EFFECTS OF FIBER WAVINESS ON COMPOSITES FOR WIND TURBINE BLADES

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ABSTRACT

Composite materials of interest for wind turbine blades use relatively low cost fibers, resins and processes. Material micro-structures are heterogeneous, using large tows, often with stitched or woven architectures. The reinforcements usually contain significant fiber waviness and misorientation. Resin infusion processes may exacerbate the waviness problem, particularly with loose fabrics. Severe fiber misorientation reduces properties like tensile strength, but even mild waviness can cause significant reductions in compressive strength.

This paper presents the results of static and fatigue tests on laminates containing a variety of commercial glass and large tow carbon fabrics with several resins. The results show a systematic reduction in compressive properties with increasing waviness, such as that in woven versus stitched fabrics or near flaws and ply-drops. This effect is particularly important with large tow carbon fabrics, since their compressive strain capabilities are borderline. Prepreg laminates generally show the least waviness, but significant fiber misorientation can occur at ply drops and ply joints depending on geometry and processing conditions. Results are also presented from a study where in-plane waviness was systematically varied, establishing relationships between wave parameters and compressive strength for a fiberglass laminate.

KEY WORDS: Composite Materials, Fiber Waviness, Compressive Strength

1. INTRODUCTION

Wind turbine blades have become a major application of composite materials. Depending upon the location along the blade, designs are often strength and fatigue driven, as opposed to stiffness driven. Since blades must be produced at a finished cost in the range of $10/Kg, only relatively inexpensive resins, reinforcements and processes are competitive. The low cost materials and processes combined with strength-driven designs produce a significant concern with the effects of flaws on the various strength-based properties. The results of a fourteen-year study of blade materials, including many flaw types, can be found in the DOE/MSU Composite Materials Fatigue Database [1] and other reports and papers related to the database [2-4], which are available on the Sandia National Laboratories Website www.sandia.gov/Renewable_Energy /wind_energy/. This paper reports on the effects of both in-plane and through-thickness fiber waviness primarily on the compressive properties. Waviness is both artificially induced for parametric studies and naturally occurring in reinforcing fabrics and at structural details.

Fiber waviness has been the subject of many studies, with most of the attention on prepreg laminates [5-9]. Waviness is expected to reduce compressive strength due to two factors: (1) the fibers may be put into a geometry which exacerbates the basic fiber, strand, or layer buckling mode of failure, and (2) the waviness shifts the fiber orientation off the axis of the ply longitudinal direction, producing matrix dominated failures for plies nominally orientated in the primary load direction (0°). The second factor may also affect tensile strength in severe cases.

Compared with typical prepreg laminates, blade fabrics tend to be thicker and more heterogeneous, with strands of fiber either woven (usually over a small strand) or stitched together (Figure 1). Wet processing methods such as hand lay-up and variants of resin transfer molding (RTM) can induce severe waviness under some conditions. Severe in-plane waviness in a large-tow carbon fiber stitched fabric induced during RTM processing is shown in Figure 2. This is an example of extreme waviness unintentionally introduced during a resin infusion process. Based on the findings of this study, waviness of this severity would be expected to reduce strength properties by a factor of at least two to three relative to a laminate with straight 0° fibers; less severe waviness as in woven fabrics can also cause serious reductions in strength properties.

2. EXPERIMENTAL METHODS

2.1 Materials

The 0° (load direction) reinforcing fabrics included in this study are shown in Figure 1. Of the E-glass fabrics, stitched weft unidirectional fabric D155 has very straight strands with high strand integrity and is used as a control (despite being of limited practical interest, since it is available only as a weft unidirectional, with fibers orientated perpendicular to the main fabric roll direction). The A130 fabric is representative of a family of warp unidirectional fabrics with similar strands to D155, but woven over a small thermoplastic coated strand. The Ahlstrom 42024L/M50 is a warp unidirectional with the large strands stitched to a light random mat, typical of a number of similar fabrics. Other glass fabrics of interest would be woven roving, where large strands are woven over each other and triax, where warp unidirectional strands are stitched to a ±45° fabric. Glass fabric is also used for the ±45° layers, where present; stitched DB120 is used in most cases.

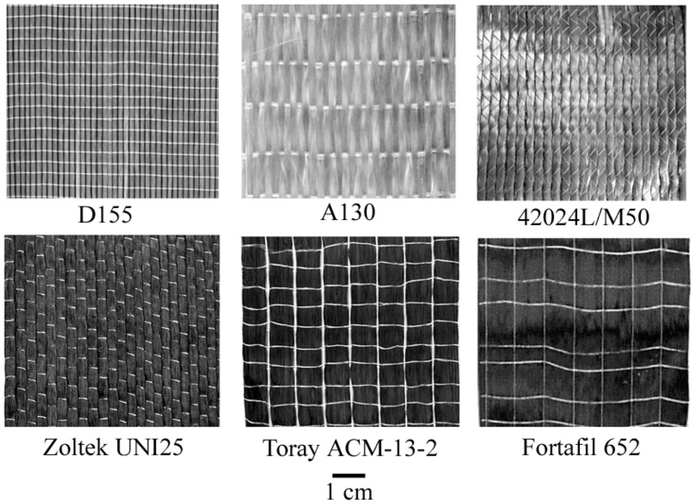


Figure 1. Glass (top) and Carbon Fabrics Used in This Study.

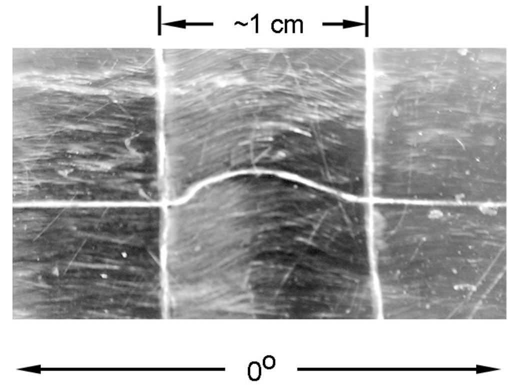


Figure 2. In-Plane Waviness in a Single-Ply Laminate of Fortafil 652 Carbon Fiber/Epoxy Processed by RTM [4].

The carbon fiber materials (Figure 1) have been limited to evolving large tow materials because of their potentially lower cost. The baseline material here is prepreg (SP Systems SE84LV/SC300C/300/400/37% with Toray 300S fibers). The stitched fabrics, Toray ACM-13-2 and Fortafil 652 are warp unidirectional, relatively loose construction with some inherent waviness evident (the Fortafil 652 actually has a thermoplastic bead bonded to the surface of the fabric as opposed to stitching). The woven fabric is Zoltek UNI25, which is tighter and more handleable than the stitched cases. Laminates with 0° carbon layers were either unidirectional, combined with dry DB120 ±45° glass layers, or with ±45° glass prepreg (Hexcel M9.6/35%/BB600/G).

Except for prepreg, resins were low viscosity, room temperature infusion resins: ortho polyester (CoRezyn 63-AX-051) with 1.5 to 2.0 % by volume Lupersol DDM9, vinyl ester (Derakane 411C50 or 8084) cured with 1.5 to 2.0 % Trigonox 239A, or epoxy (SP Systems Prime 20).

Processing was by hand lay-up for the fiberglass laminates with induced waviness and RTM for other glass and carbon fiber laminates with various fabrics. The hand lay-up and RTM laminates were cured at room temperature and post cured at 65°C for 2 hours. The prepreg was cured for 2 hours at 100°C in a vacuum bag setup with a vacuum of 75 kPa; some cases used additional over pressure as noted. Fiber contents and other details are given with the results.

2.2 Artificially Induced Waviness

Artificial in-plane waviness was introduced into laminates by selectively removing weft threads and displacing strands in D155 fabric. More details of this study can be found in Reference 10. The wavelength (λ) and amplitude (δ) were varied independently. The base laminate configuration was $(0/\pm45/0)_S$, with different 0° layers containing waviness at the same position in the laminate. A typical laminate with waviness indicated by ink markings on the initially straight strands is shown in Figure 3. The ±45° layers did not contain waves. The definition of wavelength, amplitude, wave severity (δ/λ), and maximum off-axis misorientation, θ, are shown in Figure 3. These plates were hand layed-up ply by ply, with impregnation at each step.

Through-thickness waviness was introduced into one set of laminates by adding local layers of 90° material in one area, distorting the other layers (shown later). These laminates were then processed by RTM. Similar effects are found near typical 0° ply drops and ply joints.

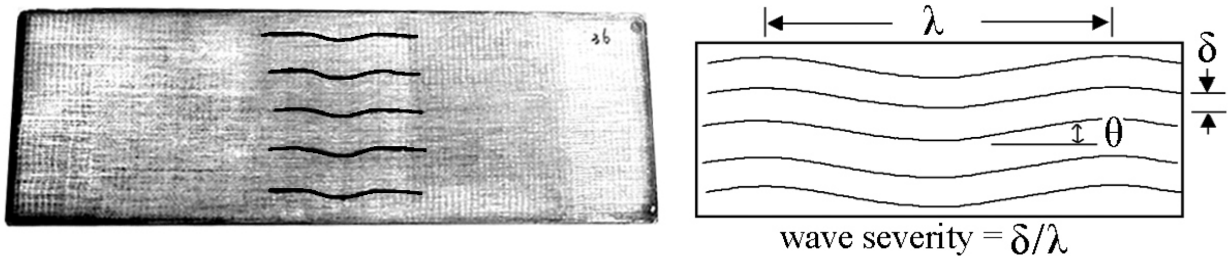


Figure 3. Laminate with Introduced Waviness (left) and Waviness Characterization (Right) [4].

2.3 Test Methods

Compression tests of materials without induced in-plane waviness used 25 mm wide rectangular specimens having a gage length of 13 mm, with no lateral constraint. Specimens were held in hydraulic grips with special anti-rotation and anti-deflection restraints described in References 2 and 3, which provide many details of test development for various materials. Compression tests are designed and validated for materials based failure without elastic buckling. A major issue is whether to provide lateral constraint against out-of-plane movement such as local strand buckling on surfaces. These tests did not use such constraint, to be representative of most blade service loading conditions. The same was true for compression fatigue tests. The specimens with in-plane waviness required a gage section which would encompass the entire wavelength. A special device providing lateral constraint over a 25 mm gage length was developed, as shown in Figure 4.

The displacement rate used in compression tests was relatively fast, 13 mm/s, to be consistent with fatigue loading rates. It should be noted that the compression strength varies significantly with loading rate for these materials, so that lower rates would provide lower strengths than reported here, decreasing by approximately 8 % per order of magnitude decrease in rate for the glass laminates in this study [2].

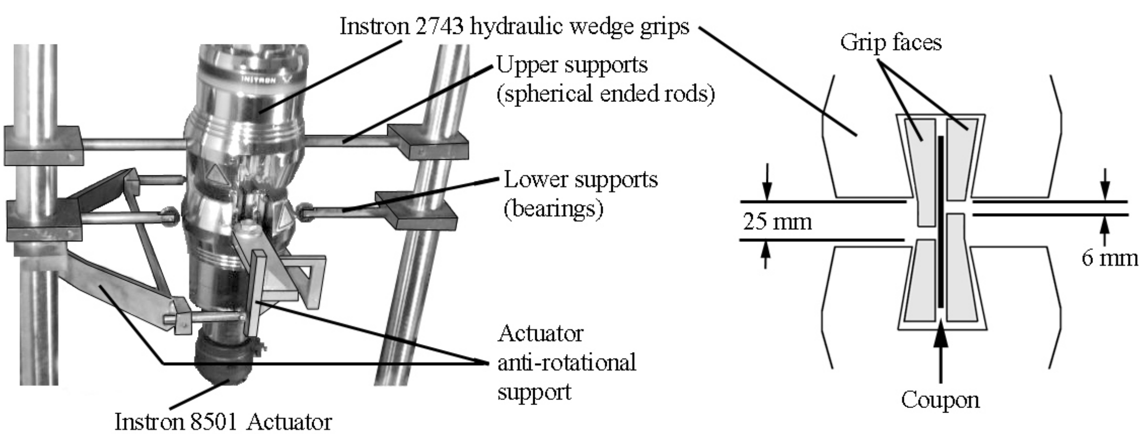


Figure 4. Actuator Lateral and Rotational Constraints for Compression Tests (left) and Coupon Wedge Grips (Right).

3. RESULTS AND DISCUSSION

3.1 Though-Thickness Waviness

3.1.1 Glass Fiber Laminates. Through-thickness waviness tends to exacerbate the fiber or strand buckling compression failure mode of most composites, evident for the typical straight fiber system using D155 fabric, shown in Figure 5. Even relatively low wave severities, such as those which occur with the A130 fabric in Figure 1, can significantly reduce the compressive strength by predisposing the fabric to the buckling geometry.

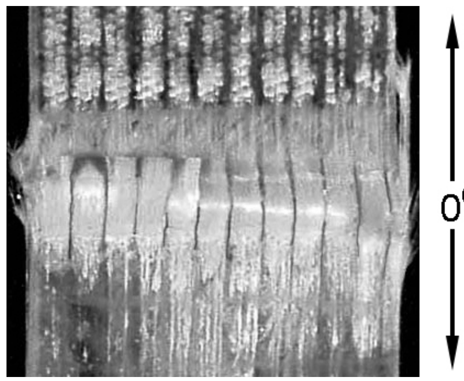


Figure 5. Static Compression Failure Mode for a Typical [0/±45/0]S Laminate Containing D155 Unidirectional Fabric for the 0° Plies (Figure 1).

The compressive strengths and strains to failure for laminates constructed from several types of fabric are listed in Table 1. The waviness inherent in the A130 fabric (Figure 1) at a fiber volume fraction of 43% (Material DD12 in the DOE/MSU Database [1]), is about $\delta/\lambda = 0.04$, the ply thickness divided by the weave spacing. Comparing this laminate, DD12, with a similar laminate made with a straight-fiber D155 fabric, DD8, the compressive ultimate strain drops from 2.1% to 1.1%. This nearly 50% reduction in compressive strength and strain to failure is caused by a wave having an amplitude of about one ply-thickness, which would also be expected around flaws and structural details like ply drops.

Other glass fabrics containing inherent waviness show similarly reduced compressive strength. The traditional woven roving laminate (ROV2) shows a compressive failure strain similar to the woven unidirectional fabrics, about 1.1%. A material form which contains rovings like the D155 fabric, but stitched to a thin mat to provide a nearly unidirectional warp fabric is the Ahlstrom 42024/M50 in Figure 1. However, close inspection of the strands shows significant waviness around the stitches. The compressive ultimate strains for laminates using this fabric, DD27A and DD27B, are also well below the corresponding values for the D155 fabric laminates, DD5P and DD8, at corresponding fiber contents.

3.1.2 Carbon Fiber Laminates and Hybrids. Laminates with 0° layers composed of large tow carbon fibers show similar effects, but at significantly higher compressive strengths and lower ultimate compressive strains. The latter property is of particular concern in wind turbine blades. Laminates with large-tow carbon fabricated using prepreg contain relatively straight fibers. The ultimate compressive strains for these materials in Table 1 are in the 1.0 to 1.2% range, which, as expected, is at the low end of data for aerospace carbon fiber prepreg materials which have smaller tow sizes. These values are in the same range as those for woven unidirectional glass laminates such as DD11 - 13 in Table 1, which are currently used in blades in heavier weight versions.

When the carbon fabrics in Figure 1 are processed by RTM into carbon laminates or hybrid laminates with glass ±45° layers, materials CGD4, CGD4E and UNI25 in Table 1, the compressive strains are significantly below 1%, down to the 0.6% range for the woven UNI25 material. Those compressive strains are further reduced in fatigue, as shown in Figure 6. These low compressive strains may limit blade designs using carbon fiber.

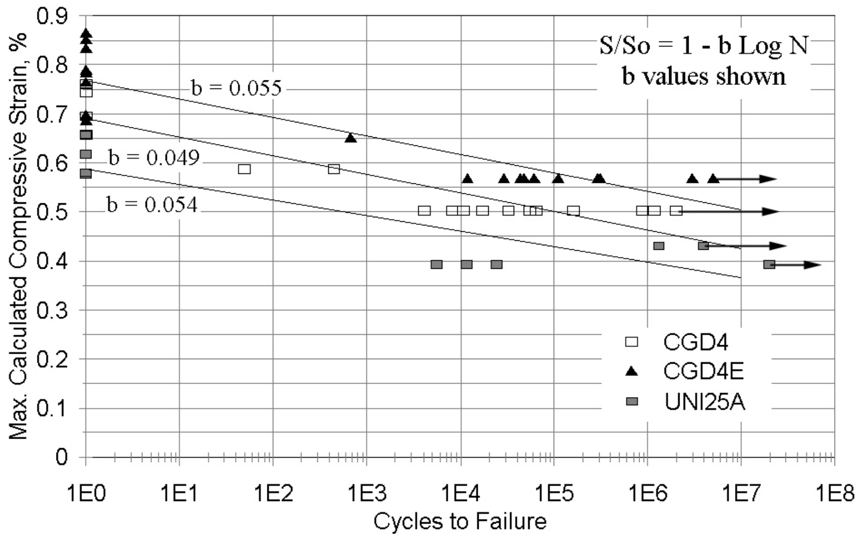


Figure 6. Compression Fatigue Data for Carbon Fiber and Hybrid Laminates: CGD4 and CGD4E, ($\pm45/0_3/\mp45$), 0°: Toray Stitched Carbon Fabric ACM-13-2, ±45: DB120 Glass; UNI25A, Unidirectional [0_3], Zoltek UNI25 Woven Carbon Fabric. Resins are Derakane 8084 Vinyl Ester for CGD4 and UNI25A, and Prime 20 Epoxy for CGD4E.

3.1.3 Effects of Flaws and Ply Drops. Factors such as ply drops, inclusions between plies, and complex substructure geometries can introduce local through-thickness waviness into laminates. Figure 7 and Table 2 illustrate typical geometries. (Note: the non-symmetrical geometries (ply drops, ply joints) were compression tested in a symmetrical geometry by bonding two specimens back-to-back on the flat sides to avoid bending and elastic buckling.) The 90° material inclusion is intended to represent a resin-rich area or a loose strand, etc. The reductions in compression ultimate strain correlate with the maximum ply or strand misorientation angle, as expected from literature studies [5]. The reduction in strength and ultimate strain are expected to be reduced for thicker laminates if a lower fraction of plies contain misalignment. Also, distortions like Figure 7 case (6), a double ply joint with a 6 mm gap and higher processing pressure, would be reduced for thicker laminates.

The glass laminates based on stitched D155- 0° fabric show little strain reduction for the double ply drop case, but a more significant reduction for the 90° material inclusion. These reductions are consistent with the measured strand angles. The glass laminates based on the woven A130- 0° fabric show less reduction in strain relative to the control value using this fabric. The inherent waviness in the woven fabric is nearly as bad as that near the inclusion, and the already low ultimate compressive strain is not further reduced to the extent that it is with the straight fiber D155 fabric.

Table 1. Static Compressive Strength of Laminates Using Commercial Fabrics (Figure 1) which Containing Varying Amounts of Waviness in 0^{O} layers (all non-0^{O} layers are $\pm 45^{O}$ DB120 glass fabric).

Database Designation	0^{O} Layers	% 0^{O}	V_F, %	Resin	Compressive Strength, MPa	Compressive Strain to Failure, %	Remarks
Glass Fibers							
DD5P	D155	72	37	Polyester	574	2.4	stitched straight strands
DD8	D155	72	44		582	2.1	
DD11	A130	68	30		319	1.6	woven strands
DD12	A130	68	43		302	1.1	
DD13	A130	68	46		314	1.1	
ROV2	----	50	35		362	1.1	woven roving
DD27A	Ahlstrom	76	32		381	1.9	stitched to mat, wavy strands
DD27B	Ahlstrom	76	42		321	1.2	
Carbon Fibers and Hybrids							
CGD4	ACM-13-2	76	51	Vinyl ester	588	0.71	carbon, stitched fabrics, low waviness
CGD4E	ACM-13-2	76	51	Epoxy	684	0.81	
UNI25A	UNI25	100	45	Vinyl ester	535	0.61	woven large tow carbon
CGD5E	Fortafil 652	71	35	Epoxy	565	1.15	bonded carbon
CGD5E2	Fortafil 652	71	51	Epoxy	546	0.73	
CGB4	se84lv/hsc	72	43	Epoxy	828	1.0	prepreg
CGB5	se84lv/sc300c	63	49	Epoxy	831	1.2	prepreg
CGB6	se84lv/hsc	80	65	Epoxy	1027	1.0	prepreg with glass 45's
SE84LV/SC300C/300/37%		100	55	Epoxy	1310	1.05	0_5, prepreg

Knockdown factors in fatigue for the glass laminates are similar to static factors for the 90° inclusion. However, the double ply drop now produces a much greater knockdown, about a factor of four in compression fatigue [2], as delamination grows suddenly and catastrophically from the ply drop area.

The prepreg based carbon fiber laminates and carbon/glass hybrids in Table 2 show differing effects at ply joints and ply drops. The most severe reduction in compressive strain capacity occurred with case 6, the double ply joint, where higher molding pressure produced a more severe misalignment (Figure 7, (6)). Here, the compressive ultimate strain value was reduced to only about a third of the control value. Ply drops with less severe geometries still showed reduced compressive ultimate strains to about 60% of the control range. Absolute strain values on the order of 0.6% may produce a significant limitation on the use of carbon in blades. However, single ply drops in thick laminates may produce much less severe effects, following Reference 11 and the following discussion on in-plane waviness. Fatigue tests have not yet been conducted on the carbon fiber laminates with ply drops and joints. These results indicate that a severe loss in compressive strength and ultimate strain are possible with carbon prepreg if care is not taken to avoid the type of distortion evident in Figure 7(6). Lower pressures and single ply drops would reduce the severity of the distortion.

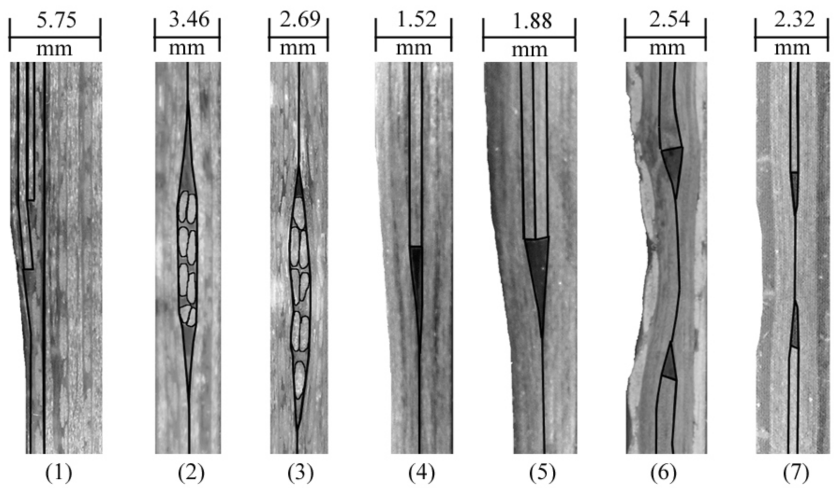


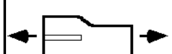
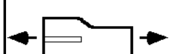
Figure 7. Enhanced Cross-Sectional Views of Materials Containing Ply Drops, Joints and Inclusions (See Table 2 for details).

3.2 In-Plane Waviness

In-plane waviness may occur in resin transfer processes due to fiber wash effects. Figure 2 is an example of unidirectional waviness which occurred during RTM processing of a single ply of Fortafil 652 fabric with the Prime 20 epoxy, at a fiber volume content of about 40%. Compressive strength was not measured for this case, but the tensile strength was only 329 MPa. When the same fabric was molded in the ply configuration [$\pm 45/0_3/\mp 45$], where the 0's are the carbon fabric and the ±45's are DB120 glass, severe in-plane waviness like Figure 2 was not observed, and the tensile strength was 764 MPa.

A systematic study was carried out to explore the effects of introduced in-plane waviness on the static and fatigue strength. The fabrication and testing details were described earlier. The parameters of wave length, λ, wave amplitude, δ, and maximum misorientation angle, θ, were given in Figure 3. Figure 8 shows that the wave severity, δ/λ, correlates well with the maximum misorientation angle, θ, for the cases studied. The ply configuration studied for most cases was $[0/\pm 45/0]_S$, where waviness was introduced to one or more of the 0° D155 fabric plies. When waviness was introduced only to one surface 0° ply, the data in Figure 9 were obtained for systematic variations in wave amplitude and length. Based upon Figure 8, this variation also held for compressive strength as a factor of θ [10]. A laminate with waviness in a single interior 0° ply gave approximately 10% higher compressive strength than for the surface ply waviness, for typical wave severities.

Table 2 Effects of Through-Thickness Flaws and Ply Drops on Compressive Strain to Failure (CSF)

Material and Detail	Edge View Sketch	Control (No Flaw) CSF[1] (%)	V_F (%)	0° Ply Thickness (mm)	Thickness Change (%)	Angle[2] θ (deg)	CSF[1] with Flaw (%)
(1) ESH: Double interior D155 0° ply drop (RTM) 0°: D155 Glass Fiber ±45°: DB120 $[0/0^*/0^*/\pm45/0/(0/\pm45/0)_2]$		2.4	35	0.55	-16	8	1.7
(2) 90° Material Inclusion (2-90° D155 plies in center) (RTM) 0°: D155 Glass ±45°: DB120 DD19, $(0/\pm45/0/90^*)_S$		2.4	34 / 47	0.56	0 (30% more fibers)	8	1.7
(3) 90° Material Inclusion (2-90° D155 plies in center) (RTM) 0°: A130 Glass ±45°: DB120 DD19A, $(0/\pm45/0/90^*)_S$		1.6	35 / 50	0.55	0 (37% more fibers)	10	1.3
(4) One central 0° ply drop 0°: Carbon fiber prepreg $[0_5] \rightarrow [0_4]$		1.0 to 1.2	55	0.31	-20	4	0.66
(5) Two central 0° ply drop 0°: Carbon fiber prepreg $[0_6] \rightarrow [0_4]$		1.0 to 1.2	55	0.31	-32	7	0.59
(6) Central 6 mm long ply joint gap in two 0° plies 0°: Carbon fiber prepreg ±45°: dry DB120 $(\pm45/0_2/0_2^*/0_2/\pm45)$		1.0 to 1.2	48	0.33	-24	16	0.34
(7) Central 6 mm long ply joint gap in one 0° ply 0°: Carbon fiber prepreg ±45°: Glass fiber prepreg $(\pm45/0_2/0^*/0_2/\pm45)$		1.0 to 1.2	52	0.34	-4	7	0.55

[1]CSF - Compressive Strain to Failure. [2]Angle θ is the Maximum Ply Misorientation Angle
Note: an * on the ply configuration indicates the ply which was dropped or added.
Carbon fiber (0°) prepreg: SE84LV/SC300C/300/300 (SP Systems)
Glass fiber (±45°) prepreg: M9.6/35%/BB600/G (Hexcel)
Prepreg processing involved a vacuum of 75 kPa and an over pressure of 103 kPa, except for case 6, which used an over pressure of 276 kPa. Prepreg materials were processed with a bag on one side, while RTM cases have a hard mold on both sides.

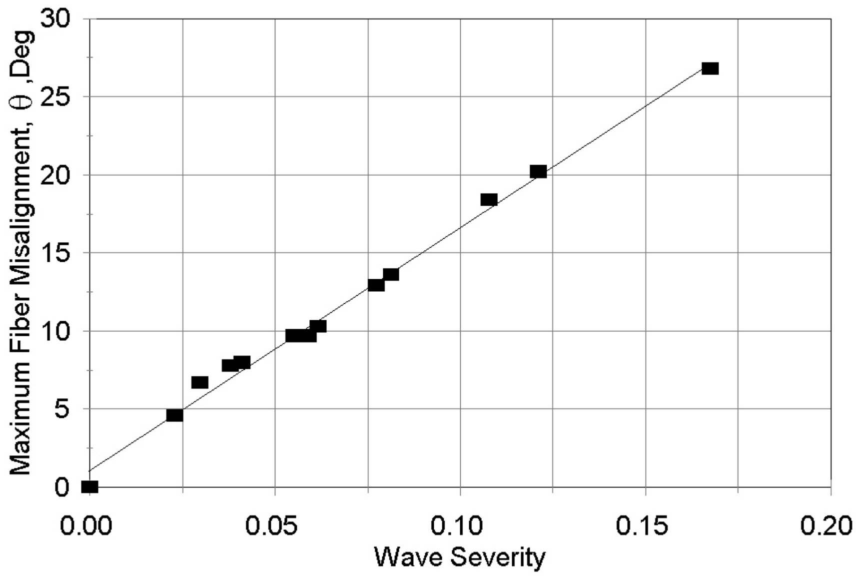


Figure 8. Correlation between Wave Severity and Maximum Angle of Fiber Misalignment, θ.

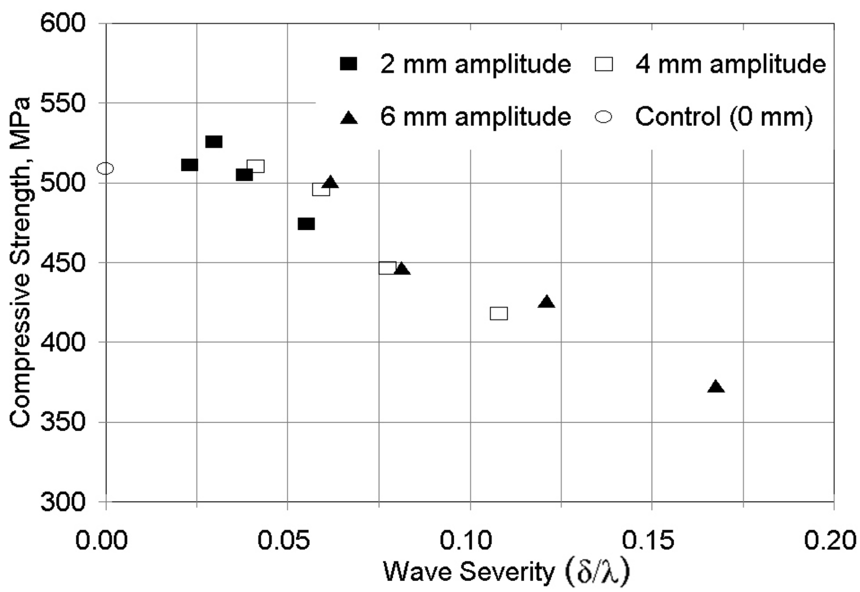


Figure 9. Effects of Wave Severity on Compressive Strength; Waviness in a Single Surface Ply of a $[0/\pm45/0]_S$ Laminate.

The fraction of 0° plies with waviness was also varied. Figure 10 is a schematic of the construction of a laminate where three of the four 0° plies contain waviness. The compressive strength as a function of the fraction of 0° plies with waviness is given in Figure 11, for three wave severities in each case. The single layer (25%) case is for a surface 0° layer; the two-layer case (50%) is for the two internal 0° layers; the three layer case (75%) is illustrated in Figure 10. The compressive strength steadily decreases as the wave severity and percent of 0° plies with waviness increase. By comparison, the through-thickness case reported in Reference 7 showed a leveling-off of the strength decrease when more than 33% of the 0° plies contained waviness. The lowest compressive strength in Figure 11 is 179 MPa, which is similar to the 174 MPa compressive strength for an all ±45° specimen at a similar fiber content [1]. By way of comparison, the tensile strength was not significantly reduced by in-plane waviness of severity 0.014, but was reduced by about 40% for a severity of 0.107 (waviness in all 0° plies) [10].

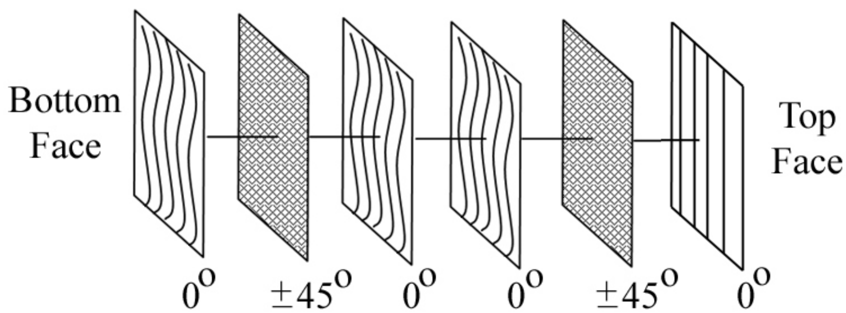


Figure 10. Laminate Configuration with Three Layers of In-Plane Waviness.

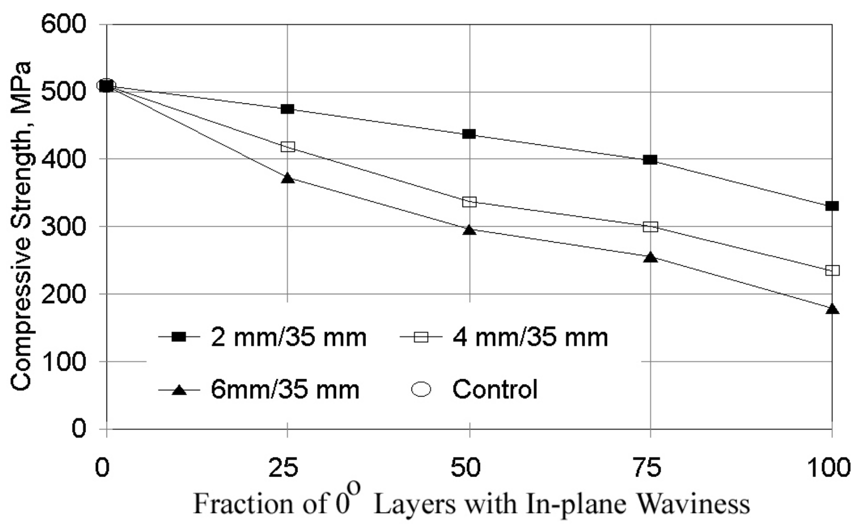


Figure 11. Effects of Multi-layer In-plane Waviness on Compressive Strength for various wave parameters δ/λ.

The effects of resin toughness on waviness were investigated by comparing a toughened vinyl ester resin, Derakane 8084, with the baseline orthopolyester, CoRezyn 63-AX-051. The toughened vinyl ester produces about two to three times higher interlaminar fracture toughness [1, 2]. Figure 12 indicates only a slight improvement in compressive strength retention for laminates with the tougher resin.

Figure 9 indicates a good correlation of compressive strength with wave severity, as expected from Reference 5; Figure 8 indicates that this correlation would also hold for the maximum misorientation angle, θ. The origin of the strength loss appears to be the misorientation of the fibers. A comparison of the compressive strength for laminates with introduced waviness (all four 0° plies) and off-axis ±θ laminates, for the same material system and approximately the same fiber content, is presented in Figure 13. The data are very similar, supporting the view that the in-plane waviness effects are simply a manifestation of the misorientation of the fibers. The failure modes (Figure 14) show matrix dominated cracking with in-plane waviness compared with the control case in Figure 5, which shows strand buckling.

The effect of in-plane and through-thickness on fatigue strength is illustrated in Figure 15. The baseline laminate with D155 fabric 0° plies is much stronger under both static and fatigue loading as compared with either the laminate containing waviness in all four 0° (D155) plies or the laminate based upon woven A130 fabric (Figure 1, Table 1), which contains no introduced waviness. The laminates with both in-plane introduced waviness and severe through-thickness waviness due to the A130 weave, behave similarly under both static and fatigue loading. This again illustrates that strong effects of even slight through-thickness waviness associated with woven fabrics.

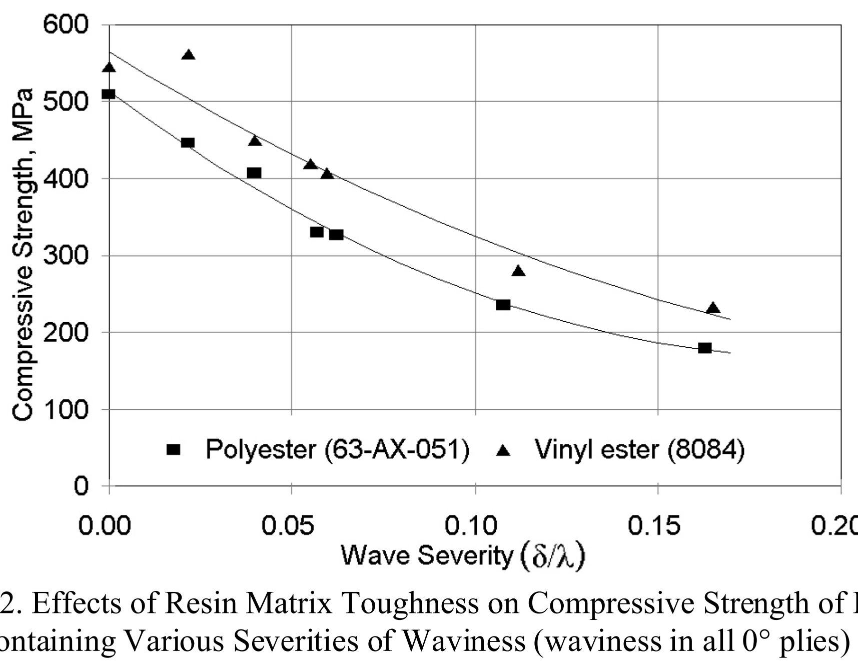


Figure 12. Effects of Resin Matrix Toughness on Compressive Strength of Laminates Containing Various Severities of Waviness (waviness in all 0° plies) [4].

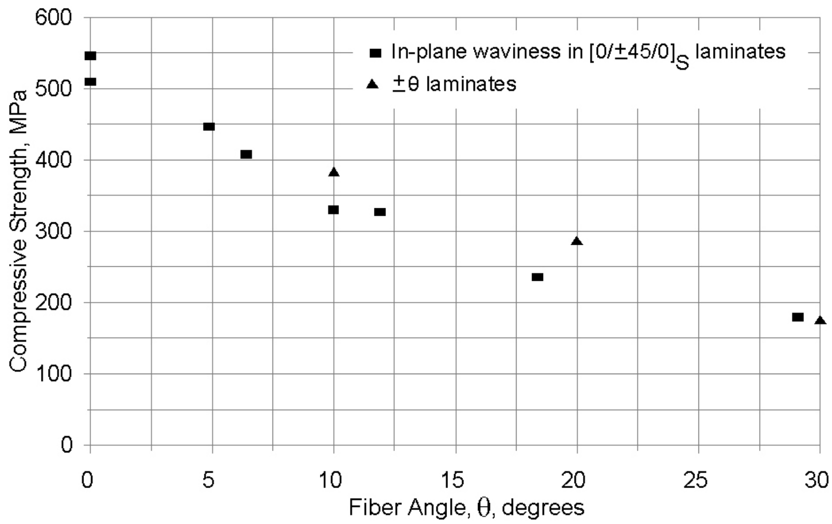


Figure 13. Compressive Strength With Waviness in all 0° Plies versus Maximum Misalignment Angle (θ), Compared with Data from ±θ Off-Axis Laminates [4].

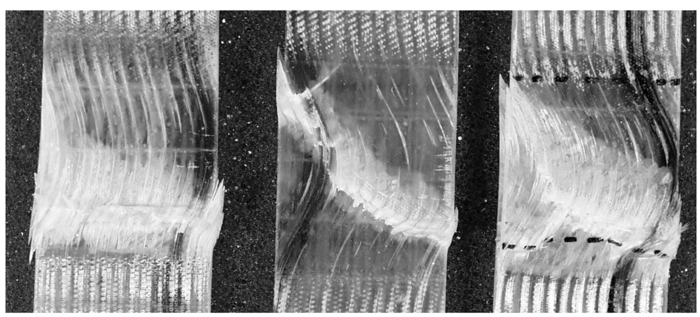


Figure 14. Static Compression Failures and Fatigue Compression Failures (left: static/ vinyl ester resin; center: static/ polyester resin; right: fatigue/ polyester resin) [4].

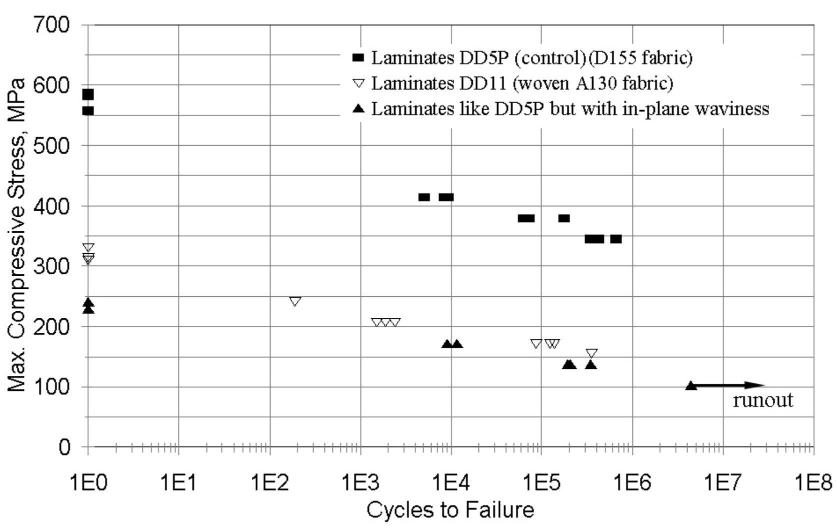


Figure 15. Compressive Fatigue Properties for Laminates with Four Layer In-Plane (4 mm/35mm) Waviness and Through-Thickness (DD11) Waviness Compared With Control Laminate DD5P, R = 10 [4].

CONCLUSIONS

Fiber waviness is inherent in many reinforcing fabrics used in low-cost composites typical of the wind turbine blade industry, and may also be introduced during processing. Through-thickness waviness in typical woven fabrics and waviness occurring near ply-drops and flaws tends to exacerbate the usual strand buckling mode of compressive failure. Relative to straight fiber laminates, laminates with moderate through-thickness waviness show a loss in compressive strength up to the order of 50%, which persists under fatigue loading. However, laminates with reduced compressive strength due to fabric weave are less affected by additional waviness introduced near flaws.

Prepreg laminates contain the least waviness in control cases. However, details like ply drops and ply joints can produce significant misorientation and compression strength loss. Geometrical and processing parameters can be chosen to reduce this effect.

In-plane waviness tends to change the failure mode in compression to a matrix dominated mode. Reductions in compressive strength correlate with the effects of fiber misorientation produced by typical off-axis composites. The reduction in strength was found to increase steadily with the degree of misorientation (or wave severity) and the fraction of 0° plies containing waviness. Tensile strength was also affected for severe waviness.

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