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Standard Methods for Filled 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 test method effects with textile composites, Ref. [1].

This report evaluates the filled hole tension test results obtained by Boeing and other investigators in the ACT program. The intention is to develop a standard Filled Hole Tension Test method for textile composites. The effects of specimen width and width-to-hole diameter ratio on strength are evaluated. Since testing standards do not 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 compares the results of two research programs evaluating the material response of similar textile architectures. Test results from independent studies conducted at Lockheed Aeronautical Systems, and Boeing Defense and Space Group will be evaluated and compared.

Description of Materials

The test data evaluated in this report was generated by Boeing Defense and Space Group in Philadelphia, PA. and Lockheed Aeronautical Systems in Marietta, GA. Results from testing of two-dimensional (2-D) triaxial braids, three-dimensional (3-D) braids, and three-dimensional (3-D) interlocking weaves are presented.

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 Filled Hole Tension Tests conducted by Boeing featured 2-D triaxially braided fibrous preforms. The preforms were braided by Fiber Innovations Inc., Norwood, MA. The Boeing 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 measured the filled hole tensile strength of three different braided architectures. The specifics of each are given in Table 1. 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 for yarn size, percent of axial yarns, and braid angle. The "S" and "L" mean "Small" and "Large", respectively. For example, the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ braid contains 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

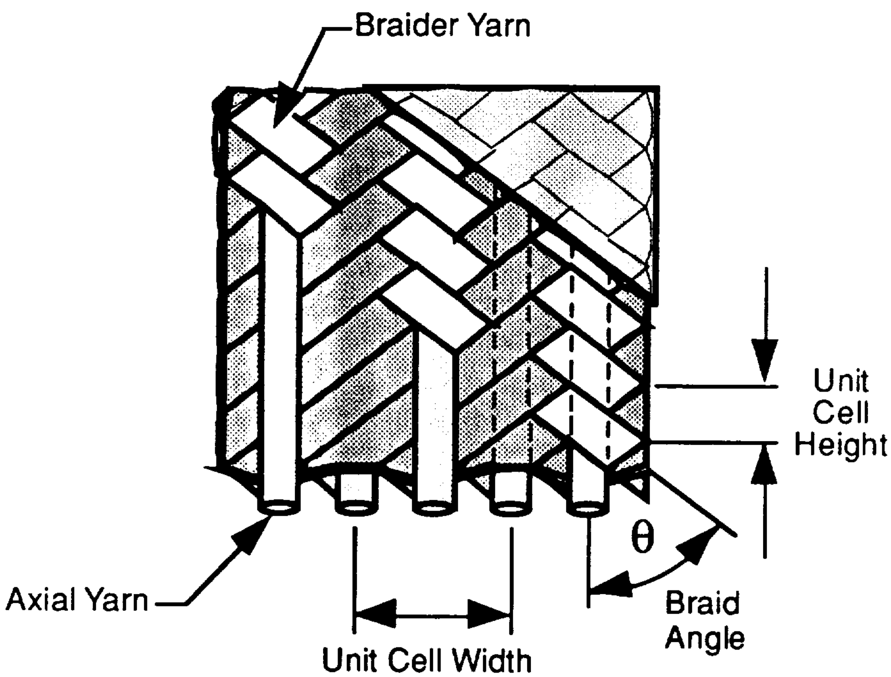

Figure 1. Illustration of a typical 2-D Triaxial Braid Configuration.

3-Dimensional Architectures

All the Filled Hole Tension Tests conducted at Lockheed featured either 3-D woven or braided architectures. Two different 3-D woven composite architectures were evaluated in this investigation. A schematic illustration of each is shown in Figure 2. 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.

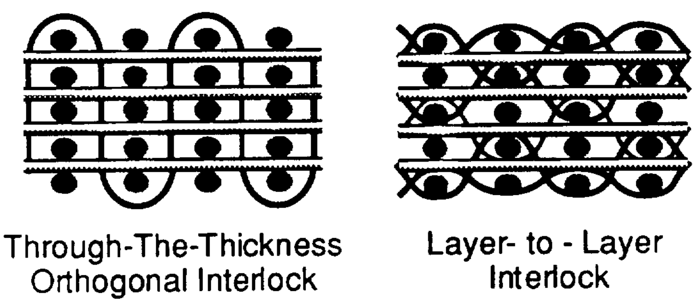

Figure 2. Depiction of 3-D Interlock Woven Materials.

The two different interlocking woven configurations Lockheed looked at in filled hole tension are described in Table 2. Tow size and percent, along with an architectural description of each are provided. Specimen size studies were not conducted using these material forms. Due to of the complex nature of these materials, unit cell measurements have not been conducted. Lockheed preforms were similar 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 2. Lockheed's 3-D Woven Orthogonal Interlock 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%)
	Orthogonal Interlock			
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%)

Lockheed also produced and tested a series of three dimensional braids. Three braid configurations were evaluated. The specifics of each are described in Table 3. These 3-D fabrics were braided by Atlantic Research Corp. and then RTM'd at Lockheed using PR-500 epoxy resin.

Table 3. 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%)

Test Specimen Configuration & Testing Methodology

Boeing's Filled Hole Tension Test Program

The basic specimen used in this program is a straight sided coupon and is illustrated in Figure 3. Only 1/8" thick specimens were investigated. The specimen length was kept constant at 11.5 inches. Several specimen widths were evaluated. Width to diameter (W/D) ratios of 4, 6, and 8 were used. A titanium Hilok fastener was installed in the hole and torqued to 25-30 in•lbf.

The test matrix used by Boeing is given in Table 4. This test matrix was chosen to optimize the information obtained from the limited number of test specimens. Three test specimens for each of the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$, LLS $[0_{36K}/\pm45_{15K}]_{46\%}$, and LLL $[0_{75K}/\pm70_{15K}]_{46\%}$ architectures were evaluated.

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.

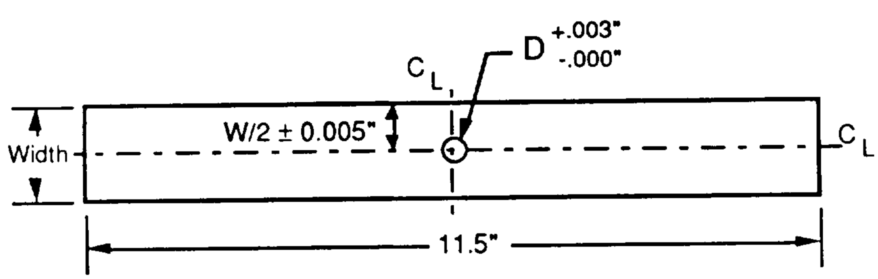

Figure 3. Boeing Used a Straight Sided Tension Coupon a Titanium Hilok Fastener was Installed in the Hole.

Table 4. Boeing's Filled Hole Tension Test Program.

Width [in]	W/D	SLL	LLS	LLL
1.00	4	3		
1.50	6	3	3	3
2.00	8	3		

Lockheed's Filled Hole Tension Test Program

Investigators at Lockheed utilized a specimen with a constant W/D ratio of 5 and a hole diameter of 0.25 inch. A titanium Hilok fastener was installed in the hole and torqued to 25-30 in•lbf. Lockheed's test specimen is illustrated below in Figure 4.

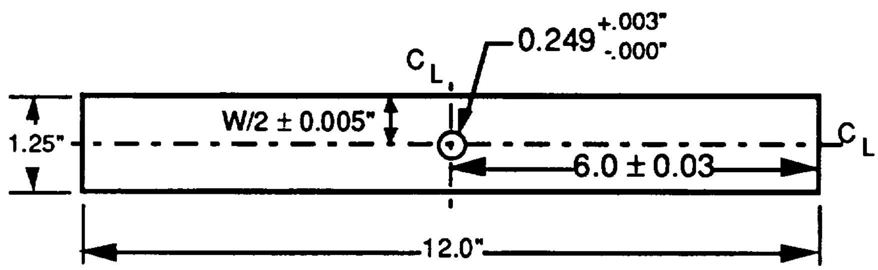

Figure 4. Lockheed Used Its Open Hole Tension Coupon with a 1/4" Titanium Hilok Fastener Installed in the Hole.

Data Reduction Method

Filled hole tension strengths, like open hole tension strengths, can be calculated several ways. Failure stress can be calculated using either the gross or the net section area. Gross stress calculations can also be corrected for finite width effects. The gross stress, corrected for finite width effects, is more readily used in design.

Net section stress, the least conservative of the two methods, varies with specimen width to hole diameter ratio. Thus, open hole test data should not be reported using net section stress. Gross stress calculations are acceptable, but need to be corrected for finite width to evaluate for specimen size effects.

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. [3]. 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 infinitely wide orthotropic plate with a hole (Figure 5), the stress at the edge of the hole is given by:

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

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

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

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

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

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.

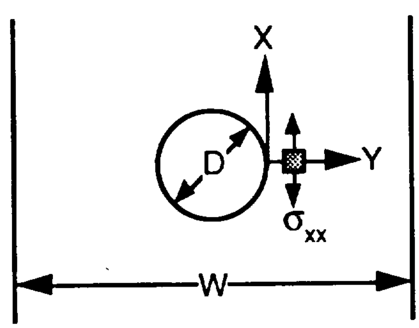

Figure 5. Illustration of the Stress Tensor in an Orthotropic Plate of Finite Width with a Hole.

Discussion of Results

The ultimate strengths of conventional tape composite materials have been shown to be greatly influenced by the presence of a notch or a hole. Their open-hole strengths have also been shown to be greater than their filled hole strengths. Since the open-hole tension response of textile composites is similar to the tape composite material's, it is likely that filled hole tension strength may also be a design limiting factor for textile composites.

The effect of a filled hole on the tension strength of a textile composite material has been evaluated through a comparison with its open-hole strength. The effect of specimen size (width and W/D ratio) was investigated to determine its effect on the test results. Data generated by Boeing on 2-D braided material was the primary source of information. The data developed by Lockheed on 3-D braids and weaves supplemented the Boeing results.

The results of Boeing's test programs are listed in Table 5; Lockheed's test results are listed in Tables 6 and 7. Each of the values listed in the Table are averages of three test specimens. The coefficient of variation (CoV%) is also given for each set of experiments. The finite width correction factors discussed earlier in this report have been applied to all the data.

Table 5. Boeing's 2-D Braid Test Results.

W/D	Property	SLL	LLS	LLL
4	Strength [ksi] CoV [%]	81.2 4.6	66.1 7.1	-
6	Strength [ksi] CoV [%]	84.2 8.7	72.3 3.8	72.0 2.7
8	Strength [ksi] CoV [%]	84.7 1.7	76.0 6.3	-

Table 6. Lockheed's 3-D Weave Test Results.

Property	LTL-1	LTL-2	TTT-1
Strength [ksi] CoV [%]	80.03 0.2	60.19 2.1	61.79 1.4
Fiber Volume Fraction, %	60.0	55.63	53.82
Nominal Thickness, in	0.16	0.16	0.16

Table 7. Lockheed's 3-D Braid Test Results

Property	TTT-1	TTT-2
Strength [ksi] CoV [%]	46.24 7.7	66.14 3.7
Fiber Volume Fraction, %	56.28	61.17
Nominal Thickness, in	0.12	0.12

Width and W/D Ratio Effects

Three 2-D braided textile materials were tested in Boeing's filled hole tension investigation. Although three specimen widths were evaluated, hole diameter and specimen thickness were held constant. The results of these experiments are presented in Figure 6. It plots the filled hole tension strength versus the ratio of specimen width to the hole diameter (W/D) for the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$, LLS $[0_{36K}/\pm45_{15K}]_{46\%}$, and LLL $[0_{75K}/\pm70_{15K}]_{46\%}$ braids. Linear curves have been fit to the data; each data point represents a single test specimen. For purposes of comparison specimen width is shown on the top horizontal axis. Because of the limited number of test specimens, the LLL $[0_{75K}/\pm70_{15K}]_{46\%}$ material was evaluated at only one width.

The figure provides a measure of the effectiveness of the finite width correction factors discussed in the "Test Specimen Configuration & Testing Methodology" section. 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 and the lines fit to the corrected data should be horizontal.

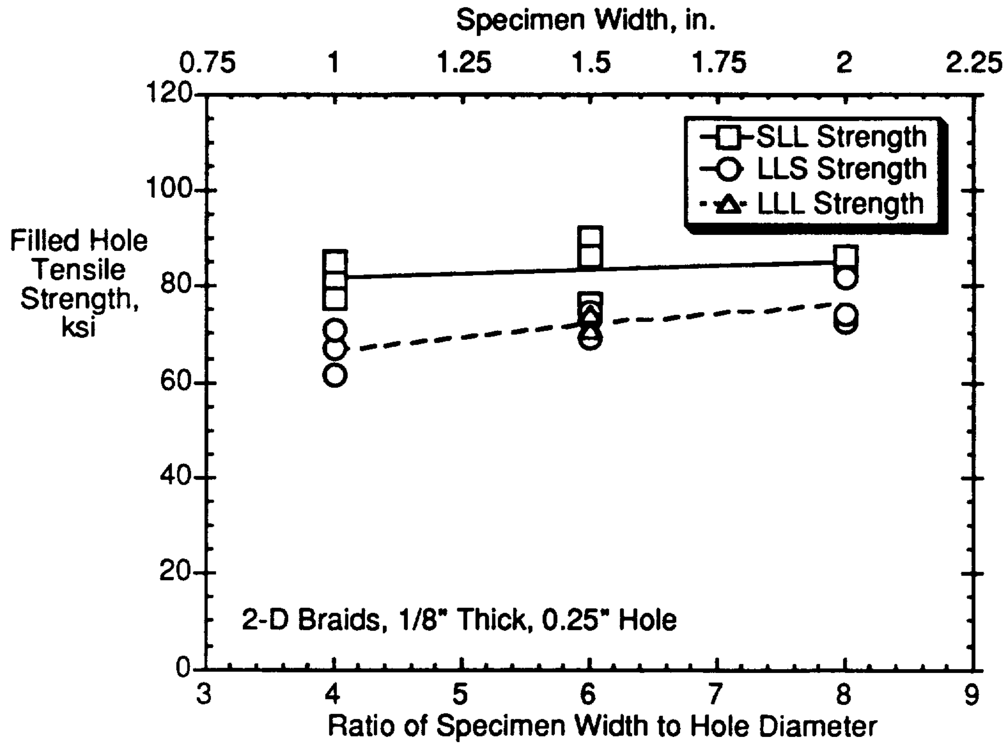

Figure 6. Effect of Specimen Width and Width to Hole Diameter Ratio on Filled Hole Tension Strength.

The data indicates, however, that the failure stress increases somewhat with increasing W/D ratio, even after being corrected for finite width. This trend is more apparent in the LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ laminates than in the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ laminates. The latter material was less sensitive to changes in the W/D ratio than the former. The increases in the LLS $[0_{36K}/\pm45_{15K}]_{46\%}$ materials' average failure stress with increasing W/D ratios are, however, not much greater than one standard deviation in the data. They increased 6 ksi as the W/D ratio increased from 4 to 6 and 3.7 ksi as the ratio increased to 8. The standard deviations in these data were 4.7 ksi, 2.8 ksi, and 4.8 ksi, for W/D = 4, 6, and 8, respectively.

An analogous response was seen in the open-hole tension test data Ref. [4]. However, the SLL $[0_{30K}/\pm70_{6K}]_{46\%}$ laminates were more sensitive to W/D changes in those tests.

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

Comparison of Filled Hole to Open Hole Strength

Figure 7 is a plot of filled hole (FHT) versus open hole tension (OHT) strength for each of the three 2-D braids tested by Boeing. Error bars equal to one standard deviation are given to show scatter in the data and each bar represents the average of three experiments. This data is for 1/8 inch nominal thickness specimens with a 1/4 inch filled hole. The hole contained a 1/4 inch titanium Hilok fastener torqued to approximately 30 in•lbs. Data for both W/D=6 and W/D=8 have been averaged together where available. The percent difference between the filled and open hole results are shown on the graph above each set of bars.

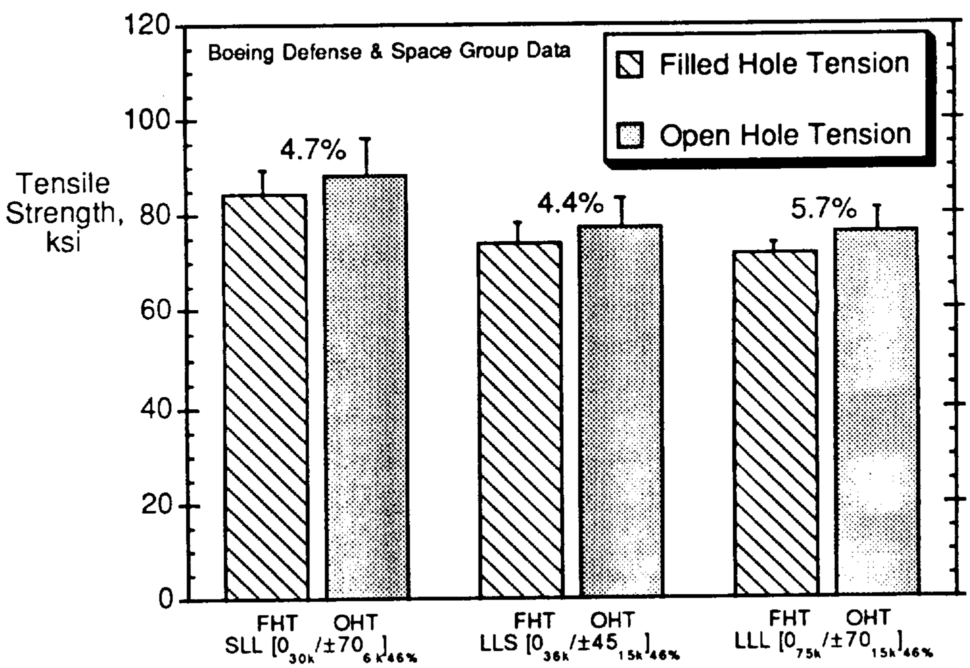

Figure 7. Comparison of Filled Hole to Open Hole Tension Strength of Boeings 2-D Braids.

An examination of this figure shows that the filled hole strengths were lower than the open hole strengths in all cases. The strength differences were small; they ranged from 4.4 to 5.7 %. This response was expected since the 2-D braids contain planes of lamination, similar to laminated tape composites. It is thought that delamination forming at the edge of a hole during testing causes a reduction in the stress concentration factor (SCF) associated with the hole. This reduction in the SCF yields an improvement in strength. It is likely that the clamping force applied by the fastener induces a compression stress around the boundary of the hole, reducing the initiation and growth of delamination, thus suppressing any reduction in the SCF that delamination may provide. As a consequence, the effect of the hole is more pronounced and failure results at a lower load.

Figure 8 is a plot of test data generated at Lockheed for 3-D braids and 3-D weaves. Filled and open hole test results are compared. Again, error bars equal to one standard deviation are given to show scatter in the data and each bar represents the average of three experiments. This data is again for 1/8 inch nominal thickness specimens with a 1/4 inch filled hole containing a 1/4 inch titanium Hilok fastener torqued to approximately 30 in•lbs. The percent difference between the filled and open hole results are shown on the graph above each set of bars.

An examination of the figure shows that the 3-D weaves' filled-hole tension strengths were lower than their open-hole tension strengths. These strength reductions ranged from as little as 1.8 % to as much as 15.4 %. On the other hand, the 3-D braids' strengths improved by approximately 4.5 %. This result was not expected and may be an artifact of scatter in the test data. However, these improvements are small compared to the scatter in the data.

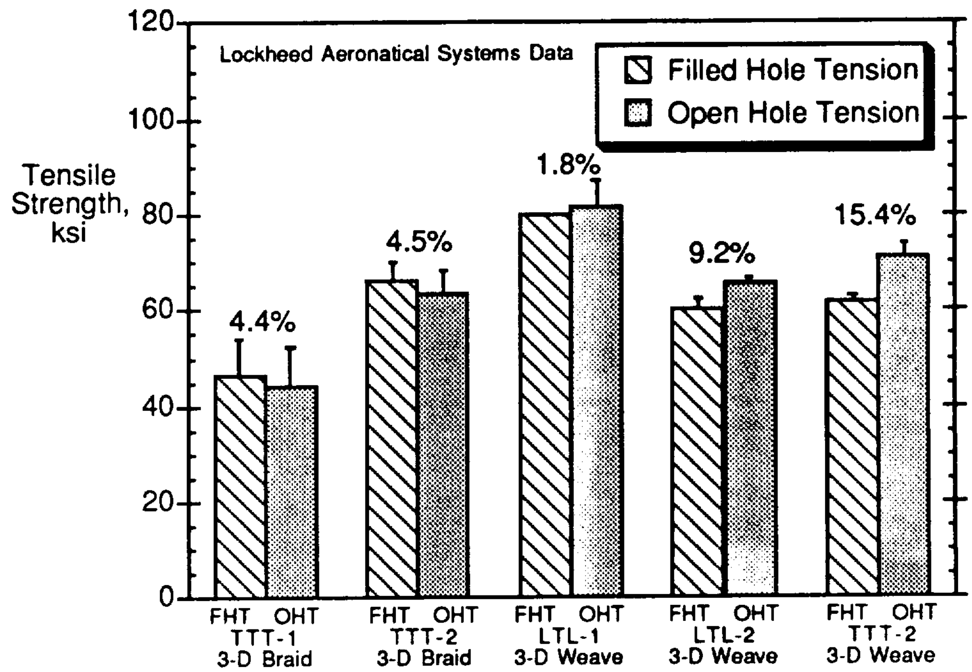

Figure 8. Comparison of Filled Hole to Open Hole Tension Strength of Lockheed's 3-D Braids and Weaves.

Conclusions and Recommendations

The effect of a filled hole on the tension strength of a textile composite material has been evaluated through a comparison with its open hole strength. The effect of specimen width and W/D ratio was investigated to determine its effect on the test results. Data generated by Boeing and Lockheed on 2-D and 3-D braids, and 3-D weaves were used to make these comparisons.

An investigation of the effect of specimen width and W/D ratio on filled hole tension strength showed little sensitivity to specimen geometry when the ratio of specimen width to the hole diameter (W/D) is ≥ 6. Test specimen configurations used for open hole tension tests, such as those suggested by ASTM D5766 - *Standard Test Method for Open Hole Tensile Strength of Polymer Matrix Composite Laminates,* or those proposed by MIL-HDBK-17-1D [Ref. 5] section 7.2.6.2. should provide adequate results for material comparisons studies.

A review of the data also indicated that the isotropic finite width correction factors were generally effective in accounting for the width effects.

The 2-D braids' and 3-D weaves' filled-hole tension strengths was shown to be 2 to 15% lower than their open hole strengths. Thus, filled hole tension may be a critical design consideration for these materials. On the other hand, the 3-D braids' filled-hole strength was unexpectedly 4% larger than its open-hole strength. This improvement, however, is small compared to the scatter in the data.

References

1. Minguet, P., Fedro, M., Gunther, C., "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.

3. Peterson, R. E., "Stress Concentration Factors," Second edition John Wiley & Sons, Inc., Publishers, New York, 1974.

4. Portanova, M. A., Masters, J. E., "Standard Methods for Open Hole Tension Testing of Textile Composites," NASA CR 198262, December 1995.

5. DODSSP, Polymer Matrix Composites, MIL-HDBK-17, DODSSP, Naval Publications and Forms Center, Standardization Documents Order Desk, Building 4D, 700 Robbins Ave., Philadelphia, PA 19111-5094

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The effects of two test specimen geometry parameters, the specimen width and W/D ratio, on filled-hole tensile strength were determined for textile composite materials. Test data generated by Boeing and Lockheed on 2-D and 3-D braids, and 3-D weaves were used to make these evaluations. The investigation indicated that filled-hole tensile strength showed little sensitivity to either parameter. Test specimen configurations used in open-hole tension tests, such as those suggested by ASTM D5766 - *Standard Test Method for Open Hole Tensile Strength of Polymer Matrix Composite Laminates*, or those proposed by MIL-HDBK-17-1D [Ref. 5] Section 7.2.6.2. should provide adequate results for material comparisons studies.

Comparisons of the materials' open-hole and filled-hole tensile strengths indicated that the latter were generally lower than the former. The 3-D braids were the exception; their filled-hole strengths were unexpected larger than their open-hole strengths. However, these increases were small compared to the scatter in the data. Thus, filled hole tension may be a critical design consideration for textile composite materials.

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