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A COMPARISON OF GRAPHITE/EPOXY TAPE LAMINATES AND 2-D BRAIDED COMPOSITES MECHANICAL PROPERTIES*

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ABSTRACT

A comparison of the mechanical properties of unidirectional composite tape laminates and of 2-dimensional triaxially braided composite was conducted. The tape laminate layups were designed to match the percentage of axial fibers and the angle of the bias tows in the braided composite. The material system used for the laminates is AS4/3501-6 which was chosen as the closest available match to AS4/1895 used for the braids. The strength and stiffness properties measured here include tension, open-hole tension, filled-hole tension, compression and open-hole compression, all of these in both the longitudinal and transverse direction.

Results show that the longitudinal modulus of both material forms is quite similar, but that the transverse modulus of the braids is lower. In terms of strength, the longitudinal unnotched strength of the braids is lower than that of the laminates, while the transverse strength is significantly lower. For both strength and stiffness, the crimp in the bias tows of the braid is probably the main cause for reduced properties. On the other hand, a very significant increase in open-hole and filled-hole tension strength was observed for the braids compared to the tape laminates. However, this was not observed in compression where all the braid properties are lower than for the laminates.

INTRODUCTION

Carbon/Epoxy composites made from textile fiber preforms manufactured with a Resin-Transfer-Molding (RTM) process have some potential for reducing costs and increasing damage tolerance of aerospace structures. One form of textile preform which is under consideration is a 2-dimensional triaxially braided fabric. A large amount of test data has been generated recently to quantify the mechanical properties of various 2-D braided configurations loaded in tension, with and without holes, compression, with and without holes, shear and bolt bearing [1].

The key question is then to determine and quantify the benefits and drawbacks of this material form. Because of the nature of the triaxial fabric (e.g., no 90° fibers), little data which could be used for a direct comparison of mechanical performance is available for more conventional material forms (i.e. tape or biaxial fabric laminates). Therefore, tape laminates with the same ply orientation and percentage of 0° fibers as the previously tested braided composites were manufactured and tested. More detailed results of the effort reported here can be found in Reference 2.

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TEST PROGRAM DESCRIPTION

Four configurations of 2-D braided composite were extensively tested in a previous investigation as reported in Reference 1. The 2-D braided fabric contains two types of tows, the longitudinal (axial, or 0°) tow and the braided (or bias) tows oriented at angle θ of the axial tow. The braid pattern used is 2X2 pattern, meaning that each braided tow goes over and under two tows at a time. As shown in Table 1, the first three architectures contain a large percentage of axial fiber typical of a composite optimized for a predominantly longitudinal loading. The first architecture, SLL, was braided with small tows to provide a fine architecture, while the third one, LLL, was braided with 2.5 times larger tows, thus allowing to examine the influence of tow sizes. The second architecture, LLS was braided with a 45° bias angle, thus allowing one to examine the influence of braid angles. For practical applications, braid angles will often be limited to the 45° to 70° range, and the comparison of LLS and LLL allows one to examine both upper and lower bounds on that parameter. Finally, the fourth architecture, LSS, contains a larger amount of ±45° tows more typical of a composite optimized for shear loading.

Three laminates were designed to match the bias angle and percentage of axial fibers of these braids. Two of the braids, SLL and LLL, have the same layup with different tow sizes and thus will be compared with the same laminate. The material system used is AS4/3501-6 (4.4 oz/yd^2) which closely matches the AS4/1895 system used for the braids. The following laminates were used:

Laminate 1: $[(45/0/-45/0)_2/45/0/-45]_s$
22 Plies Total, 10 0° Plies (45.4%), 12 45° Plies, to match LLS.

Laminate 2: $[(70/0/-70/0)_2/70/0/-70]_s$
22 Plies Total, 10 0° Plies (45.4%), 12 70° Plies, to match SLL and LLL.

Laminate 3: $[(\pm45)_2/0/(\pm45)_3/0(\pm45)_3/0/(\pm45)_2]_t$
23 Plies Total, 3 0° Plies (13.0%), 20 45° Plies, to match LSS.

Table 1 Description of 2-D braid architectures

Name	Longitudinal Tow Size	Braided Tow Size	% Longitudinal Tow	Braid Angle [°]	Unit Cell Width [in]	Unit Cell Length [in]
SLL	30 K	6 K	46	70	0.458	0.083
LLS	36 K	15 K	46	45	0.415	0.207
LLL	75 K	15 K	46	70	0.829	0.151
LSS	6 K	15 K	12	45	0.415	0.207

Three specimens were used for each test configuration. Standard size specimen, 12" long and 1.5" wide, were used for the tension tests. Modified IITRI specimens, 1.5" long by 1.5" wide test section, were used for the compression tests. The laminate thickness was doubled for the compression specimen to insure specimen stability. A hole diameter of 0.188" was mistakenly used in the compression test instead of the standard 0.250".

The same approach used in Reference 1 was used here to make all results directly comparable. **All results are normalized to a 60% fiber volume fraction.** Fiber volume fraction and thickness were measured on all manufactured panels. After averaging these data over all panels, a nominal ply thickness of **0.0054"** was calculated. All stiffness moduli and Poisson's coefficients are the initial value of these properties and were measured with a linear regression between 0.001 and 0.003 strain levels. Wherever a nominal strain is reported, it is equal to the strength divided by the initial modulus. Actual strain is the last reading obtained from a strain gage prior to failure. Strength is always calculated as load divided by actual width and nominal thickness.

Open-hole and filled-hole strength results were corrected to infinite plate width with the following formula for a hole diameter d, a nominal thickness t_{nom} and a plate width w :

$$\sigma_\infty = \left[\frac{2 + \left(1 - \frac{d}{w}\right)^3}{3\left(1 - \frac{d}{w}\right)} \right] \cdot \frac{P}{w\ t_{nom}}$$

TENSION PROPERTIES

Tension properties for all laminates were measured in both the longitudinal (0°) and transverse (90°) directions. Properties included stiffness modulus, Poisson's coefficient, open-hole strength (01.88" and 0.250" diameters) and filled-hole strength using a fully-torqued 0.25" titanium hilock fastener. All the tension properties measured in the longitudinal (0°) direction are shown in Table 2, while all the properties measured in the transverse (90°) direction are shown in Table 3.

Table 2 Laminate Longitudinal Tension Properties

Property	Laminate 1	Laminate 2	Laminate 3
Modulus [msi]	10.33	9.63	4.92
CoV [%]	0.8	2.8	0.5
Poisson's Coefficient	0.663	0.157	0.713
CoV [%]	2.3	3.7	0.8
Unnotched Strength [ksi]	131	132	63
Nominal Strain [µs]	12,690	13,750	12,840
CoV [%]	12.5	6.3	1.8
Actual Strain [µs]	12,300	13,400	15,200
0.188" OHT Strength [ksi]	72	66	42
OHT Nom. Strain [µs]	6,960	6,860	8,460
CoV [%]	4.4	1.0	2.0
0.250" OHT Strength [ksi]	69	66	40
OHT Nom. Strain [µs]	6,640	6,820	8,080
CoV [%]	3.8	3.6	1.2
0.250" FHT Strength [ksi]	60	49	42
FHT Strain [µs]	5,820	5,090	8,560
CoV [%]	2.1	1.8	2.7

Note: Laminate 1 $[(45/0/-45/0)_2/45/0/-45]_s$
Laminate 2 $[(70/0/-70/0)_2/70/0/-70]_s$
Laminate 3 $[(\pm45)_2/0/(\pm45)_3/0/(\pm45)_3/0/(\pm45)_2]_t$

Coefficients of variation were generally quite low and well within the typical values obtained when testing composites. The only exception was the unnotched 0° strength of L1 for which one specimen failed prematurely. If that data point was excluded, L1 strength would be 141 ksi (13,600 μs). Laminate 1 and 2 were linear to failure, as indicated by the fact that actual and nominal strains are virtually equal, while laminate 3 (with a high percentage of ±45° plies) had a softening behavior with the actual strain much higher than nominal. Failure for L1 and L2 occurred close to the tabs. L3 exhibited a large amount of delamination.

Somewhat different failure modes were observed in the 90° unnotched tension tests. Laminates 1 and 2 exhibited a clean straight break well inside the test section. Laminate 3 also failed inside the test section and showed mostly an in-plane shear failure mode, along with some visible edge delaminations. Laminate 1 and 3 had a softening behavior because of their 45° ply angle. The strain levels in L2 were much below that in the 0° tests, indicating that pure fiber fracture was not the dominant failure mode.

All laminates but L3 show a strong sensitivity to the presence of a fully torque fastener in the longitudinal tension test. Strength reductions were 13% for L1, 26% for L2. In the transverse direction, the influence of the fastener was quite different. A strength increase was observed for L1 (+18%) and L2 (+3%), while a strength decrease was observed for L2 (-10%). Note that the strength increase was observed for the two laminates with a low transverse modulus.

Table 3 Laminate Transverse Tension Properties

Property	Laminate 1	Laminate 2	Laminate 3
Modulus [msi]	3.37	8.96	3.48
CoV [%]	0.9	0.6	1.5
Poisson's Coefficient	0.225	0.147	0.513
CoV [%]	9.4	3.9	1.1
Unnotched Strength [ksi]	35	72	35
Nominal Strain [μs]	10,480	8,020	10,030
CoV [%]	1.8	3.3	0.9
Actual Strain [μs]	15,600	8,300	14,800
0.188" OHT Strength [ksi]	31	59	33
OHT Nom. Strain [μs]	9,210	6,580	9,520
CoV [%]	1.2	3.5	0.6
0.250" OHT Strength [ksi]	28	53	32
OHT Nom. Strain [μs]	8,359	5,910	9,140
CoV [%]	2.7	3.4	0.8
0.250" FHT Strength [ksi]	33	50	33
FHT Strain [μs]	9,660	5,580	9,430
CoV [%]	2.3	3.1	0.5

Note: Laminate 1 $[(45/0/-45/0)_2/45/0/-45]_s$
Laminate 2 $[(70/0/-70/0)_2/70/0/-70]_s$
Laminate 3 $[(\pm45)_2/0/(\pm45)_3/0/(\pm45)_3/0/(\pm45)_2]_t$

The first comparison, shown in Figure 1, is for longitudinal modulus. Minimal differences were found between braids and tape laminates: +0.4% for SLL, -4.6% for LLL, -0.9% for LLS, and -0.6% for LSS. Considering experimental scatter and the slight differences in percentage of 0°, it is fair to say that there is no difference between longitudinal moduli for the two material forms. The slight reduction for LLL is probably due to the additional tow waviness introduced by the use of large tow sizes.

The comparison is quite different for the transverse modulus. As shown in Figure 1, the braided material is substantially less stiff: -19% for SLL, -24% for LLL, -22% for LLS, and -16% for LSS. The primary cause for this reduction is the crimp in the bias tows.

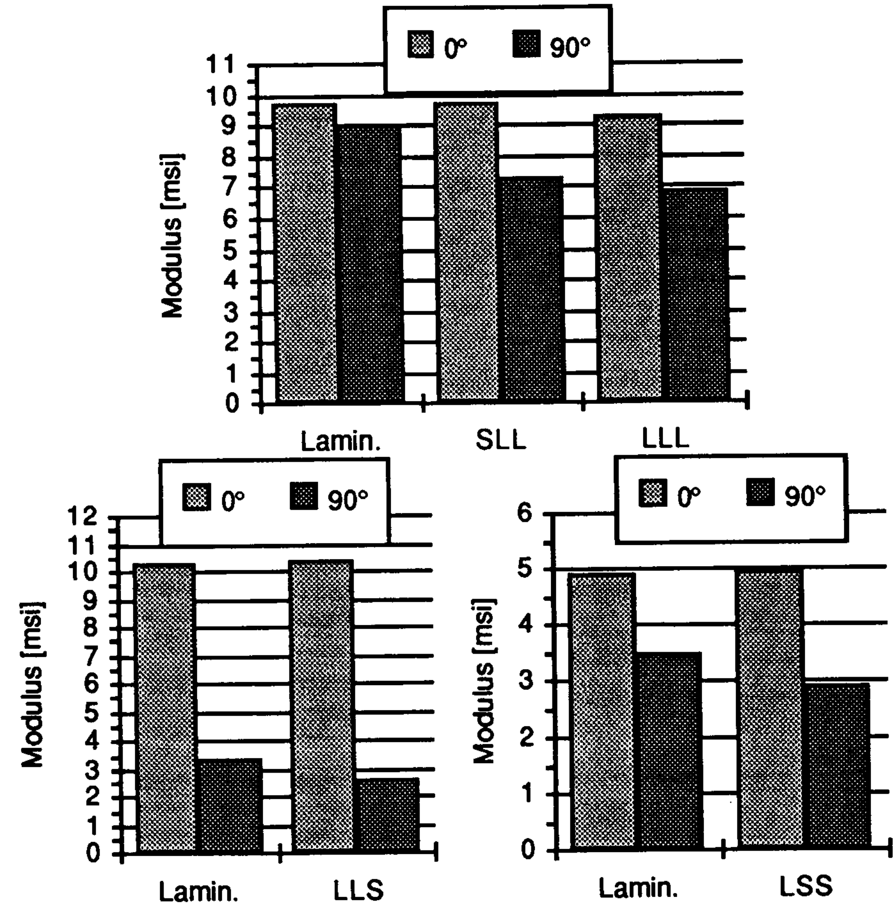

Figure 1 Comparison of Longitudinal and Transverse Tension Modulus.

The comparison for unnotched longitudinal tension strength is show in Figure 2.a to 2.c. A notably lower strength was obtained for all the braids: -17% for SLL, -34% for LLL, -31% for LLS, and -16% for LSS. Once again, the tow waviness is a probable contributor to this loss of strength. However, it is somewhat surprising that there was so little difference in modulus and such difference in strength. Another possible contributor is the matrix material. Although 1895 and 3501-6 are rather similar epoxys, it is possible that 1895 is more brittle or has a lower strain to failure than 3501-6.

The open-hole tension strength comparison is based on the standard 1/4" diameter hole which is often used in developing material allowables. In Reference 1, several hole diameters were tested for each braided material. A log-log best fir curve of strength versus hole diameter was then calculated. This procedure showed that the data at some of the hole diameters did not follow the overall trend due to experimental scatter. This was the case for the 1/4″ hole in the SLL and LLS architecture. Thus, instead of using the data for the 1/4″ hole, the strength is calculated with the following best fit equations:

SLL: $\sigma = 72.2 * d^{-.165}$ LLL: $\sigma = 53.0 * d^{-.315}$

LLS: $\sigma = 61.3 * d^{-.208}$ LLS: $\sigma = 28.8 * d^{-.265}$

Results in Figure 2 show a clear strength advantage for the braided materials. The relative differences between braid and laminate strength were +37% for SLL, +24% for LLL, +20% for LLS, and +4% for LSS. Since moduli are quite similar for each braid and equivalent laminate, the differences in term of nominal strain are about the same.

This strength difference is further magnified in the filled-hole tension test. As mentioned above, the laminated material was quite sensitive to the presence of a fastener, while the data in Ref. 1 showed that the braids were not. The relative differences in term of strength were: +72% for SLL, +47% for LLL, and +19% for LLS (no data is available for LSS).

Post-failure examination of the braided specimens revealed extensive matrix failure between the axial and bias tows which would tend to reduce the stress concentration for axial yarns. On the other hand, examination of the laminated specimen showed a fairly clean fracture surface across the specimen net section. Because these are such significant differences and because this is such an important property in terms of design, this topic would warrant further work to confirm these experimental results and explain this apparent advantage of braids over tape laminate.

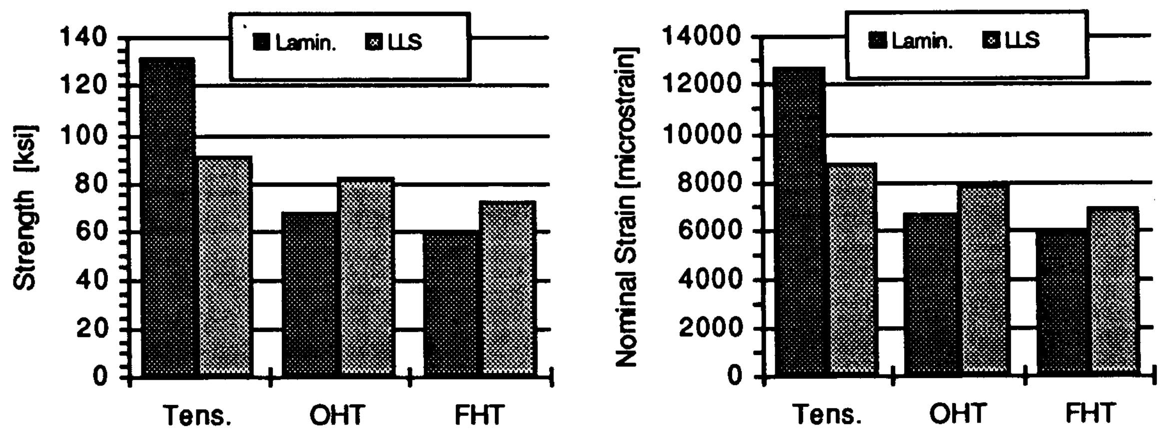

Figure 2.a Comparison of 0° Tension Strength for Tape Laminate 1 and LLS.

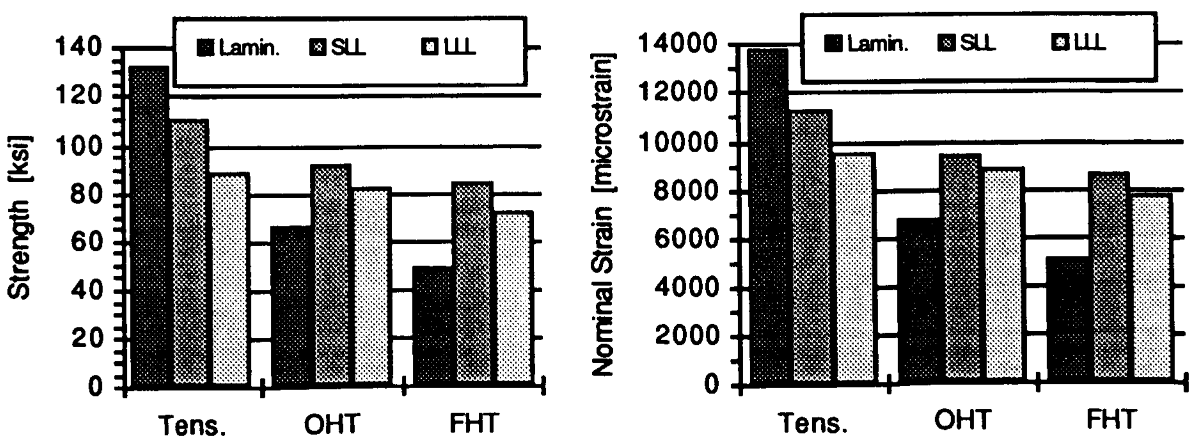

Figure 2.b Comparison of 0° Tension Strength for Tape Laminate 2, SLL and LLL.

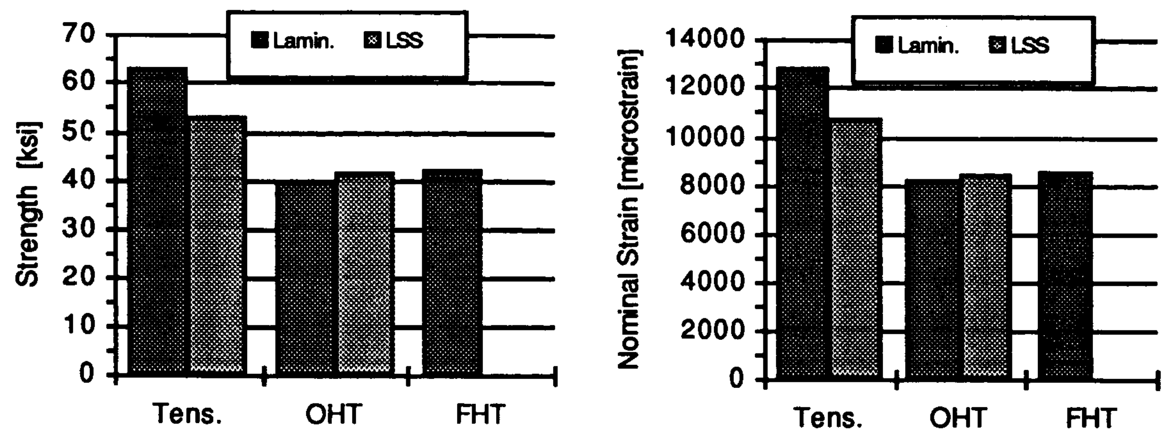

Figure 2.c Comparison of 0° Tension Strength for Tape Laminate 3 and LSS.

Strength measured along the transverse direction for these materials is shown in Figure 3.a to 3.c. For the unnotched case, the braided material show a severe strength reduction compared to the tape laminates: -51% for SLL, -57% for LLL, -57% for LLS, and -29% for LSS. Once again, the crimp in the bias tows is the likely cause for the strength reduction.

Only a limited set of data is available for the transverse open-hole tension strength of the braided material. A single hole size of 1/4" was tested and is used for comparison. Somewhat surprisingly, these materials exhibited no notch sensitivity, and in some cases, the strength was slightly higher than that for the unnotched case. The data is probably too limited at this point to draw any definite conclusion. The tape laminates did show some notch sensitivity, and thus the differences in strength between the two material forms are reduced compared to the unnotched case: -36% for SLL, -43% for LLL, -46% for LLS, and -16% for LSS.

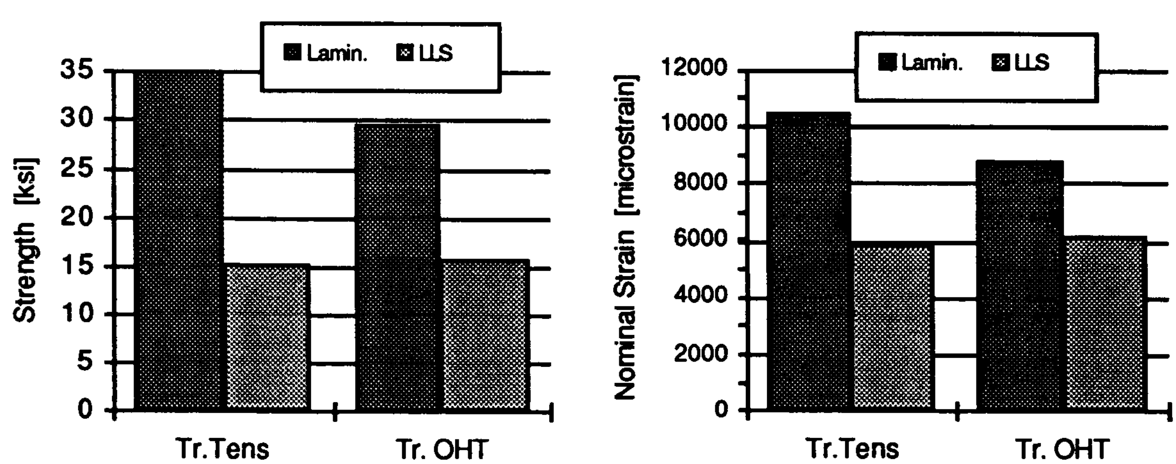

Figure 3.a Comparison of 90° Tension Strength for Tape Laminate 2 and LLS.

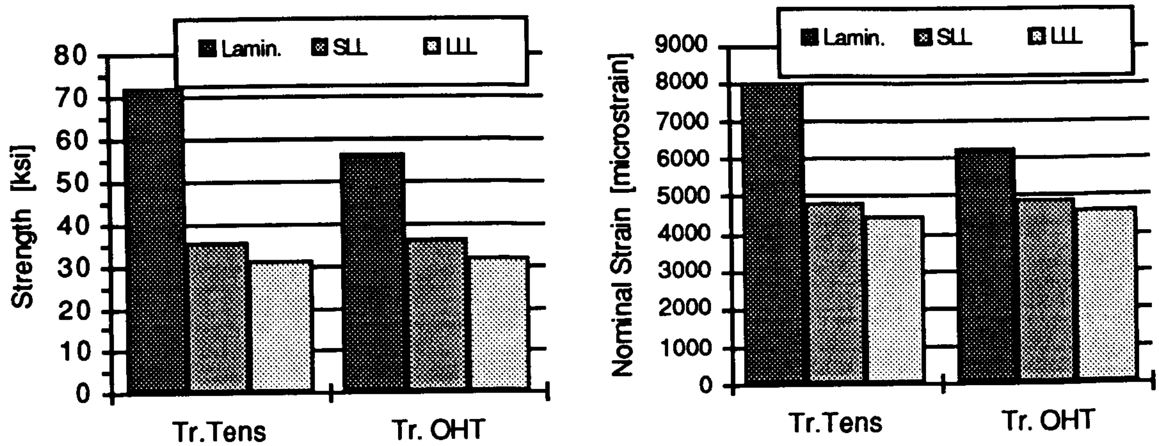

Figure 3.b Comparison of 90° Tension Strength for Tape Laminate 2, SLL and LLL.

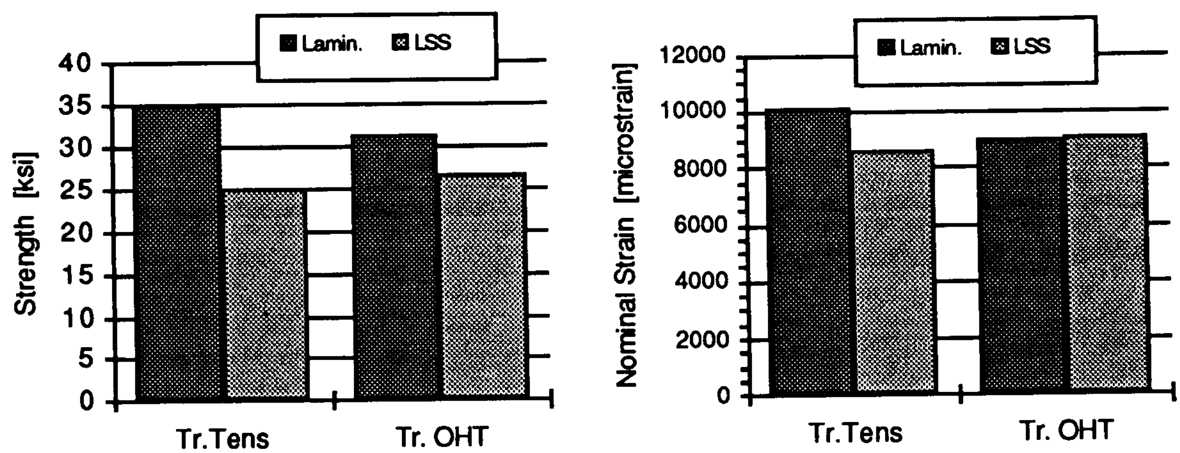

Figure 3.c Comparison of 90° Tension Strength for Tape Laminate 3 and LSS.

COMPRESSION PROPERTIES

Compression properties for all four laminates were also measured in both the longitudinal (0°) and transverse (90°) directions. Properties included stiffness modulus, Poisson's coefficient and open-hole strength (0.188" diameter). A modified IITRI test specimen [1] with a test section of 1.5" by 1.5" was used for all tests.

All the compression properties measured in the longitudinal (0°) direction are shown in Table 4, while all the properties measured in the transverse (90°) direction are shown in Table 5. Coefficients of variation were generally quite low and well within the typical values obtained when testing composites. Some of the exceptions were the unnotched 0° strength of L1, notched 90° strength of L1 and unnotched 90° strength of L2. The nominal strains reported in this section were always calculated with the compression modulus. When comparing the compression moduli to the ones measured in tension, significant differences were observed, 17% lower for L1, 13% for L2 and 16% for L3. A similar observation can me made for the transverse modulus: 8% lower for L1, 14% for L2 and 13% for L3. Although it is typical for composites to be softer in compression, these differences are slightly higher than expected. The test specimen itself, with a short and wide test section, is believed to be partly responsible for this effect. Longitudinal fiber strains at failure were fairly typical of this type of material, ranging from 0.95% to 1.1%. High strains to failure were measured wherever there was large percentage of ±45° fibers, such as in the 0° and 90° test of L3 and in the 90° test of L1.

Table 4 Laminate Longitudinal Compression Properties

Property	Laminate 1	Laminate 2	Laminate 3
Modulus [msi]	8.84	8.53	4.25
CoV [%]	1.0	2.1	1.6
Poisson's Coefficient	0.704	0.172	0.712
CoV [%]	3.0	1.8	3.2
Unnotched Strength [ksi]	84	82	58
Nominal Strain [µs]	9,500	9,640	13,560
CoV [%]	9.9	5.5	5.1
0.188" OHT Strength [ksi]	65	75	43
OHT Nom. Strain [µs]	7,330	8,770	10,210
CoV [%]	1.5	2.0	1.4

Note: Laminate 1 $[(45/0/-45/0)_2/45/0/-45]_s$
Laminate 2 $[(70/0/-70/0)_2/70/0/-70]_s$
Laminate 3 $[(\pm45)_2/0/(\pm45)_3/0/(\pm45)_3/0/(\pm45)_2]_t$

Table 5 Laminate Transverse Compression Properties

Property	Laminate 1	Laminate 2	Laminate 3
Modulus [msi]	3.13	7.84	3.08
CoV [%]	0.6	1.3	1.5
Poisson's Coefficient	0.237	0.151	0.525
CoV [%]	2.1	6.7	2.5
Unnotched Strength [ksi]	50	70	48
Nominal Strain [µs]	15,880	8,930	15,720
CoV [%]	4.9	12.3	1.5
0.188" OHT Strength [ksi]	42	61	44
OHT Nom. Strain [µs]	13,520	7,830	14,220
CoV [%]	7.6	1.3	0.4

Note: Laminate 1 $[(45/0/-45/0)_2/45/0/-45]_s$
Laminate 2 $[(70/0/-70/0)_2/70/0/-70]_s$
Laminate 3 $[(\pm45)_2/0/(\pm45)_3/0/(\pm45)_3/0/(\pm45)_2]_t$

The first comparison, shown in Figure 4, is for modulus. Small differences were found between braids and tape laminates for the longitudinal modulus, +4.6% for SLL, -1.9% for LLL, -0.2% for LLS, and 3.1% for LSS, and for the transverse modulus, +7.5% for SLL, -5.4% for LLL, -3.2% for LLS, and -1.6% for LSS. The differences for the transverse modulus are less than those observed in the tension case. Based on these observations, it would appear that the modulus measured in the laminated specimen might be somewhat under-estimated, although no precise cause was found for this effect.

The comparison for unnotched longitudinal compression strength is shown in Figure 5.a to 5.c. As anticipated, a lower strength was obtained for all the braids: -14% for SLL, -28% for

LLL, -31% for LLS, and -16% for LSS. Once again, the tow waviness is a probable contributor to this loss of strength. Unlike in the tension case, the notched strength of the braids came in lower than that of the tape laminates in all cases. The comparison of the transverse strength shown in Figure 6.a to 6.c reveals the same poor performance of the braids that was also observed in the tension case. A strength reduction of up to 57% for the case of the LLL architecture was measured.

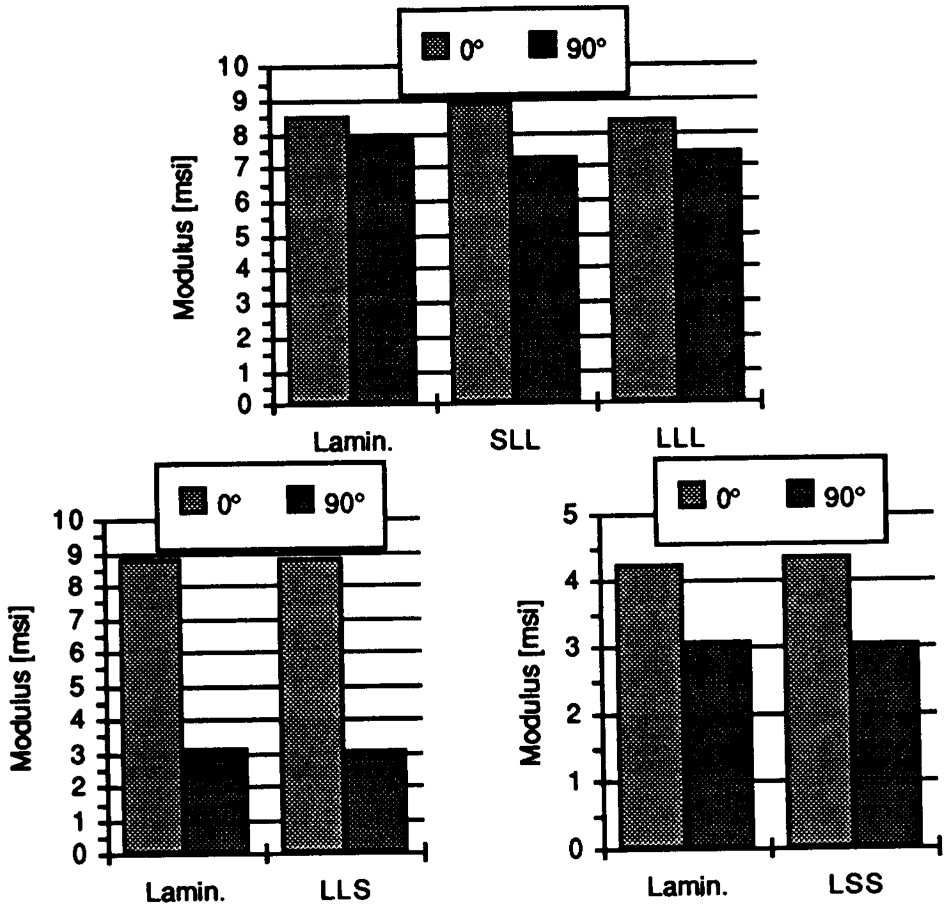

Figure 4 Comparison of Longitudinal and Transverse Compression Modulus.

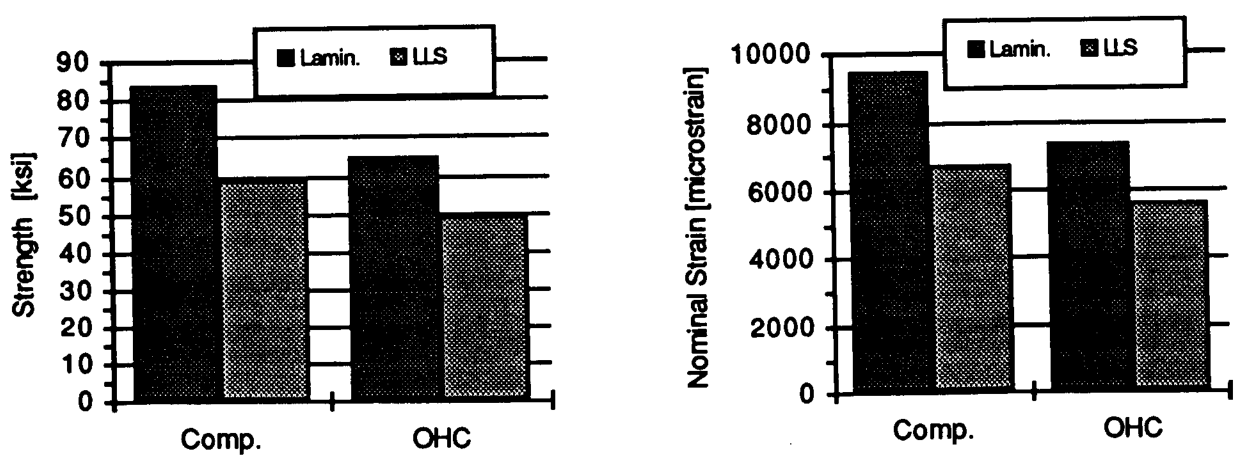

Figure 5.a Comparison of 0° Compression Strength for Tape Laminate 1, LLS.

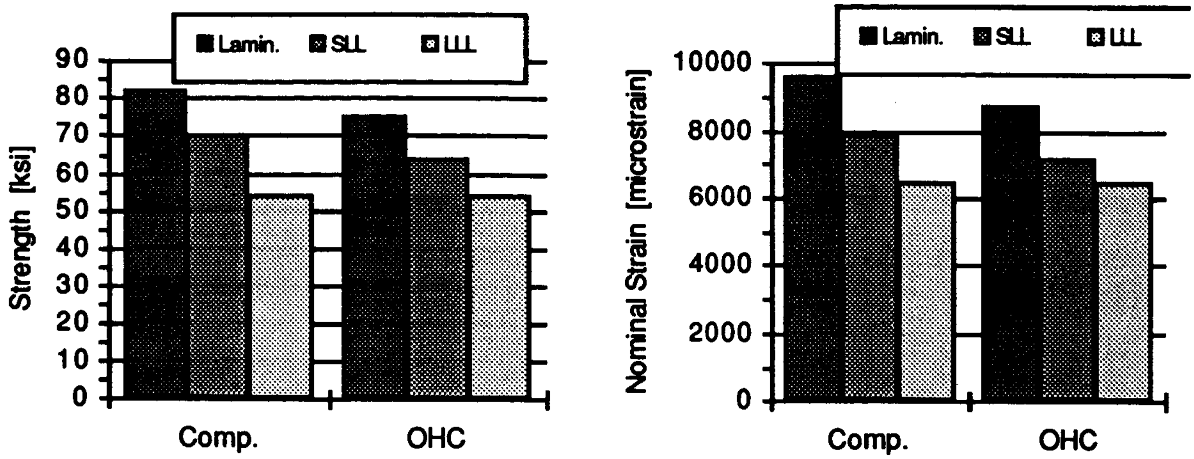

Figure 5.b Comparison of 0° Compression Strength for Tape Laminate 2, SLL and LLL.

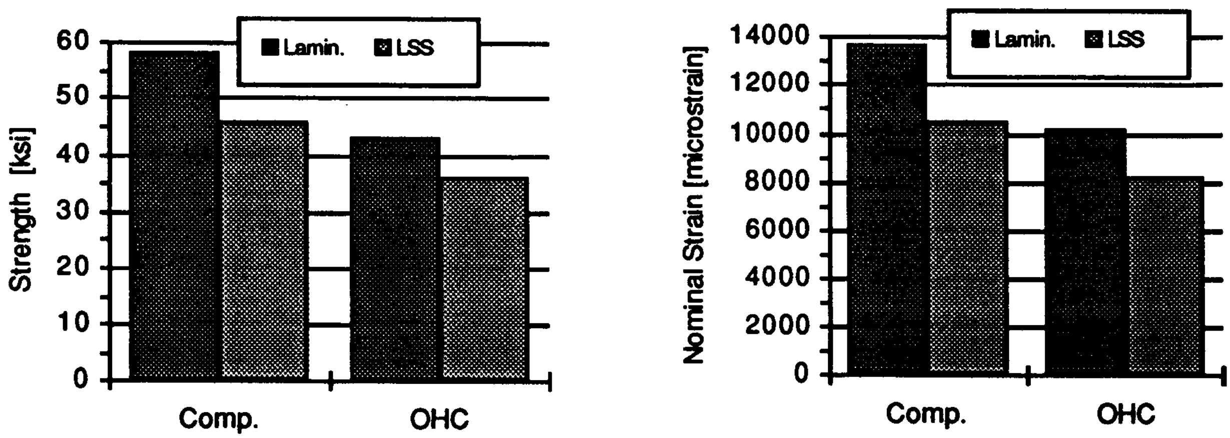

Figure 5.c Comparison of 0° Compression Strength for Tape Laminate 3, LSS.

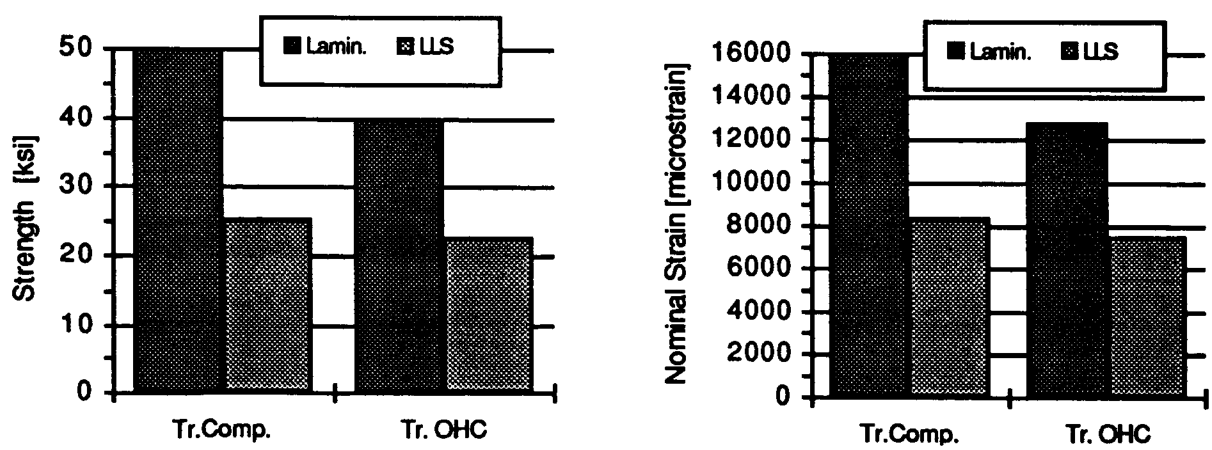

Figure 6.a Comparison of 90° Compression Strength for Tape Laminate 1, LLS.

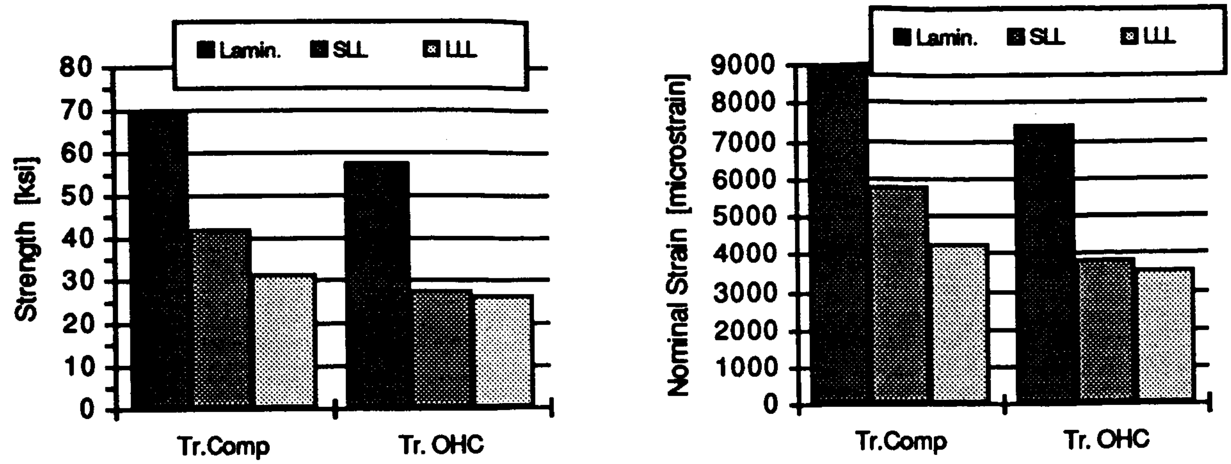

Figure 6.b Comparison of 90° Compression Strength for Tape Laminate 2, SLL and LLL.

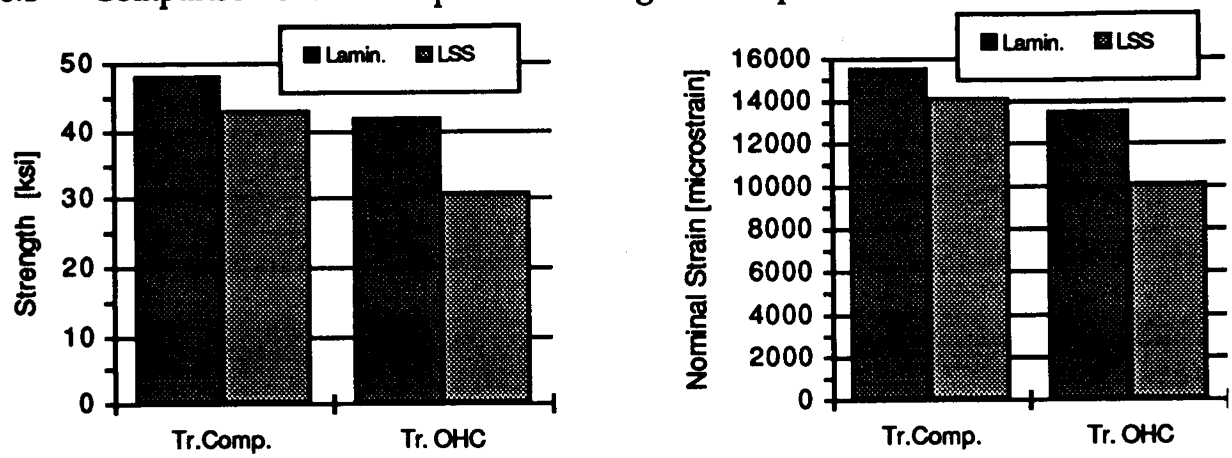

Figure 6.c Comparison of 90° Compression Strength for Tape Laminate 3, LSS.

SUMMARY

Results of the comparison between the two material forms show that the longitudinal modulus of both material forms is quite similar, but that the transverse modulus of the braids is lower. In terms of strength, the longitudinal unnotched strength of the braids is lower than that of the laminates. On the positive side, a very significant increase in open-hole and filled-hole tension strength was observed for the braids compared to the tape laminates. However, this was not observed in compression where all the braid properties are lower than for the laminates. The very low strength of the braids should be considered in more details and could be a concern depending on the type of structural application.

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2. Minguet, P.J., Gunther, C.K., "A Comparison of Graphite/Epoxy Tape Laminates and 2-D Braided Composites Mechanical Properties", NASA CR-4610, July 1994.