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Standard Methods for Bolt-Bearing Testing of Textile Composites

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Introduction

Bolted joints are an important design consideration for composite structures. Although bolt bearing is not a material property, test results from bolt bearing experiments are used extensively in the aerospace industry to design composite structures. The test methods developed to evaluate the response of composites constructed from laminated tape may not be adequate to characterize textile materials. The intent of this investigation is to determine the applicability of standard bolt bearing test specimen geometry to textile materials.

Most of the test data used in this investigation was generated by Boeing Defense and Space Group in Philadelphia, PA. [Ref. 1]. They evaluated three bolt bearing test methods: Stabilized Single Shear, Unstabilized Single Shear, and Double Shear. Some data generated by Lockheed Aeronautical Systems in Marietta, GA. will also be presented. Lockheed tested only one specimen configuration. It was similar to Boeing's Double Shear specimen.

Open hole tension tests have shown that textile materials display a sensitivity to specimen width-to-hole diameter ratio [Ref. 2]. A similar sensitivity is expected in bolt bearing testing. Two geometric parameters, the W/D ratio and the e/D ratio, were varied in each of the three bolt bearing test specimen configurations evaluated. The W/D ratio is the ratio of the specimen width (W) to the hole diameter (D). The e/D ratio is the ratio of the distance from the hole center to the specimen edge (e) to the hole diameter (D).

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. was also examined. Most of this evaluation was based on experiments conducted by Boeing on two-dimensional (2-D) triaxial braids. Lockheed tested a 3-D weave, a 3-D Braid, and a 2-D Braid in bolt bearing. The materials tested by Boeing and Lockheed are described in the following sections.

2-Dimensional Triaxial Braids

All the 2-D fabric preforms tested in this program were braided by Fiber Innovations Inc., Norwood, MA. An illustration of a typical 2-D braid is given in Figure 1.

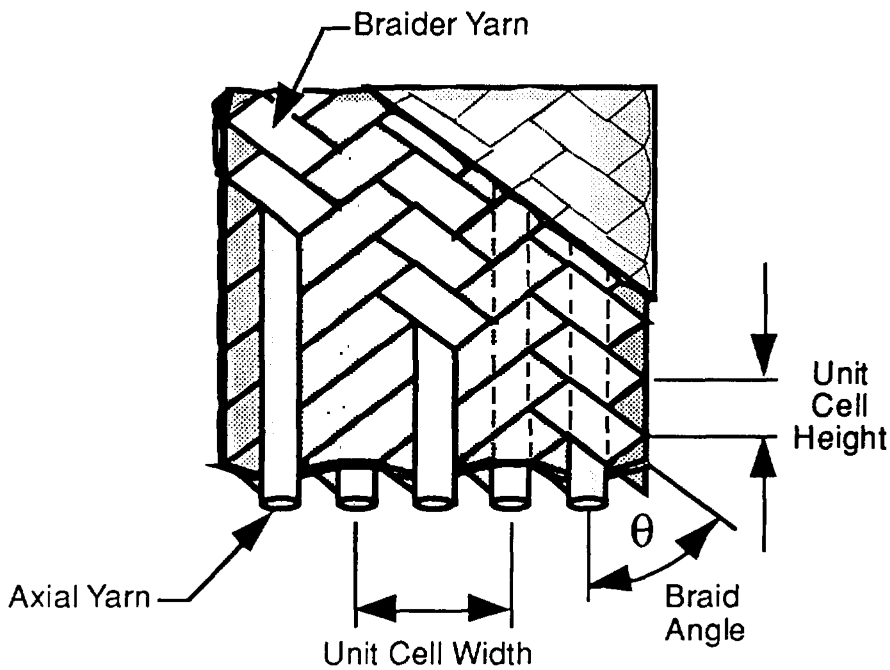

Figure 1. Illustration of a Typical 2-D Triaxial Braid Configuration.

The following nomenclature has been adopted to describe the fiber orientation in the braids:

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

Where XX indicates the yarn size, k indicates thousands and Y indicates the percentage of axial yarns in the preform.

The details of the 2-D braids evaluated by Boeing and Lockheed are given in Tables 1 and 2, respectively. The three letters preceding the "$[0_{XXK}/\pm\theta_{XXK}]$ Y% Axial" nomenclature in Table 1 are intended as shorthand notation for yarn size, axial yarn content, and braid angle. An "S" indicates Small; an "L" indicates Large. For example, the SLL $[0_{30K}/\pm70_{6K}]46\%$ braid is deciphered as containing a small (6K) braider yarn, a large (46%) percentage of axial yarns, and a large (70°) braid angle.

Table 1. Boeing's 2-D Braid 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

Note: All laminates tested had a nominal thickness of 0.250 in.

The braid architectures evaluated at Boeing were chosen to isolate the effects yarn size and braid angle on bearing strength. This is illustrated by considering the architectures in pairs. For example, the SLL and LLL architectures have the same braid angle (70°) and axial yarn content (46%). Their yarn sizes, however, differ by a factor of 2.5. Similarly, the SLL and LLS architectures have the same axial yarn content and similar yarn sizes; but differ in braid angle.

Boeing's test panels were resin transfer molded (RTM) using Shell RSL-1895 epoxy resin and cured at Boeing. Details of Boeing's manufacturing process can be obtained in [Ref. 3], "Resin Transfer Molding of Textile Composites."

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 Braid Architectures

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

3-Dimensional Architectures

In addition to the 2-D braids described above, Lockheed also evaluated several 3-D woven and braided architectures.

Six interlocking weave architectures were evaluated. They may be divided into two groups depending upon the orientation of the interlocking weaver tows. They schematically illustrated in Figure 2 and defined in Table 3. All configurations 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.

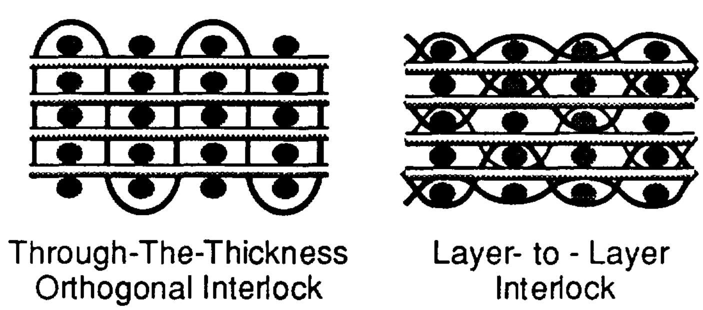

Figure 2. Illustration of 3-D Interlock Woven Materials.

Table 3. Lockheed's 3-D Weave Architectures

Name	Description	Warp Tow	Weft Tow	Weaver Tow
TTT-1	Through-The-Thickness	6 K (24.7%)	6 K (24.7%)	3 K (4.1%)
TTT-2	Orthogonal Interlock	12 K (47.7%)	6 K (44.4%)	3 K (7.9%)
TTT-3		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 produced and tested three 3-D braid configurations. The specifics of each are described in Table 4. These 3-D fabrics were braided by Atlantic Research Corp. and then RTM'd at Lockheed using PR-500 epoxy resin.

Table 4. 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 evaluated three specimen configurations: the Stabilized Single Shear, Unstabilized Single Shear, and Double Shear bearing specimens. In addition, they also investigated the sensitivities of these methods to changes in specimen geometry. Lockheed, on the other hand, used a single specimen, which was similar to Boeing's Double Shear specimen, in its materials evaluation program. They did not vary the specimen's geometry. Descriptions of these specimens will follow.

Boeing's Test Specimens

The configurations of the three specimens evaluated at Boeing are illustrated in Figures 3, 4, and 5. The Unstabilized Single Shear Bearing test specimen is shown in Figure 3. This test specimen typically yields lower strengths than the other methods as a result of bending that develops during loading. Bending is eliminated in the Double Shear (Fig. 4) specimen due to its configuration. As a result, it typically yields the highest failure strengths. The final specimen tested was the Stabilized Single Shear Bearing specimen which is shown in Figure 5. It was designed to represent joints with several rows of fasteners that are typically encountered in commercial aircraft applications. It provides a single lap joint with a small amount of bending.

The influence of two geometric parameters was examined for each test specimen configuration. These parameters were the specimen width to hole diameter ratio (W/D) and the ratio of the distance of the hole center to the specimens edge (e/D). They are defined in Figure 6.

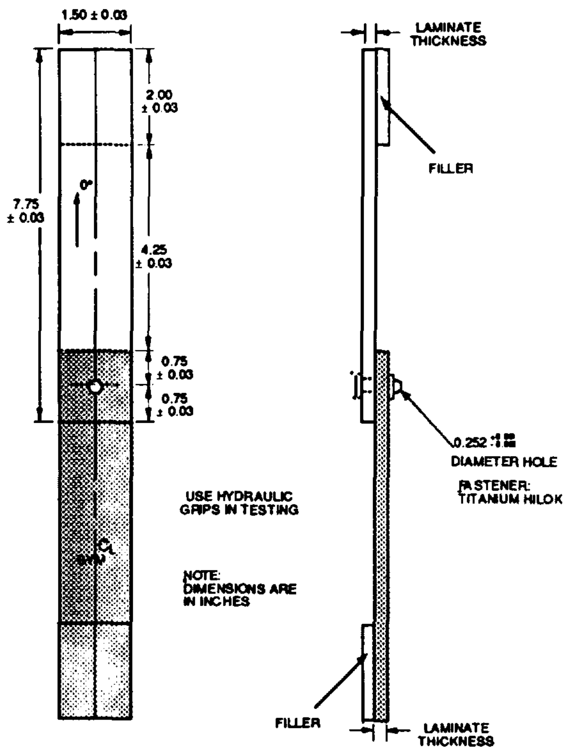

Figure 3. Boeing's Unstabilized Single Shear Test Specimen.

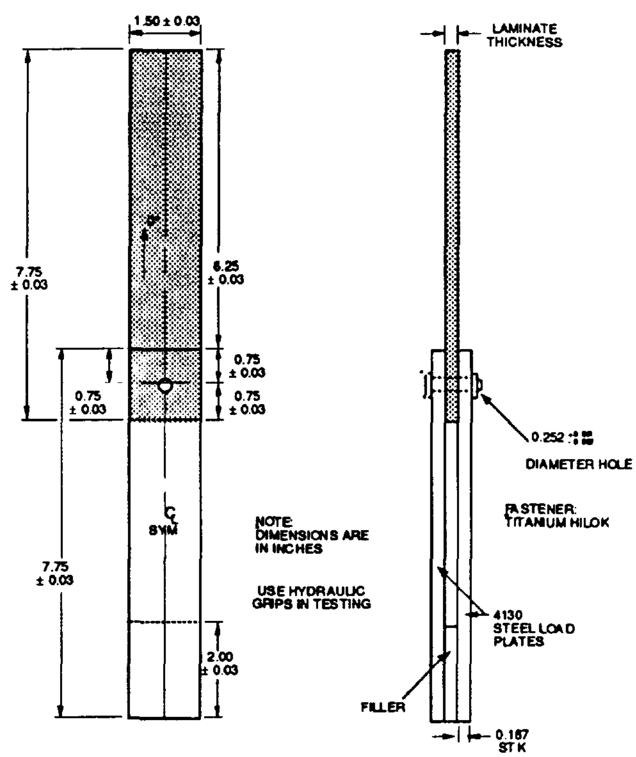

Figure 4. Boeing's Double Shear Test Specimen.

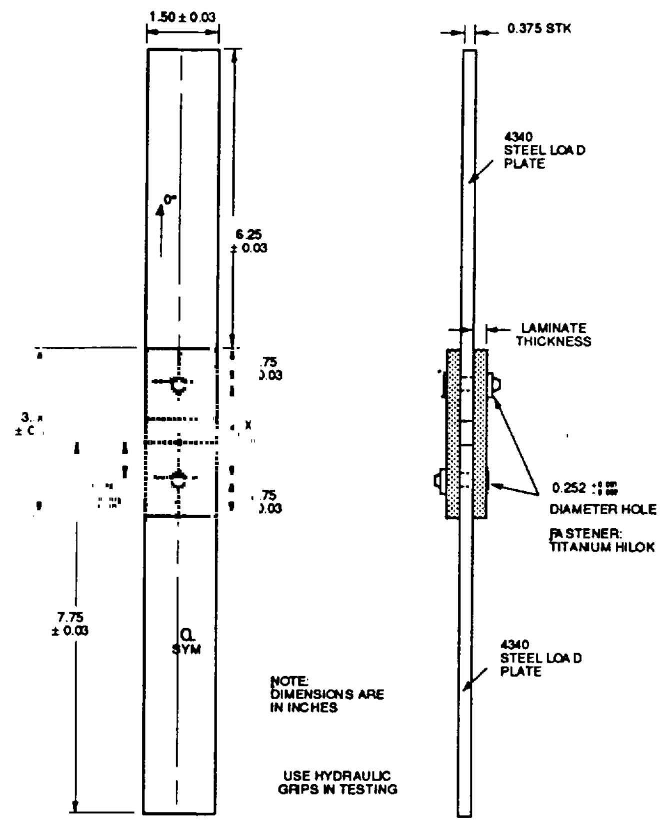

Figure 5. Boeing's Stabilized Single Shear Specimen.

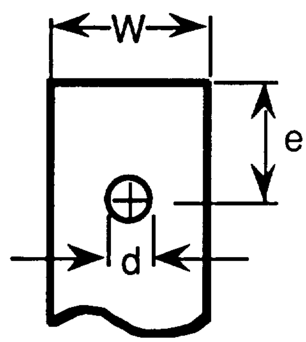

Figure 6. Illustration of Bolt Bearing Specimen Dimensions.

The hole diameter, d, was a constant at 0.25 inches in all tests; specimen width, W, varied from 1.0 to 2.0 inches. Thus, width to diameter (W/D) ratios of 4, 6, and 8 were evaluated. The edge distance was varied to produce e/D ratios of 2, 3, and 4. A titanium Hilok fastener was installed in the hole and torqued to 25-30 in•lbf.

The test matrix used by Boeing to evaluate the three bolt bearing test methods is given in Table 5. Each of the 2-D braided architectures were evaluated in three specimen configurations. The majority of the experiments were performed on the $[0_{30K}/\pm70_{6K}]46\%$ (SLL) and $[0_{36K}/\pm45_{15K}]46\%$ (LLS) materials. Consequently, most of the discussion will be focused on these two material architectures.

Table 5. Boeing's Bolt-Bearing Test Matrix

W/D	e/D	SLL	LLS	LLL
		Stabilized Single Shear and Double Shear		
4	2	3	3	
4	3	3	3	
4	4	3	3	
6	2	3	3	
6	3	3	3	3[1]
6	4	3	3	
8	2	3	3	
8	3	3	3	
8	4	3	3	
		Unstabilized Single Shear		
6	2	3	3	
6	3	3	3	3
6	4	3	3	

Note: [1] Single Shear Only

All of the 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.

Bearing Stress Calculations

Bolted joints create stresses along their bearing surfaces during loading. The applied load is distributed on the inside surface of a half-cylinder of diameter *d*, equal to the bolt diameter, and of length *t*, equal to the thickness of the plate (See Figure 7). The distribution of force is complicated. Thus, in practice an average nominal value of the bearing stress σ_b is determined. The expression for calculating bearing stress is given by Equation 1.

$$\sigma_b = \frac{P}{td} \tag{1}$$

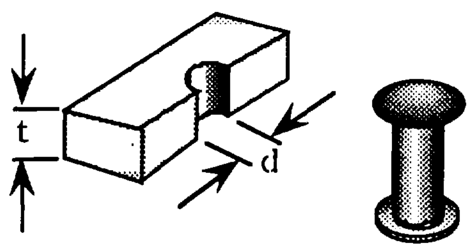

Figure 7. Illustration of Bolt Bearing Loading Area.

For the three specimen configurations discussed in this investigation, bearing stress has been determined based upon the individual loading condition of each test method. For the Stabilized Single Shear and Unstabilized Single Shear, bearing stress was determined by Equation 1. The expression given in Equation 2 was used to calculate stress in the Double Shear specimens.

$$\sigma_b = \frac{P}{2td} \tag{2}$$

Discussion of Results

The influence of the W/D and e/D ratios will be examined in the following sections. A comparison of the failure strength at each of the ratios tested will be made on the $[0_{30K}/\pm70_{6K}]46\%$ (SLL) and $[0_{36K}/\pm45_{15K}]46\%$ (LLS) architectures. The Stabilized Single Shear and Double Shear test methods are used for this comparison. Data for the Unstabilized Single Shear was not available at all W/D ratios. All of Boeing's test results are listed in Appendix A (Lockheed's test results are summarized in Appendix B.)

SLL $[0_{30K}/\pm70_{6K}]46\%$ Test Results

The average strength of the SLL material tested using the Stabilized Single Shear method is plotted verses the e/D ratio in Figure 8. Test results for three W/D ratios are shown in the figure. Each symbol is an average of three experiments. One standard deviation in the test data is given by the error bars shown with each data point.

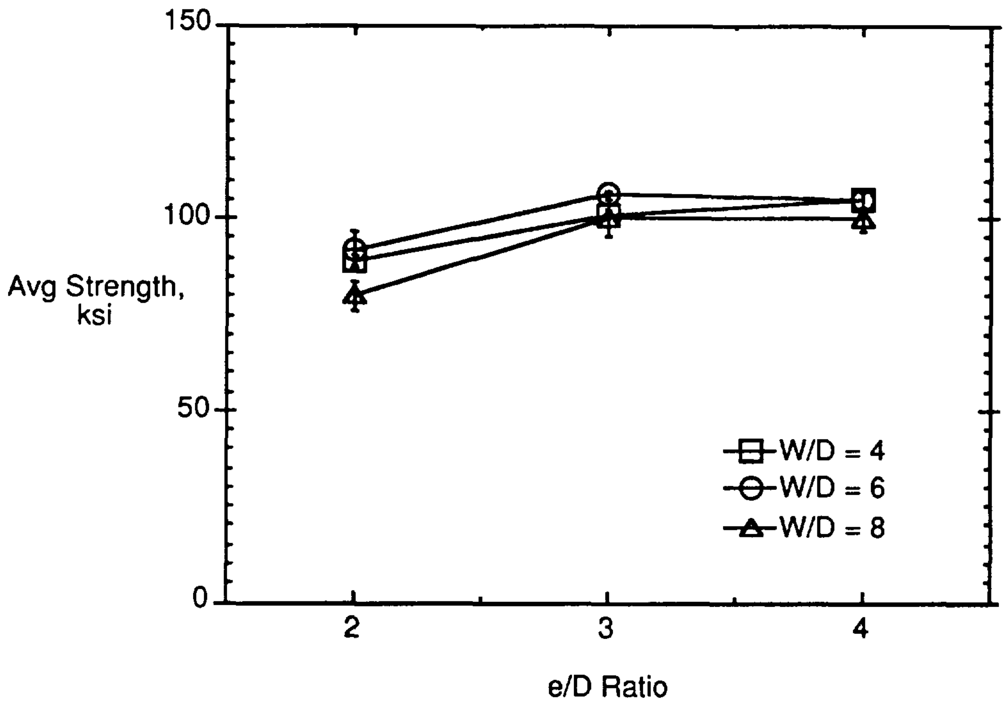

Figure 8. Stabilized Single Shear Results: $[0_{30K}/\pm70_{6K}]46\%$ Braid.

An examination of Figure 8 shows that the $[0_{30K}/\pm70_{6K}]46\%$ (SLL) material's bearing strength is sensitive to the e/D ratio. This sensitivity to edge distance is seen in the reduced strength of the specimens tested at the e/D = 2. Strength increased on average 18 % as the e/D ratio increased from 2 to 3. The strengths of specimens with e/D ratios of 3 and 4 were about equal. This suggests that the effect was a result of edge distance, not specimen width.

The data in the figure also indicates that the W/D ratio appears to have only a small effect on strength for this test method. This is consistent with this material's open hole tension test results [Ref. 3]. Scatter in the test data was low. The coefficient of variation (CoV) averaged 3.1 ±1.7% %.

Figure 9 is a plot of the $[0_{30K}/\pm70_{6K}]46\%$ (SLL) material loaded in Double Shear. The average stress is again plotted versus the e/D ratio for each W/D ratio. Each symbol is the average of three experiments; error bars, representing one standard deviation in the test results, are shown.

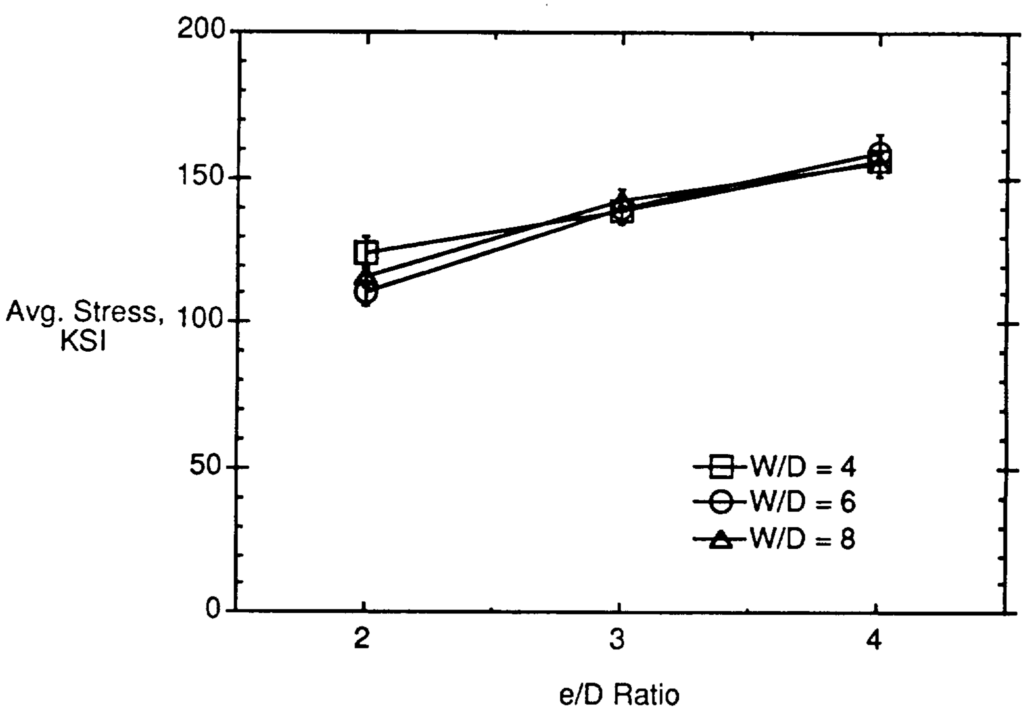

Figure 9. Double Shear Test Results: $[0_{30K}/\pm70_{6K}]46\%$ (SLL) Braid.

Figure 9 shows the SLL material is also sensitive to e/D ratio effects when loaded in Double Shear. Its strength improves as the distance from the hole center to the specimen edge increases. The strength improved 21% on average between e/D = 2 and e/D = 3. However, this trend does not level out as it did in the Stabilized Single Shear experiments. This continuous improvement in strength may be an artifact of the test method. The test specimen is clamped between two steel plates during loading. This clamping restricts the damaged material from spreading our of plane during loading. Consequently, the subsequent failure of the fiber/matrix material in the bearing area beneath the hole is impeded. This restriction may result in an artificial improvement in strength [Ref. 1].

As in the case of the Stabilized Single Shear tests, no W/D effects are indicated by the $[0_{30K}/\pm70_{6K}]46\%$ (SLL) test results shown in Figure 9. Scatter in the test data was low; the experiments' coefficients of variation averaged 3.05 ± 1.13 %.

LLS $[0_{36K}/\pm45_{15K}]46\%$ Test Results

The LLS material is evaluated in Stabilized Single Shear in Figure 10. The average stress is again plotted versus the e/D ratio for each W/D ratio examined. As in Figures 8 and 9, each symbol is an average of three experiments and the error bars represent one standard deviation in the data.

The response of the $[0_{36K}/\pm45_{15K}]46\%$ (LLS) material in Stabilized Single Shear is consistent with the $[0_{30K}/\pm70_{6K}]46\%$ (SLL) material's. However, a greater increase in strength was seen in the $[0_{36K}/\pm45_{15K}]46\%$ (LLS) material than in the SLL material as their e/D ratios increased. The LLS material's strength increased 38% on average as the e/D ratio increased from 2 to 3. The effects of specimen width to hole diameter ratio were again small. Data scatter was moderate; the average CoV was 4.5%.

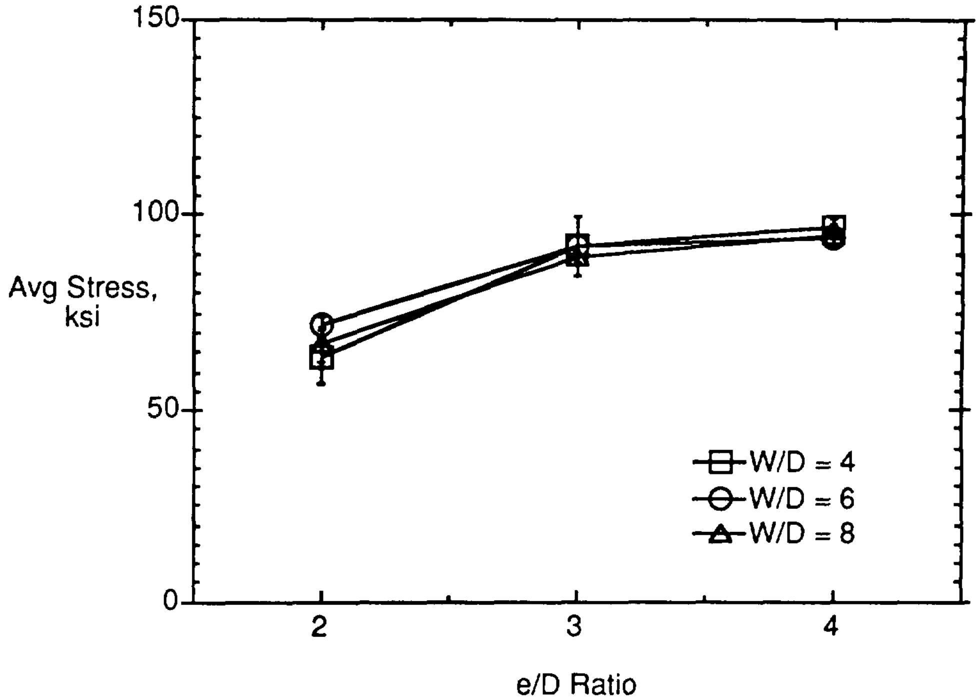

Figure 10. Stabilized Single Shear Results: $[0_{36K}/\pm45_{15K}]46\%$ Braid.

The sensitivity of the $[0_{36K}/\pm45_{15K}]46\%$ (LLS) braid's Double Shear strength to changes in specimen geometry is shown in Figure 11 which plots average strength versus the e/D ratio for W/D = 4, 6, and 8 data. Scatter in the data is shown as error bars representing one standard deviation from the mean.

A comparison of Figures 10 and 11 reveals that, as with the $[0_{30K}/\pm70_{6K}]46\%$ (SLL) material, Double Shear test method produces the highest strengths. The effect of e/D ratio is much as it was in Figure 9. Strength increases as the distanced of the hole to the specimens edge increases. Strength improved 23 % between e/D = 2 and e/D = 3 and another 14 % at e/D = 4. Again, these higher strength values may have been caused by the specimen clamping.

No effect of specimen width to hole diameter is apparent. Data scatter was moderate in some cases but in general strength was similar at each W/D ratio.

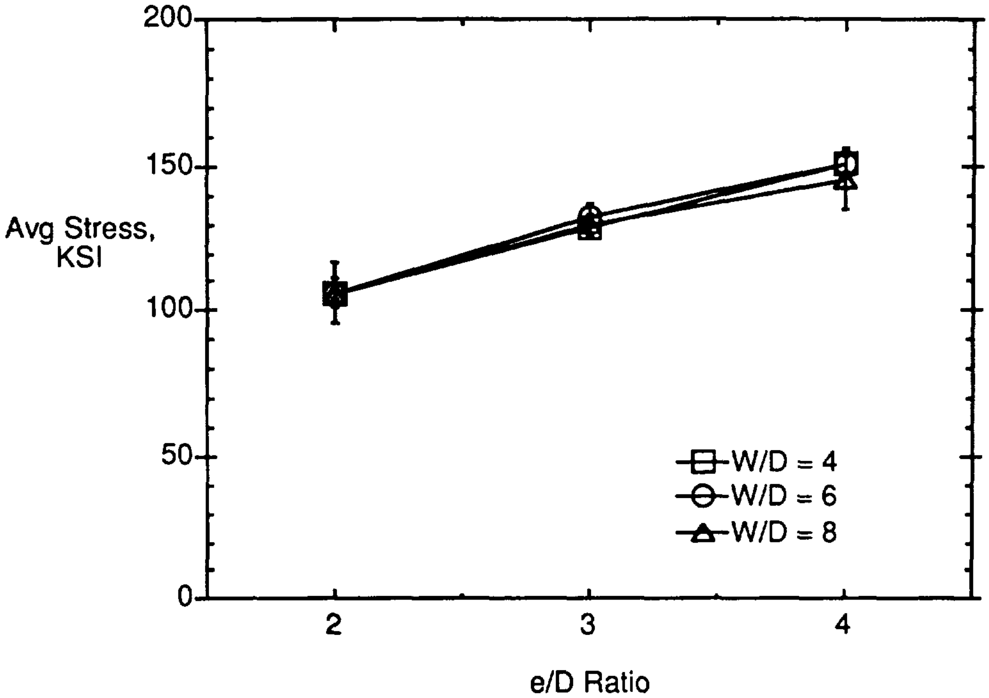

Figure 11. Double Shear Test Results: $[0_{36K}/\pm45_{15K}]46\%$ (LLS) Braid.

Test Method Comparisons

Standard design practices, such as those described in Mil-HDBK-17, suggest that bolt bearing specimens should be constructed with a minimum W/D ratio of 6 and an e/D ratio of 3. In an attempt to evaluate the sensitivity of each test method to material architecture, data from different test methods will be compared at constant W/D ratios. Due to the limited availability of test data, results for the $[0_{30K}/\pm70_{6K}]46\%$ (SLL) and $[0_{36K}/\pm45_{15K}]46\%$ (LLS) materials will be presented at W/D = 6 and 8 only. The W/D=4 test results will be neglected in this comparison because Open Hole Tension tests have shown this ratio may produce lower strengths [Ref. 3].

Strength of the SLL material tested in Stabilized Single Shear, Unstabilized Single Shear, and Double Shear are compared in Figure 12. The data is presented for a constant ratio of W/D=6. Results for three e/D ratios are given, as are error bars representing one standard deviation from the mean in the test averages.

An examination of the figure shows the effect of each test method at various e/D ratios. In all cases, strength increased with decreasing out of plane loading. As previously indicated, the Double Shear test yields the highest strength. Recall, however, that the double shear bearing strengths may be artificially increased at large e/D ratios due to the clamped loading condition. The Stabilized Single Shear experiments produced greater strength results than the Unstabilized Single Shear tests.

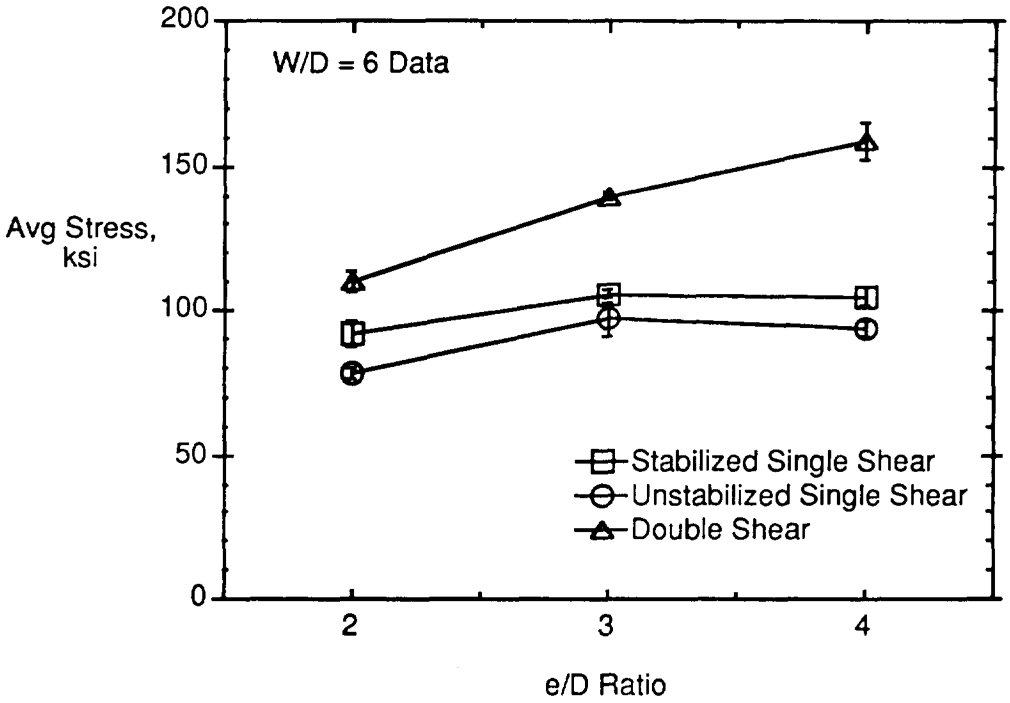

Figure 12. Test Method Comparison: $[0_{30K}/\pm70_{6K}]46\%$ Braid (W/D = 6).

At e/D = 3, strength improved 9.3% between the Stabilized and Unstabilized Single Shear test results. Strength improved 44.3% in Double Shear over the Unstabilized Single Shear and 32.1% over the stabilized test results. At e/D = 6 the Stabilized Single Shear results were 11.7% greater the Unstabilized Single Shear values. The Double Shear strength was 69.1% greater than the Unstabilized Single Shear strength and 51.4% larger than the Stabilized Single Shear value. The difference in strength between the single shear methods was fairly constant while the double shear method seems to continued to increase.

Figure 13 is a comparison of strength at each e/D ratio for the SLL material tested at W/D = 8. Results from only two test methods were available; Unstabilized Single Shear tests were conducted at W/D=6 only. Each data point is an average of three experiments and error bars representing one standard deviation from the mean are shown.

The results shown in Figure 13 are similar to the W/D = 6 results shown in Figure 12. The Double Shear test continues to have greater strength than the stabilized specimens and the Double Shear strength increases with increasing e/D ratio. Data scatter was small; the Stabilized Single Shear specimens had an average CoV of 3.31 ±1.5%, the Double Shear tests averaged 2.94 ±0.5%.

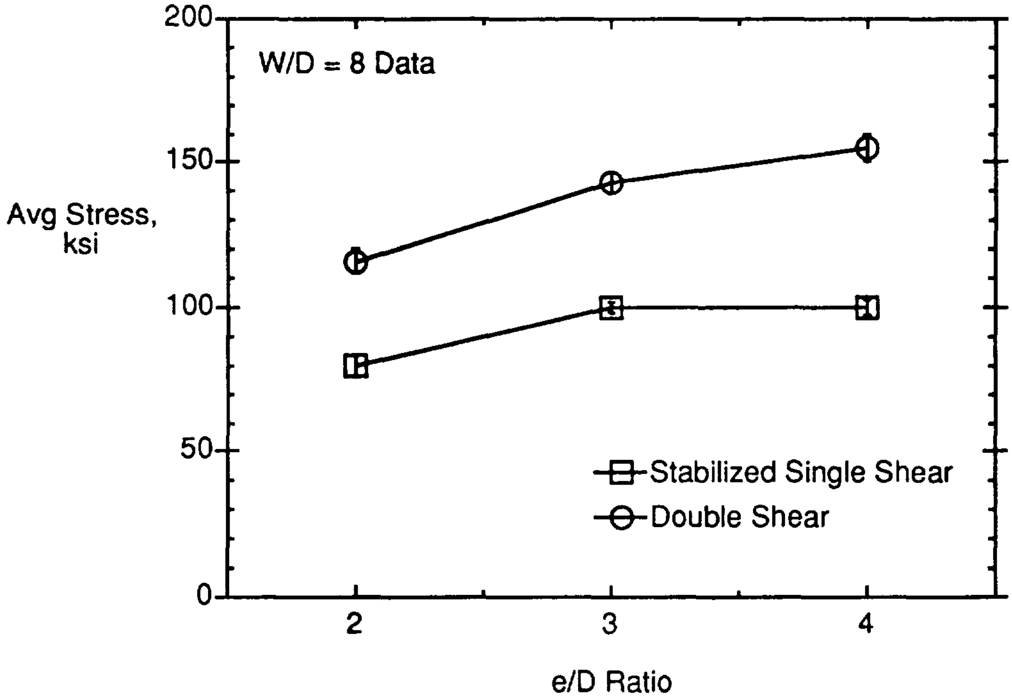

Figure 13. Test Method Comparison: $[0_{30K}/\pm70_{6K}]46\%$ Braid (W/D = 8).

The Stabilized Single Shear test results were slightly lower at W/D = 8 than at W/D = 6. The difference was about 15 % at the lowest e/D ratio but was not significant at e/D > 3. The Double Shear results were about the same at both W/D ratios. Both Filled Hole Tension and Open Hole Tension tests of these materials suggests that a W/D ratio greater than 6 will not produce any significant improvement in strength [Ref. 3,5]. Thus, this response was similar to that of the open hole tension results.

A comparison of test methods with the $[0_{36K}/\pm45_{15K}]46\%$ (LLS) material tested at W/D = 6 is shown in Figure 14. Averages for three experiments are plotted against e/D ratio for three different bolt bearing test methods. Scatter in the data is shown as error bars representing one standard deviation from the mean.

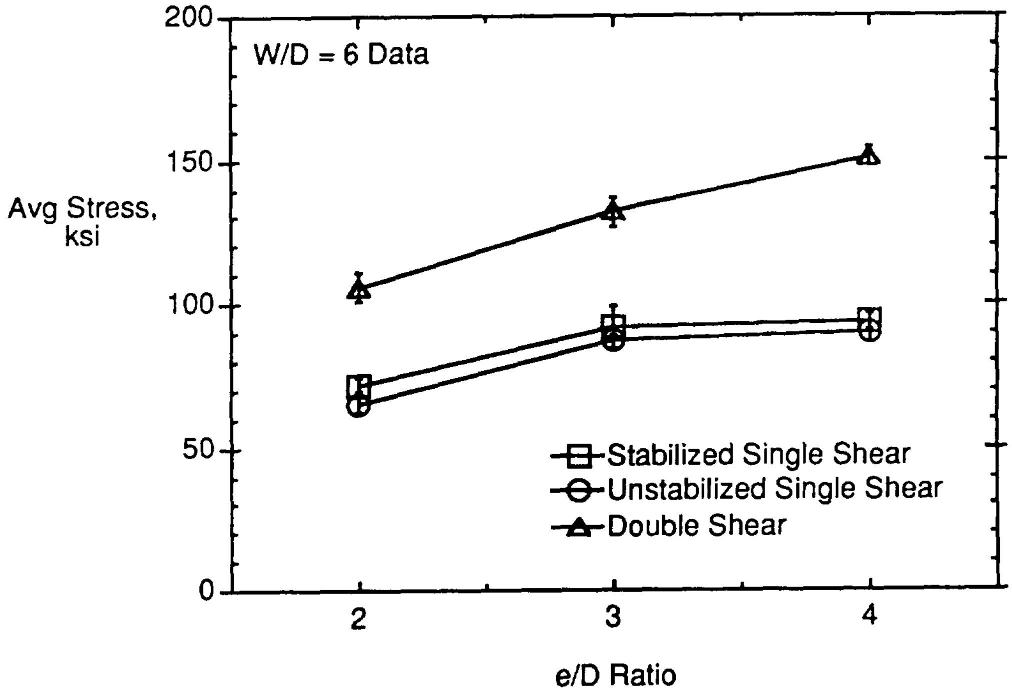

Figure 14. Test Method Comparison: $[0_{36K}/\pm45_{15K}]46\%$ Braid (W/D = 6).

Figure 14 shows that little difference was obtained between the Unstabilized Single Shear and Stabilized Single Shear test methods. The Stabilized Single Shear strengths were 10.7, 5.7, and 4.4 % greater than the Unstabilized Single Shear results at e/D = 2, 3, and 4, respectively. The strengths measured using the Double Shear method were significantly higher. These results were 63, 52, and 68% greater than the Unstabilized Single Shear values and 47, 43, and 60% greater the Stabilized Single Shear results at the same e/D ratios.

A comparison of the response to two different bolt bearing test methods at W/D = 8 has been made in Figure 15 for the $[0_{36K}/\pm45_{15K}]46\%$ material. Averages of three experiments are represented by each data point and scatter in the test results is displayed by error bars representing one standard deviation from the mean.

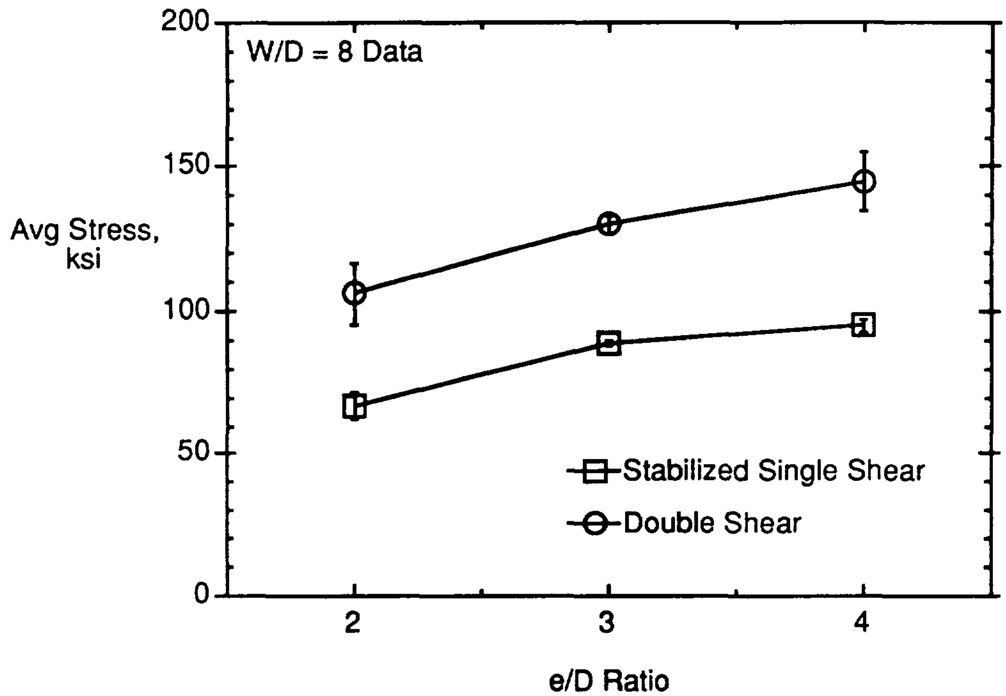

Figure 15. Test Method Comparison: $[0_{36K}/\pm45_{15K}]46\%$ Braid (W/D = 8).

The response of the $[0_{36K}/\pm45_{15K}]46\%$ (LLS) material measured at W/D = 8 is similar to its response at W/D = 6. The Stabilized Single Shear method shows little improvement in strength beyond e/D = 3. The strength measured using the Double Shear test method continues to increase with increasing e/D ratio much as it did in Figure 13 for the $[0_{30K}/\pm70_{6K}]46\%$ (SLL) material.

Data scatter is slightly higher in the LLS material than in the SLL material. An average CoV of 6.4 ± 3.8% was measured for the Stabilized Single Shear experiments; the Double Shear results averaged 3.4 ± 2.8%. As with the SLL material, the W/D = 8 test results were slightly lower (7.2%) than the W/D = 6 results for the Stabilized Single Shear test method at e/D = 3, and about the same at larger e/D ratios. The Double Shear test results at W/D = 6 and 8 were similar.

Average strength from each of the test methods has been plotted for each material in Figure 16. Test data acquired at W/D = 6 and e/D = 3 are given. Each bar represents an average of three experiments and one standard deviation from the average is shown with the error bars. The Double Shear test method yielded much greater strengths than the other methods. For example, its strengths were 44 t0 53% higher than the Unstabilized Single Shear values. However, these results may be inflated since the Double Shear specimens were clamped across their width. The Stabilized Single Shear specimen yielded only slightly higher strengths than the Unstabilized Single Shear specimens (6 to 10%).

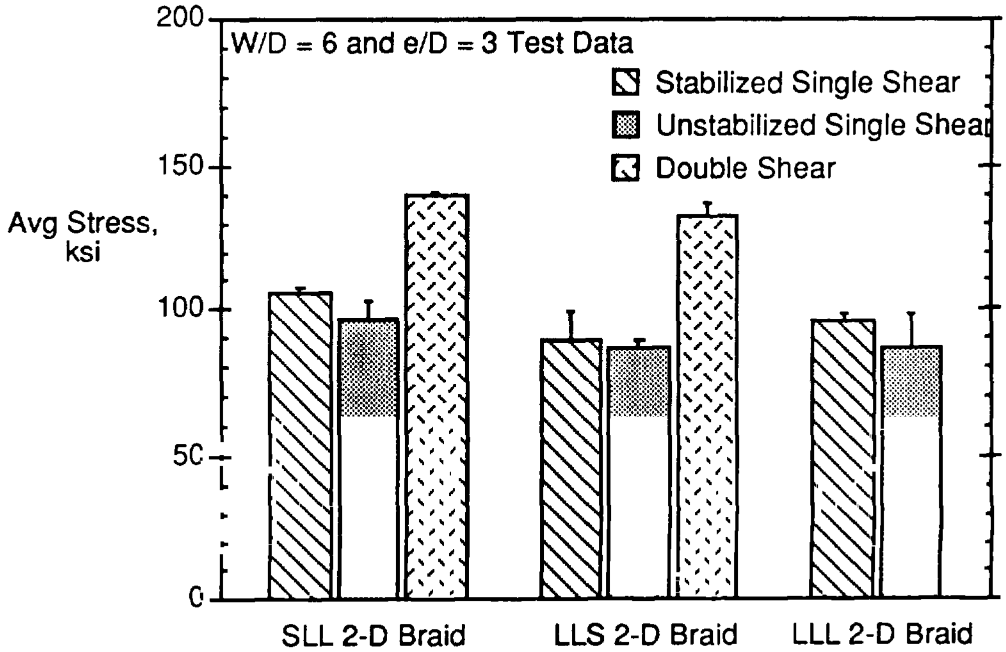

Figure 16. Comparison of the Bolt Bearing Test Methods for Three 2-D Braided Architectures (W/D = 6 and e/D = 3).

Strength results for a given test method were somewhat similar for each material. Strength for the Stabilized Single Shear test method ranged about 15%, varying from 92 to 106 ksi. The Unstabilized Single Shear test results ranged from 87 to 97 ksi., or about 12%. The range of the Double Shear test method results was small, varying only 6% from 132 to 140 ksi.

Summary and Conclusions

The applicability of three bolt bearing test methods, Stabilized Single Shear, Unstabilized Single Shear, and Double Shear, to textile composite materials was evaluated.

Three 2-D braids were used in this evaluation: $[0_{30K}/\pm70_{6K}]46\%$ (SLL), $[0_{36K}/\pm45_{15K}]46\%$ (LLS), and $[0_{75K}/\pm70_{15K}]46\%$ (LLL). The three letters shown in parentheses are a shorthand notation for yarn size, axial yarn content, and braid angle. An "S" indicates Small; an "L" indicates Large. They were chosen to isolate the effects of these braid parameters on bearing strength. For example, the SLL and LLL architectures have the same braid angle (70°) and axial yarn content (46%). Their yarn sizes, however, differ by a factor of 2.5. Similarly, the SLL and LLS architectures have the same axial yarn content and similar yarn sizes; but differ in braid angle.

The effect of the specimen width to hole diameter ratio (W/D) was studied, as was the effect of the proximity of the hole to the specimens edge (e/D). Data generated by Boeing Defense and Space Group in Philadelphia, PA, was used for these evaluations.

The $[0_{30K}/\pm70_{6K}]46\%$ (SLL) and $[0_{36K}/\pm45_{15K}]46\%$ (LLS) braids were the primary textile architectures used in this investigation. Both the SLL and LLS materials behaved in a similar fashion for each of the test methods. A limited number of experiments were conducted using the $[0_{75K}/\pm70_{15K}]46\%$ (LLL) architecture. However, the response seen in the tests of the LLL material was consistent with that of the other braids. Thus, variations in the response can be attributed to the test method and not to the architecture.

An evaluation of the effect of specimen width to hole diameter ratio (W/D) concluded that the response of these materials is consistent with their Open Hole Tension test results. There was, however, some disagreement at low e/D ratios. At e/D ratios of 3 or greater, little difference was observed by varying the W/D ratio.

The proximity of the hole to the specimens edge was found to affect strength significantly. In all cases, strength was improved by increasing the e/D ratio above 2. The $[0_{30K}/\pm70_{6K}]46\%$ material's strength increases by approximately 20% regardless of the test method used. The $[0_{36K}/\pm45_{15K}]46\%$ material showed as much as a 38% improvement in strength in Stabilized Single Shear when the e/D ratio was increased above 3.

A comparison of test methods was also made. The Stabilized and Unstabilized Single Shear tests produced consistent results. In all cases, strength was 6 to 10% higher for the Stabilized Single Shear method than for the unstabilized method. The unstabilized method suffers from bending, thus it was expected to yield lower strength values.

The Double Shear test method always produced the highest strengths but these results may be somewhat misleading. The Double Shear method has no bending but restricts specimen bulging at the bearing surface. Strengths of specimens with large edge distances were more adversely affected by this clamping effect. Boeing reported that failed material accumulating between the loading plates, delaying the final shear-out failure [Ref. 1]. Thus, these results can be misleading.

Differences between braid architectures were small. Recall that the $[0_{75K}/\pm70_{15K}]46\%$ construction was the same as the $[0_{30K}/\pm70_{6K}]46\%$ but using tows 2.5 times as large. The smaller tow size may account for the strength improvement between the two architectures. The $[0_{36K}/\pm45_{15K}]46\%$ (LLS) material had a significantly smaller braid angle than either the $[0_{30K}/\pm70_{6K}]46\%$ (SLL) or $[0_{75K}/\pm70_{15K}]46\%$ (LLL) braids. It also has the lowest average strength, regardless of test method. These differences are consistence with other tension test results on the these same textile materials [Ref. 3,4,5].

In general, these braided composites were found to be sensitive to bolt bearing test methods. The results from this study suggest that a hole diameter to specimen edge distance ratio (e/D) of 3 or greater should be used. A hole diameter to specimen width ratio of W/D = 6 or greater should also be maintained. It is further recommended that standard material comparisons be made using the Stabilized Single Shear test method. Design allowables may require various test methods and specimen configurations, such as those proposed by MIL-HDBK-17 [Ref. 6].

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Appendix A: Boeing Test Data

Table A1. Results of Double Shear Bearing Tests.

		SLL		LLS	
W/D	e/D	Strength (ksi)	Std. Dev. (ksi)	Strength (ksi)	Std. Dev. (ksi)
4	2	124	5.51	106	2.0
4	3	139	4.93	129	3.05
4	4	156	3.61	151	5.03
6	2	110	3.79	106	4.93
6	3	140	1.0	132	5.01
6	4	159	6.66	151	2.88
8	2	116	4.04	106	10.54
8	3	143	3.61	130	3.21
8	4	155	4.36	145	10.06

Table A2. Results of Stabilized Single Shear Bearing Tests.

		SLL		LLS		LLL	
W/D	e/D	Strength (ksi)	Std. Dev. (ksi)	Strength (ksi)	Std. Dev. (ksi)	Strength (ksi)	Std. Dev. (ksi)
4	2	89	1.26	64	6.81		
4	3	101	5.89	92	3.01		
4	4	105	1.92	97	1.97		
6	2	92	4.63	72	2.32		
6	3	106	1.33	92	7.57	96	2.64
6	4	105	3.06	94	2.73		
8	2	80	3.88	67	4.43		
8	3	100	1.94	89	1.17		
8	4	100	3.14	95	2.26		

Table A3. Results of Unstabilized Single Shear Bearing Tests.

		SLL		LLS		LLL	
W/D	e/D	Strength (ksi)	Std. Dev. (ksi)	Strength (ksi)	Std. Dev. (ksi)	Strength (ksi)	Std. Dev. (ksi)
6	2	78	2.17	65	2.81		
6	3	97	5.56	87	2.23	87	11.57
6	4	94	2.73	90	3.95		

Appendix B:
Lockheed's Stabilized Single Shear Bearing Test Data

Table B1. Through-the-Thickness 3-D Weave Test Results.

		TTT-1		TTT-2		TTT-3	
W/D	e/D	Strength (ksi)	CoV (%)	Strength (ksi)	CoV (%)	Strength (ksi)	CoV (%)
5	3	109.4	4.21	105.8	2.7	85.9	2.5

Table B2. Layer-to-Layer 3-D Woven Test Results.

		LTL-1		LTL-2		LTL-3	
W/D	e/D	Strength (ksi)	CoV (%)	Strength (ksi)	CoV (%)	Strength (ksi)	CoV (%)
5	3	107.2	3.8	100.2	0.9	91.4	0.2

Table B3. 3-D Braid Test Results.

		TTT-1		TTT-2		TTT-3	
W/D	e/D	Strength (ksi)	CoV (%)	Strength (ksi)	CoV (%)	Strength (ksi)	CoV (%)
5	3	139.0	3.8	127.7	3.8	104.9	9.3

Table B4. 2-D Braid Test Results.

		Braid-1		Braid-2	
W/D	e/D	Strength (ksi)	CoV (%)	Strength (ksi)	CoV (%)
5	2.5	141.7	3.0	130.5	3.2

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13. ABSTRACT (*Maximum 200 words*)

The response of three 2-D braided materials to bolt bearing loading was evaluated using data generated by Boeing Defense and Space Group in Philadelphia, PA. Three test methods, Stabilized Single Shear, Unstabilized Single Shear, and Double Shear, were compared. In general, these textile composites were found to be sensitive to bolt bearing test methods. The Stabilized Single Shear method yielded higher strengths than the Unstabilized Single Shear method in all cases. The Double Shear test method always produced the highest strengths but these results may be somewhat misleading. It is therefore recommended that standard material comparisons be made using the Stabilized Single Shear test method.

The effects of two geometric parameters, W/D and e/D, were also studied. An evaluation of the effect of the specimen width (W) to hole diameter (D) ratio concluded that bolt bearing responses were consistent with open hole tension results. A W/D ratio of 6 or greater should be maintained. The proximity of the hole to the specimen edge significantly affected strength. In all cases, strength was improved by increasing the ratio of the distance from the hole center to the specimen edge (e) to the hole diameter (D) above 2. An e/D ratio of 3 or greater is recommended.

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