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Standard Methods for Unnotched Tension Testing of Textile Composites

M. A. Portanova
Lockheed Martin Engineering and Sciences Company, Hampton, Virginia

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National Aeronautics and
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Introduction

Textile composite materials have been shown to have potential use in designs where delamination resistance is critical. Because of this, designers of damage tolerant structures may find that textile composites materials provide an advantage over conventional laminated tape materials constructed from similar constituents. Unfortunately, testing standards have not been established for this class of materials. Textile composites have a less homogeneous nature than composites constructed from pre-preg tape. Consequently, standard composite testing methods may not be adequate to characterize these materials. Because of concerns about this issue, NASA's Advanced Composite Technology Program (ACT) funded researchers at the Boeing Defense & Space Group to initiate an investigation of sizing effects in textile composites [1].

This report evaluates the unnotched tension test methods employed by Boeing and several other investigators. The intent here is to compare and contrast the results from the many independent researchers involved in the ACT textile composites program. Because no testing standards exist for textile composites, each of the individual test programs tended to employ slight variations in test specimen configuration and testing methodology. Most researchers used guidelines established for the testing of tape composites. Boeing conducted the only investigation explicitly designed to determine the effects of specimen width, length, and thickness on measurements of material properties. The results from the Boeing study will be the primary focus of this paper.

The intent of this investigation was to determine the effect test specimen geometry has on tensile property measurements of textile composites. Each textile architecture has an independent unit cell size. This repeating inhomogeneity may cause variability in the test results if specimens are sized using guidelines established for tape materials. To this end, an investigation has been conducted to determine the appropriate size and shape required for test coupons to yield accurate and repeatable test results. Test specimens with varying widths, lengths, and thicknesses were used to accomplish this goal.

Description of Materials

The primary contributor of test data to this report was Boeing Defense and Space Group in Philadelphia, PA. Supplemental data, obtained from Lockheed Aeronautical Systems in Marietta, GA and West Virginia University (WVU), is also presented. Most of the data was derived from tests on two dimensional triaxial braids and three dimensional interlocking weaves. Lockheed also evaluated a three dimensional braid. Some results for stitched uniweaves, tested at Boeing, are also presented.

Boeing and WVU evaluated the exact same 2-D braided architectures while Lockheed's braids were slightly different. All of the 2-D and 3-D fabric preforms were manufactured by an outside source and then resin transfer molded (RTM) at Boeing or Lockheed facilities. The specifics of each test material are described in the following sections. All of the fabrics were constructed using Hercules AS4 fibers. The various resin systems employed were formulated to have similar properties as Hercules 3501-6. They are low-cost brittle epoxy systems with low viscosity's at melt temperature that lend themselves to the resin transfer molding process.

2-Dimensional Triaxial Braids

All of the 2-D fabric preforms were braided by Fiber Innovations Inc., Norwood, MA. Boeing and WVU material was RTM'd using Shell RSL-1895 epoxy resin and cured at Boeing. Details of their manufacturing process can be obtained from ref. [2], "Resin Transfer Molding of Textile Composites".

Boeing compared four different braided architectures. The specifics of each are given in Table 1. In Tables 1 & 2, the following nomenclature has been adopted to describe the layup:

$$[0_{XXK}/\pm\theta_{XXK}]\ Y\%\ \text{Axial}$$

where XX indicates the yarn size, k indicates thousands and Y indicates the percentage of axial yarns in the preform. An illustration of the 2-D braided architecture is given in Figure 1.

In Table 1, the three letters preceding the "$[0_{XXK}/\pm\theta_{XXK}]$ Y% Axial" nomenclature are intended as abbreviations where "S" and "L" mean "Small" and "Large", respectively. For example, the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ braid is deciphered as containing a small (6K) braider yarn, a large (46%) percent of axial yarns, and a large (70°) braid angle. Thus, SLL indicates that this braid contains Small, Large, Large braider yarns, % axials, and braid angle.

Table 1. Boeing's 2-D Braided Composites Architectures.

Braid Code	Axial Tow Size	Braided Tow Size	% Axial Tow	Braid Angle [°]	Unit Cell Width [in]	Unit Cell Length [in]
SLL $[0_{30K}/\pm70_{6K}]_{46\%}$	30 K	6 K	46	0±70	0.458	0.083
LLS $[0_{36K}/\pm45_{15K}]_{46\%}$	36 K	15 K	46	0±45	0.415	0.207
LLL $[0_{75K}/\pm70_{15K}]_{46\%}$	75 K	15 K	46	0±70	0.829	0.151
LSS $[0_{6K}/\pm45_{15K}]_{12\%}$	6 K	15 K	12	0±45	0.415	0.207

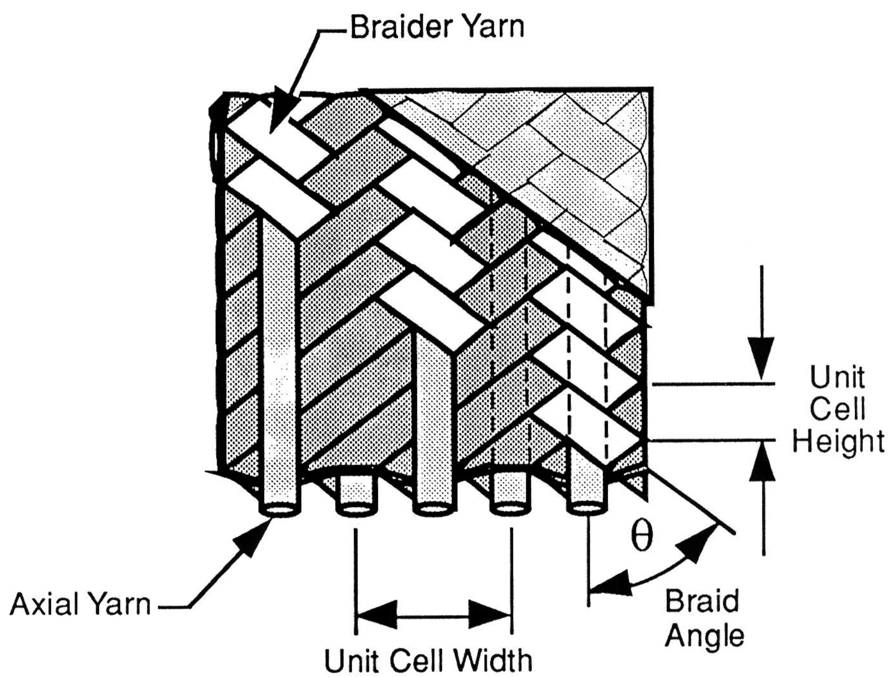

Figure 1. Illustration of a typical 2-D Triaxial Braid Configuration.

Lockheed's 2-D material was RTM'd using PR-500 epoxy resin and cured at Lockheed's facility in Marietta, GA. Lockheed looked at the two different triaxial braided architectures described in Table 2.

Table 2. Lockheed's 2-D Braided Composite Architectures.

Braid Code	Longitudinal Tow Size	Braided Tow Size	% Axial Tow	Braid Angle [°]
SSL $[0_{12K}/\pm60_{6K}]_{33\%}$	12 K	6 K	33.3	0±60
SLL $[0_{24K}/\pm60_{6K}]_{50\%}$	24K	6 K	50	0±60

3-Dimensional Braids and Weaves

Three different types of 3-D woven composites are evaluated in this investigation. All provide true through the thickness reinforcement by interlacing yarns in the z direction. An illustration of each is shown in Figure 2. Tow size and bias along with an architectural description of each are provided in Tables 3, 4 and 5. The effect test specimen geometry has on tensile properties was not evaluated using these material forms. Because of the complex nature of these materials, unit cell measurements have not been calculated.

The 3-D woven architectures that were evaluated by Boeing are described in detail in Table 3. The preforms were produced by Textiles Technologies Inc. and, like the 2-D braids, RTM'd at Boeing using Shell RSL-1895 epoxy and cured. All three architectures provided Z direction reinforcement by interlacing yarns through the thickness. Three different interlocking configurations were tested.

Table 3. Description of Boeing's 3-D Interlock Woven Materials.

Name	Description	Warp Tow	Weft Tow	Weaver Tow
OS-1	Through-the-thickness orthogonal interlock	24 K (59%)	12 K (33%)	6 K (7.4%)
OS-2		12 K (58%)	6 K (37%)	3 K (6.1%)
TS-1	Through-the-thickness angle interlock	24 K (57%)	12 K (33%)	6 K (9.8%)
TS-2		12 K (56%)	6 K (38%)	3 K (5.8%)
LS-1	Layer-to-layer interlock	24 K (58%)	12 K (34%)	6 K (6.8%)
LS-2		12 K (57%)	6 K (36%)	3 K (5.9%)

Lockheed looked at two different interlocking woven configurations in tension. These are described in Table 4. The preforms were produced by Textiles Technologies Inc. and then RTM'd at Lockheed using PR-500 epoxy. Lockheed preforms were similar in design to those tested by Boeing but were constructed with different size tows and a different percent of axial yarns. Thus, a direct comparison can not be made with Boeing's results.

Table 4. Lockheed's 3-D Woven Composite Architectures

Name	Description	Warp Tow	Weft Tow	Weaver Tow
TTT-2	Through-the-thickness	12 K (47.7%)	6 K (44.4%)	3 K (7.9%)
	angle interlock	-----	-----	-----
LTL-1	Layer-to-layer	6 K (45.7%)	6 K (46.1%)	3 K (8.2%)
LTL-2	interlock	12 K (46.3%)	6 K (45.6%)	3 K (8.1%)

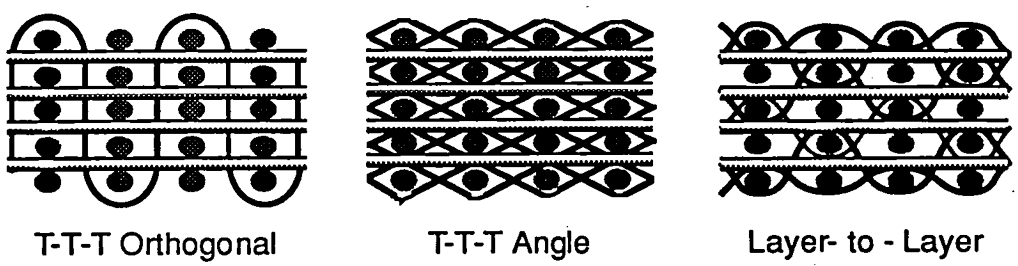

Figure 2. Depiction of 3-D Interlock Woven Materials.

Lockheed also produced and tested a three dimensional braided material. Two different configurations were evaluated. The specifics of each are described in Table 5. This 3-D fabric was braided by Atlantic Research` Corp. and then RTM'd at Lockheed using PR-500 epoxy resin.

Table 5. Lockheed's 3-D Braided Architectures.

Name	Braid Angle	Axial Tow	Bias Tow
TTT-1	±60	6 K (30.3%)	6 K (69.7%)
TTT-2	±60	18K (56.3%)	6 K (43.7%)

Stitched Uniweaves

Stitched uniweaves, tested by Boeing, were also evaluated. The uniweave fabric was produced by Textile Technologies Inc. and then RTM'd at Boeing. Stitching of the uniweaves was performed outside Boeing by Cooper Composites. All of the materials tested were quasi-isotropic $[+45/0/-45/90]_{6S}$ layup. Stitching media and density was varied. The specifics of each preform are described below in Table 6. An illustration of a typical stitched uniweave is shown in Figure 3.

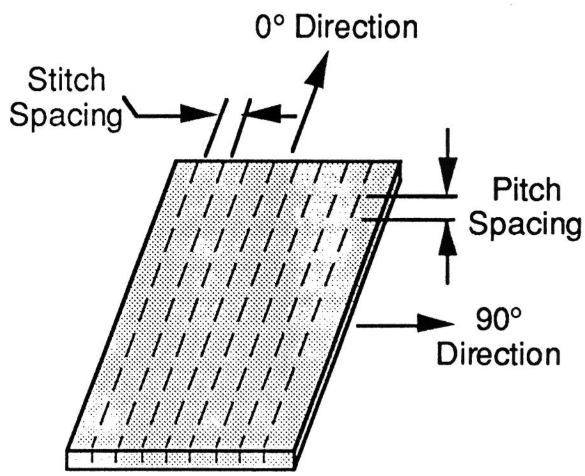

Figure 3. Depiction of Boeing's Stitched Uniweave.

Table 6. Description of Boeings Stitched Uniweaves.

Name	Stitch Material	Pitch Spacing Stitches per inch	Stitch Spacing [in]	Stitch Tow Size
SU-1	S2 Glass	8	0.125	3 K
SU-2	S2 Glass	8	0.125	6 K
SU-3	Kevlar 29	8	0.125	6 K
SU-4	Kevlar 29	4	0.250	6 K
SU-5	Kevlar 29	8	0.125	12 K

The Unit Cell

In theory, textile composites have a repeating geometrical pattern based on manufacturing perameters. This repeating pattern is often called the material's "unit cell". It is defined as the smallest section of architecture required to repeat the textile pattern. Handling and processing can distort the "theoretical" unit cell. For 2-D braids, only the individual layers have well defined unit cells.

One purpose of this investigation was to define a test specimen geometry that will ensure that representative volumes of material are tested and that valid material properties are established.

Although some braid parameters, such as tow size and braid angle, may be explicitly defined, calculation of unit cell dimensions tend to be somewhat subjective. Unit cell dimensions are based on varying interpretations of the textile architecture. For the purpose of this paper, unit cell width is defined as twice the spacing of the axial tows while unit cell length is calculated by multiplying the cotangent of the braid angle by half the unit cell width. Axial tow spacing can be calculated by multiplying the braider mandrel diameter by π, then dividing the result by the number of axial carrier yarns. An illustration of the unit cell width and length are provided in Figure 1.

Unit cell dimensions vary between each of the braided material forms. The SLL $[0_{30K}/\pm70_{6K}]_{46\%}$, LLS $[0_{36K}/\pm45_{15K}]_{46\%}$, and LSS $[0_{6K}/\pm45_{15K}]_{12\%}$ all had unit cells of similar width but with the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ material, the unit cell length was less that half that of the other architecture's. The LLL $[0_{75K}/\pm70_{15K}]_{46\%}$ material's unit cell was approximately twice as wide as the other three architectures but it's length was shorter than all but one of the braids. These various perameters are a result of the braiding process, tow size used, and braid angle.

Test Specimen Configuration & Testing Methodology

Boeings Test Matrix

The test matrix used by Boeing is given in Table 7. Although Boeing tested braided, woven, and stitched materials, they conducted specimen size experiments on the 2-D braided materials only. The results of these sizing experiments were then used to develop test specimen dimensions for the 3-D weaves and stitched laminates.

For the specimen sizing study, both 1/8" and 1/4" nominal thickness coupons were used. Various widths and lengths were used to enable evaluation of width, length, and thickness effects. The basic specimen used in this program is a straight sided coupon described by ASTM D3039 and illustrated in Figure 3. Some dog-bone and net-shape coupons were also evaluated. Boeing found that the dog-bone and net-shape coupons did not produce significantly different failure strengths or percent coefficient of variation (%CoV) than those obtained from straight sided coupons. Because dog-bone and net-shape coupons are more complicated to prepare, only straight sided specimens were used for the remainder of their test program.

Boeing tested stitched uniweaves and 3-D weaves using the straight sided coupon described in Figure 3. A 2-inch-wide and 7-inch-long coupon was used for all of these experiments. Unfortunately, most of the uniweaves failed near or under the fiberglass tabs. This was due in part to the specimens being fairly thick and generating stress concentrations in the outer plies during load introduction.

All of the Boeing specimens were loaded in tension in a servo-hydraulic load frame using hydraulic grips. Load was induced at a constant stroke rate of 0.05 inches per minute. Strain was measured with an extensometer on all specimens while some specimens also had 1/2 inch square strain gages attached to both faces. The Boeing straight sided and dog bone test specimens are shown in Figures 3 and 4, respectively.

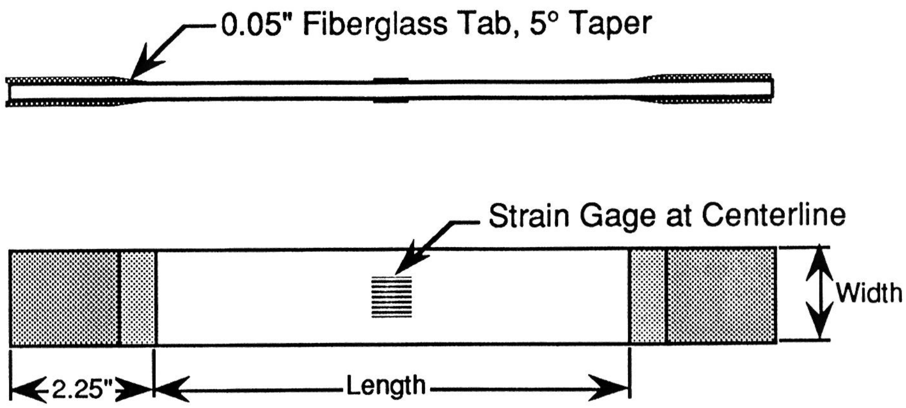

Figure 3 Boeing Straight Sided Tension Coupon.

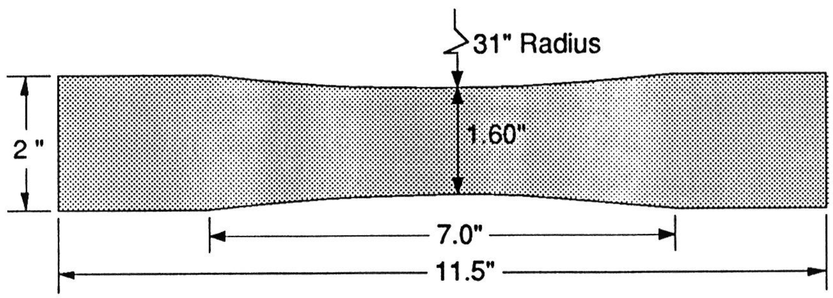

Figure 4. Boeing Dog-bone Tension Coupon.

Table 7. Boeing Test Matrix for Tension Test Program.

Gage Section Dimensions			Material Systems							
Width [in]	Length [in]	Specimen Type	SLL 1/8″	SLL 1/4″	LLS 1/8″	LLS 1/4″	LLL 1/8″	LLL 1/4″	LSS 1/8″	LSS 1/4″
1.00	3.50		3	3	3	3	3	3	3	3
1.50	5.25		3	3	3	3	3	3	3	3
2.00	5.50		3	3	3	3				
2.00	7.00		3	3	3	3	3	3	3	3
2.00	8.50		3	3	3	3				
2.50	8.75		3	3	3	3	3	3	3	3
1.60	7.00	Dog-Bone	3		3		3		3	
1.50	7.00	Net-Shape	3		3		3		3	
2.00	7.00	Transverse	3		3		3		3	
		Total	27	18	27	18	21	12	21	12

The Boeings test matrix is shown in Table 7. As previously stated, the various widths, lengths, and thickness allowed for examination of geometrical sizing effects. Table 8 shows how the test matrix in Table 7 was used to make comparisons.

Table 8. Evaluation of Boeing Unnotched Tension Test Results.

	Width	Length	
Width Effects	1.0	3.5	Compare Strengths at Constant W to L ratio
	1.5	5.25	
	2.0	7.0	
	2.5	8.25	
Length Effects	2.0	5.5	Compare Strengths at Constant W with increasing L
	2.0	7.0	
	2.0	8.5	
Thickness Effects	1.0	3.5	Compare Strengths at each thickness for all W & L
	1.5	5.25	
	2.0	7.0	
	2.5	8.75	

Other Data Evaluated

Lockheed's test program included both 2-D and 3-D materials. All of the testing was performed using a coupon with a reduced test section. An illustration is provided in Figure 5. Only one thickness was tested. Length and width effects were not investigated.

All specimens were loaded in a servo-hydraulic load frame using hydraulic grips at a constant stroke rate of 0.05 inches per minute. Strains were measured with strain gages attached to the face of the coupon.

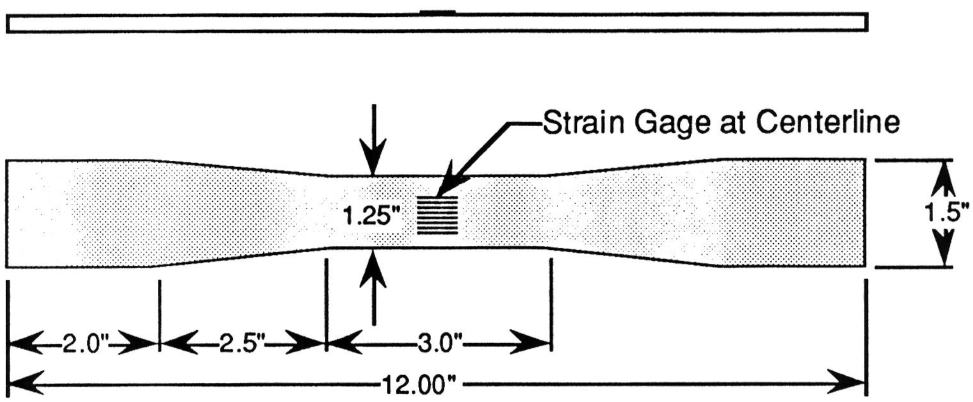

Figure 5. Lockheed's Unnotched Tension Coupon.

Investigators at West Virginia University (WVU) conducted a notch sensitivity study of textile composites using the same 2-D textile architecture as those used in Boeing's sizing effects study. Although the object of the WVU study was to examine the effects of notches on 2-D braided materials, they generated a limited number of unnotched data to use as a baseline. These test results are compared in this study. They used a straight sided test specimen with a 4 inch gage length and 1 inch width. All specimens discussed were loaded to failure in a servo-hydraulic load frame using hydraulic grips. A constant stroke rate of 0.01 inches per minute was used.

Discussion of Results

Size effects have been investigated by comparing the failure strengths of each of the four different braided architectures as a function of specimen width, length, or thickness. The data used to make these comparisons was generated by Boeing and is available in Appendix A. Comparisons of these results were made with Boeing's stitched uniweaves, Lockheed's 2-D braids and 3-D weaves, and West Virginia University's 3-D weaves. Summaries of the test results for the stitched and 3-D materials are given in Appendix B. Test results from Lockheed's and West Virginia University's test programs are given in Appendix C and D.

Width Effects

Four sets of specimens were tested to examine the effect of specimen width on tensile properties. Each had a constant width to length ratio. Failure strength was used as the initial discriminator. Figures 6 through 9 are plots of failure strength versus specimen width for the SLL $[0_{30K}/\pm70_{6K}]46\%$, LLS $[0_{36K}/\pm45_{15K}]46\%$, LLL $[0_{75K}/\pm70_{15K}]46\%$, and LSS $[0_{6K}/\pm45_{15K}]12\%$ 2-D braided materials. For purposes of clarity these figures were not combined. The filled symbols are for data averages while the open symbols display data for each specimen so that data scatter is evident. The circles are for non-normalized stress while the squares are for data normalized to a constant fiber volume fraction. The fiber volume fraction used was an average for the material type plotted and is given on each of the figures. Later in this paper it will be shown that specimen thickness had no apparent effect on the tensile failure strength. In an effort to provide a better average result, both the 1/8" and 1/4" nominal thickness specimen data have been combined in these figures.

An initial inspection of Figures 6 through 9 shows there to be a fairly large amount of scatter in this data. Any trends with width shown in the data plots may be artifacts of this scatter, rather than effects of specimen configuration.

Figure 6 is a plot of results for the SLL $[0_{30K}/\pm70_{6K}]46\%$ material. Fiber volume fraction was fairly consistent so there is not much difference between the normalized and non-normalized data. Notice that the unnotched failure strength is fairly constant with increasing width until the specimen width reaches 2.5 inches. At this point the failure stress increases, suggesting that some critical width has been met or exceeded. As discussed earlier, this may only be an artifact of the data scatter. One interesting thing to notice is that the 2.5 inch width data not only shows the highest strength but also has the least amount of scatter.

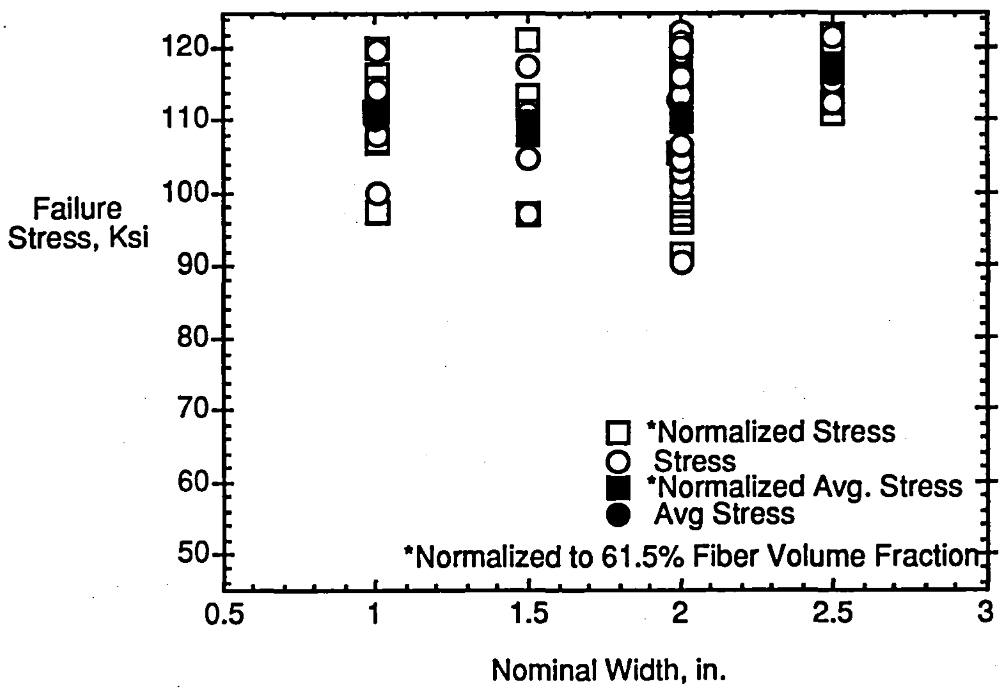

Figure 6. SLL $[0_{30K}/\pm 70_{6K}]_{46\%}$ Specimen Width Effects.

Examination of Figure 7, a plot of the LLS $[0_{36K}/\pm 45_{15K}]_{46\%}$ material, shows large variations in strength with width. Little improvement is obtained by normalizing the data. The maximum average failure strength for this material is found at a specimen width of 1.5 inches. Again, data scatter is significant and failure strengths for both the 2 inch and 2.5 inch specimen widths were within 10 percent of the 1.5 inch average values. Notice also that in both Figures 6 and 7, data scatter is most significant at the 2.0 inch width.

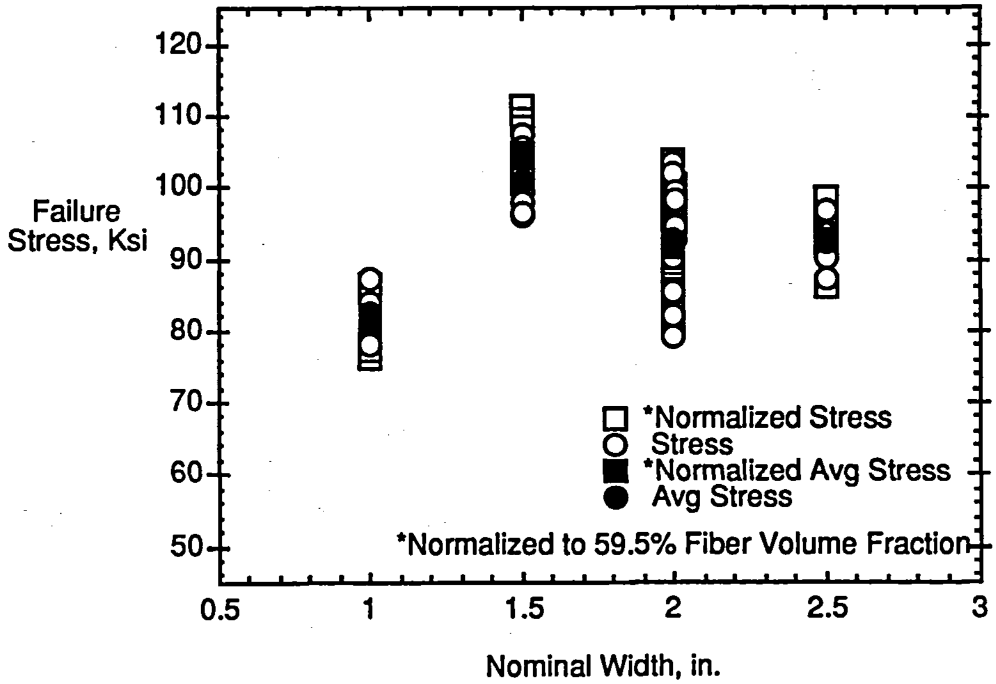

Figure 7. LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ Specimen Width Effects.

Figures 8 and 9, plots of the LLL $[0_{75K}/\pm70_{15K}]_{46\%}$ and LSS $[0_{6K}/\pm45_{15K}]_{12\%}$ materials, have similar responses. Notice that in both of these figures, variations in average strength with width are significantly smaller than in the preceding two data figures. Again, normalizing the data had little effect on the test results. Further examination of Figures 8 and 9 shows no obvious trends in failure strength as a function of specimen width. Figure 9, the LSS $[0_{6K}/\pm45_{15K}]_{12\%}$ material had noticeably lower strength than the other braids. This is explained by the fact that the LSS $[0_{6K}/\pm45_{15K}]_{12\%}$ braid contained significantly fewer axial tows than any of the other braids, thus it's lower tension carrying capability was to be expected.

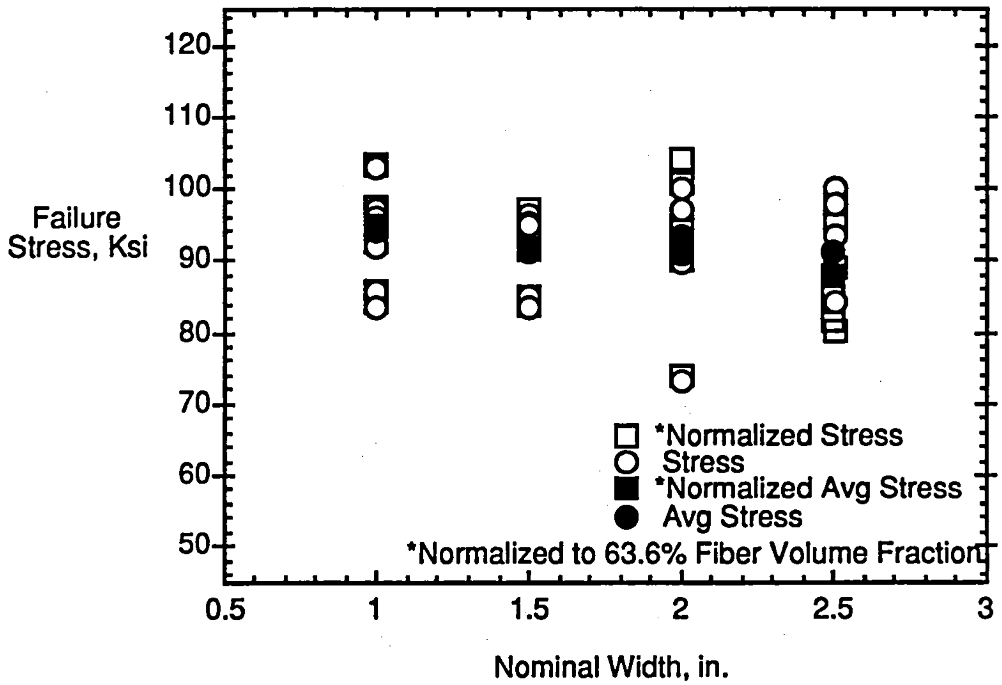

Figure 8. LLL $[0_{75K}/\pm70_{15K}]_{46\%}$ Specimen Width Effects.

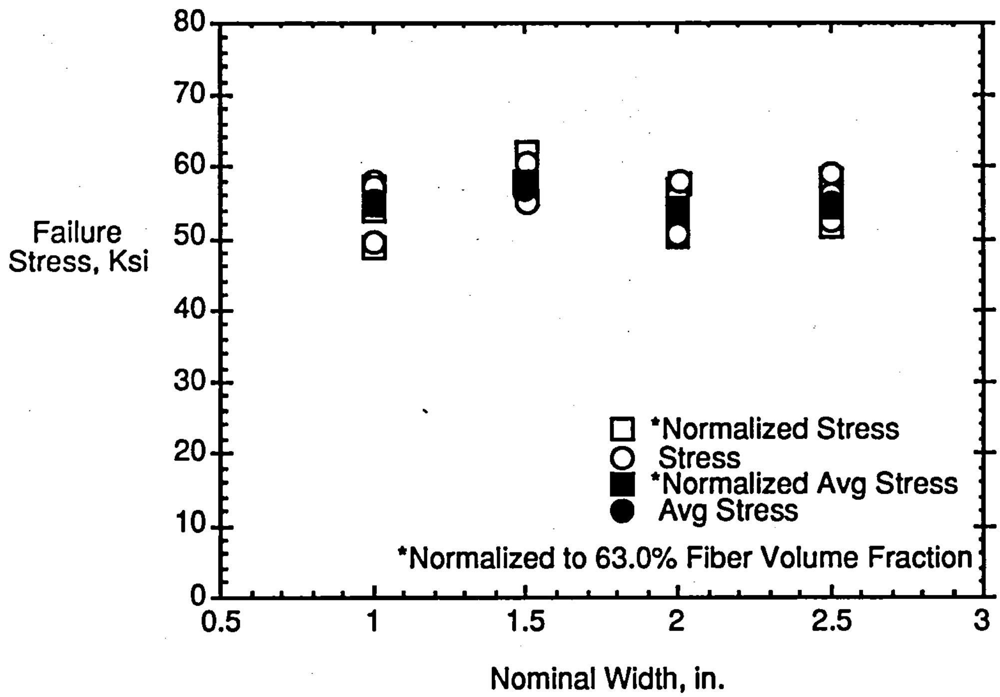

Figure 9. LSS $[0_{6K}/\pm45_{15K}]_{12\%}$ Specimen Width Effects.

Summarizing Figures 6 through 9, no obvious effects of width could be identified by this type of investigation. As stated earlier, unit cell size provides a convenient way to measure or track potential size effects because strains are periodic on a scale of unit cell size. For this reason, it was decided to normalize specimen width by unit cell size to further investigate the issue of width effects.

Figure 10 is a plot of average failing stress versus specimen width, normalized by unit cell width for each of the four braided architectures. Strengths have been normalized by fiber volume fraction. The volume fractions used for normalization are averages for each material type and are given in this figure.

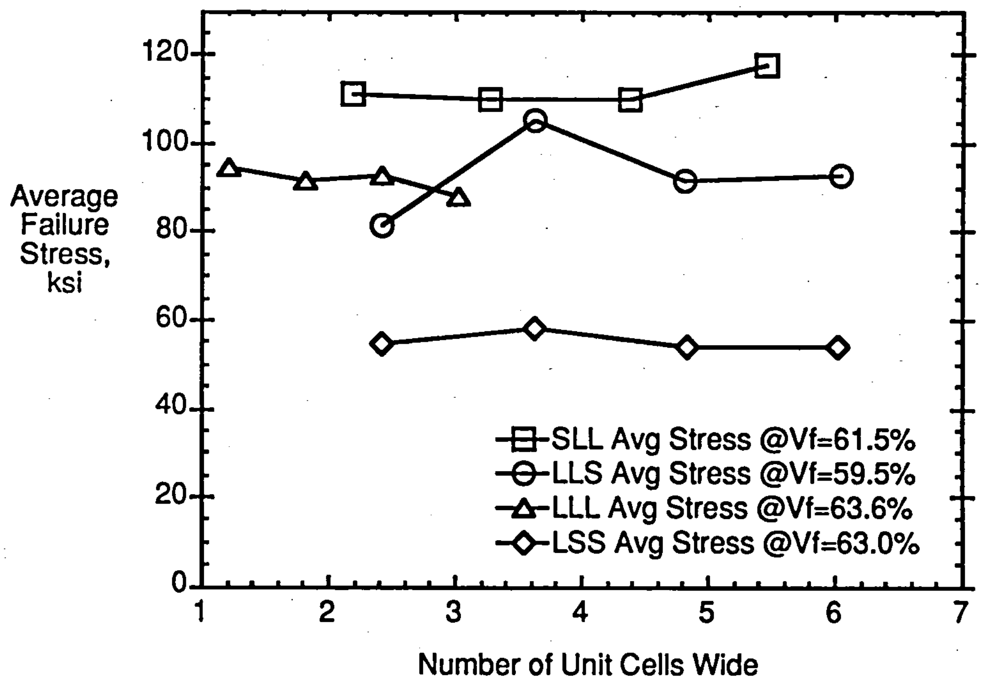

Figure 10. Effect of Unit Cell Size on Strength for the 2-D Braid Materials.

Figure 10 shows the effect on strength of increasing the number of unit cells across the width for each of the four architectures. With the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ material, the data tends to suggest that failure stress increases with an increasing number of unit cells. Further investigation reveals that this may not be the case. Notice that the difference between the minimum and maximum failure stress is about 8 ksi or approximately 7 percent. The scatter in the data for a given width ranges from approximately 13 percent to as much as 27 percent. Thus, this increase in strength may only be a function of data scatter and a smaller number of specimens tested at the greatest width.

Figure 10 shows large fluctuations in failure stress as a function of unit cell size for the LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ Material. Again notice the significant amount of data scatter and that minimum and maximum values in failure strength overlap for most of the specimen widths plotted. The range in failure strength was large at approximately 23 ksi (21 percent). Data scatter ranged from around 10 percent to as much as 25 percent. Again, a width effect trend cannot be substantiated

As a consequence of the LLL $[0_{75K}/\pm70_{15K}]_{46\%}$ materials large tow size, the number of unit cells across the width was limited to about three. Figure 10 shows that failure stresses were on the same order as the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ and LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ architectures. Again, no obvious trend in the data is noticeable. The range between the minimum and maximum average failure stress for all widths was small, at about 7 ksi or 9 percent. The data scatter at each width varied from 13 percent to 33 percent. Again the variation in average strength was less than the range of the data scatter so no trend can be established.

Also notice in Figure 10 that the LSS $[0_{6K}/\pm45_{15K}]_{12\%}$ material has a much lower failure stress than the other three material forms. This is due in part to the smaller 0° tow size. Notice that the LSS $[0_{6K}/\pm45_{15K}]_{12\%}$ material also had the smallest amount of data scatter. The difference between the minimum and maximum value of failure stress was only about 4 ksi or 7 percent. Scatter in the data ranged from 6 percent to 15 percent.

In general, little or no effect of specimen width could be found. In most cases, data scatter was significant. Expanding the investigation to include an evaluation of width effects as a function of unit cell size produced no conclusive result. No clear trend was found in any of the 2-D braids that would suggest that specimen configuration warranted different geometrical considerations than those used for tape materials.

Comparison of both the Lockheed data and WVU data with that obtained by Boeing tended to support these findings. Data scatter was similar, as were failure stresses. Calculations of the %CoV and the standard deviation were similar among all three studies, suggesting that the data scatter may be typical for textile composite tension test results. Failure strengths from Boeing's and WVU's independent test programs agree to within ≈10 percent. Lockheed's strengths, although from a different textile architecture, were on the same order as those of the other braids and their %CoV's were similar.

Length Effects

Three different specimen lengths were compared in this part of the study. The specimen width was kept constant. Again, strength was used as the discriminator. Because of the limited number of test specimens, Boeing only evaluated the SLL $[0_{30K}/\pm 70_{6K}]_{46\%}$ and LLS $[0_{36K}/\pm 45_{15K}]_{46\%}$ architectures for this part of their investigation.

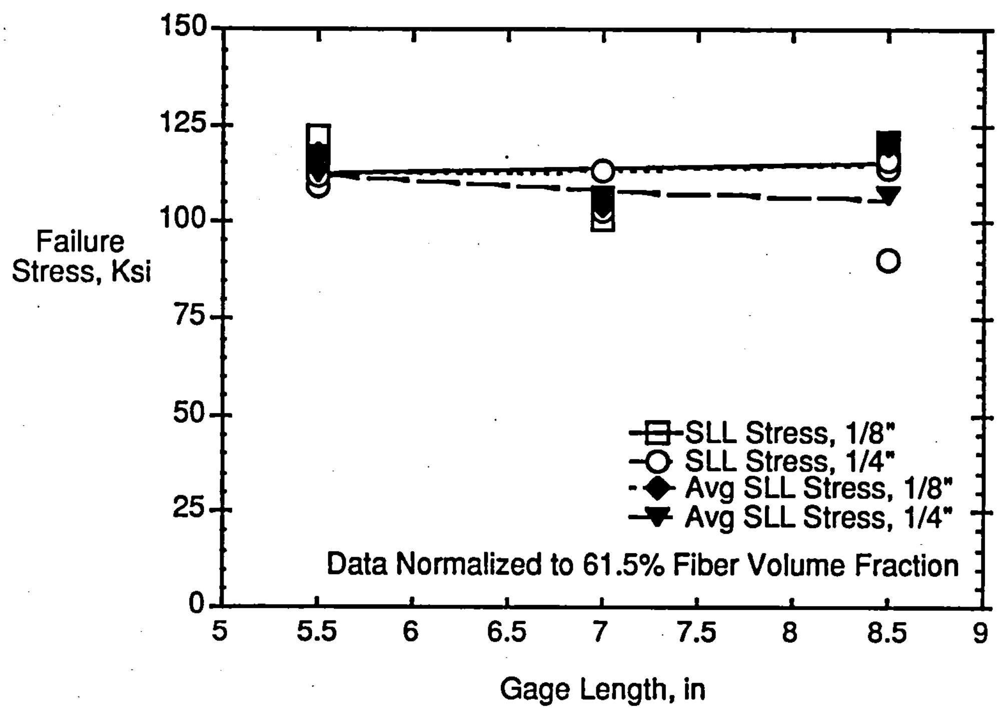

Figure 11. Length Effects for the SLL $[0_{30K}/\pm 70_{6K}]_{46\%}$ Material.

Figures 11 and 12 are plots of failure stress versus specimen gage length for the SLL $[0_{30K}/\pm 70_{6K}]_{46\%}$ and LLS $[0_{36K}/\pm 45_{15K}]_{46\%}$ materials, respectively. Test data from both plate thicknesses have been plotted. The open symbols are for individual test specimens while filled symbols are for data averages. Again, failure stress has been normalized to a constant fiber volume fraction. The fiber volume fraction used was an average for the material type plotted and is given on each of the figures.

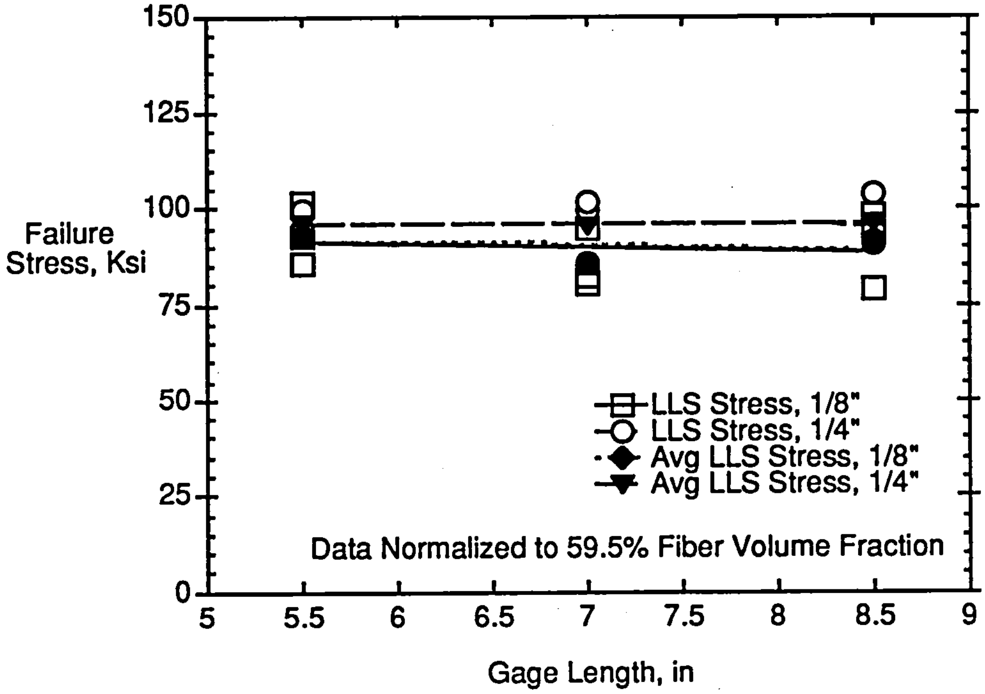

Figure 12. Length Effects for the LLS $[0_{36K}/\pm 45_{15K}]_{46\%}$ Material.

Examination of Figures 11 and 12 show no clear trend in failure strength as a function of specimen gage length or thickness. Examination of Figure 11 shows that the average failure stress varied with length by a maximum of only 13 ksi or about 12 percent. The range of scatter in the data is as much as 32 ksi or 35 percent. In Figure 12, the difference between the minimum and maximum value of average failure stress was about 10 ksi or 12 percent. Scatter in this data was as much as 31 percent. Curves fit to the data using a linear least squares regression are fairly flat. Thus, these materials appear to be insensitive to changes in gage length over the range tested.

Figures 13 and 14 are again data plots of the SLL $[0_{30K}/\pm 70_{6K}]_{46\%}$ and LLS $[0_{36K}/\pm 45_{15K}]_{46\%}$ materials. This time specimen length has been normalized by the corresponding specimen width to show the results of increasing the L/W ratio.

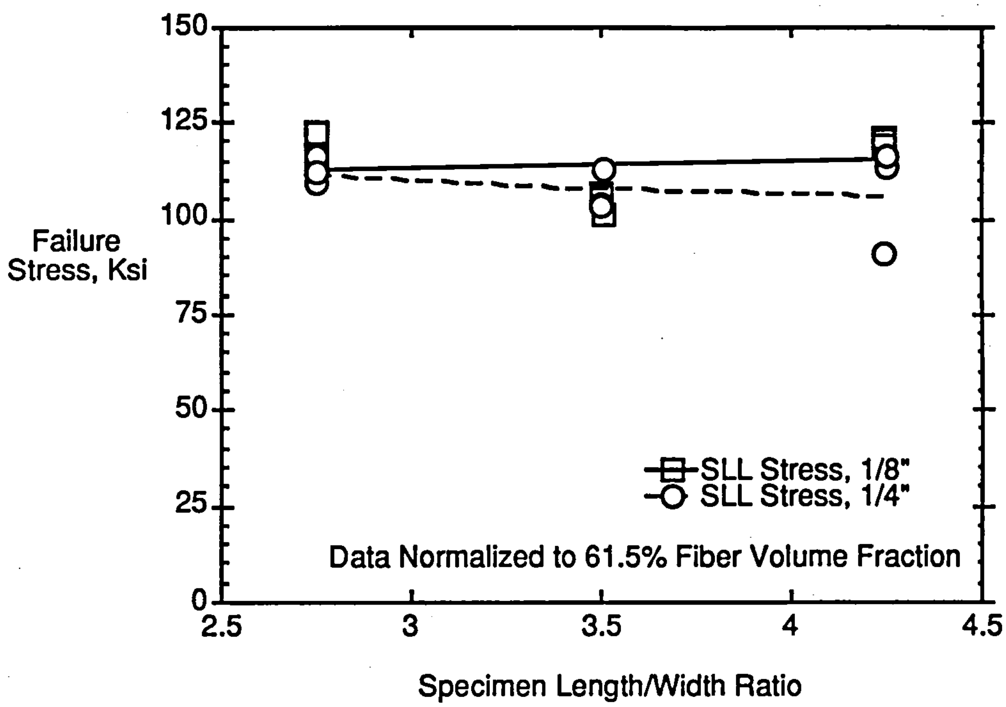

Figure 13. Effect of Length to Width Ratio on Failure Strength for the SLL $[0_{30K}/\pm 70_{6K}]_{46\%}$ Material.

Examination of Figure 13 shows that again, no clear trend was found. Normalizing this data by specimen width did not demonstrate a different behavior from that shown in Figure 11. Strength did vary by as much as 32 ksi in one discreet case but in general was fairly constant. Specimen thickness also had little or no effect on strength. Some difference is seen with increasing length to width ratio but this is mostly the result of data scatter.

Figure 14, a plot of the LLS $[0_{36K}/\pm 45_{15K}]_{46\%}$ material, shows a similar behavior. Curve fits to the data are basically flat. Thus no improvement in failure strength is obtained by increasing the specimen width to length ratio or by varying thickness. Strength did vary by as much as 24 ksi or 30 percent, but the averages were again fairly constant.

In general, no effect of specimen length to width was found. Two material architectures were investigated at two different thicknesses. Failure stress appeared to not be influenced by specimen length or thickness.

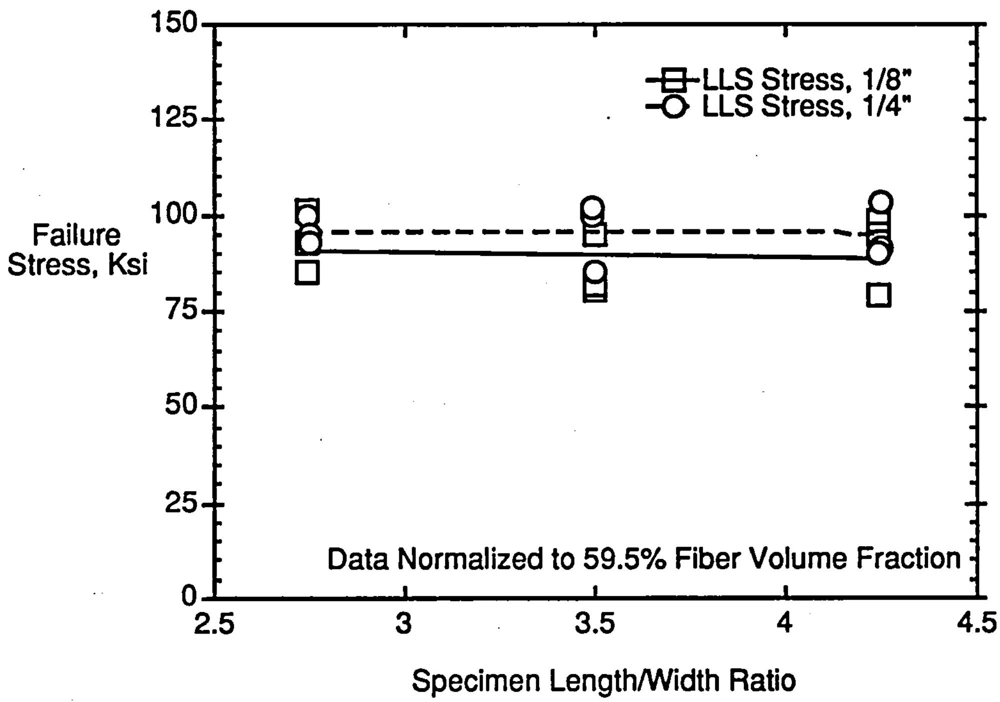

Figure 14. Effect of Length to Width Ratio on Failure Strength for the LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ Material.

Comparison of this data with WVU's data suggests similar results. Their average data is given in Appendix D. WVU only tested nominal 1/8" thick plates. Their average failure stresses were similar to Boeing's test results. The LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ material varied only 1.5 percent from Boeing's average. The SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ material varied 3.4 percent. These small differences suggest consistency between laboratory tests and that thickness did not effect their test results either.

Boeing and Lockheed reported results from tension testing of 3-D weaves. Boeing also tested stitched uniweaves and Lockheed tested a 3-D braid. Specimen width, length, and thickness were not varied. Examination of the scatter in the test results does, however, provide some quantitative measure of the effect of the specimen geometry on the test results. Figure 15 is a plot of the lowest and highest value of the %CoV for each of the textile architectures. Results from each of the test programs are given. Summaries of the test data are given for these materials in Appendices B and C.

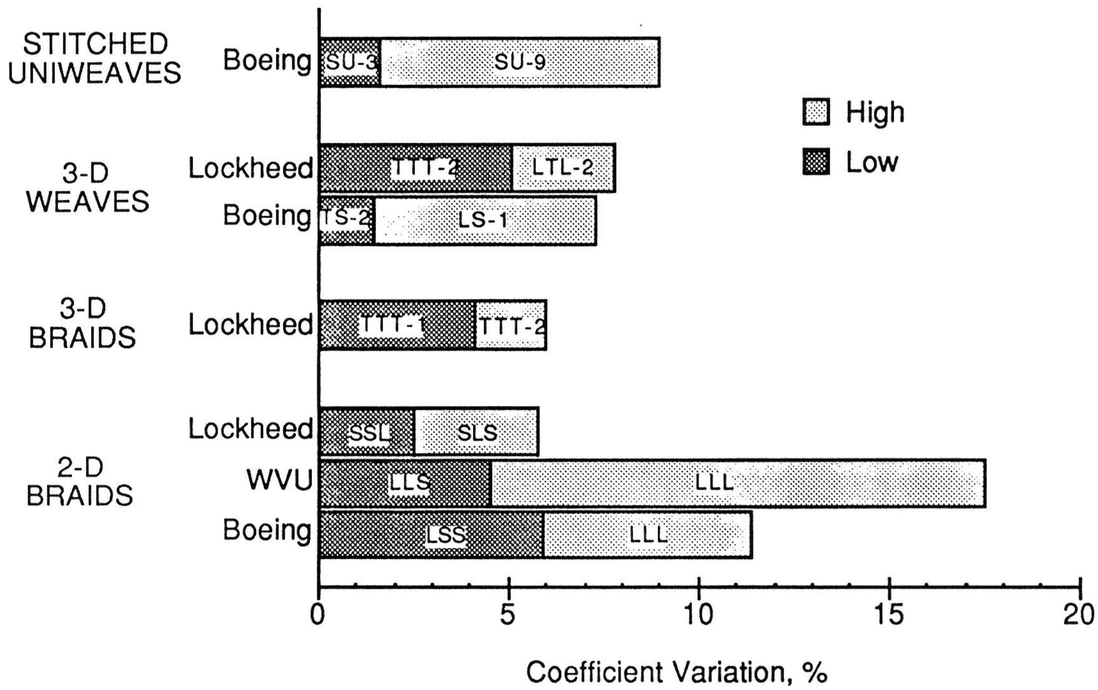

Figure 15. Plot of Each Textile Architecture's Coefficient of Variation.

With Boeing's 3-D weaves, the %CoV in failure stress was small. It ranged from as little as 1.5 percent with the TS-2 material to as much as 7.3 percent with the LS-1 material. Lockheed's weaves showed similar results. The range in %CoV of their data was 5.1 percent with the TTT-2 material to 7.8 percent with the LTL-2 material. Comparing these ranges with the results presented for the 2-D braids of similar size suggest that size effects were not present.

Boeing's stitched uniweaves had %CoV's ranging from 1.6 to 9.0. These ranges are within those obtained from the 2-D braid tests. Overall, the scatter in the stitched uniweave data was less than that obtained with the Boeing's 2-D braided material. Again this suggests that size effects were not present.

Lockheed's 3-D braids had %CoV's of 4.1 and 6.0. Comparing these results with those obtained for the 2-D braids again suggests that sizing effects were not present.

Concluding Remarks

An investigation was conducted by researchers at the Boeing Defense & Space Group to investigate the effects of specimen sizing on several braided textile materials [1]. Test results from this and other test programs were compared in an effort to determine what effect, if any, specimen size has on elastic property measurements of unnotched tension test.

In general, the unnotched tensile strength of 2-D braids was found to be insensitive to specimen width, length, or thickness effects. The results from this study suggest that standard testing methods used for tape materials may be sufficient for tension testing of textile composite materials. Specifically, the straight sided specimen geometry described in ASTM D3039, and used by Boeing, should provide acceptable results.

Further experiments performed at Boeing and by other investigators on other textile architectures suggest similar results. Although specimen size studies were not conducted, failing stresses varied on the same order as those obtained with the 2-D materials. This suggests that the accuracy of the results were consistent with those obtained with the 2-D materials.

References

1. Minguet, Pierre J., Fedro, Mark J., Gunther, Christian K., "Test Methods for Textile Composites" NASA CR 4609, July 1994.

2. Falcone, A., Dursch, H., Nelson, K., Avery, W., "Resin Transfer Molding of Textile Composites," NASA CR 191505, March 1993.

Appendix A:
Boeing's 2-D Braid Data

Table A1. SLL, $[0_{30K}/\pm70_{6K}]_{46\%}$ - 1.0 in. Nominal Width Test Data.

Vf	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.647	3.5	1.002	0.107	2.1878	120.09	114.22
0.647	3.5	1.002	0.108	2.1878	114.38	108.79
0.647	3.5	1.003	0.108	2.1900	113.52	107.97
0.647	3.5	1.002	0.109	2.1878	113.33	107.79
0.599	3.5	1.002	0.212	2.1878	106.72	109.64
0.599	3.5	1.001	0.213	2.1856	116.44	119.62
0.599	3.5	1.002	0.213	2.1878	111.12	114.16
0.599	3.5	1.001	0.214	2.1856	107.17	110.10
0.599	3.5	1.002	0.215	2.1878	97.319	99.980
			Average	2.1857	111.12	110.25
			Std Dev.	.00131	6.665	5.455
			CoV [%]	.06	5.99	4.95

Table A2. SLL, $[0_{30K}/\pm70_{6K}]_{46\%}$ - 1.5 in. Nominal Width Test Data.

Vf	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.635	5.25	1.500	0.107	3.2751	121.24	117.49
0.635	5.25	1.501	0.107	3.2773	108.08	104.74
0.635	5.25	1.501	0.107	3.2773	113.32	109.82
0.616	5.25	1.499	0.216	3.2729	108.33	108.22
0.616	5.25	1.500	0.216	3.2751	97.108	97.010
0.616	5.25	1.500	0.215	3.2751	111.12	111.01
			Average	3.2755	109.87	108.05
			Std Dev.	.001644	7.8882	6.8392
			CoV [%]	0.05	7.18	6.33

Appendix A (continued)

Table A3. SLL, $[0_{30K}/\pm70_{6K}]_{46\%}$ - 2.0 in. Nominal Width Test Data.

V_f	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.611	5.5	2.000	0.104	4.3668	115.19	116.02
0.611	5.5	2.003	0.104	4.3734	121.38	122.25
0.611	5.5	2.001	0.109	4.3690	113.14	113.95
0.623	5.5	2.001	0.207	4.3690	117.67	116.23
0.623	5.5	2.002	0.208	4.3712	110.62	109.27
0.623	5.5	2.000	0.213	4.3668	113.25	111.86
0.600	7.0	2.002	0.106	4.3712	103.70	106.36
0.600	7.0	1.999	0.107	4.3646	98.21	100.73
0.600	7.0	2.000	0.107	4.3668	103.22	105.87
0.574	7.0	1.997	0.209	4.3603	105.28	112.87
0.574	7.0	2.001	0.210	4.3690	97.11	104.11
0.574	7.0	2.000	0.214	4.3668	95.91	102.83
0.611	8.5	2.005	0.105	4.3777	119.96	120.82
0.611	8.5	2.003	0.107	4.3734	118.40	119.25
0.611	8.5	2.005	0.108	4.3777	119.27	120.13
0.623	8.5	2.004	0.204	4.3755	91.540	90.42
0.623	8.5	2.002	0.206	4.3712	114.96	113.55
0.623	8.5	2.002	0.209	4.3712	117.38	115.94
			Average	4.3701	109.79	111.25
			Std Dev.	.0045	9.46	8.27
			CoV [%]	0.10	8.62	7.44

Table A4. SLL, $[0_{30K}/\pm70_{6K}]_{46\%}$ - 2.5 in. Nominal Width Test Data.

V_f	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.647	8.75	2.501	0.106	5.4607	126.26	120.09
0.647	8.75	2.501	0.106	5.4607	121.83	115.88
0.647	8.75	2.501	0.107	5.4607	117.99	112.22
0.599	8.75	2.500	0.212	5.4585	110.79	113.82
0.599	8.75	2.501	0.212	5.4607	118.32	121.56
0.599	8.75	2.502	0.212	5.4629	112.19	115.26
			Average	5.4607	117.90	116.47
			Std Dev.	.0014	5.81	3.63
			CoV [%]	0.025	4.94	3.12

Table A5. LLS, $[0_{36K}/\pm45_{15K}]_{46\%}$ - 1.0 in. Nominal Width Test Data.

V_f	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.589	3.5	1.001	0.115	2.412	86.446	87.350
0.589	3.5	1.000	0.117	2.410	82.141	83.000
0.589	3.5	1.000	0.119	2.410	82.507	83.370
0.589	3.5	1.002	0.120	2.414	83.259	84.130
0.582	3.5	1.002	0.220	2.414	76.363	78.090
0.582	3.5	1.000	0.221	2.410	77.527	79.280
0.582	3.5	1.000	0.222	2.410	81.468	83.310
			Average	2.411	81.38	82.65
			Std Dev.	0.002	3.44	3.09
			CoV [%]	0.09	4.22	3.75

Table A6. LLS, $[0_{36K}/\pm45_{15K}]_{46\%}$ - 1.5 in. Nominal Width Test Data.

V_f	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.618	5.25	1.502	0.108	3.619	109.470	105.420
0.618	5.25	1.501	0.109	3.617	111.630	107.500
0.618	5.25	1.504	0.111	3.624	104.600	100.730
0.624	5.25	1.500	0.220	3.615	102.680	97.930
0.624	5.25	1.499	0.223	3.612	100.600	95.950
0.624	5.25	1.501	0.225	3.617	101.130	96.460
			Average	3.6173	105.02	100.66
			Std Dev.	0.004	4.55	4.83
			CoV [%]	0.11	4.34	4.80

Appendix A (continued)

Table A7. LLS, $[0_{36K}/\pm45_{15K}]_{46\%}$ - 2.0 in. Nominal Width Test Data.

V_f	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.608	5.50	2.003	0.109	4.826	94.639	92.640
0.608	5.50	2.002	0.109	4.824	103.630	101.440
0.608	5.50	2.002	0.109	4.824	87.396	85.550
0.570	5.50	2.002	0.220	4.824	95.524	99.740
0.570	5.50	2.000	0.221	4.819	90.946	94.960
0.570	5.50	2.000	0.224	4.819	88.887	92.810
0.599	7.00	2.000	0.108	4.819	81.029	80.510
0.599	7.00	2.000	0.108	4.819	82.469	81.940
0.599	7.00	2.000	0.110	4.819	95.230	94.620
0.582	7.00	2.003	0.218	4.826	97.290	99.490
0.582	7.00	2.002	0.218	4.824	99.500	101.750
0.582	7.00	2.001	0.218	4.822	83.639	85.530
0.608	8.50	2.004	0.110	4.829	100.410	98.290
0.608	8.50	2.002	0.110	4.824	80.704	79.000
0.608	8.50	2.003	0.112	4.826	96.794	94.750
0.570	8.50	2.000	0.219	4.819	99.115	103.490
0.570	8.50	1.999	0.220	4.817	87.651	91.520
0.570	8.50	2.001	0.227	4.822	86.454	90.270
			Average	4.8225	91.739	92.68
			Std Dev.	0.003	7.21	7.58
			CoV [%]	0.07	7.85	8.09

Table A8. LLS, $[0_{36K}/\pm45_{15K}]_{46\%}$ - 2.5 in. Nominal Width Test Data.

V_f	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.589	8.75	2.503	0.109	6.031	86.218	87.120
0.589	8.75	2.501	0.110	6.027	91.780	92.740
0.589	8.75	2.505	0.111	6.036	93.007	93.980
0.605	8.75	2.505	0.214	6.036	94.944	93.400
0.605	8.75	2.503	0.218	6.031	98.543	96.940
0.605	8.75	2.502	0.224	6.029	91.752	90.260
			Average	6.032	92.71	92.41
			Std Dev.	.004	4.07	3.37
			CoV [%]	0.06	4.39	3.64

Table A9. LLL, $[0_{75K}/\pm70_{15K}]_{46\%}$ - 1.0 in. Nominal Width Test Data.

V_f	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.638	3.50	0.999	0.106	1.205	103.360	103.080
0.638	3.50	0.996	0.106	1.201	97.484	97.220
0.638	3.50	0.999	0.107	1.205	85.843	85.610
0.638	3.50	1.000	0.108	1.206	103.190	102.910
0.641	3.50	1.000	0.217	1.206	84.201	83.580
0.641	3.50	0.999	0.219	1.205	96.512	95.800
0.641	3.50	1.000	0.220	1.206	92.613	91.930
			Average	1.2052	94.743	94.304
			Std Dev.	0.002	7.65	7.72
			CoV [%]	0.14	8.07	8.19

Table A10. LLL, $[0_{75K}/\pm70_{15K}]_{46\%}$ - 1.5 in. Nominal Width Test Data.

V_f	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.638	5.25	1.500	0.109	1.809	95.409	95.150
0.638	5.25	1.500	0.112	1.809	85.071	84.840
0.638	5.25	1.503	0.113	1.813	83.908	83.680
0.641	5.25	1.500	0.218	1.809	97.006	96.290
0.641	5.25	1.501	0.219	1.811	95.696	94.990
0.641	5.25	1.501	0.224	1.811	92.754	92.070
			Average	1.8104	91.641	91.17
			Std Dev.	0.001	5.72	5.54
			CoV [%]	0.08	6.24	6.08

Table A11. LLL, $[0_{75K}/\pm70_{15K}]_{46\%}$ - 2.0 in. Nominal Width Test Data.

V_f	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.661	7.00	2.003	0.109	2.416	100.720	96.950
0.661	7.00	2.003	0.110	2.416	103.940	100.050
0.661	7.00	2.003	0.111	2.416	94.942	91.390
0.641	7.00	2.004	0.222	2.417	73.835	73.290
0.641	7.00	2.003	0.223	2.416	94.034	93.340
0.641	7.00	2.001	0.223	2.414	90.266	89.600
			Average	2.416	92.956	90.77
			Std Dev.	0.001	10.57	9.36
			CoV [%]	0.05	11.37	10.31

Table A12. LLL, $[0_{75K}/\pm70_{15K}]_{46\%}$ - 2.5 in. Nominal Width Test Data.

V_f	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.606	8.75	2.502	0.107	3.018	81.690	85.770
0.606	8.75	2.503	0.108	3.019	88.928	93.370
0.606	8.75	2.503	0.110	3.019	80.156	84.160
0.622	8.75	2.505	0.211	3.022	95.450	97.640
0.622	8.75	2.504	0.213	3.020	97.738	99.980
0.622	8.75	2.501	0.217	3.017	84.277	86.210
			Average	3.0193	88.040	91.188
			Std Dev.	0.002	7.29	6.74
			CoV [%]	0.06	8.29	7.39

Table A13. LSS, $[0_{6K}/\pm45_{15K}]_{12\%}$ - 1.0 in. Nominal Width Test Data.

Vf	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.619	3.50	1.000	0.105	2.410	55.304	56.300
0.619	3.50	1.001	0.109	2.412	48.604	49.480
0.619	3.50	0.999	0.111	2.407	54.852	55.840
0.622	3.50	0.999	0.204	2.407	53.923	54.630
0.622	3.50	1.001	0.206	2.412	56.223	56.960
0.622	3.50	0.999	0.208	2.407	57.131	57.880
0.622	3.50	1.000	0.212	2.410	56.431	57.170
			Average	2.409	54.638	55.46
			Std Dev.	0.002	2.87	2.84
			CoV [%]	0.09	5.25	5.12

Table A14. LSS, $[0_{6K}/\pm45_{15K}]_{12\%}$ - 1.5 in. Nominal Width Test Data.

Vf	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.645	5.25	1.502	0.105	3.619	61.813	60.390
0.645	5.25	1.501	0.105	3.617	58.036	56.700
0.645	5.25	1.500	0.107	3.615	57.934	56.600
0.642	5.25	1.507	0.202	3.631	56.004	54.970
0.642	5.25	1.502	0.203	3.619	56.727	55.680
0.642	5.25	1.503	0.204	3.622	57.196	56.140
0.642	5.25	1.504	0.207	3.624	58.021	56.950
			Average	3.621	57.962	56.77
			Std Dev.	0.005	1.86	1.73
			CoV [%]	0.15	3.21	3.05

Appendix A (continued)

Table A15. LSS, $[0_{6K}/\pm45_{15K}]_{12\%}$ - 2.0 in. Nominal Width Test Data.

V_f	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.629	7.00	2.006	0.105	4.834	57.645	57.750
0.629	7.00	2.003	0.107	4.826	50.278	50.370
0.629	7.00	2.001	0.107	4.822	50.418	50.510
0.642	7.00	2.001	0.203	4.822	53.620	52.630
0.642	7.00	2.003	0.205	4.826	56.788	55.740
0.642	7.00	2.003	0.209	4.826	55.759	54.730
			Average	4.8261	54.088	53.63
			Std Dev.	0.004	3.19	2.96
			CoV [%]	0.009	5.90	5.53

Table A16. LSS, $[0_{6K}/\pm45_{15K}]_{12\%}$ - 2.5 in. Nominal Width Test Data.

V_f	Length in.	Width in.	Thickness in.	Number of Unit Cells	Normalized Stress, ksi	Stress ksi
0.619	8.75	2.504	0.104	6.034	53.555	54.520
0.619	8.75	2.502	0.104	6.029	53.133	54.090
0.619	8.75	2.501	0.104	6.027	55.009	56.000
0.622	8.75	2.500	0.199	6.024	51.703	52.380
0.622	8.75	2.504	0.202	6.034	53.844	54.550
0.622	8.75	2.502	0.204	6.029	58.089	58.850
			Average	6.029	54.222	55.06
			Std Dev.	0.004	2.17	2.18
			CoV [%]	0.06	4.01	3.97

Appendix B:
Boeing's 3-D Weave and Stitched Laminate Data

Table B1. Tensile Properties of 3-D Weaves.

Property	OS-1	OS-2	TS-1	TS-2	LS-1	LS-2
Strength [ksi]	137.4	92.9	137.6	131.8	138.9	96.1
Nominal Strain [ms]	11,900	7,890	10,950	11,350	11,300	7,870
CoV [%]	2.9	2.6	1.8	1.5	7.3	5.1
Modulus [msi]	11.55	11.78	12.57	11.61	12.29	12.22
CoV [%]	1.8	0.4	0.6	0.1	2.0	0.4
Poisson's Coefficient	0.034	0.046	0.060	0.040	0.060	0.040
CoV [%]	14.9	9.8	7.2	19.0	7.2	19.0

Table B2. Tensile Properties of Stitched Uniweave.

Property	SU-1	SU-2	SU-3	SU-4	SU-5
Strength [ksi]	85.8	75.9	79.0	82.2	70.3
Nominal Strain [ms]	12,410	11,700	11,430	11,630	10,460
CoV [%]	3.0	2.1	1.6	2.8	9.0
Modulus [msi]	6.92	6.49	6.91	7.06	6.72
CoV [%]	0.8	1.5	2.0	0.3	0.8
Poisson's Ratio	0.306	0.293	0.341	0.303	0.304

Appendix C:
Lockheed's Unnotched Tension Test Data

Table C1. Summary of 3-D Weave Test Results.

Property	TTT-2	LTL-1	LTL-2
Strength [ksi]	108.47	123.04	102.31
CoV [%]	5.1	6.0	7.8
Nominal Strain [ms]	11,633	11,307	10,666
Modulus [msi]	9.27	10.37	9.28
CoV [%]	4.0	1.5	2.0
Poisson's Ratio	0.057	0.047	0.062

Table C2. Summary of 2-D Triaxial Braid Test Results.

Material	V_f	Failure Stress, ksi	% COV
SSL $[0_{12K}/\pm60_{6K}]_{33\%}$	54.94	72.78	2.50
SLL $[0_{24K}/\pm60_{6K}]_{46\%}$	64.97	96.90	5.81

Table C3. Summary of 3-D Braid Test Results.

Material	V_f	Failure Stress, ksi	% COV
TTT-1	56.53	80.94	4.1
TTT-2	57.7	104.34	6.0

Appendix D:
West Virginia University's Unnotched Tension Test Data

Table D1. Summary of 2-D Braid Results.

Material	Failure Stress, ksi	Std. Dev.
SLL $[0_{30K}/\pm70_{6K}]_{46\%}$	108.1	10.9
LLS $[0_{36K}/\pm45_{15K}]_{46\%}$	94.1	4.2
LLL $[0_{75K}/\pm70_{15K}]_{46\%}$	77.7	13.6
LSS $[0_{6K}/\pm45_{15K}]_{12\%}$	50.7	2.8

Note: Strengths Normalized to 60% Fiber Volume Fraction

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6. AUTHOR(S)

M. A. Portanova

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Lockheed Martin Engineering & Sciences
144 Research Drive
Hampton, VA 23666

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13. ABSTRACT (*Maximum 200 words*)

An investigation was conducted by researchers at the Boeing Defense & Space Group to investigate the effects of specimen sizing on several braided textile materials. Test results from this and other test programs were compared in an effort to determine what effect, if any, specimen size has on elastic property measurements of unnotched tension test.

In general, the unnotched tensile strength of 2-D braids was found to be insensitive to specimen width, length, or thickness effects. The results from this study suggest that standard testing methods used for tape materials may be sufficient for tension testing of textile composite materials. Specifically, the straight sided specimen geometry described in ASTM 3034, and used by Boeing, should provide acceptable results. Further experiments performed at Boeing and by other investigators on other textile architectures suggest similar results. Although specimen size studies were not conducted, failing stresses varied on the same order as those obtained with the 2-D materials. This suggests that the accuracy of the results were consistent with those obtained with the 2-D materials.

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