FATIGUE RESISTANT FIBERGLASS LAMINATES FOR WIND TURBINE BLADES

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ABSTRACT

Recent test results show that fiberglass laminates composed of unidirectional (0°) and ±45 stranded fabric layers, typical blade materials, vary significantly in tensile fatigue resistance depending on the overall fiber content and the relative amounts of reinforcement in each direction. S-N fatigue data are presented for a range of laminates under both tensile and compressive fatigue loading. The results show poorer than expected fatigue performance for laminates composed of stranded fabrics at (a) high fiber contents and (b) high relative amounts of ±45° reinforcement. Optimum fatigue resistant materials appropriate for both flange areas and webs of blades are identified. Laminates which fall into the poor fatigue resistance category (similar to woven fabrics and triax stitched fabrics) do not behave in a fiber-dominated manner which is required for application of the high cycle DOE/MSU database to lifetime prediction as described in Ref. [1].

INTRODUCTION

Most U.S. fiberglass wind turbine blades are constructed of marine-type stranded E-glass fabrics stitched together for handling purposes with an organic yarn, then impregnated with a polyester, vinyl ester, or epoxy matrix. The reinforcing fabrics may be unidirectional (Figure 1) or multilayered with orientations such as 0°, +45°, and -45° stitched tightly together, termed Triax fabrics.

The fatigue program at Montana State University (MSU)[2-4] has developed a database with over 2000 tests covering a broad range of primarily hand lay-up industry laminates and laminates resin transfer molded (RTM) at MSU [3] with the same fabrics and matrix resins. Figure 2 shows tensile fatigue strain based constant amplitude S-N data for a typical sampling of the database with about half industry laminates and half MSU RTM laminates. The laminates represented in Figure 2 contain variations in fabric type, fiber content, fraction of fibers in the 0° and ±45° directions, and matrix resin. All tests used standard fatigue coupons and test methods [2-3] and were run at frequencies in the 10-15 cycle/second (Hz) range to avoid significant hysteretic heating. It is notable that the best materials in Figure 2 outperform the worst materials in the 10^6 cycle range by a factor of about three in allowable strain. That is, better material constructions can withstand about three times higher maximum tensile strains for 10^6 fatigue cycles than can the worst materials. This is of practical significance in design and materials selection for blades.

Previous reports have identified one source of poor fatigue performance [2,3]. The best materials perform the same as other E-glass based materials with more refined structures such as prepreg for aerospace applications, which do not use the stranded, stitched fabrics [5]. Most of the poorly performing industry laminates used Triax reinforcing fabrics. As described previously [3], these fabrics force the 0° and ±45° strands into close contact with no separating matrix layer. Detailed finite element modelling of cracks around strand junctions has shown that matrix cracking in the ±45° strands, which occurs at lower strains than does fiber failure, will produce significant stress concentrations in the adjacent 0° strands and lead to their premature failure [3]. This problem is greatly reduced by a thin layer of matrix between strands, as usually occurs when the 0° layers are not stitched tightly to the ±45° layers [3].

This paper gives the results of a systematic study of laminates with separate 0° and ±45° layers, molded with a range of fiber contents and fractions of 0° and ±45° reinforcement, and three matrix resins, to represent a broad range of potential laminate performance in blades. Based on previous experience, it was expected that all of the laminates with separate 0° and ±45° layers would perform well in fatigue. However, the data for these (RTM) materials in Figure 2 show the same range of poor to good performance as experienced with industry laminates. Based on these systematic results, it is believed that the range of parameters controlling fatigue resistance is now more fully understood than was the case previously, as described in the foregoing.

EXPERIMENTAL METHODS

The laminates for this study were resin transfer molded using the Knytex E-glass fabrics indicated in the results section. Most of the laminates were prepared with an unsaturated orthophthalic polyester resin (Coresyn 63-AX-051 cured with 2% MEKP) as the matrix; Material DD5V contained a vinyl ester resin (Derakane 411-C-50, cured with 1.5% MEKP) and Material DD5E contained an epoxy resin (Epon 9410 cured with 9450 curing agent). The laminates were molded as flat plates 22 cm wide by 84 cm long; the thickness ranged from 2 to 5 mm depending on fabric and fiber content. The plates were initially cured at ambient temperature, followed by postcuring at 60°C overnight. Fatigue test coupons were machined from the plates and tested following procedures described in detail elsewhere [2,3]. Tensile coupons were 2.5 to 5.0 cm wide, with a gage length of at least three times the width between end tabs or grip faces. Tensile fatigue coupons were machined with a slightly reduced width in the gage section (dumb-bell shape) to reduce grip failures in cases where necessary. Compression fatigue specimens were straight-sided with a gage length of approximately 1.3 cm; no lateral support was used in the gage length.

Tests were conducted in servohydraulic testing machines under load control constant amplitude sine waveform. One-cycle static strengths were obtained under ramp loading at a strain rate which was consistent with that used in the low cycle fatigue tests. Maximum test frequency was 15 Hz in most cases, with reduced frequency at higher stresses. Full test details can be found in Refs. 2 and 3. The initial maximum strain and modulus given in the results were obtained with an extensometer early in the specimen lifetime. While strain generally increased slightly during the test, this was difficult to follow reliably due to extensometer slippage. Failure was taken as complete separation of the specimen.

The parameters used in this paper include S_o, the single cycle ultimate strength, S, the maximum (absolute) stress in the fatigue test, and R, the ratio of minimum to maximum stress, which is maintained for the entire S-N curve.

RESULTS AND DISCUSSION

Table 1 gives a description of the 30 materials characterized for tensile and compressive fatigue performance in this study. The DD materials represent a range of laminates typical of the main load carrying structure of the blade, where 0° is the load direction. The CH series represent laminates more typical of internal webs, where shear resistance is needed, or blade skins. The total percent fiber by volume is given by V_f, while the relative percentages of 0° and ±45° fibers are given along with the Knytex fabric designation. The fabric designation D155, for example, is unidirectional with a weight of 15.5 oz/yd^2 (526g/m^2) of fabric. The ply geometry follows the standard format for laminates [2], giving the ply orientation in order from the top surface, where S means symmetrical about the mid- thickness.

Figure 3 and 4 give the results of this study in bar chart form. The fatigue resistance for each material in tension (R=0.1) and compression (R=10) is represented by a single number in each case, the maximum strain which can be withstood for 10^6 cycles. This strain value is derived from a least squares curve fit to a complete S-N dataset in each case, 30 S-N curves at R=0.1 and another 30 at R=10, each with about 12 to 15 datapoints. The CH materials in Figure 3 also include the fiber content, the percent 0° material, and a figure of merit for web-type applications, the shear modulus (calculated from laminate theory for measured ply properties). The DD materials contain a different figure of merit for the structural blade application, the (measured) elastic (Young's) modulus in the 0° direction. Ultimate tensile and compressive strengths are given in Table 1.

The major unexpected finding from these results is that the tensile fatigue resistance drops rapidly as the fiber volume content is increased above the 40 to 45% range. Figure 5 gives the S-N tensile fatigue data for five of the structural DD materials, and Figure 6 shows the slope of the normalized S-N curve as a function of fiber content. This increase in fatigue sensitivity at higher fiber content is not offset by the higher initial strength, S_o. The bar chart in Figure 4 shows a drop in 10^6 cycle strain capability from over 1.1% at low V_f to less than 0.5% at 54% fiber. As indicated in Figure 7, the matrix material has no measurable effect in this closely controlled comparison; this has been observed previously [2,3].

This major loss in tensile fatigue resistance at higher fiber content is counter to efforts to increase blade performance and efficiency by increasing fiber content. The same trend is observed in the CH materials, which overall are somewhat more fatigue sensitive than the DD materials due to the lower percent 0° material (higher ±45° content). The reason for reduced fatigue resistance at high fiber content is apparently the same as that discussed earlier for Triax fabrics: the 0° strands are forced too tightly against the ±45° strands, so that, when the matrix cracks in the ±45° strands, failure soon occurs in the main load bearing 0° strands. This effect is not seen when the 0° fibers are more uniformly distributed, as in many prepreg materials, where good fatigue resistance is maintained at least up to the range of 60% fiber by volume [5]. Adjustments to the stitched, stranded fabrics are required to accommodate manufacturing requirements while maintaining good fatigue resistance, if higher fiber content laminates are to be employed.

CONCLUSIONS

The results in Figures 3 and 4 lead to the following detailed conclusions regarding the fatigue resistance of this class of fiberglass laminates:

1. Fabrics containing 0° and ±45° stitched, stranded layers show significantly reduced tensile fatigue resistance above 40-45% E-glass fiber by volume.
2. The tensile fatigue resistance is also reduced for laminates with a lower fraction of 0° material relative to ±45° material.
3. Considering the appropriate shear or Young's modulus as a figure of merit, optimal composites for structural areas are between DD2(42%) and DD5(36%) in fiber content. Optimal CH materials are in the range of CH12 and CH15 and 16. Further characterization of these apparently optimal material ranges is underway.
4. No measurable effect of matrix material was observed, consistent with previous studies [2-4].
5. The effects of fiber content and percent 0° material on compressive fatigue resistance was less strong, as indicated in Figure 6 as well as Figs. 3 and 4.
6. These results, supported by selected results from other industry materials, show that improved fabric characteristics will be required for good fatigue resistance in high fiber content materials.
7. As noted in the Introduction, Triax fabrics show poor tensile fatigue resistance even at the lower fiber contents used with hand lay up processes.
8. To use the high cycle database as demonstrated in Ref. 1, the laminate must be fiber dominated, with fatigue resistance similar to the more fatigue resistant laminates shown here ($b \cong 0.10$).

ACKNOWLEDGEMENTS

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Table 1

MSU MANUFACTURED (RTM) FIBERGLASS MATERIALS (POLYESTER MATRIX UNLESS NOTED)					
Material	V_F,%	Ply Geometry	Compressive, S_O, MPa	Tensile, S_O, MPa	Description
CH	42	$[(\pm45)_3]_S$	-178	145	45's-DB240
CH2	44	$[\pm45/0/\pm45]_S$	-342	362	0's-D155 (25%), 45's-DB240 (75%)
CH3	37	$[\pm45/0/\pm45]_S$	-306	336	0's-D155 (25%), 45's-DB240 (75%)
CH4	37	$[(\pm45)_3]_S$	-171	155	45's-DB120
CH5	28	$[(\pm45)_3]_S$	-190	139	45's-DB120
CH6	49	$[\pm45/0/\pm45]_S$	-408	502	0's-D155 (40%), 45's-DB120 (60%)
CH7	55	$[(\pm45)_3]_S$	-168	114	45's-DB400
CH8	38	$[(\pm45)_3]_S$	-146	93	45's-DB400
CH9	46	$[(\pm45)_3]_S$	-174	151	45's-DB120
CH10	32	$[(\pm45)_3]_S$	-163	120	45's-DB240
CH11	51	$[(\pm45)_3]_S$	-189	134	45's-DB240
CH12	34	$[\pm45/0/\pm45]_S$	-451	398	0's-D155 (40%), 45's-DB120 (60%)
CH13	49	$[\pm45/0/\pm45]_S$	-385	423	0's-D155 (25%), 45's-DB240 (75%)
CH14	41	$[\pm45/0/\pm45]_S$	-412	517	0's-D155 (40%), 45's-DB120 (60%)
CH15	32	$[\pm45/0/\pm45]_S$	-345	309	0's-D092 (28%), 45's-DB120 (72%)
CH16	39	$[\pm45/0/\pm45]_S$	-309	360	0's-D092 (28%), 45's-DB120 (72%)
CH17	45	$[\pm45/0/\pm45]_S$	-301	359	0's-D092 (28%), 45's-DB120 (72%)
CH18	46	$[\pm45/0/\pm45]_S$	-298	294	0's-D092 (16%), 45's-DB240 (84%)
CH19	32	$[\pm45/0/\pm45]_S$	-252	193	0's-D092 (16%), 45's-DB240 (84%)
DD	49	$(0/\pm45/0_3/\pm45/0)$	-788	910	0's-D155 (78%), 45's-DB120 (22%)
DD2	42	$(0/\pm45/0)_S$	-581	752	0's-D155 (75%), 45's-DB120 (25%)
DD4	48	$(0/\pm45/0)_S$	-517	895	
DD5	36	$(0/\pm45/0)_S$	-534	724	
DD5E*	36	$(0/\pm45/0)_S$	-521	674	
DD5P*	36	$(0/\pm45/0)_S$	-574	661	
DD5V*	36	$(0/\pm45/0)_S$	-530	675	
DD6	31	$(0/\pm45/0)_S$	-451	605	
DD7	54	$(0/\pm45/0)_S$	-455	832	
DD8	42	$(0/\pm45/0)_S$	-581	778	0's-D155 (75%), 45's-DB120 (25%) All fabric stitching yarn removed
DD9	54	$(0/\pm45/0)_S$	-556	907	
*Matrix Abbreviations: E - Epoxy , P - Polyester, V- Vinylester					

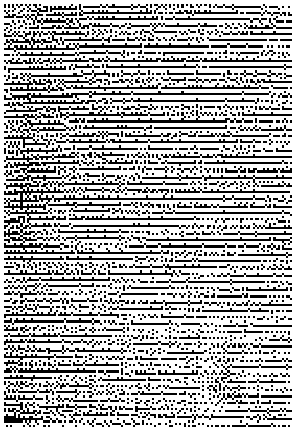


Figure 1.Unidirectional E-glass fabric Knytex D155

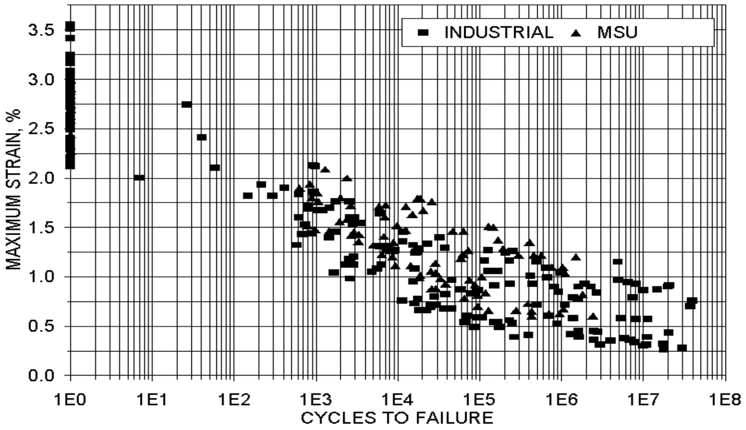


Figure 2. Strain S - N data of Industrial and MSU Materials From Database, R = 0.1

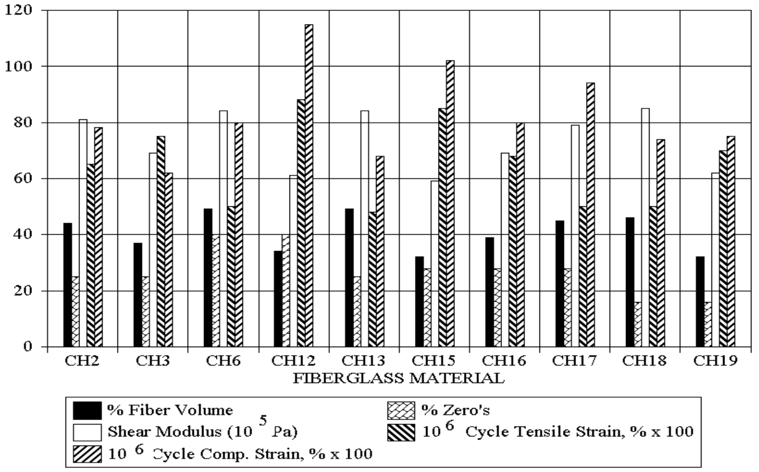


Figure 3a. Comparison of CH Materials $[\pm45/0/\mp45]_S$

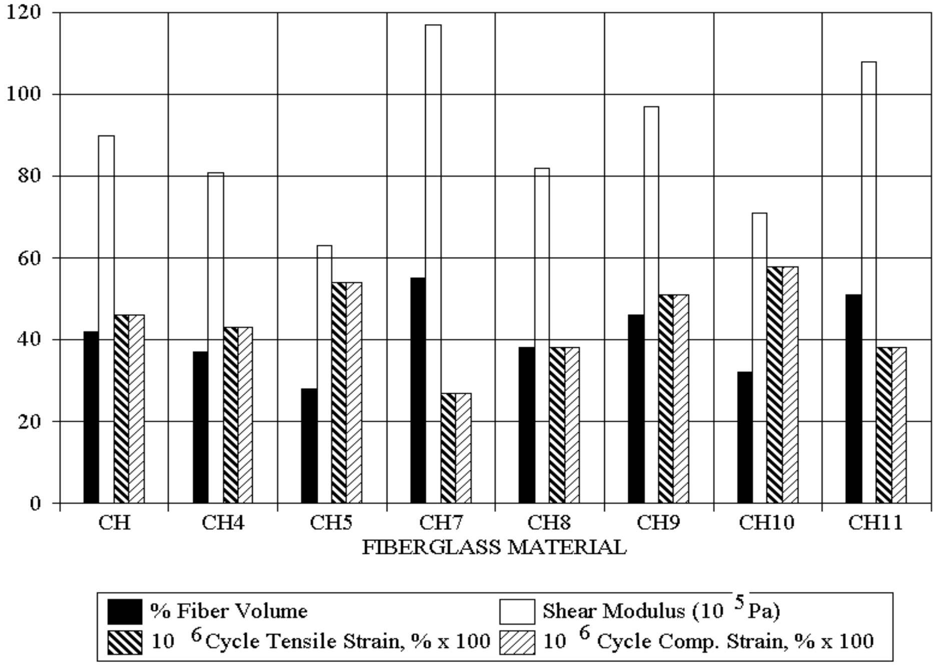


Figure 3b. Comparison of CH Materials $[\pm45]_N$

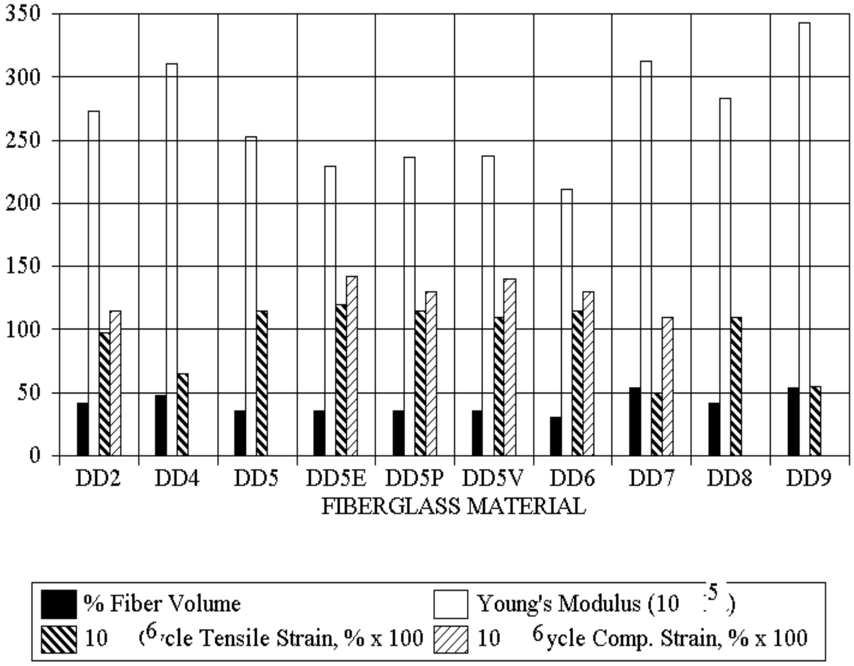
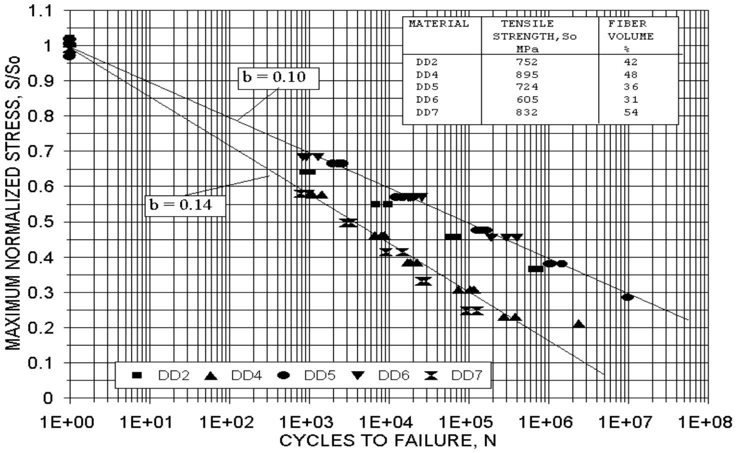


Figure 4. Comparison of DD Structural Materials $[0/\pm45/0]_S$, 75% Zero Degree Fibers



MATERIAL	TENSILE STRENGTH, So MPa	FIBER VOLUME %
DD2	752	42
DD4	895	48
DD5	724	36
DD6	605	31
DD7	832	54

Figure 5. Normalized Tensile Fatigue Data for DD Materials $[0/\pm45/0]_S$, R=0.1 (Trend Lines $S/S_O = 1 - b \text{ Log } N$)

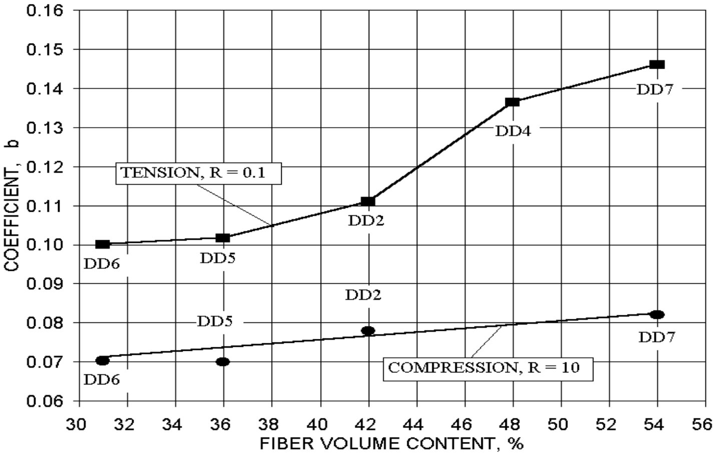


Figure 6. Fiber Content vs. Fatigue Sensitivity Coefficient, b, for DD Materials $[0/\pm45/0]_S$, $S/S_O = 1 - b \text{ Log } N$

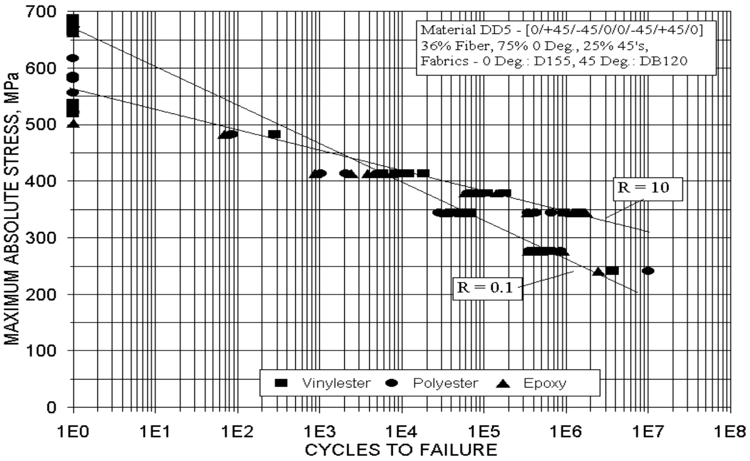


Figure 7. Effect of Matrix on Fatigue of DD5 Material (R = 0.1 and 10)