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Standard Methods for Open Hole Tension Testing of Textile Composites

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Introduction

Textile composites are candidate materials for damage tolerant designs because they offer through-the-thickness reinforcement which aids in the prevention of damage progression. Textile composites have a less homogeneous nature than composites constructed from pre-preg tape. Consequently, standard testing methods developed for tape composites may not be adequate to characterize these materials. Because of this concern, NASA's Advanced Composite Technology Program (ACT) funded researchers at the Boeing Defense & Space Group to investigate the effects of specimen geometry and loading mode on the measurement of the textile composites' mechanical properties, Ref. [1].

This report evaluates the open hole tension test methods used by Boeing and other investigators in the ACT program. The intention is to develop a standard open hole tension test method that considers the effects of hole size, hole size to specimen width ratio, specimen thickness, and the architectural variation in textile composite forms. Because no testing standards exist for textile composites, most researchers use guidelines established for the testing of tape composites. One aspect of this investigation is to determine if these standard testing methods are suitable for use on textile materials.

This investigation will compare the results of several research programs evaluating the material response of similar textile architectures. Test results from independent studies conducted at West Virginia University (WVU), Lockheed Aeronautical Systems, and Boeing Defense and Space Group will be evaluated and compared. Boeing conducted the only investigation explicitly designed to determine the effects of specimen thickness, width, and hole size on measurements of material properties. The results from the Boeing study will be the primary focus of this paper.

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 (2-D) triaxial braids and three-dimensional (3-D) interlocking weaves. Lockheed also evaluated a three dimensional braid. Some results for stitched uniweaves, tested at Boeing, are also presented.

Boeing and WVU evaluated identical 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 properties similar to Hercules 3501-6. Each resin system is a low-cost brittle epoxy system with low viscosity at melt temperature, thereby lending themselves to the resin transfer molding process.

2-Dimensional Triaxial Braid Architectures

All of the 2-D fabric preforms were braided by Fiber Innovations Inc., Norwood, MA. The Boeing and WVU materials featured Shell RSL-1895 epoxy resin. Details of their manufacture, which was performed at Boeing, 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.

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	±70	0.458	0.083
LLS $[0_{36K}/\pm45_{15K}]_{46\%}$	36 K	15 K	46	±45	0.415	0.207
LLL $[0_{75K}/\pm70_{15K}]_{46\%}$	75 K	15 K	46	±70	0.829	0.151
LSS $[0_{6K}/\pm45_{15K}]_{12\%}$	6 K	15 K	12	±45	0.415	0.207

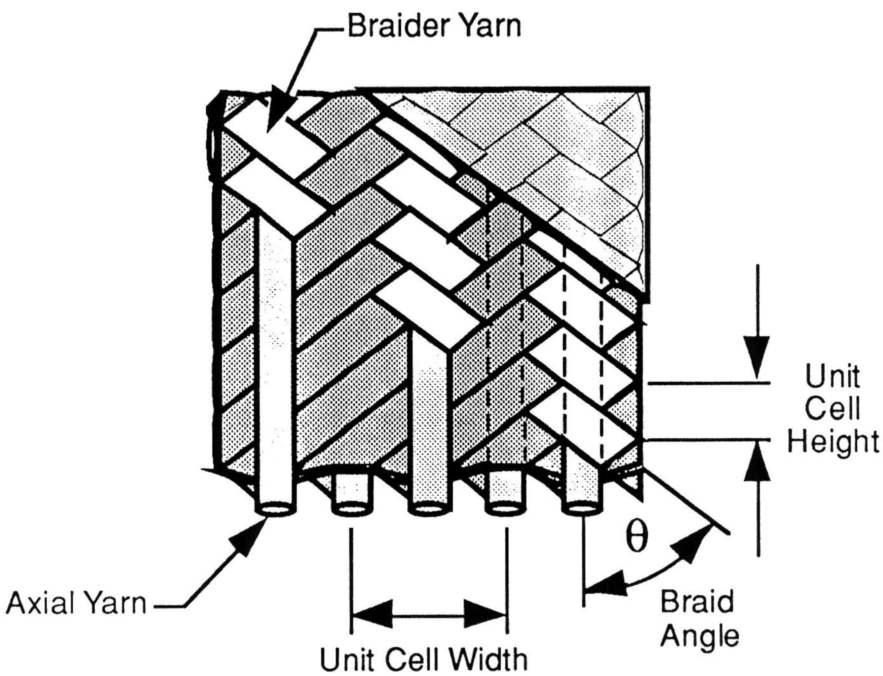

Figure 1. Illustration of a typical 2-D Triaxial Braid Configuration.

Lockheed's 2-D braids featured PR-500 epoxy resin. These laminates, which were manufactured at Lockheed's facility in Marietta, GA, utilized 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 [°]
$[0_{12K}/\pm 60_{6K}]_{33\%}$	12 K	6 K	33.3	±60
$[0_{24K}/\pm 60_{6K}]_{50\%}$	24K	6 K	50	±60

The Unit Cell

Textile composites have been shown to have a repeating geometrical pattern based on manufacturing parameters. This repeating pattern is often called the "unit cell." It is defined as the smallest section of architecture required to repeat the textile pattern.

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, the unit cell width is defined as two times the spacing of the axial tows. The 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 yarn carriers. 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. As shown in Table 1, the SLL $[0_{30K}/\pm 70_{6K}]_{46\%}$, LLS $[0_{36K}/\pm 45_{15K}]_{46\%}$, and LSS $[0_{6K}/\pm 45_{15K}]_{12\%}$ all had unit cells of similar width but for the SLL $[0_{30K}/\pm 70_{6K}]_{46\%}$ material, the unit cell length was less that half that of the other architectures. The LLL $[0_{75K}/\pm 70_{15K}]_{46\%}$ 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 parameters are a result of the braiding process, tow size used, and braid angle.

3-Dimensional Architectures

Three different 3-D composite architectures are evaluated in this investigation. An illustration of each is shown in Figure 2. Tow size and percent, along with an architectural description of each are provided in Tables 3, 4, and 5. Specimen sizing studies were not conducted using these material forms. Because of the complex nature of these materials, unit cell measurements have not been calculated.

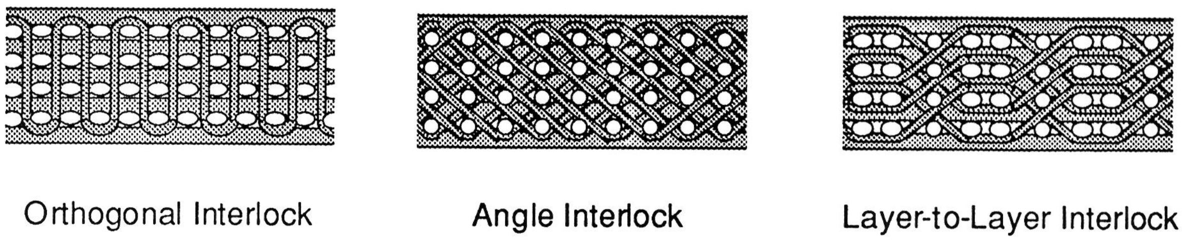

Figure 2. Depiction of 3-D Interlock Woven Materials.

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	24 K (59%)	12 K (33%)	6 K (7.4%)
OS-2	Orthogonal Interlock	12 K (58%)	6 K (37%)	3 K (6.1%)
TS-1	Through-The-Thickness	24 K (57%)	12 K (33%)	6 K (9.8%)
TS-2	Angle Interlock	12 K (56%)	6 K (38%)	3 K (5.8%)
LS-1	Layer-To-Layer	24 K (58%)	12 K (34%)	6 K (6.8%)
LS-2	Interlock	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. Both provided true through the thickness reinforcement by interlacing yarns in the z direction. 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 Orthogonal Interlock 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%)
TTT-3	Orthogonal Interlock	6 K (46.1%)	6 K (46.5%)	3 K (7.4%)
LTL-1	Layer-to-Layer	6 K (45.7%)	6 K (46.1%)	3 K (8.2%)
LTL-2	Orthogonal Interlock	12 K (46.3%)	6 K (45.6%)	3 K (8.1%)
LTL-3		6 K (46.3%)	6 K (46.7%)	3 K (7.0%)

Lockheed also produced and tested a series of three dimensional braids. Three braid configurations were evaluated. The specifics of each are described in Table 5. These 3-D fabrics were 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%)
TTT-3	±60	6 K (38.9%)	6 K (61.1%)

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.

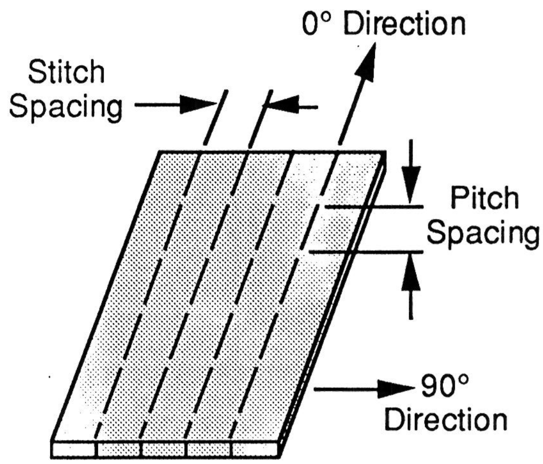

Figure 3. Depiction of Boeing's Stitched Uniweave.

Table 6. Description of Boeing's 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

Test Specimen Configuration & Testing Methodology

Boeing's Open Hole Tension Test Matrix

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 establish the test specimen dimensions for the 3-D weaves and stitched laminates.

The basic specimen used in this program is a straight sided coupon and is illustrated in Figure 4. Two specimen thickness, 1/8" and 1/4" were investigated. The specimen length was kept constant at 11.5 inches Various specimen widths and hole diameters were evaluated. Width to diameter (W/D) ratios of 4, 6, and 8 were used.

The test matrix used by Boeing is given in Table 7. This test matrix was chosen to optimize the information obtained from the limited number of test specimens to allow the investigation of thickness, hole diameter, and W/D ratio effects. Only the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ and LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ architectures have test results available at a common hole size for each of the W/D ratios evaluated. Consequently most of the analysis will be based on the results from these two materials.

Boeing tested stitched uniweaves and 3-D weaves using a more limited number of test specimens. Five different stitched uniweaves and six different 3-D weaves were tested to failure. Again, the straight sided coupon described in Figure 4 was used.

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. Load cell output and machine stroke were recorded. No strain measurements were made.

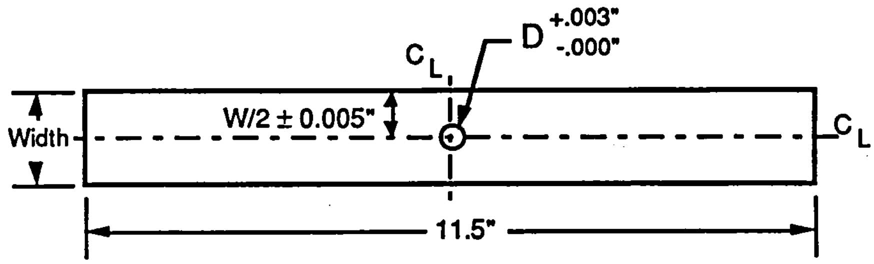

Figure 4. Boeing Straight Sided Tension Coupon.

Table 7. Boeing Test Matrix for Open Hole Tension Test Program.

Dimensions			Material Systems								
Width [in]	Diameter [in]	W/D	SLL 1/8"	SLL 1/4"	LLS 1/8"	LLS 1/4"	LLL 1/8"	LLL 1/4"	LSS 1/8"	LSS 1/4"	Others (1)
1.50	.375	4	3	3	3	3					3
1.50	.250	6	3	3	3	3					3
1.50	.188	8	3	3	3	3					3
2.25	.562	4	3	3	3	3	3	3	3	3	
2.25	.375	6	3	3	3	3	3	3	3	3	
2.25	.281	8	3	3	3	3	3	3	3	3	
3.00	.750	4	3	3	3	3					
3.00	.500	6	3	3	3	3					
3.00	.375	8	3	3	3	3					
			27	27	27	27	9	9	9	9	99

(1) Five Stitched Uniweave and Six 3-D Woven Materials.

Other Data Evaluated

Investigators at West Virginia University (WVU) conducted a notch sensitivity study of textile composites using the same 2-D textile architecture used in Boeing's sizing effects study, Ref. [3]. The object of the WVU study was to examine the effect of notches on the 2-D braided materials. The test matrix used in this study is given in Table 8. Specimen width to hole diameter ratio was kept constant with W/D = 4. Aluminum end tabs were bonded to the ends of the coupons. An illustration of WVU test specimen is given in Figure 5.

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 mounted to the face of the coupon and by a 1.0 inch gage length extensometer.

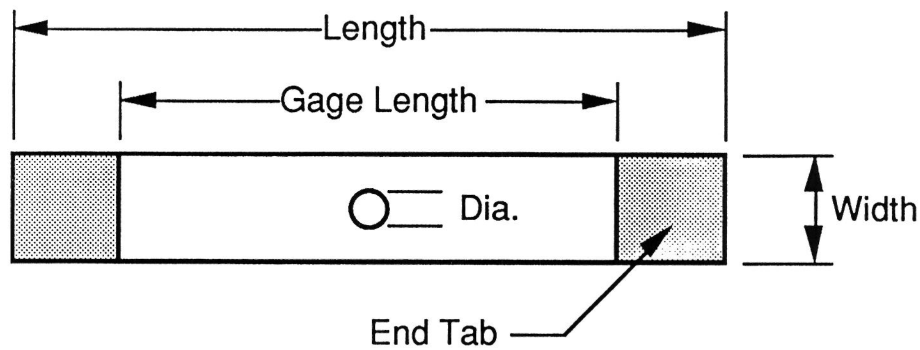

Figure 5. WVU Open Hole Tension Coupon.

Investigators at Lockheed also tested open hole tension specimens. Their study utilized a specimen with a constant W/D ratio of 5 and a hole diameter of 0.25 inch. Lockheed's test specimen is illustrated below in Figure 6. Although Lockheed tested entirely different braids and weaves than Boeing or WVU, the results of their study are provided in Appendices B and C for completeness.

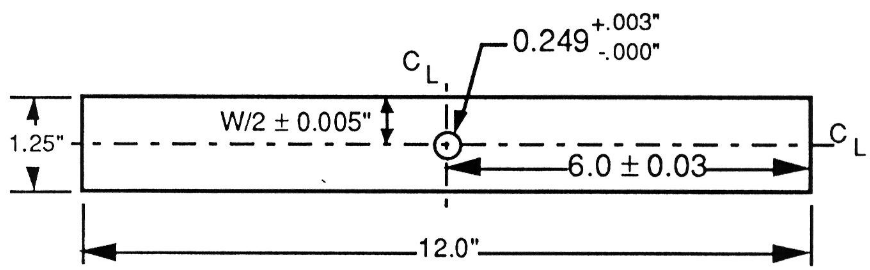

Figure 6. Lockheed Open Hole Tension Coupon.

Table 8. WVU Open Hole Tension Test Specimens.

Specimen Width	Specimen Length	Hole Diameter	Gage Length	Number of Specimens
1.0	6.0	0.25	4	*12, 15
2.0	11.0	0.50	8	5
4.0	12.0	1.0	9	5

*Number of Unnotched specimens

Data Reduction Method

Open hole tension strengths can be calculated using either the gross area or the net section area. Gross stress calculations can also be corrected for finite width effects. The corrected gross stress is the most readily used in design when size is large.

For an infinitely wide orthotropic plate with a hole (Figure 7), the stress at the edge of the hole is given by:

$$\sigma_{xx}(y=0) = K_{t\infty} S \tag{1}$$

where: σ_{xx} is the local stress in the loading direction,
S is the remote stress, and

$$K_{t\infty} = 1 + \sqrt{2(\sqrt{E_x / E_y} - \nu_{xy}) + E_x / G_{xy}} \tag{2}$$

For the isotropic case where $E_x/E_y = 1$, this reduces to

$$K_{t\infty} = 3$$

A method of correcting gross stress for finite width was used for all data analysis presented in this paper. An isotropic finite width correction factor was obtained from Ref. [4]. This factor is defined as the ratio of the stress concentration factor (SCF) in the finite width coupon to the SCF for a hole in an infinite plate.

For an isotropic plate of finite width, the stress at the edge of the hole is given by:

$$\hat{\sigma}_{xx}(y=0)=\frac{[2+(1-D/W)^3]}{3(1-D/W)}\sigma_{xx}(y=0) \qquad (3)$$

Expression 3 was used to correct all of the open hole data for finite width. Substituting W/D = 4, 6, and 8 into this expression yields correction factors of 1.076, 1.031, and 1.017, respectively.

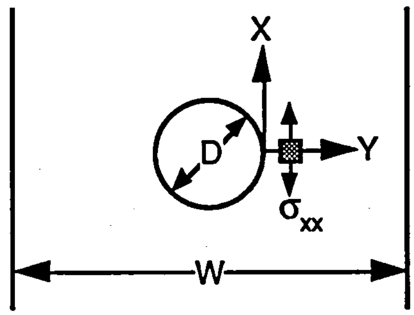

Figure 7. Illustration of the Stress Tensor in an Orthotropic Plate of Finite Width with a Hole.

Discussion of Results

Sizing effects have been investigated by comparing the open hole failure strengths of each of the four braided architectures listed in Table 1. Three parameters; specimen thickness, hole diameter, and the ratio of width to hole diameter were investigated. The data used were generated by Boeing and are 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 WVU's 3-D weaves. Summaries of the test results for the stitched and 3-D materials are given in Appendix B and C. Each of the values listed in the appendices are the average of three tests. The percent coefficients of variation (CoV%) for each set of test are also given.

Thickness Effects

Boeing's test matrix included both 1/8" and 1/4" nominal thickness 2-D braids. WVU tested the same 2-D braided architecture as Boeing, but only at the 1/8" thickness. No common width/hole size existed between the test matrices. Lockheeds 2-D Braids, although similar in thickness to the 1/8 braids tested at WVU and Boeing, were of a completely different architecture. Unfortunately, a direct comparison can not be made between Lockheed's and WVU test results and those from Boeing.

Boeing's test matrix permitted an evaluation of thickness effects for two of the four braided architectures studied. Test results are available for the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ and the LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ architectures with a common hole diameter of 0.375 inches (3/8") at each W/D ratio. In an attempt to investigate if thickness has an effect on ultimate strength, average failure strength has been plotted against the W/D ratio for a constant hole diameter in Figures 8 and 9. Failure strength for both 1/8" and 1/4" thickness are given. Each symbol is an average of three experiments. One standard deviation from the mean is indicated by the error bars. Linear curves are fit to the data using a least squares fit routine. Failure stress has been corrected for finite width and the W/D ratios plotted are nominal values.

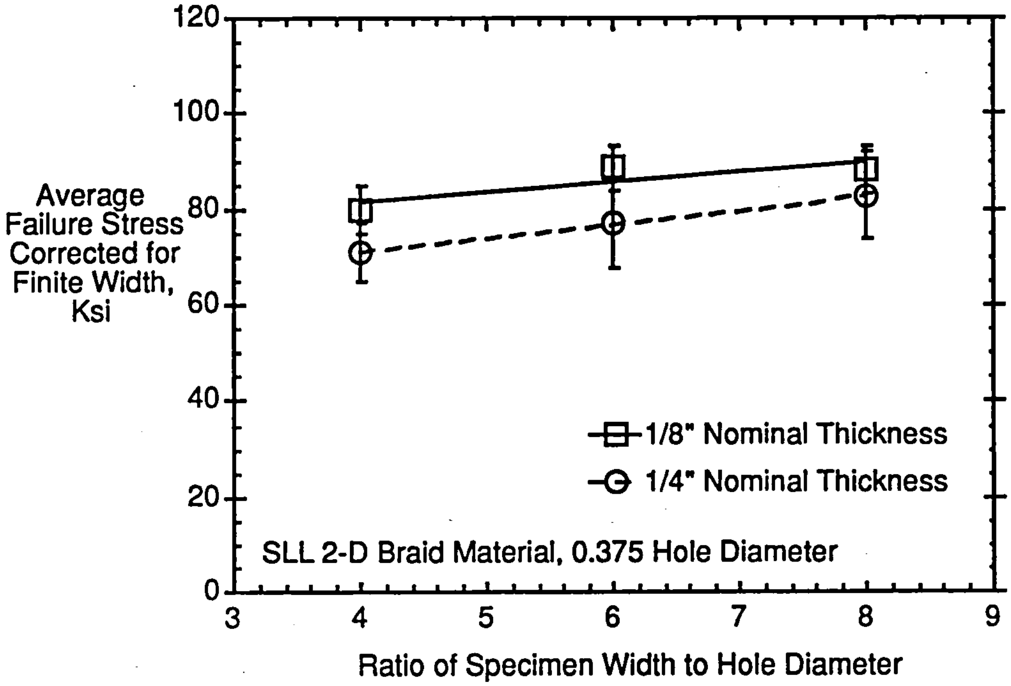

Figure 8. Effect of Specimen Thickness on Open Hole Tension Strength. SLL 2-D Braid with a 0.375 Diameter Hole.

Figure 8 is a plot of the average corrected failure strength versus specimen width to hole diameter for the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ material. A lower average failure stress was obtained with the thicker specimens. Their strengths were as much as 17 ksi, or 24 percent, lower. However, the scatter in the data, displayed by the error bars, overlapped, in all cases. The standard deviations measured for these data ranged from 4.5 to 9.3 ksi. Thus, the effect of thickness is small compared to the data scatter.

Figure 9, a plot of the average corrected failure strength versus specimen width to hole diameter for the LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ material, shows similar results. This material's failure strength varied by as much at 13 ksi, or 19 percent. The range of standard deviations was from 1.1 to 5.8 ksi. Notice that at W/D = 6, one standard deviation from the mean was from 1.1 to just 2.1 ksi and that the mean values were within 5 percent of each other. Again, the effect of thickness is small.

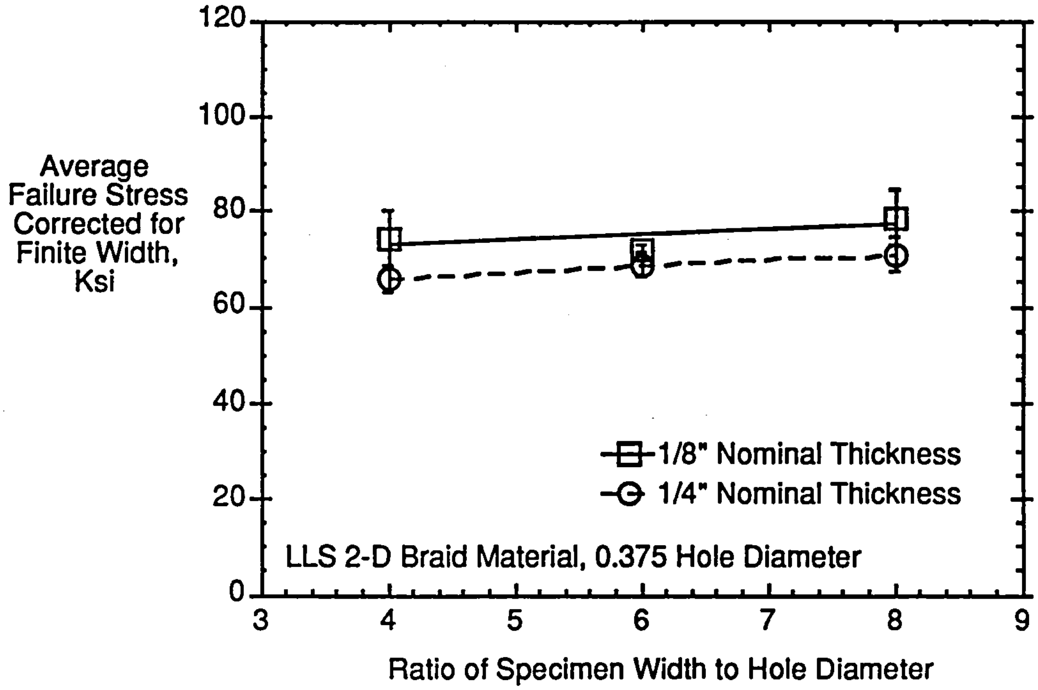

Figure 9. Effect of Specimen Thickness on Open Hole Tension Strength. LLS 2-D Braid with a 0.375 Diameter Hole.

Hole Diameter Effects

The failure strength of conventional composite materials are greatly influenced by the presence of a notch or hole. Composite materials that have linear stress-strain relationships to failure tend to be very notch sensitive. Textile composites having a balanced architecture, such as those tested by Boeing and WVU, have a stress-strain behavior similar to that of a quasi-isotropic tape laminate. They tend to exhibit fairly linear response during loading until failure. Because of this similarity to tape laminates, it is suspected that textile composites may be fairly notch sensitive.

The effect of hole size on failure strength has been evaluated using the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ and LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ architectures. In order to limit the dependent variable to just hole size, failure stress has been averaged for each hole size and plotted individually against the various W/D ratios in Figures 10 and 11. The results for each thickness have been plotted separately. Error bars, displaying one standard deviation from the mean of the failure strength are shown and logarithmic curves have been fit to the data. Failure stress was corrected for finite width and hole diameters plotted are nominal values.

Figure 10 is a plot of the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ data for the nominal 1/8 inch thick test coupons. Data from the Boeing and WVU test programs are shown. Failure stress tends to decrease with increasing hole size at all W/D ratios. This effect is most significant in the WVU W/D = 4 data. The WVU data, which contains holes of up to 1 inch in diameter, have as much as a 34 ksi, or 65 percent, decrease in failure strength over the range of hole sizes tested. The standard deviations of these data ranged from 1.7 to 0.74 ksi. Thus, the hole diameter has a significant effect.

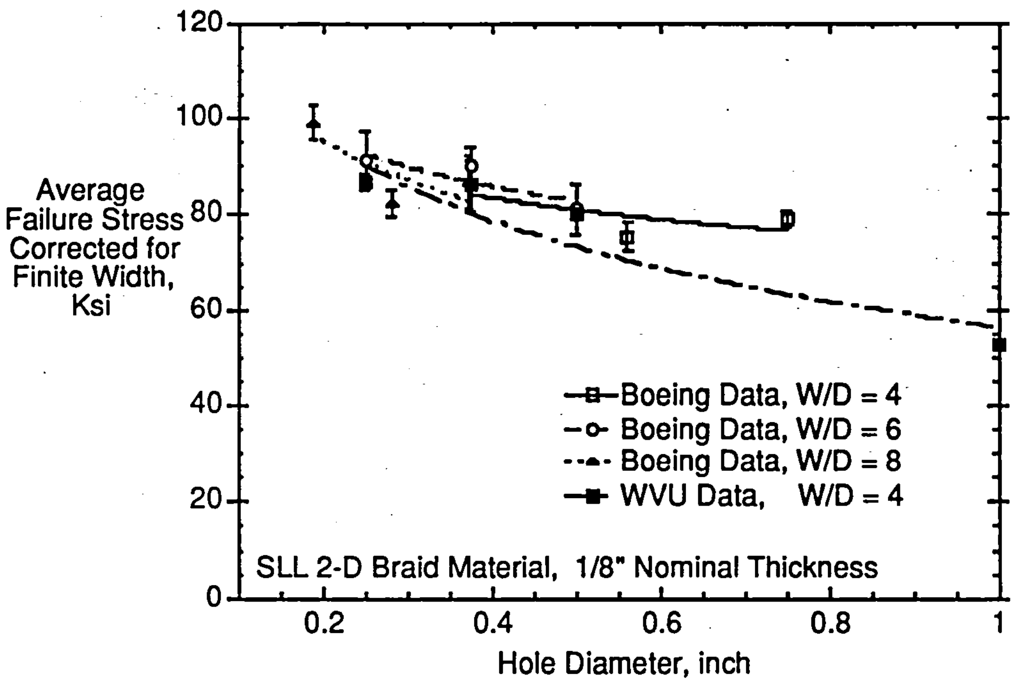

Figure 10. Effect of Hole Diameter on Open Hole Tension Strength. SLL 2-D Braid at 1/8" Nominal Thickness.

Hole size appears to have much less effect on the Boeing test results. At W/D = 4, the Boeing data showed a 14 percent or 11 ksi difference between the minimum and maximum value in failure strength over the range tested. At this W/D ratio, one standard deviation in the test results ranged from 1.8 to 5.2 ksi. The W/D = 6 data behaved in a similar fashion. These experiments resulted in a

13 percent or 10 ksi decrease in failure strength over the range of hole sizes tested. One standard deviation from the mean ranged from 4.3 to 6.1 ksi. Again, data scatter is reasonably small. The test results for the W/D ratio = 8 show a greater decrease in failure strength than the other ratios, but not as large as the WVU tests. At W/D = 8, failure strength decreased as much as 20 percent, or 17 ksi, over the range of hole sizes tested. One standard deviation from the mean for these experiments range from 0.74 to 1.72 ksi. This scatter is very small.

Figure 11 is a plot of the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ data for the nominal 1/4 inch thick test coupons. In this figure the effect of hole size on failure strength varies considerably. At both W/D = 4 and W/D = 6, failure strength appears to remain fairly constant over the range of hole sizes tested. The scatter in these data is large in some cases compared to the effect of the hole size. The W/D = 4 tests resulted in decreases in average failure strength of as much as 8.4 percent, or 6 ksi. The standard deviations of these data ranged from 3.4 to 6.1 ksi. The W/D = 6 test had failure strength reductions of as much as 7 percent, or 5 ksi, but the range for one standard deviation in the test results was large. It varied from 3.6 to 15.2 ksi. At W/D = 8 the test results varied as much as 11 percent or 9 ksi over the range of hole sizes tested. One standard deviation from the mean in these results ranged from 1.4 to 9.1 ksi. These experiments had the largest range in data scatter of all the tests. Consequently, hole size effects may not be statistically significant.

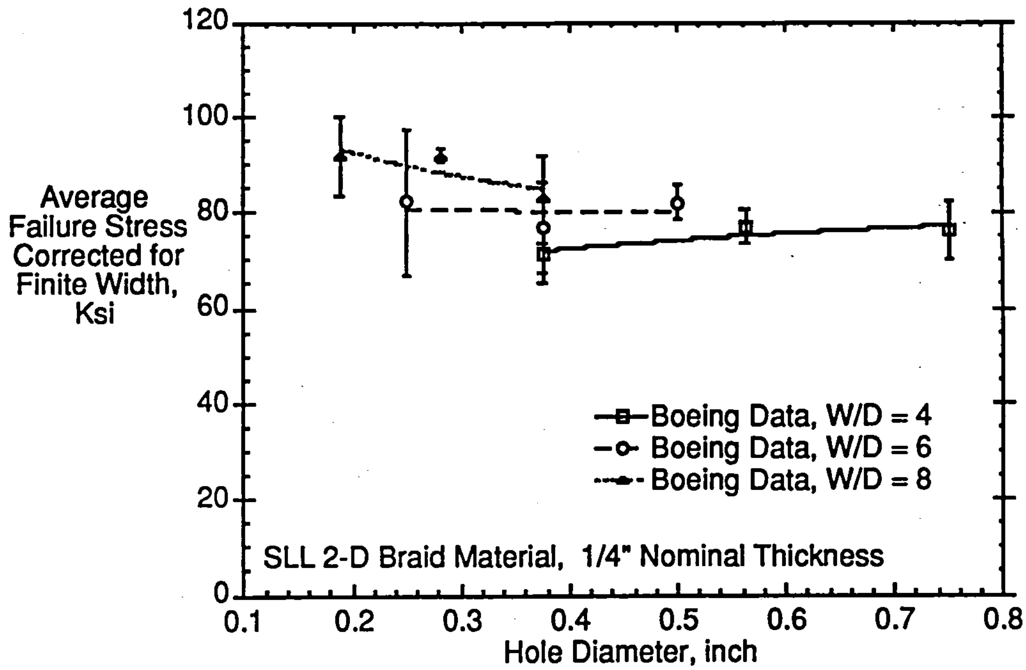

Figure 11. Effect of Hole Diameter on Open Hole Tension Strength. SLL 2-D Braid at 1/4" Nominal Thickness.

Figure 12 is a plot of the LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ test results for the nominal 1/8 inch thick test specimens. Data from both Boeing and WVU are shown. As with the 1/8" thick SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ material, failure strength appears to decrease with increasing hole size. The hole size effect is less evident in the WVU data in these experiments. Their failure strength decreased a maximum of 13 ksi, or 21 percent, over the range shown. The range for one standard deviation from the test average was from 0.74 to 1.5 ksi.

Boeing's W/D = 4 data was similar to WVU's but showed a larger decrease in average strength. These experiments showed as much as a 24 percent, or 15 ksi, decrease in failure strength. The data's standard deviations ranging from 2.4 to 6.2 ksi. At W/D = 6 there is little effect of hole size on this material form. Failure strength decreased only 6.5 percent, or 4.7 ksi. The standard deviations in these data were small; they ranged from 0.09 to 4.8 ksi. The W/D = 8 data have a decrease in failure strength of 16 percent, or 12 ksi. The range for one standard deviation in these data is from 0.7 to 5.8 ksi.

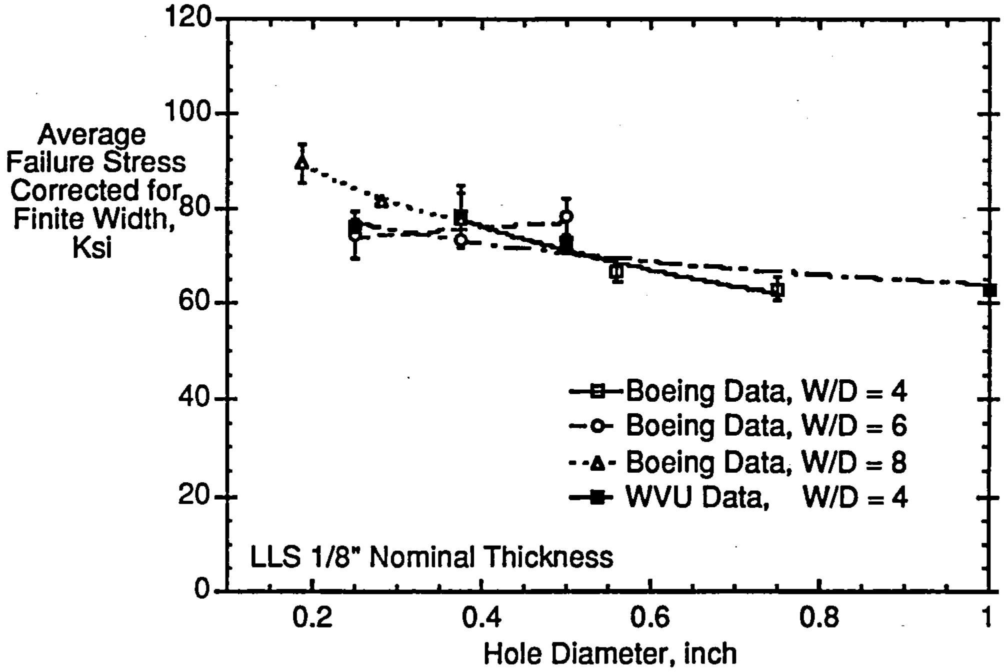

Figure 12. Effect of Hole Diameter on Open Hole Tension Strength. LLS 2-D Braid at 1/8" Nominal Thickness.

The hole size response of the LLS $[0_{36K}/\pm 45_{15K}]_{46\%}$ material with a 1/4 inch nominal plate thickness is shown in Figure 13. At this plate thickness the W/D = 4 data had a decrease in failure strength of up to 10 percent, or 6 ksi. The standard deviations in the data ranged from 2.9 to 3.1 ksi. The W/D = 6 data were similar. In fact, the two curves fit to these data overlap. The W/D = 6 data showed a maximum strength decreased of 10 ksi (15 percent). The range for one standard deviation in these test results was from 1.6 to 2.7. The W/D = 8 test results showed the greatest apparent effect of hole size. Strength decreased up to 22 percent or 15 ksi over the range of hole sizes tested. The data's scatter ranged from 1.8 to 3.6 ksi.

In general, the failure strength decreases somewhat with hole size. This is more pronounced at the smaller W/D ratios. The WVU data suggested a similar response to hole size as Boeing's LLS $[0_{36K}/\pm 45_{15K}]_{46\%}$ results. The SLL $[0_{30K}/\pm 70_{6K}]_{46\%}$ material appears to be more adversely affected by the large, 1 inch diameter hole tested at WVU. In most cases, the smaller hole sizes gave higher failure strength with a smaller amounts of data scatter. Both materials have similar unit cell sizes; thus, there was no opportunity to see the effect of unit cell size.

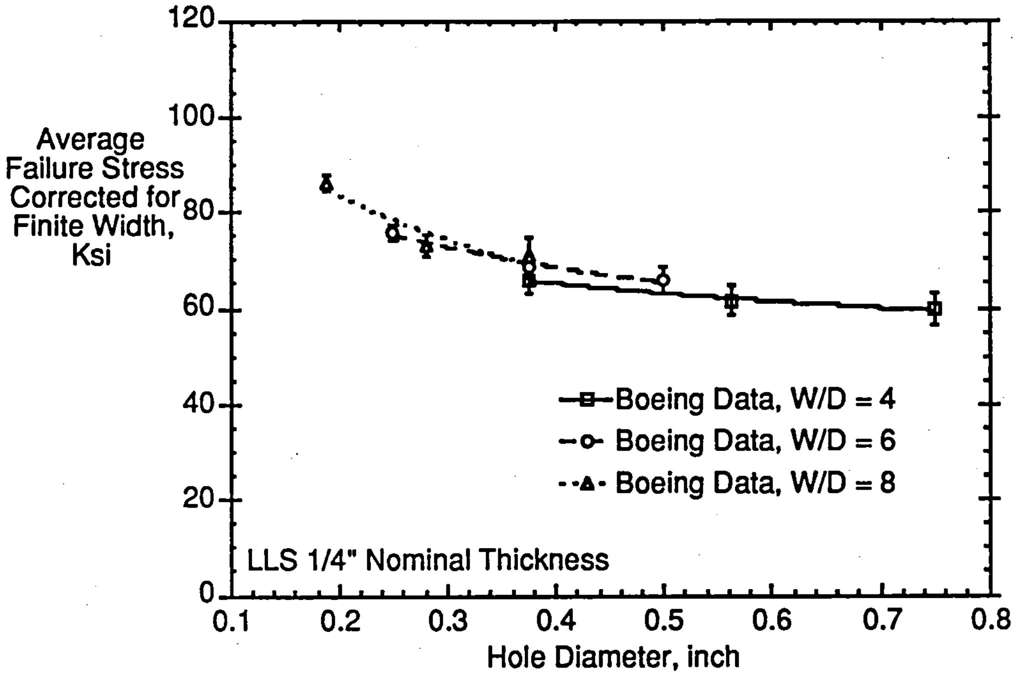

Figure 13. Effect of Hole Diameter on Open Hole Tension Strength. LLS 2-D Braid at 1/4" Nominal Thickness.

Specimen Width to Hole Size (W/D) Effects

The effect of specimen width to hole diameter is complicated. Stress risers, such as holes or notches have a pronounced effect on the ultimate strength of a composite material. The study of the mechanics of materials tells us that the effect of a hole or notch is related to its distance from a free edge. In the open hole tension test, when the distance from the edge of the hole to the edge of the specimen is small, the stress at the edge of the hole is large, compared to the remote stress. When the plate is wide compared to the hole diameter, the net effect of the hole is reduced.

As stated in the "Test Specimen Configuration & Testing Methodology" section, failure stress has been corrected using an isotropic finite width correction factor. In theory, if the finite width correction factor is accurate, and there is no size effect, the corrected stress should be the same for all specimen configurations.

Figures 8 and 9 provide a measure of the effectiveness of the correction factors employed in this analysis. The figures plot the average corrected failure stresses vs. the W/D ratios for the 1/8" and 1/4" thick SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ and LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ materials. The error bars shown in the figures represent one standard deviation in the data. Straight lines have been fit to the data through linear regression. If the width corrections were effective, the failure strengths should be insensitive to the W/D ratio and the lines fit to the corrected data should be horizontal.

The figures indicate, however, that the failure stress increases with increasing W/D ratio, even after being corrected for finite width. This trend is more apparent for the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ laminates (Fig. 8) than in the LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ laminates (Fig. 9). The latter material was less sensitive to changes in the W/D ratio than the former. For example, the failure stress measured for the 1/4" LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ specimens, increased 3 ksi (4%) as the W/D ratio increased from 4 to 6 and only 2 ksi (3%) when the W/D ratio increased to 8.

The increases in SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ materials' average failure stress with increasing W/D ratios are, however, comparable to the scatter in the data. They were not much greater than one standard deviation in the data. For example, the 1/4" SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ material showed a somewhat linear improvement in the average failure strength with increasing W/D ratio. Failure strength increased 6 ksi as the W/D ratio increased from 4 to 6; strength increased another 6 ksi as the ratio increased to 8. The standard deviations in these data were 6.0 ksi, 9.3 ksi, and 9.1 ksi, for W/D = 4, 6, and 8, respectively.

In general, the isotropic finite width correction factors were effective in accounting for the width effects in these tests.

Conclusions and Recommendations

The effects of three test specimen parameters, thickness, hole diameter, and the ratio of specimen width to hole diameter, have been investigated by comparing the open hole strengths of four braided architectures. The data used to make these comparisons was primarily generated by Boeing. Direct comparisons of Boeing's results were made with experiments conducted at West Virginia University whenever possible. Indirect comparisons were made with test results for other 2-D braids and 3-D weaves tested by Boeing and Lockheed.

In general, failure strength (corrected for width effects) was found to decrease with increasing plate thickness and increase with decreasing hole size. A review of the data also indicated that the isotropic finite width correction factors were generally effective in accounting for the width effects.

Of the two braids used for this evaluation, the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ material was less effected by thickness and generally had less data scatter. Both the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ and the LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ materials were somewhat sensitive to hole size. Hole size effects were more significant at smaller W/D ratios, especially at the largest hole size. Both the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ and LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ materials were relatively insensitive to W/D ratio. Strength was typically less at the smallest W/D ratio but little improvement in strength was seen at ratios above W/D = 6. The thicker specimens did exhibit a lower average failure strength, but this was not necessarily a consequence of the test method.

For open hole tension testing of textile composites, the use of standard testing practices employed by industry, such as ASTM D5766 - *Standard Test Method for Open Hole Tensile Strength of Polymer Matrix Composite Laminates*, should provide adequate results for material comparisons studies.

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Appendix A
Boeing's Open Hole Tension Data

Table A1. Mean Strength and CoV for Boeing's Open Hole Tension Tests of 2-D Braided Materials

Hole Diameter [in]	Property	SLL 1/8"	SLL 1/4"	LLS 1/8"	LLS 1/4"	LLL 1/8"	LLL 1/4"	LSS 1/8"	LSS 1/4"
0.188	Strength [ksi]	99.1	91.8	89.5	86.2				
W/D=8	CoV [%]	3.5	9.0	4.6	2.1				
0.250	Strength [ksi]	91.4	82.2	74.3	75.6				
W/D=6	CoV [%]	6.7	18.5	6.6	2.2				
0.281	Strength [ksi]	82.4	91.7	81.5	72.7	77.5	72.7	40.3	40.8
W/D=8	CoV [%]	3.5	1.5	0.9	3.0	9.2	3.0	7.9	3.7
0.375	Strength [ksi]	87.6	76.9	76.3	68.4	74.8	68.4	37.3	40.1
W/D=4, 6, 8 (1)	CoV [%]	5.4	11.4	6.4	4.9	2.5	4.9	5.9	5.0
0.500	Strength [ksi]	81.0	81.9	78.0	65.8				
W/D=6	CoV [%]	6.7	4.4	4.8	4.2				
0.562	Strength [ksi]	75.5	77.0	66.7	61.6	62.8	61.6	33.6	34.7
W/D=4	CoV [%]	4.0	4.5	3.9	5.0	4.8	5.0	6.7	4.6
0.750	Strength [ksi]	79.2	76.2	62.9	59.7				
W/D=4	CoV [%]	2.3	8.0	3.8	5.2				

(1) Average Result for W/D = 4, 6 and 8

Table A2. Mean Strength and CoV for Boeing's Open Hole Tests of Stitched Uniweave Materials

Hole Diameter [in]	Property	SU-1	SU-2	SU-3	SU-4	SU-5
0.188	Strength [ksi]	59.2	58.0	58.0	61.3	56.6
W/D=4	CoV [%]	0.9	1.8	4.6	0.9	2.8
0.250	Strength [ksi]	54.1	52.4	53.0	55.9	51.4
W/D=6	CoV [%]	2.8	0.8	7.1	2.0	2.7
0.375	Strength [ksi]	47.8	47.0	48.5	52.6	46.8
W/D=8	CoV [%]	5.1	0.9	3.0	3.1	4.2

Appendix A: Continued

Boeing's Open Hole Tension Data

Table A3. Mean Strength and CoV for Boeing's Open Hole Tests of 3-D Woven Materials

Hole Diameter [in]	Property	OS-1	OS-2	LS-1	LS-2	TS-1	TS-2
0.188	Strength [ksi]	117.5	80.0	126.5	80.9	109.3	92.6
W/D=4	CoV [%]	0.9	12.1	0.3	17.1	2.7	5.0
0.250	Strength [ksi]	101.2	87.9	119.2	99.3	100.4	87.9
W/D=6	CoV [%]	12.8	1.6	6.8	0.8	3.5	4.8
0.375	Strength [ksi]	97.7	72.9	87.1	90.3	92.2	78.2
W/D=8	CoV [%]	12.2	17.8	5.1	5.0	0.3	3.6

Appendix B
Lockheed's Open Hole Tension Data

Table B1. Summary of Lockheed's 3-D Weave Test Results

Property	LTL-1	LTL-2	LTL-3
Strength [ksi] CoV [%]	88.3 6.0	70.2 0.3	81.7 7.1
Fiber Volume Fraction, %	61.61	57.37	60.52
Nominal Thickness, in	0.16	0.16	0.16

Table B2. Summary of Lockheed's 3-D, Through-The-Thickness Orthogonal Weave Test Results

Property	TTT-2	TTT-3
Strength [ksi] CoV [%]	72.7 5.7	69.6 3.4
Fiber Volume Fraction, %	57.43	60.35
Nominal Thickness, in	0.16	0.16

Table B3. Summary of Lockheed's 2-D Triaxial Braid Test Results

Material	V_f	Failure Stress, ksi	CoV, %
$[0_{12K}/\pm 60_{6K}]_{33\%}$	54.95	58.66	4.91
$[0_{24K}/\pm 60_{6K}]_{46\%}$	58.94	69.19	2.22

Table B4. Summary of Lockheed's 3-D Braid Test Results

Material	V_f	Failure Stress, ksi	CoV, %
TTT-1	56.23	45.50	3.6
TTT-2	57.70	66.30	7.2
TTT-3	53.45	66.40	4.4

Appendix C
West Virginia University's Open Hole Tension Data

Table C1. Summary of West Virginia University's 2-D Braid Results
Strengths Normalized to 60% Fiber Volume Fraction

Material	Net Failure Stress, ksi, (Std. Dev.)			
	Unnotched	1" Notched	2" Notched	4" Notched
SLL $[0_{30K}/\pm70_{6K}]_{46\%}$	108.1 (10.9)	106.3 (10.4)	99.6 (5.3)	64.8 (2.4)
LLS $[0_{36K}/\pm45_{15K}]_{46\%}$	94.1 (4.2)	92.7 (10.3)	89.9 (6.8)	77.1 (5.5)
LLL $[0_{75K}/\pm70_{15K}]_{46\%}$	77.7 (13.6)	68.9 (14.3)	82.5 (7.3)	55.0 (1.1)
LSS $[0_{6K}/\pm45_{15K}]_{12\%}$	50.7 (2.8)	51.9 (0.6)	42.6 (1.9)	38.3 (1.0)

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13. ABSTRACT (*Maximum 200 words*)

Sizing effects have been investigated by comparing the open hole failure strengths of each of the four different braided architectures as a function of specimen thickness, hole diameter, and the ratio of specimen width to hole diameter. The data used to make these comparisons was primarily generated by Boeing. Direct comparisons of Boeing's results were made with experiments conducted at West Virginia University whenever possible. Indirect comparisons were made with test results for other 2-D braids and 3-D weaves tested by Boeing and Lockheed.

In general, failure strength was found to decrease with increasing plate thickness, increase with decreasing hole size, and decreasing with decreasing width to diameter ratio. The interpretation of the sensitive to each of these geometrical perameters was complicated by scatter in the test data. For open hole tension testing of textile composites, the use of standard testing practices employed by industry, such as ASTM D5766 - *Standard Test Method for Open Hole Tensile Strength of Polymer Matrix Composite Laminates*, should provide adequate results for material comparisons studies.

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