

INFLUENCE OF SPECIMEN PREPARATION AND SPECIMEN SIZE ON THE TRANSVERSE TENSILE STRENGTH AND SCATTER OF GLASS EPOXY LAMINATES

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SUMMARY: The influence of specimen polishing, specimen configuration, and specimen size on the transverse tension strength of two glass epoxy materials loaded in three and four point bending was evaluated. Polishing machined edges, and/or tension side failure surfaces, was detrimental to specimen strength characterization instead of yielding a higher, more accurate, strength as a result of removing inherent manufacture and handling flaws. Transverse tension strength was sensitive to span length due to the classical weakest link effect. However, strength was less sensitive to volume changes achieved by increasing specimen width. The Weibull scaling law over-predicted changes in transverse tension strengths in three point bend tests and under-predicted changes in transverse tension strengths in four point bend tests. Furthermore, the Weibull slope varied with specimen configuration, volume, and sample size. Hence, the utility of this scaling law for predicting transverse tension strength is unclear.

KEYWORDS: Transverse Tensile Strength, matrix cracking, Weibull distribution, scale effects, glass epoxy, bending tests

INTRODUCTION

Matrix ply cracking is a common initial damage mechanism in fiber reinforced composites. Because ply cracking alone is seldom catastrophic for laminates subjected to membrane loading, few researchers have tried to identify and overcome the difficulties involved in characterizing the transverse tensile strength associated with matrix ply cracking. However, for composite structures that undergo bending, or other out-of-plane loading, the formation of matrix cracks may lead to immediate catastrophic delamination formation and growth [1,2]. Hence, accurate characterization of the transverse tensile strength of composite materials is needed to accurately predict matrix ply cracking in these structures.

In this study, 90 degree unidirectional glass epoxy lamina were tested in three and four point bending to characterize composite transverse tensile strength. The influence of edge flaws due to machining, and surface flaws due to manufacture and handling, were assessed by testing specimens in their as-manufactured and machined condition, in addition to testing specimens with polished edges, bottom failure surfaces, or both. The dependence of transverse tensile strength on volume was assessed by testing specimens with different widths and span lengths.

Materials

Two sets of S2/F584 glass epoxy panels were supplied by the Boeing Company, Mesa, Arizona. The original prepreg material used to manufacture the first set was flagged by the material supplier, Hexcel Corporation, as having contaminates in the form of small spots of aluminum silicate. This material was replaced by a new prepreg material to manufacture the second set. However, because no significant flaws were detected in ultrasonic inspection, both sets of panels were tested in this study. The S2 glass fiber density for both panels was 2.48 g/cm^3 . The fiber aerial weights were 218 and 223 g/m^2 for the original and new prepreg material, respectively. For both materials, 24-ply panels, measuring $407 \times 305 \text{ mm}$, were autoclave-cured using the manufacturer's recommended curing cycle. The nominal panel thickness was 4.45 mm, corresponding to a nominal ply thickness of 0.185 mm. Nominal fiber volume fractions were 47.3% and 48.4% for the original and new prepreg panels, respectively, and were estimated using

$$\%V_f = \frac{N(\text{FAW})}{t(\text{FD})} \times 100 \quad (1)$$

where N is the number of plies, t is the panel thickness, FAW is the fiber aerial weight and FD is the fiber density. This fiber volume fraction compares well with the average volume fractions of 48.0% and 48.1% for the original and new prepreg material, respectively, measured by fiber digestion using ASTM D3171.

A single, large, S2/8552 glass epoxy panel was made from unidirectional prepreg tape by Bell Helicopter Company, Fort Worth, Texas. The S2 glass fiber density was 2.48 g/cm^3 . The Fiber aerial weight was 295 g/m^2 . The 24-ply panel, measuring 762 mm^2 , was autoclave cured using the manufacturer's recommended curing cycle. The nominal panel thickness was 5.56 mm, corresponding to a nominal ply thickness of 0.231 mm. No significant flaws were detected in ultrasonic inspection of this panel. Nominal fiber volume fraction was 51.3 %, as estimated from equation (1). This compares well with the average volume fraction of 49.8% measured using ASTM D3171.

Specimen Preparation

Specimen cutting & polishing

Test specimens oriented at ninety degrees to the longitudinal axis were cut from the panels using a diamond saw. A 6.35 mm plexi-glass sheet was placed beneath each panel to minimize any fiber spalling on the back side of the saw cut.

S2/F584 glass epoxy test specimens were cut from two panels (TO3 and TO5) made from the original prepreg material and three panels (TN2, TN3, and TN6) from the new prepreg material. Selected specimens from panels TO3, TO5, and TN2 were polished on the edges, bottom surface, or both, prior to testing. All specimens cut from panels TN3 and TN6 were polished on the edges only. The large 762 mm square S2/8552 glass epoxy panel was first cut into four 381 mm square panels to facilitate further cutting into test specimens. These four smaller panels were then cut into test specimens. Cutting patterns were chosen to minimize any strength dependence on specimen panel position. One set of 6.35 mm wide specimens was polished on the edges and bottom surface. In addition, a set of 57.2 mm long by 6.35 mm wide specimens was also polished on the edges only. All remaining specimens were tested in their as-cut, unpolished, condition.

Specimens were polished by first sanding using 600 grit sandpaper discs, and then polishing using 1200 grit silicon carbide paper discs. Final polishing was performed using a very fine nap cloth and an 0.05 micron Alumina suspension solution with a lubricant of soapy water.

Thickness and width measurement

Specimen thickness and width were measured at three points along the specimen length using flat nose digital calipers. The average of these three measurements, as well as the percentage variation in thickness and width along the specimen length, were calculated and tabulated along with the individual measurements. For specimens that were polished, thickness and width measurements were performed after polishing and before testing.

Experiments

Testing apparatus & specimen configurations

Three and four point bending tests were performed on an MTS model 858 table-top hydraulic load frame with an MTS model 458 controller. This load frame was equipped with a 22.2 kN load cell. An additional 2.22 kN load cell was placed in series with this standard load cell to more accurately measure loads. The load frame was equipped with three and four point bending fixtures consisting of individual upper and lower pieces, with load point supports machined to a radius of 3.18 mm. Supports were bolted to the cross member so that the span length could be adjusted to 25.4, 50.8, 76.2, or 101.6 mm. Three-point bending tests were performed in three configurations (A, B, and C) corresponding to span lengths of 25.4, 50.8, and 76.2 mm (figure 1(a)). Four point

For the four point bending tests shown in figure 1(b), with outer span, s , inner span, $s-l$, and width, b , specimen strengths were determined from the beam theory expression for the maximum uniform tension stress, σ_{\max} , between the inner load points using the maximum load at failure, P_c , and the average specimen thickness, t_{avg} ,

$$\sigma_{\max} = \frac{3P_c \ell}{2bt_{\text{avg}}^2} \quad (3)$$

Transverse strength Characterization

Strength is typically characterized assuming either a symmetric (normal) distribution or a skewed (Weibull) distribution. For the normal distribution, the mean strength and coefficient of variation, CV, are calculated to characterize the central tendency and scatter in the strength distribution, respectively. However, since most strength data are not normally distributed, a Weibull distribution is often assumed as an alternative.

Weibull assumed an extreme value distribution for material strength using a two parameter function for the probability of failure at a given stress level, $P(\sigma)$, as

$$P(\sigma) = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_c}\right)^m\right] \quad (4)$$

where σ_c is the location parameter known as the characteristic strength, and m is the shape parameter known as the Weibull slope [3]. The Weibull slope, m , provides a measure of the scatter in the distribution, with a small value of m corresponding to a large amount of scatter in the data. Hence, the amount of scatter is inversely proportional to m . As shown in reference 4, a least squares regression fit of the logarithmic form of equation 4 may be performed to determine m and σ_c . For both materials tested, characterization of the transverse tension strength for each configuration was performed assuming both a normal distribution and a Weibull distribution. Because the decimal value of CV and the inverse Weibull slope, $1/m$, have similar magnitudes, these quantities were both tabulated.

Weibull also postulated that the characteristic strengths for two different volumes, V_1 and V_2 , of the same material will obey the following scaling law [3]

$$\left(\frac{\sigma_c}{\sigma_c}\right)_1 = \left(\frac{\sigma_c}{\sigma_c}\right)_2 \left(\frac{V_2}{V_1}\right)^{1/m} \quad (5)$$

Experimental Results

Results for strength and scatter for the total number of specimens tested, n , for each configuration are given in Tables 1 and 2. All specimens were 6.35 mm wide, except for sets labeled B-C and B-D, which were 12.7 and 19.1 mm wide, respectively.

Table 1: S2/F584 glass epoxy strength and scatter

Panel	Config. & set	Polished surfaces	n	σ_{ult} , MPa	CV, %	σ_c , MPa	1/m
TO3	B-2	none	35	102	6.50	104	0.0592
	B-3	edges	38	100	9.30	104	0.0830
	B-4	bottom	38	91.1	6.40	93.8	0.0550
TO5	B-B	both	44	96.2	7.40	99.3	0.0610
	B-C	none	40	96.7	8.70	100	0.0776
	B-D	none	35	97.6	7.50	101	0.0641
TN2	B-A	edges	42	103	5.70	106	0.0479
	B-B	both	43	96.9	7.60	101	0.0707
	B-C	edges	40	102	5.50	105	0.0467
	B-D	edges	35	102	6.30	105	0.0539
TN3	A-1	edges	47	106	7.80	109	0.0667
	B-1	edges	47	105	7.40	108	0.0634
	C-1	edges	47	104	5.80	107	0.0491
	B3-1	edges	48	89.0	6.20	91.6	0.0530
TN6	A1-1	edges	47	98.7	6.60	102	0.0567
	A2-1	edges	47	87.8	6.90	90.5	0.0582
	B2-1	edges	48	80.5	10.1	84.3	0.0898

Table 2: S2/8552 glass epoxy strength and scatter

Panel Quad	Config. & set	Polished surfaces	n	σ_{ult} , MPa	CV, %	σ_c , MPa	1/m
I-IV	B-A	none	35	140	5.85	144	0.0503
I-IV	B-B	both	33	138	7.00	142	0.0598
I-IV	B-C	none	34	141	8.46	146	0.0733
I-IV	B-D	none	27	139	8.27	144	0.0716
I	B-1	none	51	145	6.99	150	0.0603
II	B-2	edges	51	144	6.11	148	0.0515
III	A-3	none	49	145	7.98	150	0.0682
IV	B-4	none	48	145	6.31	149	0.0533
I	C-1	none	50	136	6.25	140	0.0525
II	A1-2	none	52	131	6.54	135	0.0552
II	A2-2	none	51	125	7.39	129	0.0652
III	B2-3	none	43	115	12.17	121	0.1057
IV	B3-4	none	52	101	8.61	105	0.0724

For some comparisons, strengths and scatter parameters were recalculated for smaller sample sizes than the total number tested, n [5]. All populations were evaluated starting from the first specimen tested, up to the desired number, in the order of testing as determined by random number generation.

Influence of Specimen Preparation

For the 6.35 mm wide S2/F584 configuration B specimens from panels TO3 and TO5, there were no significant differences in the strengths of the unpolished specimens (B-2) and specimens with polished edges (B-3). Therefore, any flaws created due to cutting the plate do not appear to significantly affect the specimen strength. However, specimens with polished bottom (tension side) surfaces, either with (B-B) or without (B-4) polished edges, had lower strengths. In addition, polishing the edges resulted in greater scatter than obtained in tests with unpolished edges. Strengths and scatter for each of these configurations was also recalculated with a common sample size of $n=35$ [5]. The smaller sample size resulted in some numerical differences, but the same relative comparisons noted previously were still observed. For configuration B specimens from panel TN2, specimens with polished bottom surfaces (B-B) had lower strengths than the unpolished bottom surface specimens (B-A). Furthermore, the specimens with polished bottom surfaces had greater scatter. Hence, polishing appears to be detrimental to specimen strength instead of increasing the measured strength as a result of removing inherent flaws in the material due to manufacture and handling.

For the 6.35 mm wide S2/8552 configuration B specimens cut from all four quadrants of the original large panel (B-A, B-B), strengths for polished specimens were slightly lower than strengths for unpolished specimens. Similarly, for the configurations that were tested with specimens cut from a single quadrant of the original large panel (B-1, B-2), strengths for polished specimens were also slightly lower than strengths for unpolished specimens. This observation was also true when the sample size was reduced from 51 to 35 [5]. Hence, polishing, at most, appears to be slightly detrimental to specimen strength. For the specimens from all four quadrants of the original large panel (B-A, B-B) polishing also resulted in greater scatter than obtained in tests with unpolished edges. However, the opposite was true for specimens cut from a single quadrant of the original large panel (B-1, B-2).

Influence of Specimen Width

For the unpolished S2/F584 configuration B specimens from panels TO3 and TO5, there is no apparent trend in strength variations for different specimen widths. Strengths appeared to decrease between 6.35 mm widths (B-2) and 12.7 mm widths (B-C), then increased slightly between 12.7 mm widths and 19.1 mm widths (B-D). Similarly, there is no apparent trend in the variation in scatter with specimen width. Furthermore, for the S2/F584 configuration B specimens from a single panel (TN2) with polished edges, there is a slight decrease in strength between 6.35 mm widths (B-A) and 12.7 mm widths (B-C), but identical strengths were obtained for the 12.7 mm widths and 19.1 mm widths (B-

D) configurations. For the unpolished S2/8552 specimens (B-A, B-C, and B-D), strengths appeared to increase with increasing width and then decrease. However, because the 19.1 mm width specimens (B-D) had a smaller sample size (27), strengths for all three widths were recalculated for a common sample size of $n=25$ [5]. Still, no trend was apparent, as the strength decreased between 6.35 mm widths and 12.7 mm widths, then increased between 12.7 mm widths and 19.1 mm widths. Hence, the anticipated trend of decreasing strength with increasing width, and hence increasing volume, that would be anticipated from the Weibull scaling law (eq.5) was not clearly apparent.

Influence of Span Length

Strengths for edge polished S2/F584 specimens from panel TN3 tested in three point bending, at three different span lengths of 25.4, 50.8, and 76.2 mm (A-1, B-1, and C-1), exhibited a slight decrease in strength with increasing span length. In addition, scatter for these tests decreased significantly with increasing span length. Similar trends in strength and scatter dependence with span length were obtained for a smaller common sample size of $n=35$ [5]. Strengths for edge polished S2/F584 specimens from panel TN6 tested in four point bending (A1-1, A2-1, and B2-1) decreased with increasing span length. In addition, unlike the three point bending case, there is a noticeable trend of increasing scatter with increasing span length for these three configurations. However, edge polished specimens from panel TN3 tested at the longest span length (B3-1) had higher strengths, and less scatter, than two of the three shorter span length results from panel TN6 specimens. Hence, the anticipated trend of decreasing strength with increasing span length may be masked by significant panel-to-panel variability. Similar strength and scatter dependence with span length were obtained for a smaller common sample size of $n=35$ [5].

Strengths for unpolished S2/8552 specimens tested in three point bending, at three different span lengths of 25.4, 50.8, and 76.2 mm (A-3, B-4, and C-1), exhibited a decrease in strength with increasing span length, with the greatest decrease occurring between the two longest span lengths. In addition, scatter decreased significantly with increasing span length. Similar trends in strength and scatter dependence with span length were obtained for a smaller common sample size of $n=35$ [5]. Strengths for unpolished S2/8552 specimens tested in four point bending (A1-2, A2-2, B2-3, and B3-4) decreased noticeably with increasing span. Scatter increased with span length for all but the longest span configuration (B3-4). Further, there was a noticeable decrease in strength with increasing upper or lower span length for these configurations. In addition, strength decreased as the inner span length was increased relative to a constant outer span length, thereby increasing the volume of material subjected to the maximum bending stress. Similar trends were observed for strengths calculated for a smaller common sample size of $n=35$ [5]. These observations are consistent with the trend of decreasing strength with increasing volume anticipated from equation 5.

Analysis of Results

In reference 5, the data generated in Tables 1 and 2 were used to evaluate the Weibull scaling law (eq.5) for predicting transverse tension strength. For configuration B specimens tested in three point bending, the strengths of the wider specimens (B-C, B-D) were predicted using σ_c and $1/m$ of the 6.35 mm wide specimens and the relative volumes of the specimens in tension. This volume consisted of the product of the test span, width, and one half of the specimen thickness. In addition, 6.35 mm wide configuration B specimens were used to predict the strengths of specimens with shorter and longer spans (configurations A & C). For these cases, the change in strength predicted by equation 5 was between 2.7% and 6.5%. For most cases, this predicted strength variation is significantly greater than the measured variation in strength with width or span length. For the two materials tested, the maximum variation in strength with specimen width was only 1.4%. The maximum variation in strength with span length for the S2/F584 material was only 1.9%. However, the maximum variation in strength with span length for the S2/8552 material was 6.7%. For four point bend tests, strengths of configurations A2, B2, and B3 were predicted using σ_c and $1/m$ for configuration A1 and the relative volumes of the specimens in tension. The volume consisted of the product of the test span, s , width, and one half of the specimen thickness. For these cases, the change in strength predicted by equation 5 was between 2.2% and 3.9%. Unlike the three point bending tests, these predicted strength variations are significantly smaller than the measured variation in strengths, which ranged from 10.2% to 17.4% for the S2/F584 material and from 4.4% to 22.2% for the S2/8552 material. These same disparities between measured and predicted strengths were observed when the volumes used in equation 5 were weighted to account for the non-uniform tension stress distributions in these bending tests [5].

Equation 5 assumes that the inverse Weibull slope parameter ($1/m$) is a material constant, independent of volume. However, the three and four point bend test data indicate that the parameter ($1/m$), and hence the scatter in the data, varies with specimen size. For the three point bend tests, there was no clear trend in this variation for configuration B specimens with different widths, but for the 6.35 mm wide specimens, the parameter ($1/m$) consistently decreased with increasing span length. In contrast, for the four point bend specimens, $1/m$ typically increased with increasing span length. In addition, as noted in reference 5, the parameter ($1/m$), also varied to some degree with sample size. Hence, the utility of equation 5 for predicting transverse tension strength is unclear.

Conclusions

The influence of specimen polishing, specimen configuration, and specimen size on the transverse tension strength of two glass epoxy materials loaded in three and four point bending was evaluated. Polishing specimen edges had little, or no, effect on the transverse tension strength of 90 degree lamina tested in three and four point bending. However, polishing bottom (tension side) surfaces resulted in lower strengths. Furthermore, in most cases, specimens with polished bottom surfaces had greater scatter than unpolished specimens. Hence, polishing appears to be detrimental to specimen

strength characterization instead of yielding a higher, more accurate, strength as a result of removing inherent manufacture and handling flaws in the material.

The trend of decreasing strength with increasing specimen width, and hence increasing volume, that would be anticipated from the Weibull scaling law was not clearly apparent. In contrast, the anticipated trend of decreasing strength with increasing span length, and hence increasing volume, was observed for both three and four point bending configurations. However, this expected scaling was occasionally masked by more significant panel-to-panel variability.

The Weibull scaling law over predicted changes in transverse tension strengths in three point bend tests and under predicted changes in transverse tension strengths in four point bend tests. Furthermore, the Weibull slope varied with specimen configuration, volume and sample size. Hence, the utility of this scaling law for predicting transverse tension strength is unclear.

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