The SNL/MSU/DOE Fatigue of Composite Materials Database: Recent Trends

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Abstract

Trends of recent test data in three areas are described for wind blade materials in the SNL/MSU/DOE fatigue of composite materials database[1]. First, a complete 3-D set of static elastic constants and strength properties is given for a thick infused glass fabric/epoxy laminate. Second, results are presented which explore the effects of fabric structure and resin type on the tensile fatigue resistance. Using aligned strand structure as a baseline, the efficiency of stitched fabric reinforcement is quantified for static and fatigue properties, and the origins of poor fatigue performance with some resins are identified. Third, an overall comparison is given of the tensile fatigue sensitivity of various blade materials including laminate in-plane and interlaminar failure, epoxy based blade adhesives and core materials. Comparisons of fiber dominated and resin dominated failure modes show clear trends in the fatigue exponent, depending on the resin system.

I. Introduction

This paper presents recent trends observed in static and fatigue test results for wind blade materials available in the SNL/MSU/DOE Fatigue of Composite Materials Database, generated under the SNL/MSU fatigue testing program[1,2]. The public database, which includes more than 12,000 individual test results from over 250 materials systems relevant to wind blades, is now formatted in Excel, allowing more convenient searches and sorting by materials and properties. Materials include laminates with various fibers and fabrics, resins, fiber contents and laminate constructions, as well as adhesives and core materials. Data were obtained using a broad range of standard and specialized test methods, loading conditions, and including environmental and processing effects. The paper addresses three topics: three-dimensional static properties of thick laminates; the effects of glass fabric structure, laminate construction and resin type on the tensile fatigue resistance of infused laminates; and an overall comparison of fatigue sensitivity for the various blade component materials and materials transition areas, including laminates, adhesives, cores and ply drops.

II. Experimental Methods

Fabrics and resins which figure prominently in this paper are described in Tables 1 and 2 and Figure 1. Typical UD reinforcing fabrics contain warp-direction aligned strands stitched to a backing with organic yarn; the backing may be transverse glass strands (fabric D) or a combination of transverse and random mat glass strands (fabric H), or just mat. Laminates were resin infused under vacuum using a hard mold plate on one side, as described in Reference 2, following cure schedules given in References 1-4. Aligned strand laminates were dry wound and infused, supplied by PPG Fiber Glass. Epoxy resin laminates with a variety of fabric variations were infused and supplied by Roman Hillermeier of Devold AMT AS.

The fabrication and testing of adhesive joint coupons has been described in References 2 and 5. Thick laminates for 3-D property testing were infused as 80-ply, 100 mm thick blocks using UD fabric D (Vectorply ELT-5500) and epoxy EP1, post cured at 70^{o}C. Details of fabrication and testing for the thick laminate can be found in Reference 4. Most other experimental methods are described in more detail in Reference 2. Sandwich panels with 25 mm thick PVC core and 1.6 mm thick glass triax fabric face sheets were infused with epoxy EP1 resin; flexural fatigue testing followed ASTM C393.

Table 1. UD E-Glass Fabric Construction

Fabric[1]	Manufacturer and Product Designation	Fiber Areal Weight, g/m^2						
		Total	0°	90°	-45°	+45°	mat	stitch
D	Vectorply E-LT-5500	1875	1728	114	0	0	0	33
H	PPG-Devold L1200/G30-E07	1261	1152	52	0	0	50	7

[1]As listed in the database [1]; 0° strands are Hybon® 2026, 2400 Tex (fabric H) and 4400 Tex (fabric D).

Table 2. Infusion Resins (cure conditions listed in Ref. 1, 4)

Resin[1]	Type	Resin
EP1	Epoxy	Momentive Epicote™ RIMR 135/ Epicure™ RIMH 1366
EP5	Epoxy	Momentive Epicote™ RIMR 135/ Epicure™ RIMH 137
UP1	Polyester	U-Pica/Hexion TR-1
UP5	Polyester	Reichhold Polylite™ X4626-31
VE4	Vinyl ester	Reichhold Dion™ 4486-14
VE5	Vinyl ester	Reichhold Dion™ X4235-91
VE6	Vinyl ester	Reichhold Dion™ X4627-39

[1]As listed in the database [1].

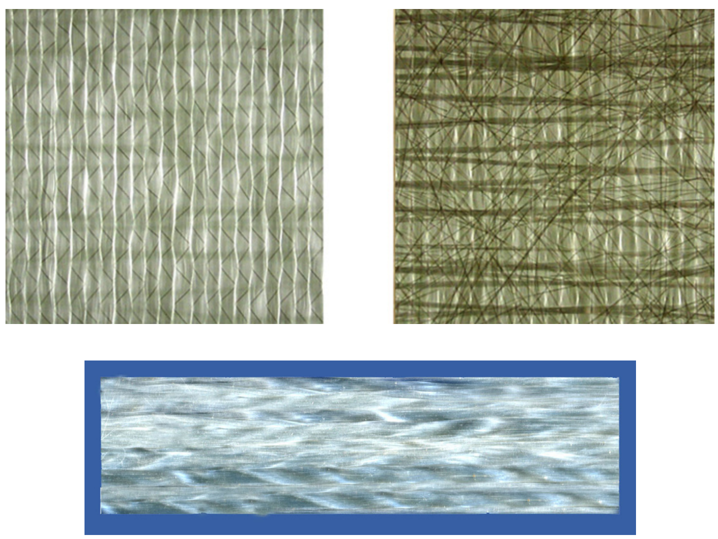


Figure 1. Top: front and back views of UD fabric H; bottom: aligned strand structure.

Laminate test coupons for UD geometries are shown in Figure 2. Most UD fatigue coupons followed ASTM D3039, while thickness tapering was added to avoid grip failures for some aligned strand laminates, as indicated in the results. MD laminate tests used a waisted dog-bone geometry given in References 2 and 3. Test coupons for 3-D static properties, sectioned from thick laminates, were straight or waisted geometries for tension and compression, and notched for shear following ASTM D5379; details of test geometries are given in Reference 4. Static tests were conducted at a constant displacement rate of 0.025 mm/s, while fatigue tests were conducted under load control at 1-4 Hz, given for each test in the database[1]. Surface cooling with forced air was used for fatigue tests. Detailed test conditions and results can be found in the current or subsequent database version[1].

Fatigue stress or strain vs. cycles data from are used to establish mean lifetime S-N curves, which represent the applied maximum stress or maximum (measured) initial strain in the fatigue test vs. log cycles to failure, fit with a power law model (Eq. 1) and plotted in a linear stress or strain - log cycles format:

$$S = A\,N^{B} \tag{1}$$

where S is the maximum stress or strain in each fatigue cycle, N is the cycles to failure (complete separation), A is the one cycle intercept, and B is the power law exponent, giving the slope of the S-N curve. The exponent can also be represented by n, where n = -1/B. The power law is fit to the fatigue data only, unless noted, and the intercept A often differs significantly from the static ultimate tensile strength (UTS). While the strain is the more general parameter for materials comparisons and many blade design procedures, only the initial strain on the first few cycles can be conveniently measured, and subsequent strain increases due to softening are not represented. Stress plots are sensitive to laminate construction (% 0-degree plies) and fiber content differences when comparing materials.

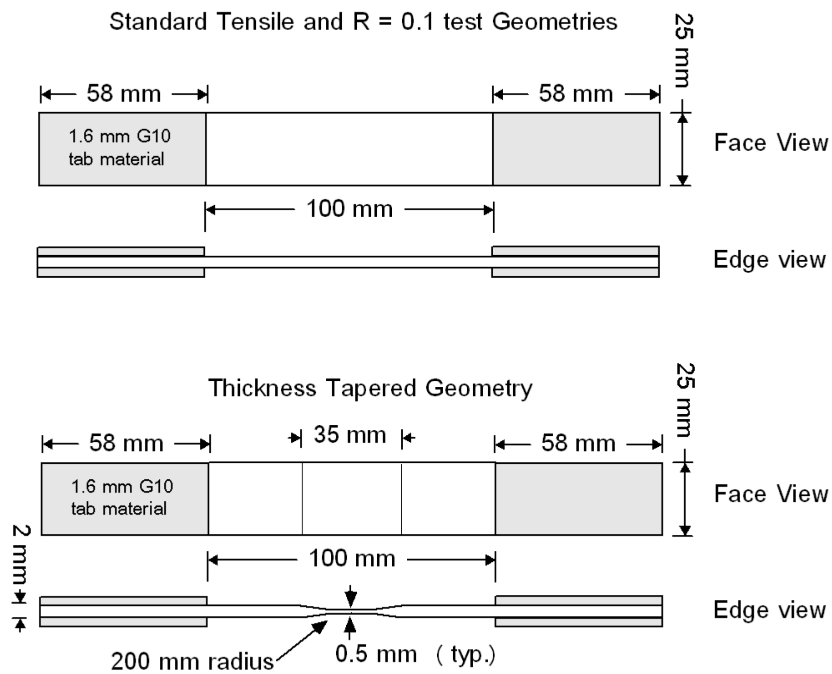


Figure 2. Standard (top, 2-mm thickness) and thickness tapered tensile fatigue coupons for UD laminates.

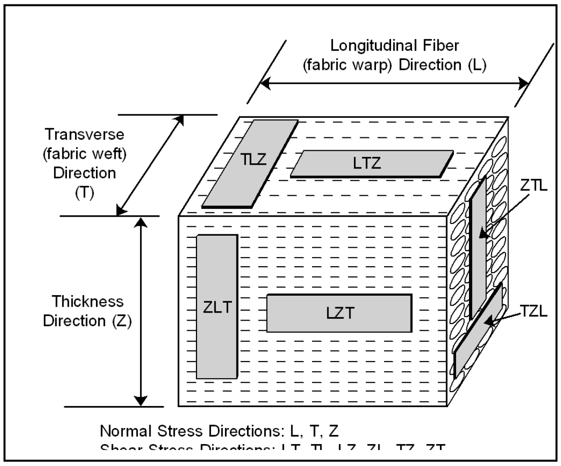
III. Test Results and Discussion

A. 3-D Static Properties for Thick Laminates

Full 3-D elastic constants and strength data have been developed for an infused fabric laminate typical of blade spar structure, for use in finite element modeling. The complex architecture of blade reinforcing fabrics raises uncertainty about typical assumptions as to properties in directions which are usually not tested. Multi-axial failure criteria for this class of laminates have also not been adequately tested. In this study, infused unidirectional (UD) 100 mm thick fabric laminates have been prepared, with shear and normal test coupons machined in various directions; in-plane properties were determined from conventional thickness specimens.

Table 3 gives a schematic of test coupon orientation and elastic constants. Table 4 gives strength values; best fit nonlinear shear stress-strain curves and failed coupon photographs are shown in Figure 2. The fabric stacking and internal structure are evident in the photographs. The relationships between elastic constants are approximately as expected[6]. All six shear moduli are in the same range; shear stress-strain curves are strongly nonlinear over the entire strain range, as expected (Figure 2). The z-component strength properties are significantly weaker than in-plane properties, the latter reflecting the transverse fabric backing strands (Table 1). The z-direction tensile strength is lower than the in-plane transverse tension strength for the same reason; the latter strength is listed as the “knee” value where most of the cross-section cracks, leaving in-tact transverse strands. Z-direction compression strength is similar to the in-plane transverse compression strength.

Table 3. Average 3-D elastic properties for thick unidirectional glass fabric/epoxy laminate.



Laminate Elastic Constants[1]	
Tensile Modulus E_L (GPa)	44.6
Tensile Modulus E_T (GPa)	17.0
Tensile Modulus E_Z (GPa)	16.7
Compressive Modulus E_L (GPa)	42.8
Compressive Modulus E_T (GPa)	16.0
Compressive Modulus E_Z (GPa)	14.2
Poisson Ratio ν_{LT}	0.262
Poisson Ratio ν_{LZ}	0.264
Poisson Ratio ν_{TL}	0.079
Poisson Ratio ν_{TZ}	0.350
Poisson Ratio ν_{ZL}	0.090
Poisson Ratio ν_{ZT}	0.353
Shear Modulus G_{LT} (GPa)	3.49
Shear Modulus G_{LZ} (GPa)	3.77
Shear Modulus G_{TL} (GPa)	3.04
Shear Modulus G_{TZ} (GPa)	3.46
Shear Modulus G_{ZL} (GPa)	3.22
Shear Modulus G_{ZT} (GPa)	3.50

[1]Tensile and compressive moduli and Poisson's ratios determined from best fit line between 0.1% and 0.3% strain; shear moduli calculated from best fit line between 0.2% and 0.6% shear strain.

Table 4. Average 3-D strength properties for thick unidirectional glass fabric/epoxy laminate.

Laminate Strength	**Stress Direction**	**Strength (MPa)**	**Ultimate Strain (%)**
Tension	L	1240	3.00
Tension[1]	T	43.9	0.28
Tension	Z	31.3	0.21
Compression	L	774	1.83
Compression	T	179	1.16
Compression	Z	185	1.44
Shear[2]	LT	55.8	5.00
Shear[2]	LZ	54.4	5.00
Shear	TL	52.0	4.60
Shear[2]	TZ	45.6	5.00
Shear	ZL	33.9	1.10
Shear	ZT	28.4	0.81

[1]Transverse tension properties given for first cracking (knee) stress
[2]Shear values given for 5% strain following ASTM D5379

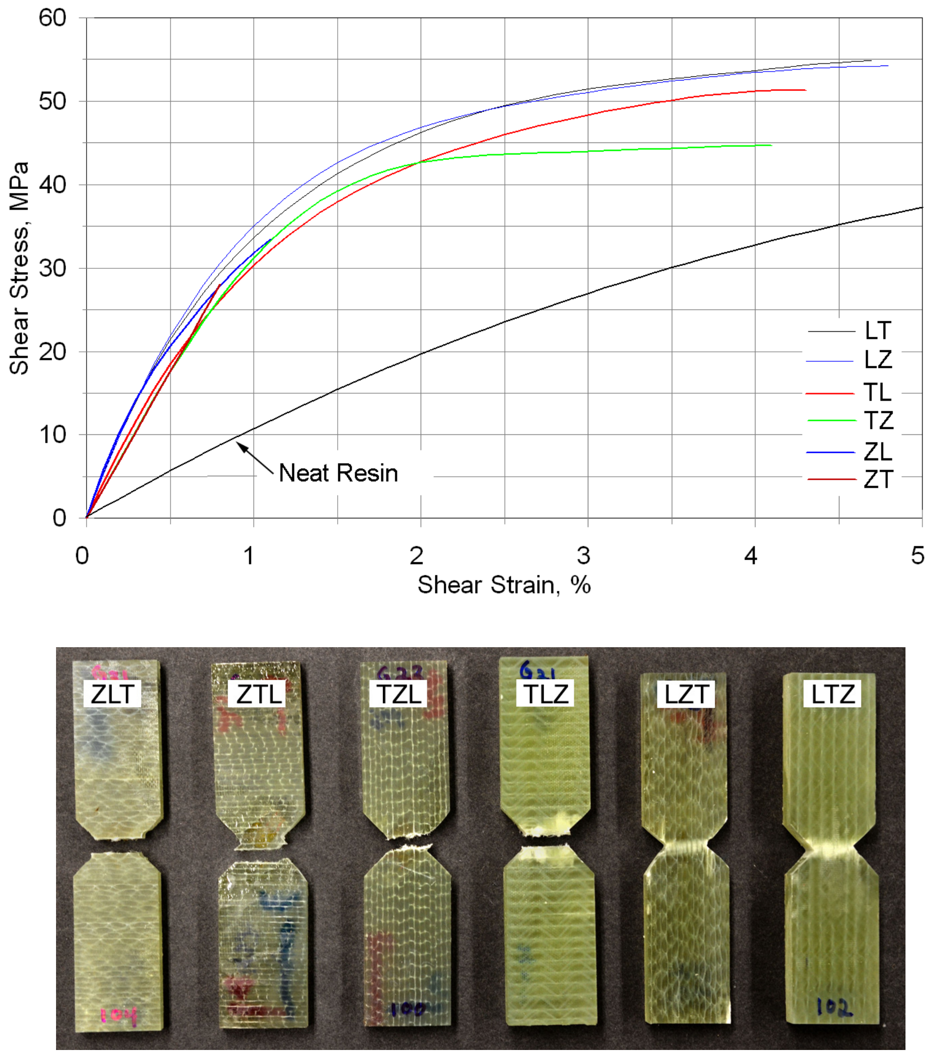


Figure 2. Best fit shear stress-strain curves (top) and failed shear coupons.

B. Effects of Fabric Construction and Resin on Blade Laminates

The tensile fatigue resistance for laminates with a range of typical wind blade reinforcing fabrics and resins has been reported in recent years[2,7]. The tensile segment of fatigue cycles for various R-values (R = minimum load/maximum load) represents the most critical fatigue response[2,3] for glass fiber laminates. Infused laminates with stitched fabrics and epoxy or polyester resins have shown significantly better performance for epoxies in terms if fatigue strains and fatigue exponents. Particular resins show consistent fatigue resistance for a range of generally similar UD reinforcing fabrics in UD and multidirectional (MD) laminates[2].

A pronounced effect of the type of resin on the fatigue resistance has been evident for epoxy, vinyl ester and polyester resins[2,3,7]. Figure 3 gives a comparison of the maximum tensile strain which can be withstood for one million cycles for typical epoxy (EP) and unsaturated polyester (UP) resins in the database, under tensile fatigue loading, R = 0.1. Various vinyl ester resin results are intermediate between epoxy and polyester[2,3,7]. These trends are for UD fabric laminates, MD laminates containing UD and biax fabrics (±45 strands plus mat and/or transverse strand backing), triax fabrics containing UD and biax layers stitched together (about 50% UD) and biax fabrics only. Earlier study of lower fiber content laminates typical of hand layup fabrication, with weft UD fabric having no backing, showed very little effect of resin type on fatigue resistance[3].

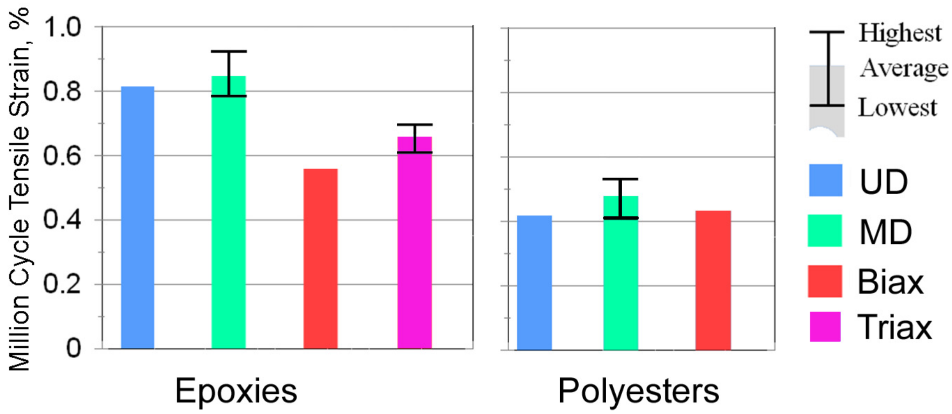


Figure 3. Comparison of million cycle fatigue strains for typical EP and UP resin laminates.

Aligned Strand vs Fabric Laminates

The sensitivity to fabric structure of the UP and VE resin infused UD laminates is evidenced in Figure 4 by coupon fatigue failures associated with the transverse backing strands, and by microscopy observation of cracking along these strands, apparently initiating at the stitching, and then failing the primary 0^o strands. In a series of specialized experiments, the transverse backing strands in fabric H were removed prior to infusion. The fatigue results in Figure 5 show that the epoxy UD laminates, which typically do not fail at the transverse backing strands (but do show cracking there), show no improvement when the strands are removed. However, the UP laminates improve significantly in fatigue resistance when the transverse strands are removed.

The aligned strand (AS) reinforced laminate structure serves as a baseline for fatigue resistance in the absence of complications from fabric structure. Stress and strain vs. cycles to failure tensile fatigue results are compared in Figure 6 for AS and fabric H reinforced laminates for three resin types. Both laminate types contain the same UD strands, PPG 2400 Tex with Hybon 2026 finish. The fabric data are typical of data for other fabrics of similar construction for the epoxy resin. (Note that epoxies EP1 and EP5 differ only slightly; both have RIMR 135 resin, but the EP1 hardener is RIMH 1366 while the EP5 hardener is very similar, RIMH137.)

The data in Figure 6 establish the following:

1. Infused laminates with only aligned strand for reinforcement significantly out-perform laminates containing typical fabric (Figure 2) in terms of both stress and strain over the entire cycle range.
2. The epoxy resin significantly out-performs the other two resins with fabric reinforcement, but the vinyl ester is similar to epoxy for AS reinforcement.

Fiber contents are about 64-68% by volume for the AS laminates, 54-58% for the fabric laminates. Additionally, fabric H is only 92% 0^o strand, the remainder being backing and stitching (Table 1). These factors contribute to an approximately 27 % higher axial fiber content for the AS structure than for the fabric. Higher axial fiber volume fractions are possible for the AS laminate structures, raising the modulus and tensile strength proportionally.

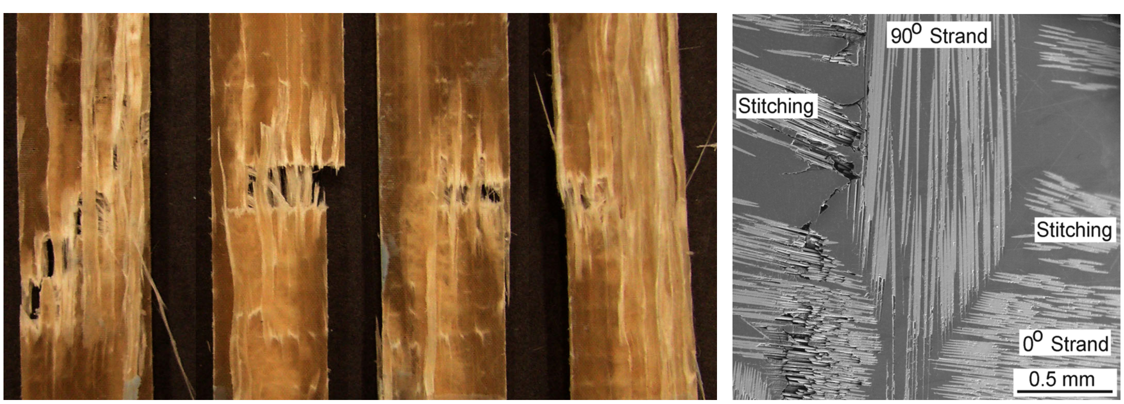


Figure 4. Cracking along transverse (90^o) backing strands of UP5/fabric laminate; left: failed coupons; right: micrograph of crack following the backing strand, and failing the 0^o strand.

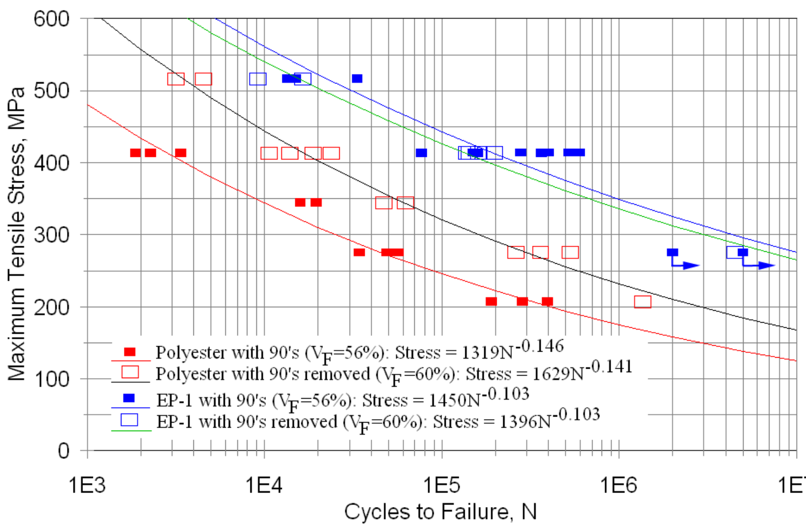


Figure 5. Effects of removing transverse backing strands on fabric data from Figure 4.

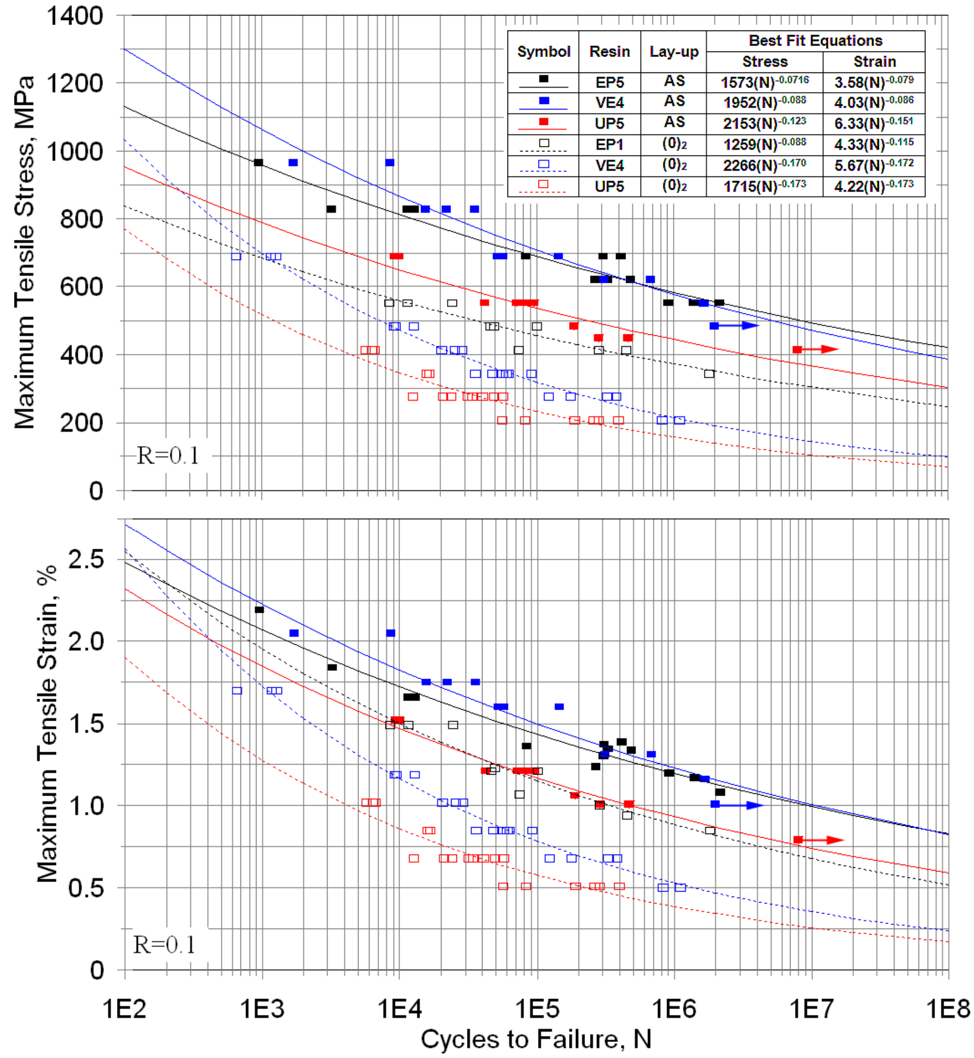


Figure 6. Comparison of stress and strain fatigue trends for aligned strand and $(0)_2$ fabric H based laminates for epoxy (EP1 and EP5), vinyl ester (VE4) and polyester (UP5) resins.

Resin Effects on UD Fabric Efficiency

The results in Figure 6 demonstrate the superiority of aligned strand reinforcement relative to fabric reinforcement. Fatigue stresses are more than double at the same lifetime for AS vs. fabric for the UP and VE resins; for the EP resin, stresses are increased on the order of 40 to 50%. These differences are due in part to overall fiber content differences, as fiber packing is improved for AS laminates. A second factor is the difference in fiber content in the axial, 0^o direction, as the transverse and mat backing strands do not contribute significantly to strength properties in the axial (load) direction. Table 5 gives the overall and 0^o-direction fiber contents. The substantial differences between 0^o fabric V_f and AS V_f help to explain the observed property differences.

A simple definition of fabric efficiency which reflects the actual laminate properties obtained is the ratio P_F/P_{AS}, where P_F is the property of the fabric laminate and P_{AS} is the property of the AS laminates without the fabric structure. The ratio for the 0^o V_f ranges from 0.76 to 0.83. The modulus ratios are slightly higher, reflecting the backing contribution to increasing the modulus relative to pure resin. The UTS and fatigue parameters fall below the ratio for 0^o V_f, indicating more than proportional decrease for these fabric properties with fiber content, particularly for the UP and VE resins.

Table 5. Fabric Efficiency Relative to Aligned Strands

Resin	EP1 /EP5[1]	VE4	UP5
Fiber Volume Fraction, V_f			
AS Laminates	0.64	0.66	0.68
Fabric Laminates	0.58	0.55	0.58
0^o V_f, Fabric Laminates	0.53	0.50	0.53
0^o Direction Fabric Efficiency: P_F/P_{AS}			
0^o V_f	0.83	0.76	0.78
Modulus, E	0.88	0.85	0.81
UTS	0.73	0.68	0.62
10^6 cycle stress	0.64	0.37	0.40
10^6 cycle strain	0.73	0.43	0.49
P_F/P_{AS} Adjusted for 0^o V_f: (P_F/P_{AS}) (AS V_f /Fabric 0^o V_f)			
Modulus, E	1.06	1.12	1.04
UTS	0.88	0.89	0.79
10^6 cycle stress	0.77	0.49	0.51
10^6 cycle strain	0.88	0.49	0.63

[1]EP1 for fabric laminates, EP5 for AS laminates

Clearer relationships emerge if the fabric efficiency is adjusted for the 0^o V_f difference by considering the parameter (P_F/P_{AS}) (AS V_f/Fabric 0^o V_f) in the bottom section of Table 5. The fully adjusted efficiency indicates fabric properties relative to expectations from AS laminates assuming proportional changes with 0^o V_f. The fabric laminate modulus now shows a value greater than 1.0 due to the small contribution of the backing strands. The UTS is 79 to 89% of the expected proportional change, probably due to relatively poor strand alignment in the fabric as can be seen in Figure 1 (top). The fatigue ratios for the epoxy are close to the UTS ratio, about as good as could be expected. However, the fatigue ratios for the UP and VE resins fall well below the UTS ratio, showing the particular sensitivity to fabric structure for these resins, apparently related to the transverse strands.

The results in Table 5 and Figure 6 relate specifically to Fabric H (Table 1). UD laminate fatigue data have also been obtained for the heavier Fabric D, which only contains transverse strands in the backing (no mat), and also has 4400 Tex warp strands (AS laminate data are not yet available with these strands). Figure 7 indicates similar fatigue trends for both fabrics for EP and UP resins, with the previously observed higher performance for the epoxy. However, the VE resin approaches the epoxy performance at higher cycles only for the fabric D laminates, as it did for AS laminates in Figure 6. Thus, the VE resin may perform on par with epoxy for some fabric structures or strands, but not others.

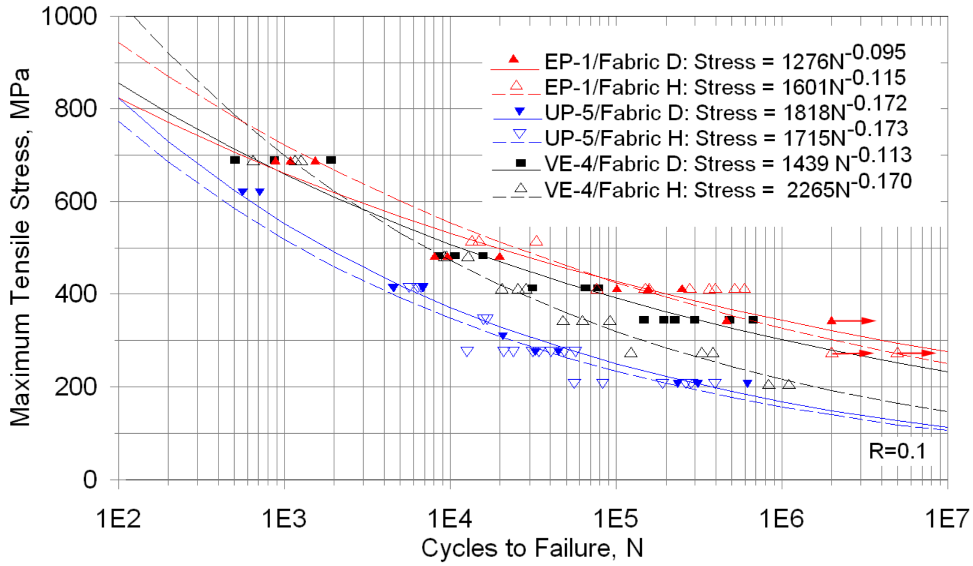


Figure 7. Effect of UD fabric D vs. fabric H, for EP, VE and UP resins, $(0)_2$ laminates.

Additional Results for Fabric Effects with Epoxy Resin Laminates

The foregoing suggests that epoxy resins like EP1 are not strongly sensitive to the fabric structures beyond changes in fiber content in the axial direction. Three series of laminate studies have been carried out to explore the influence of fabric details on fatigue sensitivity with the EP1 and EP5 epoxies described earlier. The most extensive test series was on laminates supplied by Roman Hillermeier of Devold AMT AS. Ten stitched fabrics with differences in weight, backing structure and stitching (with other parameters like yarn tension controlled) were specially prepared. Most were tested in fatigue at a single maximum stress level, while four were tested at several stress levels. All laminates were MD structure with the UD fabrics listed, combined with a Devold 800 gsm biax fabric. All laminate configurations were $(\pm 45/0_2)_S$ except for the heaviest, L2400, which used single 0 layers due to its doubled areal mass relative to the standard L1200.

Table 6. Fatigue results for ten MD laminates supplied by Devold with varied UD fabrics, epoxy EP5, R = 0.1

Material	V_F, %	Tensile Modulus, E_T, GPa	Ultimate Strain, %	Ultimate Tensile Stress (UTS), MPa	Normalized Maximum. Stress, 414 / UTS	Log Cycles to Failure at a Maximum Stress of 414 MPa	COV, %
L1200	57	35.7	2.8	891	0.465	4.77	2.7
L1400	60	38.6	2.8	896	0.462	4.91	4.3
L2400	61	35.8	2.9	920	0.450	4.80	3.2
LT1200	58	35.2	2.8	818	0.506	4.36	0.80
TLT1200	60	36.3	2.5	857	0.483	4.74	0.74
LT1200_G50	59	36.8	2.8	809	0.512	4.35	3.9
L1400_T	54	36.8	2.8	770	0.538	4.88	5.9
L1400_TCU	59	40.9	2.8	779	0.531	4.53	4.0
L1400_TCS	54	37.4	2.7	760	0.545	4.74	2.7
L1400_btw	59	38.3	3.1	946	0.437	4.89	2.5

The first three fabrics, L1200, L1400 and L2400 vary only in fabric weight. L1400 has more closely spaced yarns while 2400 has larger yarns. More complete data for different stress levels are given in Figure 7. The effect of fabric weight is not great, with only a suggestion of slightly lower cycles for the heaviest fabric at the lowest stress. The next three fabrics in Table 6 varied in backing structure: weft yarn on lower side (LT), weft yarn top and bottom (TLT), and weft yarn plus chopped strand (LT1200_G50). The bottom four fabrics in Table 6 varied in stitching details: tricot (T), un-symmetric tricot chain (UTC), symmetric tricot chain (STC), and stitch in-between roving (BTW). The log cycles to failure were not significantly affected by any of these variations for this epoxy resin.

A study of OCV™ UD fabrics in UD laminates with epoxy EP1 is represented in Figure 9, and a similar study of three different weight triax fabrics is represented in Figure 10. Only the strain is given to reduce inconsistencies due to variations in laminate fiber content. The OCV UD fabrics contain Advantex® glass fibers with an OCV™ sizing. These figures show little effect of fabric weight using the EP1 epoxy system, and fatigue resistance is similar to that for laminates based on fabrics D and H.

The sixteen different fabrics reported in this section demonstrate that tensile fatigue resistance with epoxy resin EP1 is not significantly affected by fabric details for a broad range of fabric weights, backing, stitching, orientation and strands/fibers/finishes. Strain levels are slightly lower for the triax fabrics compared with the UD fabric laminates, discussed later with Table 7.

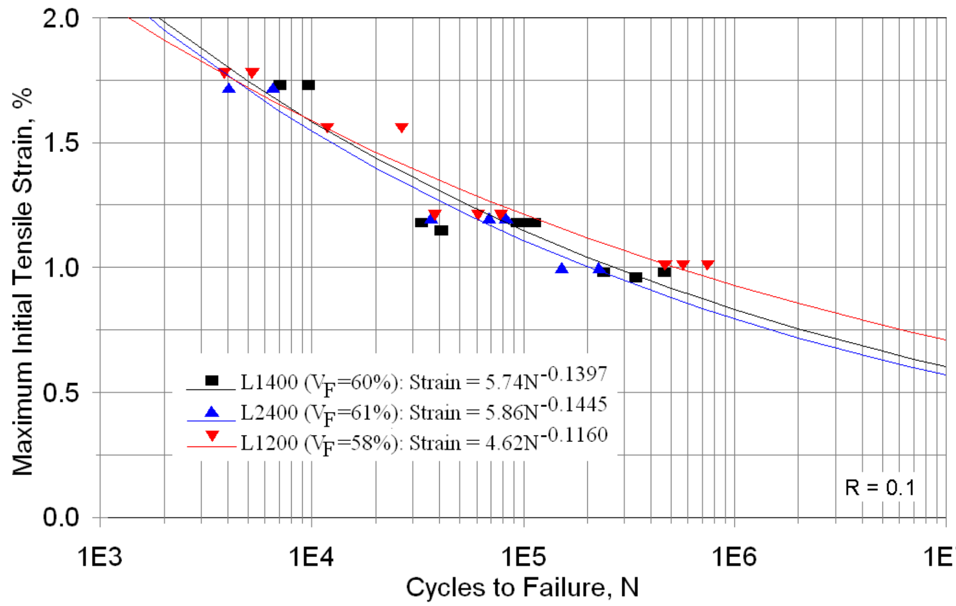


Figure 8. Stress (top) and strain (bottom) vs. cycles for MD laminates fabricated with three different weight UD fabrics from Table 6, epoxy EP5, R = 0.1.

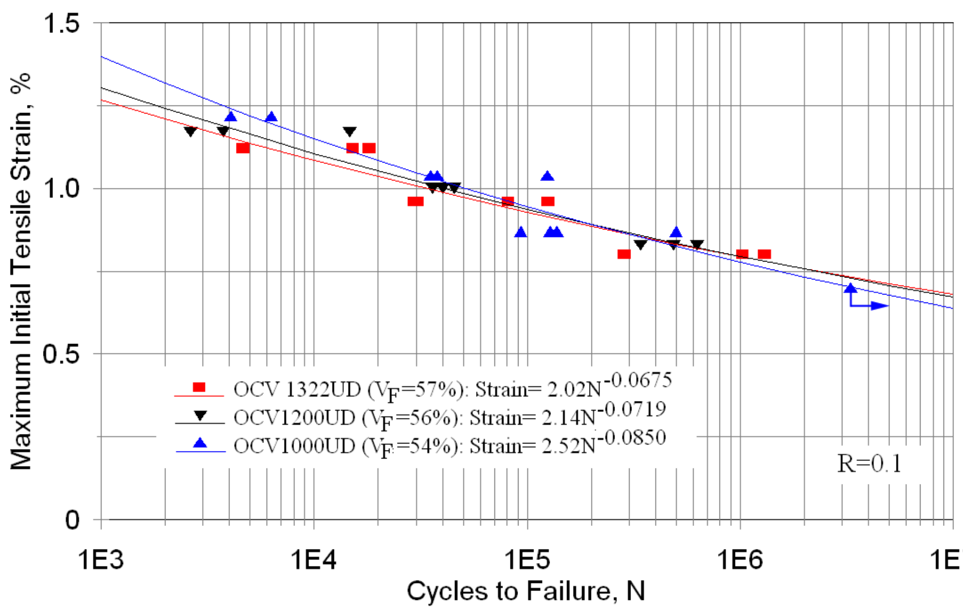


Figure 9. Strain vs. cycles for UD laminates with three different weight OCV™ fabrics, EP1 epoxy, R = 0.1.

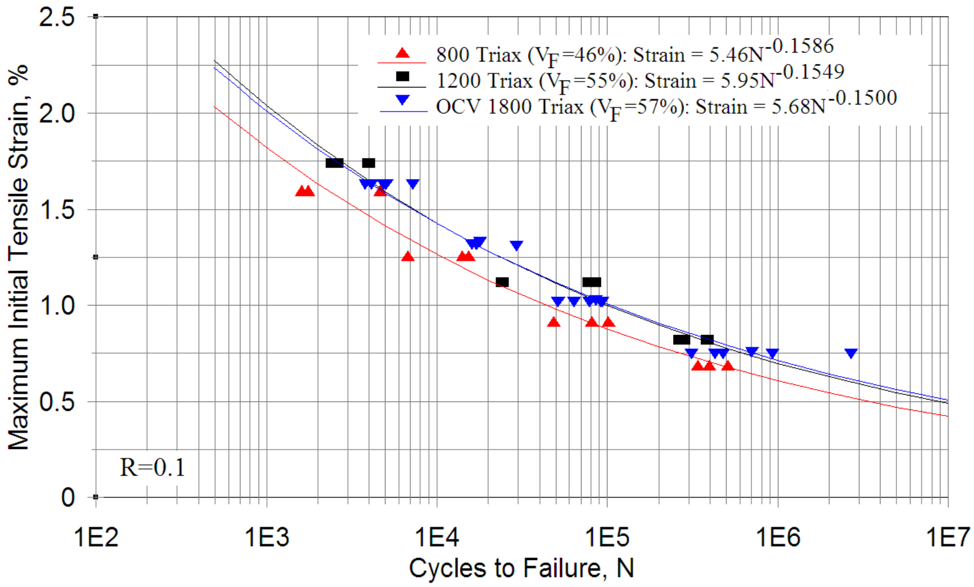


Figure 10. Strain vs. cycles to fail for triax fabric laminates with two Saertex fabrics (800 and 1200 gsm) and a heavier OCV^{TM} fabric (1800 gsm), epoxy EP1, R = 0.1.

C. Overall Blade Material Fatigue Trends

Composite structures like blades are complex in construction, containing ply drops for thickness tapering as well as other material transitions such as core materials and close-outs and intersections of spar-caps, webs and shells, and root connections. Establishing the true in-situ fatigue resistance of a material in a blade would require representative substructure testing with realistic loads, and designed to fail in the particular mode of interest. Coupon testing can include only a limited range of details, usually under uniaxial loading and with machined edges.

Material transition areas are prone to delamination between plies under fatigue loading. The database and associated reports[2,8] contain extensive results for delamination testing with standard geometries as well as mini-substructure coupons containing ply drops, and comparing the performance of various resin systems[2,3]. Most wind turbine blades also contain adhesives and core materials which are fatigue sensitive. Data for blade adhesives under fatigue loading have been presented in recent reports and papers[2,4]. Fatigue trends for these various blade components are compared to standard laminate fatigue behavior in this section.

Table 7 compares fatigue data trends from various database materials[1]. Included in Table 7(a) are laminates of increasing complexity: aligned strand, UD fabric and MD laminates, all based on the same strands and resins. Additional laminate trends are given for the transverse direction, biax fabrics and triax fabrics. In Table 7(b) data are given for structured coupons containing ply drops, where ply delamination is the dominant damage[3], as well as adhesives and core materials. Comparison of fatigue exponent B (Eq. 1), and the million cycle fatigue strain, gives some indication of the most fatigue critical areas of blades. Eq. (1) can be normalized as a function of the static tensile strength, UTS (determined at 0.0254 mm/s), which does not affect the exponent. This allows approximate comparison of critical fatigue conditions based on analysis predictions of critical loads for particular failure modes. The properties must be viewed in the context of actual blade stress distribution and the presence of flaws.

As the laminate complexity increases from AS to UD fabric to MD, the fatigue S-N curves steepen, reflected in higher absolute values for exponent B, and lower million cycle strain. This trend is particularly strong for the VE and UP resins. Resin-dominated failures for neat resin, transverse direction laminate and biax laminates (Table 7(a)) all show similar, relatively low fatigue exponents, B, compared to MD laminates and UD fabric laminates with VE and UP resins. The lower exponent B range is also observed for resin dominated delamination growth at ply drops (static delamination resistance in opening and shearing modes is significantly higher for EP1 than for UP1, with vinyl ester VE1 intermediate[2]). Resin dominated exponents indicate relatively flat S-N behavior compared to some UD and MD laminates, but the million cycle fatigue strains are lower, particularly in the transverse direction. Triax constructions have steeper S-N S-N trends in the range of the MD laminates, representing a two stage failure process in some cases, between the biax and UD layers[2,3]. The epoxy based adhesive lap shear joint fatigue exponents are relatively low, similar to the resin dominated transverse and biax trends for epoxy resin; the bulk adhesive exponent B is very low at -0.044, but joints usually fail predominantly by delamination in the laminate surface[5].

Table 7. Comparison of tensile fatigue (R = 0.1) trends for various blade materials. (a) Laminates with a progression of reinforcement structure from aligned strand to multidirectional, three resin types (B and n for stress-cycles fits).

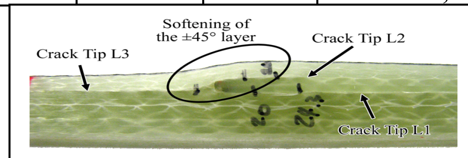
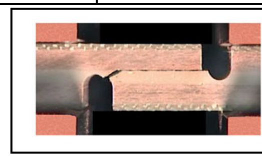
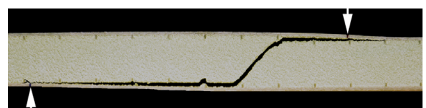
Material Form	**Resin**	**UTS, MPa**	**A, MPa**	**B**	**n**	**10^6 Cycle Strain, %**
UD Aligned Strand (AS) Laminates, PPG 2400 Tex, Hybon 2026 Finish						
AS	EP5	1369	1573	-0.072	13.9	1.20
AS	VE4	1340	1952	-0.088	11.4	1.23
AS	UP5	1382	2153	-0.123	8.13	0.79
UD Fabric H Laminates (contain PPG 2400 Tex/Hybon 2026 Strands)						
$(0)_2$ Fabric H	EP1	995	1259	-0.088	11.4	0.88
$(0)_2$ Fabric H	VE4	912	2266	-0.170	5.88	0.53
$(0)_2$ Fabric H	UP5	884	1715	-0.173	5.78	0.39
MD Laminates, UD Fabric H and Biax Fabric T						
$[(\pm45)_2/(0)_2]s$	EP1	704	1378	-0.130	7.69	0.79
$[(\pm45)_2/(0)_2]s$	VE4	628	1228	-0.146	6.85	0.53
$[(\pm45)_2/(0)_2]s$	UP5	663	1151	-0.151	6.62	0.42
Transverse Direction Fabric H, UD Laminates						
$(0)_6$ Fabric H	EP5	52.4[1]	97.3	-0.114	8.77	0.124
Neat Resin and Adhesive						
Epoxy EP1 Resin	EP1	41.0[2]	82.9	-0.081	12.3	0.77
Bulk Adhesive EP135G3/EKH1376G	ADH1	44.5[2]	57.6	-0.044	22.7	0.79
Biax Fabric M (±45/mat) Laminates						
$(\pm45/m)_3$ Fabric M	EP1	224	225	-0.092	10.9	0.53
$(\pm45/m)_3$ Fabric M	VE1	239	239	-0.090	11.1	0.44
$(\pm45/m)_3$ Fabric M	UP1	208	202	-0.098	10.2	0.41
Triax Fabric W						
(±45/0)s Fabric W	EP1	585	1287	-0.143	6.99	0.70

[1]First cracking stress; [2]0.2% offset yield stress

IV. Conclusions

This paper describes findings in three areas included in the SNL/MSU/DOE fatigue of wind blade composite materials database[1]. First, a complete 3-D set of static elastic constants and strength properties for a thick infused glass fabric/epoxy laminate is given. Second, detailed results are presented exploring the effects of fabric structure and resin type on the tensile fatigue resistance. Using aligned strand structure as a baseline, the efficiency of stitched fabric reinforcement is quantified for static and fatigue properties. The fabric efficiency is generally good for an epoxy resin, but poor in fatigue for a vinyl ester and polyester; the latter traced to sensitivity to cracking along the transverse fabric backing strands. The vinyl ester resin laminates varied with the particular UD fabric tested, approaching the epoxy performance only for fabric D and for aligned strand laminates. Laminates with the epoxy resin show little effect of broad variations in fabric weight or construction, or strand fiber and sizing, for glass fibers. The third area is a comparison of the tensile fatigue sensitivity of various blade materials including laminate in-plane and interlaminar failure, epoxy based blade adhesives and core materials. Comparisons of fiber dominated and resin dominated failure modes show clear trends in the fatigue exponent, depending on the resin system. Resin dominated, adhesive and core exponents are generally lower than fiber dominated exponents (less-steep S-N curves), but static and fatigue strains at a million cycles are also generally lower.

Table 7 (b). Fatigue trends for blade structural details including delamination at ply drops, adhesive joints and skin/core sandwich structures

Material Form	Resin	Strength	A	B	n	10^6 Cycle Strain, %
Delamination at thick ply drops[2]						
1 ply drop, Fabric D	EP1	189 kN				0.55
2 ply drop, Fabric D	EP1	135 kN		-0.120	8.3	0.39
4 ply drop, Fabric D	EP1	106 kN		-0.099	10.1	0.35
1 ply drop, Fabric D	UP-1	135 kN				0.39
Thick Adhesive Lap Shear Joints[3]						
Hexion Adhesive EP135G3/EKH1376G	N/A	13.9 MPa	22.7 MPa	-0.109	9.17	N/A
3M W1100	N/A	13.8 MPa	29.13 MPa	-0.135	7.41	N/A
Triax Skin/Core Sandwich 4-Point Bending Flexural Fatigue[4]						
Airex C70.55 GPS, 60 kg/m^3 core	EP1	50.25 N/mm	73.34 N/mm	-0.091	11.0	N/A
Airex C70.75 GPS, 80 kg/m^3 core	EP1	55.67 N/mm	46.43 N/mm	-0.026	38.9	N/A

[2]Ply drop strength is Force (kN) at 30-mm delamination length.
[3]Thick adhesive apparent lap shear strength, MPa, 3.25 mm thick adhesive, 25 mm overlap length, 5 mm thick UD Fabric D/EP-1 adherends.
[4]Sandwich Flex Fatigue per ASTM C393, 25 mm thick core, 1.6 mm thick triax glass/epoxy face-sheets. Strength is applied force, N/mm-width, at major core delamination.

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