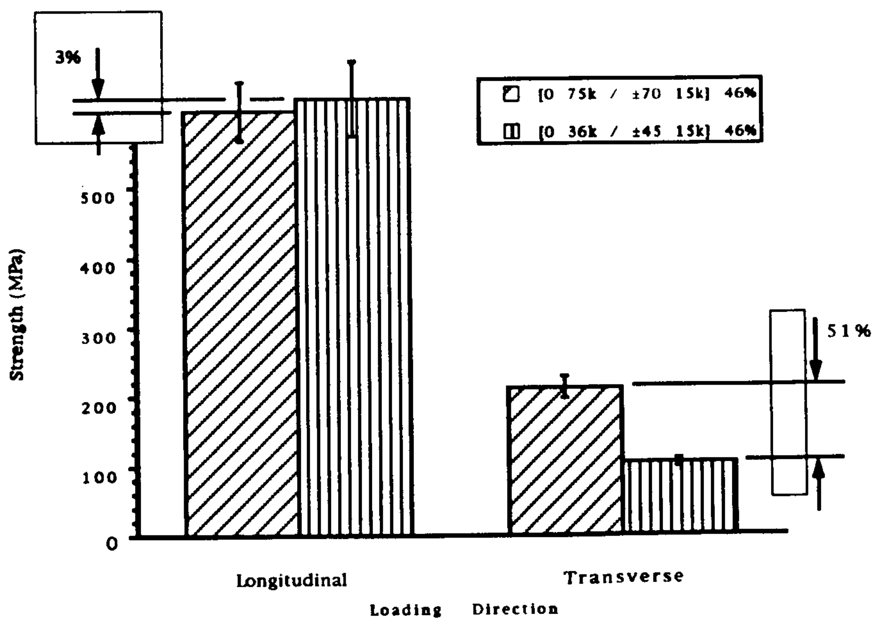


Figure 8. Effect of Braid Angle on Tensile Modulus and Strength.

EFFECT OF BRAID ANGLE ON COMPRESSION PROPERTIES

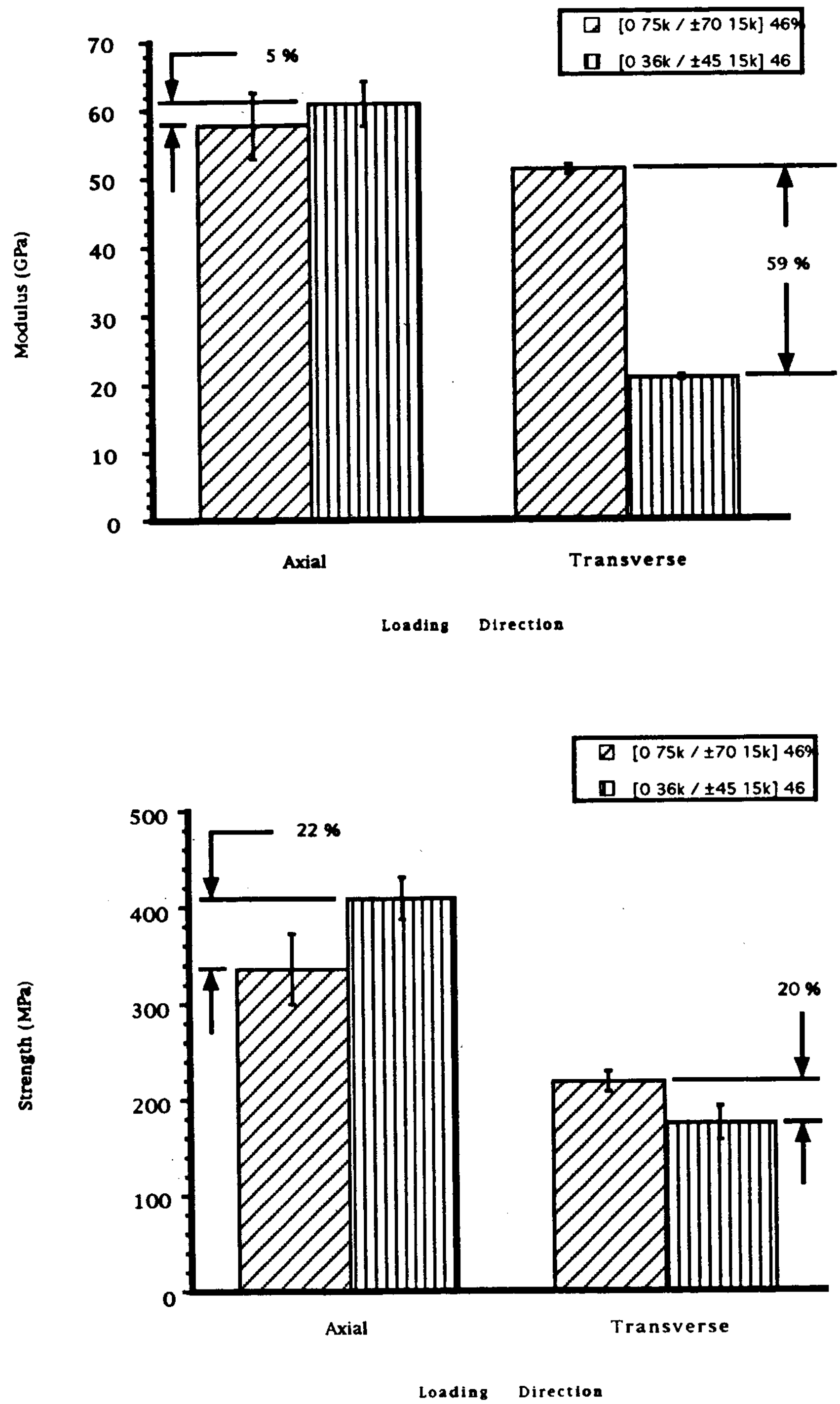


Figure 9. Effect of Braid Angle on Compression Modulus and Strength.

EFFECT OF AXIAL YARN CONTENT ON TENSILE PROPERTIES

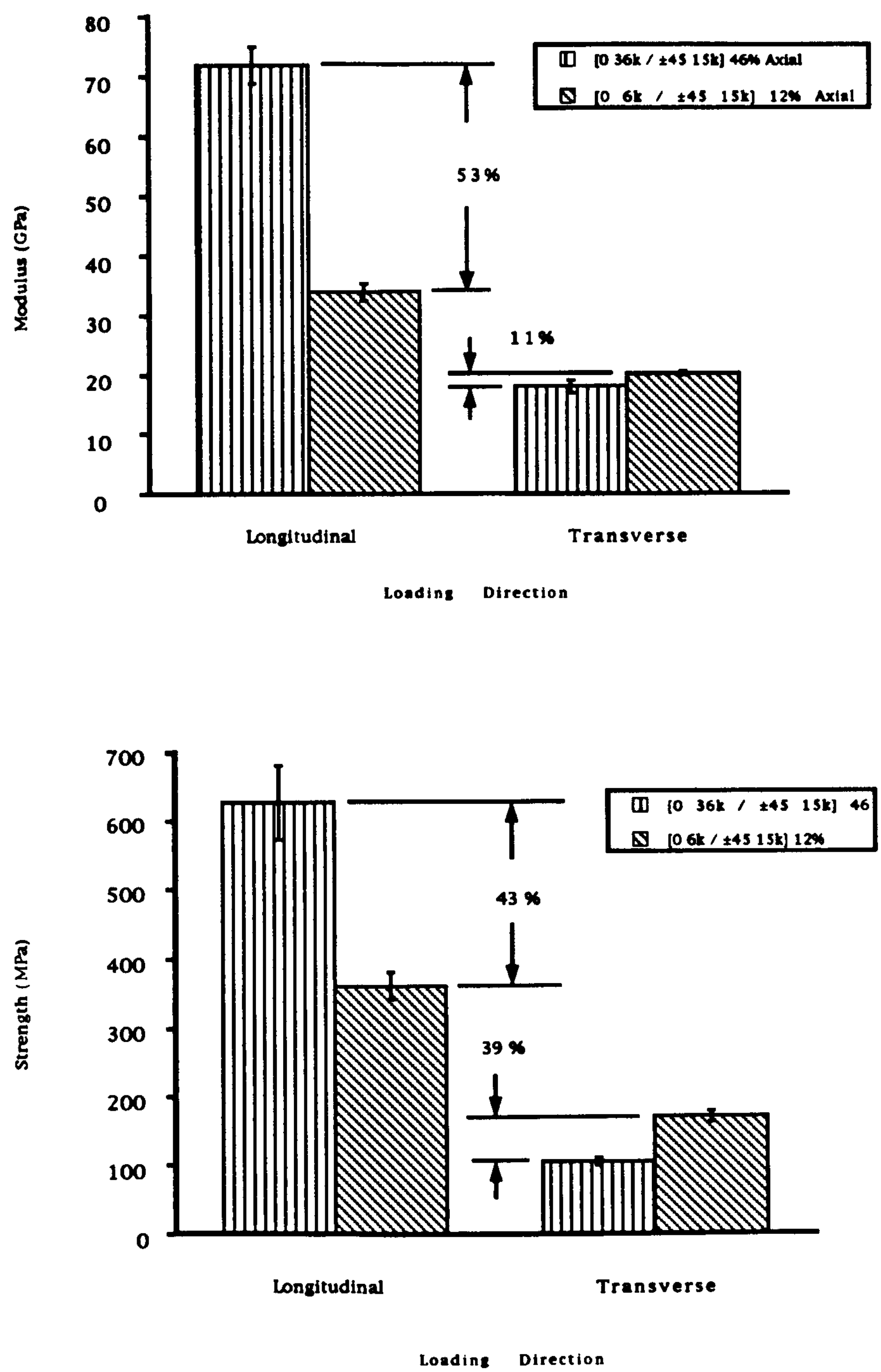


Figure 10. Effect of Axial Yarn Content on Tensile Modulus and Strength.

EFFECT OF AXIAL YARN CONTENT ON COMPRESSION PROPERTIES

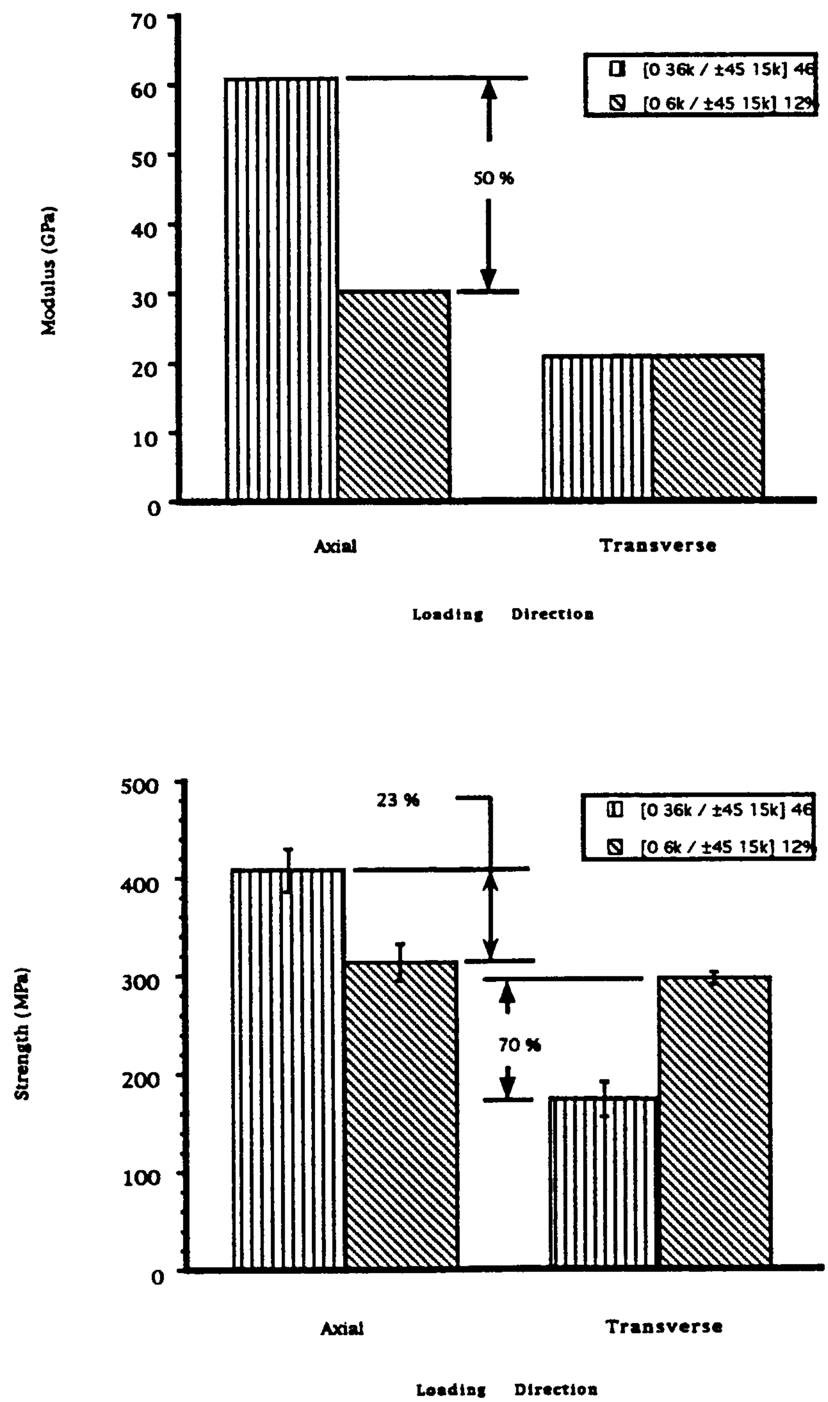


Figure 11. Effect of Axial Yarn Content on Compression Modulus and Strength.

EFFECT OF PRIMARY BRAID PARAMETERS ON LAMINATE SHEAR MODULUS

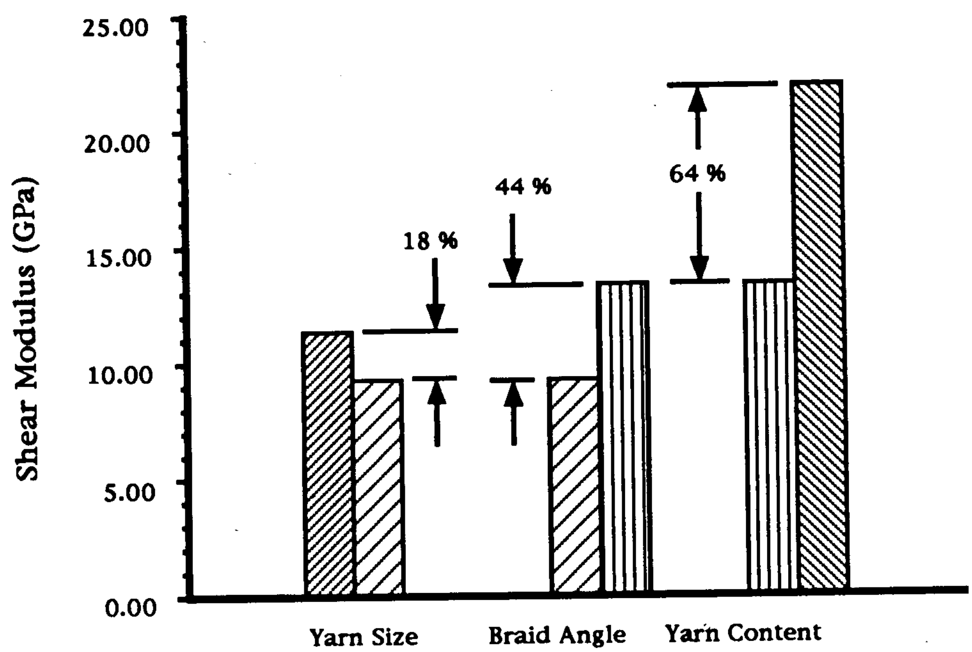


Figure 12. Effect of Primary Braid Parameters on Shear Modulus.

PRIMARY BRAID PARAMETERS & LAMINATE RESPONSE: OBSERVATIONS

Yarn Size Effects

A comparison of results obtained for the [$0_{30k}/\pm70_{6k}$] 46% Axial and [$0_{75k}/\pm70_{15k}$] 46% Axial architectures (Figures 6 and 7) indicates that a size effect is evident in these braided laminates. The axial and braider yarn tow sizes have been increased by a factor of 2.5 in these laminates. The data indicate that the materials' tensile and compression moduli showed slight decreases as yarn size increased. The changes in longitudinal and transverse moduli ranged from 2% to 6% and were within the scatter in the data. In contrast to the tensile and compression moduli, the shear modulus (Figure 12) decreased sharply as the yarn size increased.

Although the changes in elastic tensile and compression moduli were comparable to the scatter in the data, material strength was measurably lowered as yarn size increased. The longitudinal tensile strength decreased by 20% and the transverse tensile strength was reduced by 12%. As the figures indicate, the reductions in compression strength were even greater.

These results indicate that a size effect exists in textile composites. An analogous effect has been noted in composites fabricated of laminated unidirectional prepreg tape. The decreases in strength and toughness in those materials are often attributed to increases in interlaminar stresses which accompany increases in layer thickness. Increased waviness in the axial yarns of the courser braids was initially suspected to be a contributing factor in the braided laminates strength reductions. An investigation of crimp in the axial yarns was conducted. These results will be presented in a later section of this paper.

Braid Angle Effects

The effect of braid angle on material properties is seen when the data obtained for the [$0_{75k}/\pm70_{15k}$] 46% Axial and the [$0_{36k}/\pm45_{15k}$] 46% Axial architectures are examined (Figures 8 and 9). These effects were most pronounced in the materials' transverse and shear properties since the laminate response in the axial direction was dominated by the 0° yarns which constituted 46% of the preform. The axial tensile modulus showed a 12.5% increase as the braider yarns were rotated 25° in the longitudinal direction; the longitudinal compression modulus increased by only 5%. The axial tensile strengths of the two materials were also essentially equal. Their compression strengths, however, differed by 22%; strength increased with the change in braid angle.

By comparison, all the transverse properties measured decreased as the braid angle changed from 70° to 45°. This is, of course, an expected result since, when loaded in this direction, the laminates tested are effectively 90/±20 and 90/± 45. The braider yarns play a more prominent role in these laminates and the effect of the braid angle changes are more evident. The tensile and compression moduli decreased by 62% and 59%, respectively. The transverse strengths were reduced by 51% in tension and 20% in compression. The shear modulus, on the other hand, increased by 45% as the braid angle changed from 70° to 45° (Figure 12). Rotating the braider yarns from ±70° to ± 45° has more effectively aligned these yarns with the principal stress directions in the shear test.

The changes measured in the braids' elastic properties are comparable to those typically seen in laminated tape composite systems. As has been previously demonstrated [3], classical laminated plate theory does reasonably well in predicting braided laminate elastic properties even when the braider yarn crimp effects are not recognized. These predictions are most accurate for the longitudinal modulus. Their accuracy decreases for the transverse and shear moduli since braider yarn crimp plays a more dominant role in these responses. The moduli of tape laminates with fiber contents and orientations equivalent to those of the two braids discussed above were predicted using classical laminated plate theory as a comparison. Laminated plate theory predicted a 7% change in longitudinal tensile modulus and a 62% change in transverse tensile modulus. The predicted change in shear modulus was, however, far greater than the measured value; 82% versus 45%.

Axial Yarn Content Effects

The final set of data to be considered feature results measured for the $[0_{36k}/\pm45_{15k}]$ 46% Axial and $[0_{6k}/\pm45_{15k}]$ 12% Axial architectures. They were designed to measure braid sensitivity to axial yarn content. In contrast with the results noted in the previous section, the longitudinal properties were most effected in these data. This is, of course, to be expected since the axial yarn content was reduced by 34% as the axial yarn size was reduced 6 fold. As the data in Figures 10 and 11 indicate, the longitudinal tensile modulus was reduced by 53% and the tensile strength in that direction diminished by 43%. Similar changes were noted for the laminates loaded in compression. Increases in the transverse tensile and compression properties and in the shear response of the material were also anticipated since decreasing axial yarn content has, in effect, increased the ±45° braider yarn content (from 54% to 88%). Although the transverse moduli showed only a moderate increase, the large increases in transverse tensile and compression strengths are of note. Increasing the ±45° braider yarn content had a large effect on the shear modulus (Figure 12); it increased by 64%. A greater portion of the fibers in the $[0_{6k}/\pm45_{15k}]$ 12% Axial laminate are now aligned in the direction of the principal stresses due to the increased ±45° yarn content.

Laminated plate theory was again used to predict the moduli of equivalent tape laminates. The measured changes in the braids' elastic properties noted above are similar to those anticipated for laminated tape materials. Plate theory predicts, for example, a 54% decrease in longitudinal modulus and a 46% increase in shear modulus.

BRAIDS DEVELOPED FOR SECONDARY BRAID PARAMETER STUDY

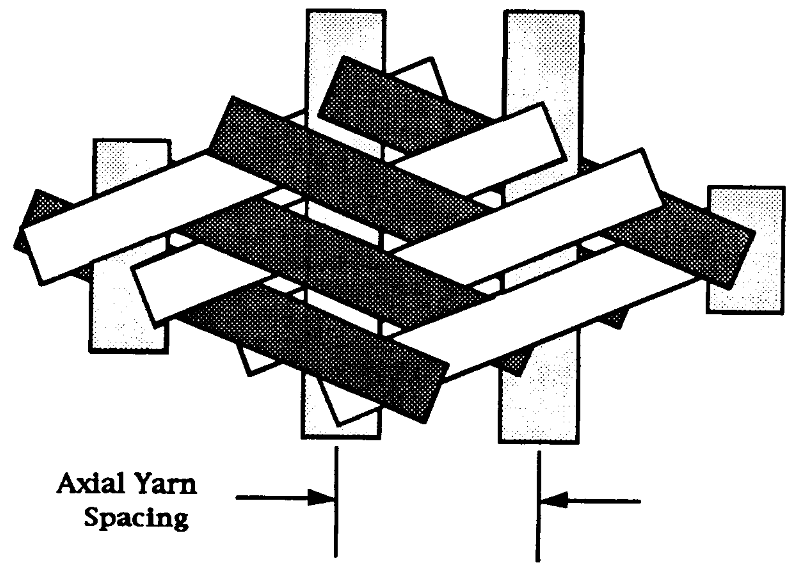


Table II. 0° Yarn Spacing and Braider Yarn Crimp of Laminates Tested in Secondary Braid Parameter Study.

Material Type	0° Yarn Density Nominal (Yarn / cm)	0° Yarn Density Measured (Yarn / cm)	0° Yarn Spacing (mm)	Braider Yarn Crimp Angle (°)
[0 18k/ ± 66.5 6k] 38% Axial	1.64	1.57 ± 0.03	6.37	10.7 ± 3.7
[0 18k/ ± 66.5 6k] 38% Axial	1.88	1.94 ± 0.05	5.15	13.9 ± 3.8
[0 18k/ ± 66.5 6k] 38% Axial	2.07	2.09 ± 0.09	4.78	16.8 ± 4.1

COMMENTS ON THE BRAID ARCHITECTURES: SECONDARY BRAID PARAMETER STUDY

Three braids were studied to determine the effects of the two secondary braid parameters on laminate response. The three braids had the same yarn sizes, braid angles, and axial yarn contents. They featured the [0 18k / ± 66.5 6k] 38% Axial braid architecture which was designed by Boeing for fuselage frame applications as a part of NASA's Advanced Composites Technology Program. The three architectures' featured different axial yarn spacing and braider yarn crimp angles, however. This was accomplished by changing the diameters of the mandrels on which the fibrous preforms were braided. Increasing the mandrel diameter increased the longitudinal yarn spacing since the total number of yarn carriers was held constant.

The yarn spacing and braider yarn crimp angles of the three braids tested in this program are listed in Table II. The table provides two measures of the interval between axial yarns : Yarn Density and Yarn Spacing. The former is expressed in terms of the number of yarns per unit length of fabric. The nominal and average measured Yarn Densities of the three architectures tested are listed in the table. The textile community typically expresses yarn spacing in these terms. The authors believe, however, that the inverse of these values, defined here as the Yarn Spacing, provide a more intuitive representation. These values are equivalent to the distance between axial yarn centerlines, as shown in the figure.

As the data in the table indicates, axial yarn spacing ranged from 4.78 to 6.37 mm. The figure shows a repeatable unit of the braid architecture that is sometimes referred to as the braid's natural unit cell. Increasing the yarn spacing to this degree will increase the unit cell's area by 64%. This opens the braid since the yarn sizes were held constant. Increasing the yarn spacing will also change the braider yarn's crimp angle significantly. The data also indicate that changing yarn spacing from 4.78 to 6.37 mm significantly increased the braider yarn crimp angle.

BRAIDER YARN CRIMP ANGLE vs. AXIAL YARN SPACING

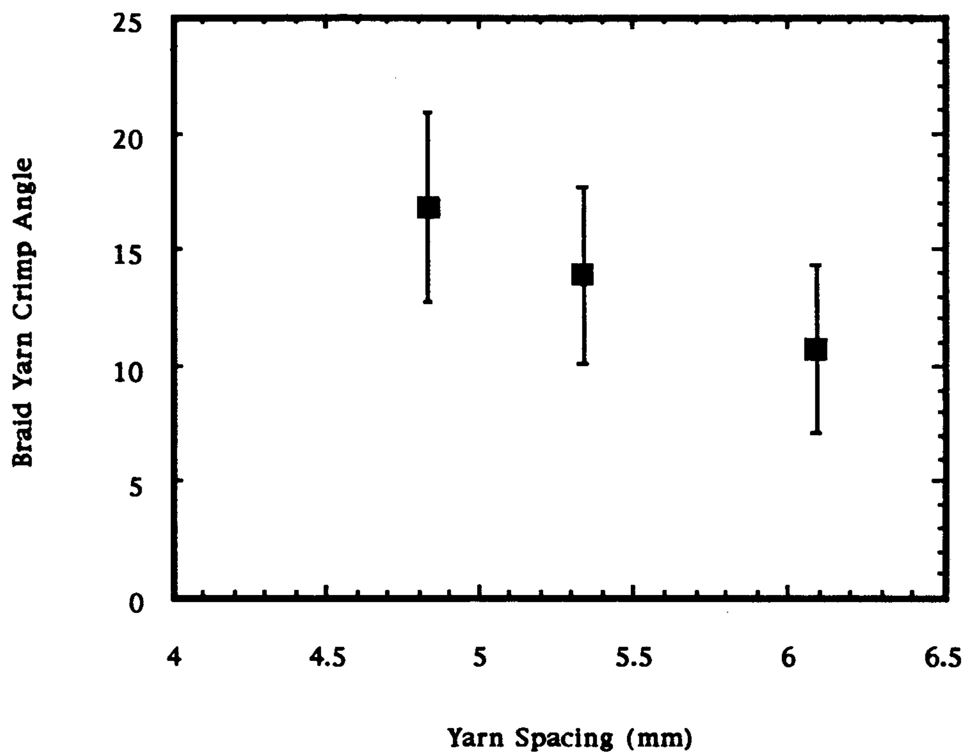


Figure 13. Empirical Data Demonstrate the Effect of Axial Yarn Spacing on Braider Yarn Crimp Angle.

As indicated earlier, the braider yarn crimp angle is a function of the axial yarn size and spacing. This figure plots the experimentally measured braider yarn crimp angles vs. axial yarn spacing for the three braids investigated in this phase of the study. Although there is wide scatter in the measured values, the crimp angle appears to be a linear function of the axial yarn spacing over the ranges studied.

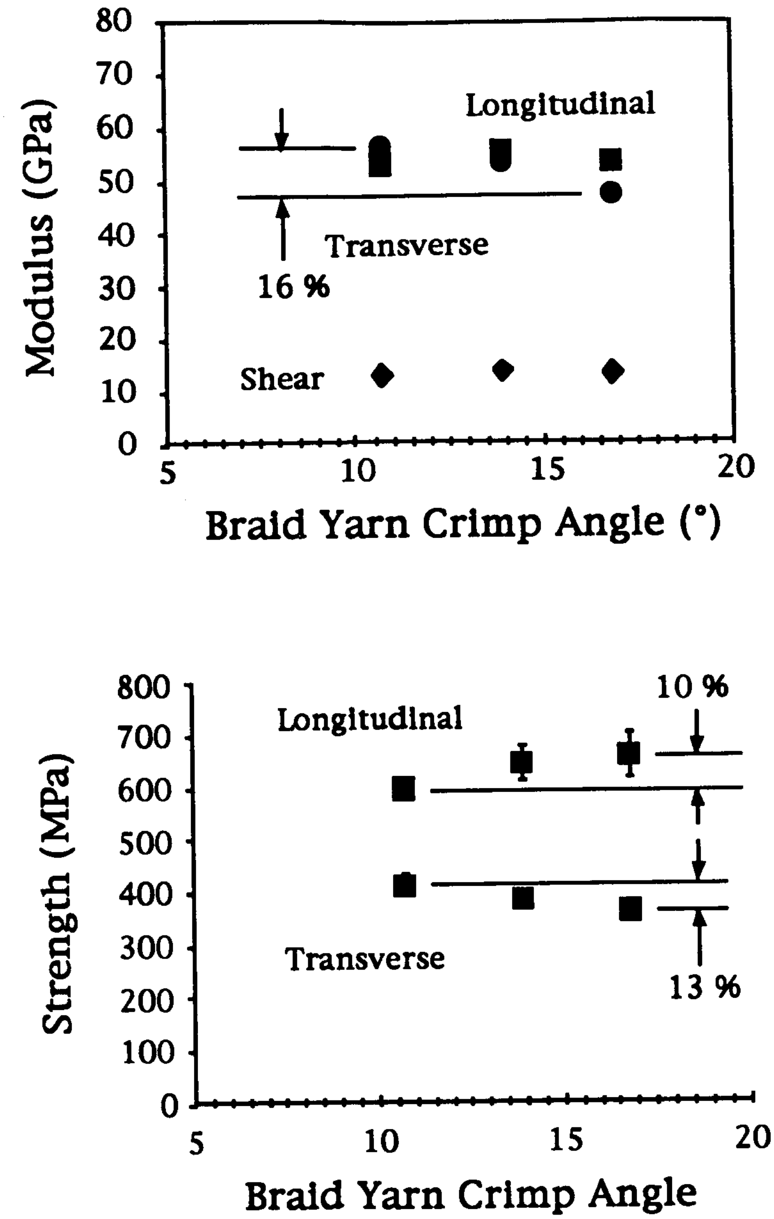


Figure 14. Braider Yarn Crimp vs. Tensile Modulus and Strength.

A review of the test results indicates that the braider yarn crimp had only a small effect on the longitudinal and shear moduli. The transverse modulus, on the other hand, decreased steadily as the braider yarn crimp increased. A 16% reduction was noted over the range tested. Changes in the laminates' strengths were not as marked. As the data in the lower figure indicates, the transverse strength, like the transverse modulus, decreased with increasing crimp in the braider yarns. Axial strength, on the other hand, increased only slightly. The total change in axial strength, however, was comparable to the scatter in the data.

MEASURED AND PREDICTED TENSILE MODULI: PRIMARY BRAID PARAMETER STUDY

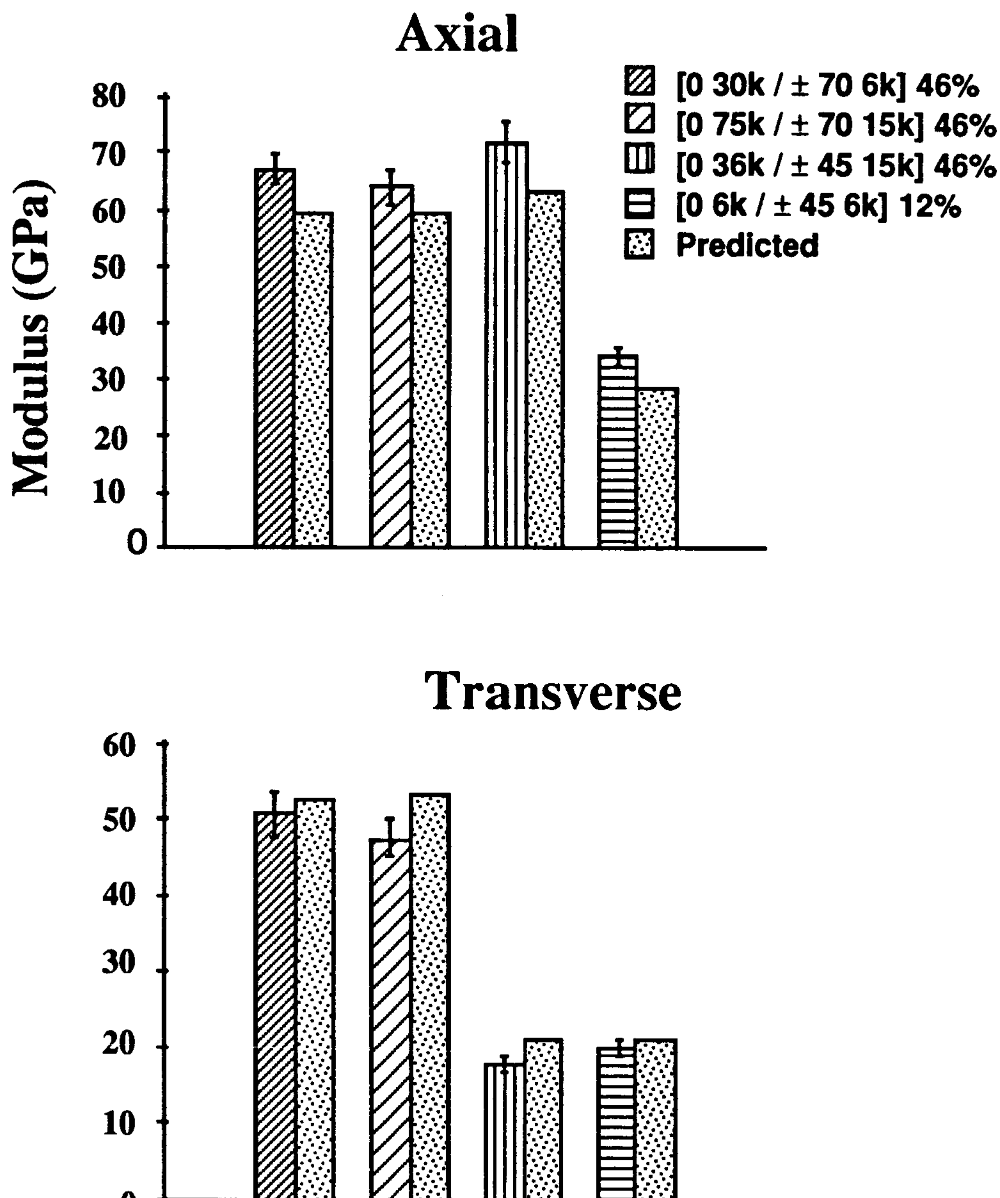


Figure 15. Measured and Predicted Tensile Moduli.

The TEXCAD analysis developed by Naik [4] was used to predict the elastic response of the four materials tested to define the effects of the primary braid parameters on laminate response. The measured and predicted results are shown in the figures. The model accurately predicted each architecture's longitudinal and transverse moduli.

Table III. 0° Yarn Crimp: Measured Values

Braid	0° Yarn Crimp
[0 30k / ± 70 6k] 46% Axial	2.85 ± 2.5
[0 75k / ± 70 15k] 46% Axial	3.10 ± 2.0
[0 36k / ± 45 15k] 46% Axial	4.00 ± 3.5
[0 6k / ± 45 15k] 12% Axial	3.20 ± 2.2

As was noted earlier, the reduction in strength noted in the [0 75k / ± 70 15k] 46% Axial laminates was initially attributed to crimp in the axial yarns. An investigation of axial yarn crimp for all the braid types investigated was conducted. Several samples of each braid type were sectioned in the longitudinal direction and metallurgically polished. Photomicrographs of these cross-sections were assembled and scanned into the computer. A series of short lines were electronically drawn tangent to the axial yarns in a piece-wise linear manner. The angle that each individual line segment made with the surface of the specimen was then measured.

The results of the measurements made for the four braid architectures investigated in the primary braid parameter study are summarized in Table III above. They indicate that significant degrees of axial yarn crimp were evident in all architectures. The data also indicate that the [0 30k / ± 70 6k] 46% Axial and [0 75k / ± 70 15k] 46% Axial laminates had comparable degrees of crimp in their 0° yarns. This latter observation, of course, indicates that the differences in the strengths of the two braids is not attributable to axial yarn crimp.

STRENGTH PREDICTIONS

In addition to its ability to predict a textile composite's modulus, TEXCAD is also capable of predicting laminate strength. The analysis was applied to the braid architectures investigated in the primary braid parameter study. The measured and predicted tensile and compression strengths of these four materials are plotted in Figure 16. The analysis was conducted twice for each architecture; first assuming no axial yarn crimp; and then with the crimp included. A 95 percentile "worst-case" scenario was modeled in the latter instance. Assuming the 0° yarn crimp measurements described above fit a normal distribution, the axial yarn crimp angle input to the model was calculated to be the mean value plus two times the standard deviation of the measurements. This in effect models the case in which all the axial yarns display this extreme defect. The two predicted values, therefore, provide an upper and lower bound on the laminate strength.

MEASURED AND PREDICTED STRENGTHS:
PRIMARY BRAID PARAMETER STUDY

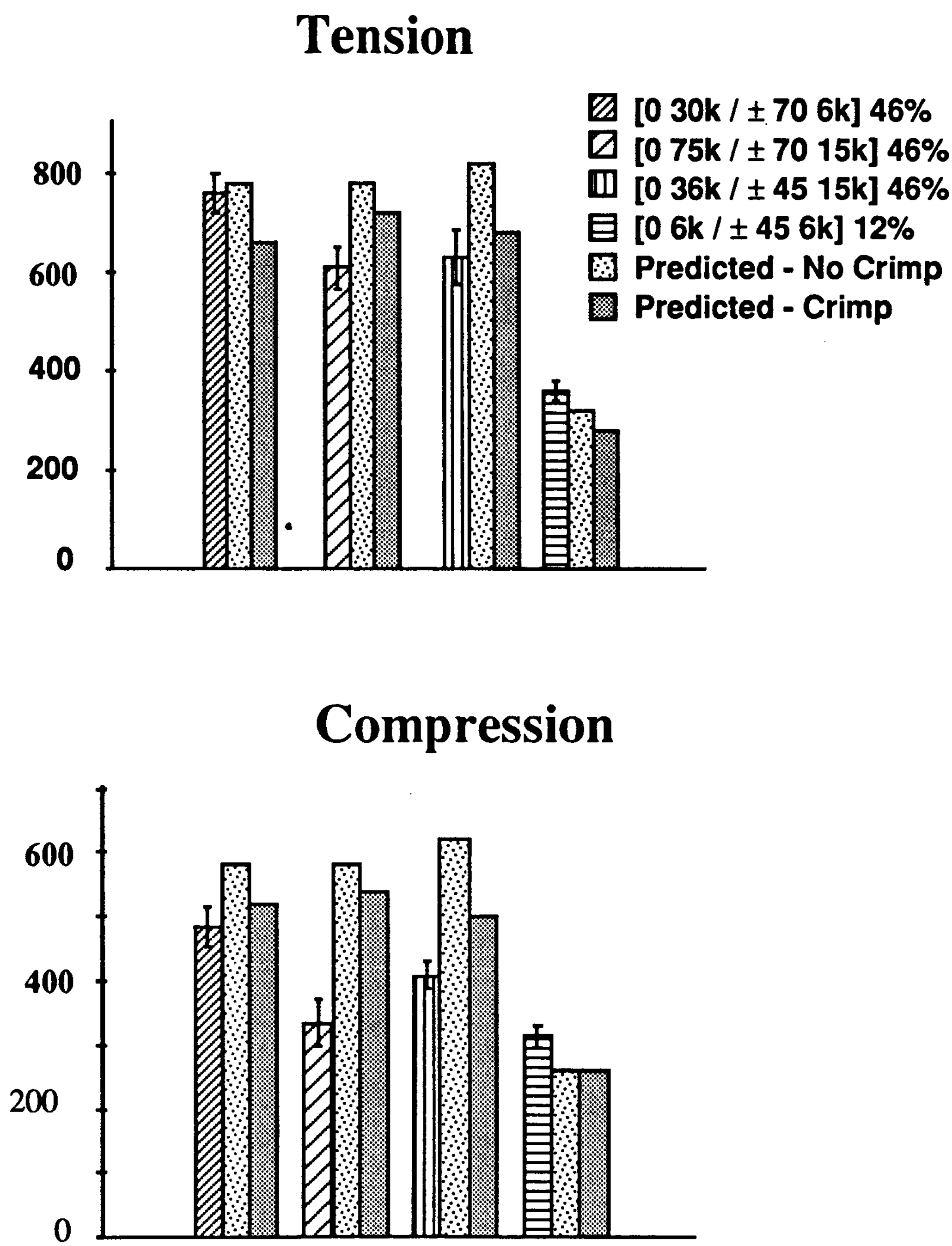


Figure 16. Measured and Predicted Tensile and Compression Strengths.

Summary:

Experimental Results

Effects of Architecture on Mechanical Response Measured

Yarn Size Effect Evident

Sensitivity to Braid Angle and Axial Yarn Content Similar to Tape Laminates

Braider Yarn Crimp and Axial Yarn Spacing Effects Minor

Significant 0° Yarn Crimp Present

Figure 17. Summary of Experimental Results.

The key points of the experimental work reported in this paper are summarized above.

The data indicate that a yarn size effect was evident in the material. Longitudinal and transverse strengths of the [0 $_{75k}$ / ± 70 $_{15k}$] 46% Axial laminates were significantly lower than the strengths of [0 $_{30k}$ / ± 70 $_{6k}$] 46% Axial laminates in both tension and compression. A mechanism that would explain this effect has not been identified. Increased axial yarn crimp in the courser braid, which was believed to be a contributing factor, does not appear to explain the results.

The test data also indicated that the sensitivities of braided laminates to changes in braid angle and axial yarn content are similar to those seen in laminates made of unidirectional prepreg tape. Applying classical laminated plate theory to tape laminates with equivalent fiber contents and orientations provides a reasonable approximation of the trends seen in the braided laminates.

The investigation of secondary braiding parameters indicated that the longitudinal tensile and shear properties of the braided laminates tested were not significantly effected by changes in the axial yarn spacing and braider yarn crimp. Their transverse moduli and strengths did, however, decrease as braider yarn crimp increased.

Finally, significant degrees of axial yarn crimping were measured in all four architectures investigated in the primary braid parameter study. It was not possible, however, to define a trend in the data; comparable degrees of crimp were measured for each architecture. Further investigation of this phenomenon is recommended. This should include examination of additional samples and a more rigorous statistical treatment of the data. In addition, several potential refinements to the yarn crimp measurement technique were suggested during discussions at the symposium.

Summary:

Analytical Results

TEXCAD Successfully Predicted Mechanical Properties

Effects of Braid Angle and Yarn Content Changes on Modulus and Strength Predicted

Effects of 0° Yarn Crimp on Laminate Strength Predicted

Figure 18. Summary of Analytical Results.

The TEXCAD analysis was used to predict the elastic response of the four materials tested to define the effects of the primary braid parameters on laminate response. The model accurately predicted each architecture's longitudinal and transverse moduli. The analysis also accurately depicted the braided laminates' sensitivity to changes in braid angle and axial yarn content.

TEXCAD's ability to predict a textile composite's strength was also exercised. It was again applied to the four braid architectures investigated in the primary braid parameter study to define the sensitivity of the materials' tensile and compression strengths to axial yarn crimp.

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