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Adaptive Blade Concept Assessment:

Curved Planform Induced Twist Investigation

Mike Zuteck
MDZ Consulting
601 Clear Lake Road
Clear Lake Shores, TX

Abstract

Improving wind turbine blades via bend-twist coupling confronts two difficult challenges. The first is that off-axis fiber for the major structure is difficult to fabricate. Suitable fabrics with the primary fiber ~20 degrees off-axis are not commonplace and may present dimensional stability problems when handled, due to a tendency to shear when tensioned along their long dimension. These are ultimately cost issues. The second category of challenges is in the area of possible fatigue limits due to ending or curving angled fibers. Spar caps with angled fibers must either end those fibers at the edge or have them carry around a web type structure. Either approach implies additional stresses in the resin system binding the fibers and may lead to lowered fatigue allowables for design.

The vision driving this work was to look at the possibility of using novel planform and structural combinations to provide response similar to classical bend twist coupling, but without the use of off-axis lay-up in the structure. Sweep distributed along the span is used to create a moment that induces twist, and airfoil thickness reduction via carbon fiber spar caps is used to increase twist response to the induced moment. If a suitable magnitude of twist response can be shown using this approach, then the blade structure might be fabricated much as it is now, without off-axis spar cap fiber, and the benefits of bend twist coupling could still be obtained.

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Background

Considerable work has been done by Sandia National Laboratories and others (Ref. 1,2,3) on the possible use of twist-coupled blades to enhance wind turbine cost efficiency and performance. This work has shown considerable promise and led to the desire to consider in more depth how such blades might be built and what their properties might be.

Motivation

Improving wind turbine blades via bend-twist coupling confronts two difficult challenges. The first is that off-axis fiber for the major structure is difficult to fabricate. Suitable fabrics with the primary fiber ~20 degrees off axis are not commonplace and may present dimensional stability problems when handled, due to a tendency to shear when tensioned along their long dimension. These are ultimately cost issues. The second category of challenges is in the area of possible fatigue limits due to ending or curving angled fibers. Spar caps with angled fibers must either end those fibers at the edge or have them carry around a web type structure. Either approach implies additional stresses in the resin system binding the fibers and may lead to lowered fatigue allowables for design.

The vision driving the work reported herein was to investigate a way to move beyond both of those challenges. The major thrust is to look at the possibility of using novel planform and structural combinations to provide response similar to classical bend twist coupling, but without the use of off-axis layup in the structure. Sweep distributed along the span is used to create a moment that induces twist, and airfoil thickness reduction via carbon fiber spar caps is used to increase twist response to the induced moment. If a suitable magnitude of twist response can be shown using this approach, then the blade structure might be fabricated much as it is now, without off-axis spar cap fiber, and the benefits of bend-twist coupling could still be obtained.

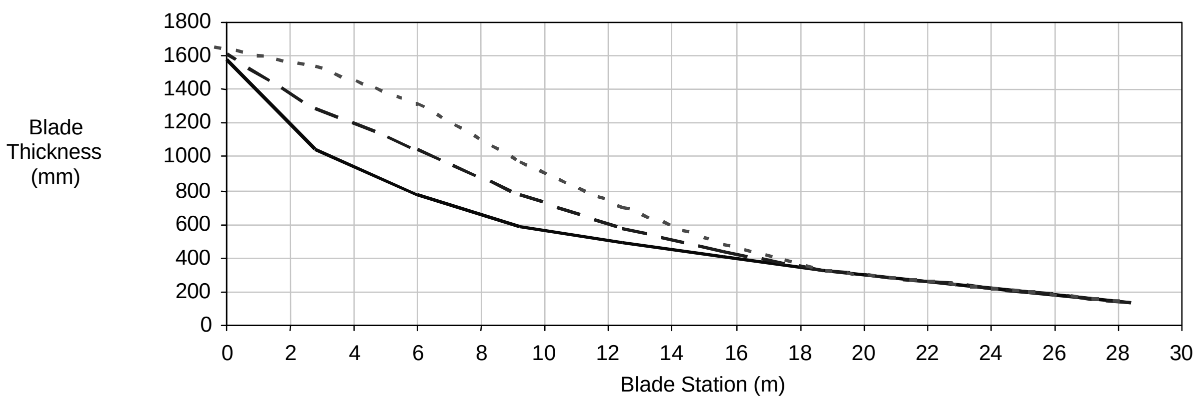
Baseline Blade

To provide results linked to other research work and current commercial turbine sizes, a 30m (98.4 ft) blade derived from a separate Sandia blade-scaling study (Ref. 4) was chosen as the baseline. This is a single shear web generic interior blade with fiberglass spar caps and skins, and balsa core for the aft panels and shear web. The basic parameters for this blade are summarized in the following table. The baseline for this work is the thinnest of the three blade variations shown.

Eolidyn Rotor Systems
Planform A / 30 meter blade

Blade Length (m) (ft)	30.0	98.4	Rotor Speed (rpm)	12.2
Hub Radius (m) (ft)	2.0	6.6	Wind Speed (m/s)	10.0
Rotor Radius (m) (ft)	32.0	105.0		

							T/C Distribution #1		T/C Distribution #2		T/C Distribution #3		Reynolds
Station Number	Radius Ratio	Radius (m)	Station (m)	Chord Ratio	Twist (deg)	Chord (m)	Thickness Ratio	Thickness (mm)	Thickness Ratio	Thickness (mm)	Thickness Ratio	Thickness (mm)	Number (Re)
1	5%	1.600	-0.400	0.0517	29.5	1.655	100.00%	1655	100.00%	1655	100.00%	1655	1.16E+06
2	15%	4.800	2.800	0.0775	19.5	2.480	42.00%	1042	52.00%	1290	62.00%	1538	1.99E+06
3	25%	8.000	6.000	0.0860	13.0	2.752	28.00%	771	38.00%	1046	48.00%	1321	2.69E+06
4	35%	11.200	9.200	0.0758	8.8	2.424	24.00%	582	32.00%	776	40.00%	970	2.90E+06
5	45%	14.400	12.400	0.0664	6.2	2.124	23.00%	489	27.00%	574	33.00%	701	3.04E+06
6	55%	17.600	15.600	0.0574	4.4	1.837	22.00%	404	24.00%	441	26.00%	478	3.10E+06
7	65%	20.800	18.800	0.0487	3.1	1.559	21.00%	327	21.00%	327	21.00%	327	3.03E+06
8	75%	24.000	22.000	0.0402	1.9	1.288	20.00%	258	20.00%	258	20.00%	258	2.84E+06
9	85%	27.200	25.200	0.0319	0.8	1.021	19.00%	194	19.00%	194	19.00%	194	2.53E+06
10	95%	30.400	28.400	0.0237	0.0	0.759	18.00%	137	18.00%	137	18.00%	137	2.08E+06



The baseline blade shown above was only the starting point for the present work. In order to enhance twist response, the outboard blade thickness was reduced, as will be discussed in the following. The length, planform, and airfoil selections remained unchanged, except that the airfoil t/c was reduced as required.

Study Approach

This study initially assumed a circular arc sweep curve whose center depth could be specified. An inverse triangle thrust distribution with zero thrust at the blade root and maximum thrust at the tip was assumed as representative of a typical operating thrust distribution near rated power. A single blade thrust of 5670 kg (12,500 lbs) was used to represent the condition of about 1MW steady power production of a three bladed turbine. For a straight blade, these loads would lie near the blade axis at all spanwise stations, but for a blade with edgewise curve, the outer blade thrust will be offset from the axis of the inner blade segments. Based on the chosen depth of the bend curve and the assumed spanwise loading distribution, it is possible to calculate the torsional moment distribution along the blade from the offset distances implied by the bend curve.

In order to compute the twist response of the baseline blade, section analysis calculations were performed at 15%, 25%, 45%, 65%, and 85% r/R. Interpolation or extrapolation as appropriate was used to give GJ values at the center of each 10% of span blade segment, based on these five evaluation stations. From this, an initial computation of blade twist was made, which indicated about 0.8° of tip twist for 0.305 m (12 in) of bend depth. This result made it clear that steps to increase the twist response of the blade were appropriate, if the amount of twist indicated in the Sandia studies was to be achieved.

Increasing the depth of the sweep curve can increase the amount of twist. However, it was a goal of this study to investigate practical ways to enhance twist response. One way to do this is by reducing the thickness of the airfoils, but that will also decrease the strength and bending stiffness, unless the amount of material in the spar caps is increased to compensate. The first step to increase the twist response of the fiberglass baseline blade was to reduce its thickness at the 45%, 65%, and 85% stations. This was done by scaling the airfoil thickness, subject to the constraints that the flatwise-bending stiffness must be held constant and that maximum spar cap thickness could not exceed 10% of airfoil thickness. An iterative process was required to find the minimum thickness that would satisfy these constraints. The 15% and 25% stations were not altered because it was judged that this would have too much impact on blade weight, which is a cost issue, and because this part of the blade is designed to match a root pitch bearing of given size. As it turned out, the spar caps at 45% and 65% were already rather near the 10% spar cap limit, so only a modest increase in tip twist to about 0.9° was possible for the thinned variant of the all fiberglass baseline blade, with 0.305 m (12 in) bend depth.

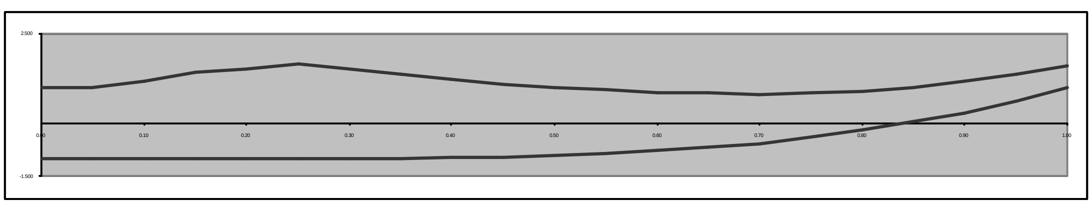
After examining the distribution of induced twist along the blade and the estimates of the resulting blade shell shear stresses, it was clear that the circular arc bend curve was producing a lot of twisting moment on the inboard part of the blade (that was too stiff torsionally to respond very much), while the torsionally softer outer part of the blade was not experiencing enough moment to twist as much as it might. This suggested that a different bend curve might produce substantially better results. While a rigorous optimization was judged to be outside the scope of this study, implementing a power law bend curve was chosen as a way to give an initial feel for what might be possible. This meant leaving behind the mathematical simplification a constant arc provided, but tip twist increased substantially to about 1.2° for 0.305 m (12 in) of bend, with a bend curve exponent of 4. This is nearly 4° tip twist for a 1 m (39.4 in) bend depth on a 30 m (98.4 ft) blade, enough to be useful.

Carbon Fiber Spar Cap Investigation

Substituting carbon fiber for the spar cap material in the outer blade was another strong candidate to increase twist response. Because this material is much stiffer than the fiberglass baseline material, it would retain bending stiffness with much thinner airfoil sections. For this study, a longitudinal modulus of 110.0E+3 MPa (16.0E+6 psi) was chosen for the carbon spar cap material, in contrast to the 37.0E+3 MPa (5.4E+6 psi) assumed for the fiberglass. This is not the most aggressive value one might assume and leaves room for some DB (double bias) material within the laminate to add toughness. Even so, it provides nearly a factor of 3 increase in the spar cap modulus, along with a small decrease in density.

It is worth noting that thinner airfoils in the outer blade are desirable for aerodynamic efficiency as well as twist enhancement, so there would be a dual motive to pursue a carbon hybrid blade with thinner outboard airfoils. But since carbon currently costs significantly more than fiberglass, there is a substantial question how much of the blade would justify using carbon spar caps. Since the relative costs may change substantially over time, it was decided to calculate three different spanwise extents of carbon spar caps. In the first case only the outer 85% station was converted to carbon, in the next the 65% station was converted as well, and in the last 45% was also converted to carbon. Because the intermediate stations are interpolated, the net effect is the same as using carbon from 75%, 55%, and 35% r/R out to the blade tip. This is how the results are designated herein. The 35%-> carbon blade shows an increase from about 4° tip twist for a 1 m (39.4 in) bend depth (with a bend curve exponent of 4), to over 7° with the same bend depth and exponent. The plot below shows the planform shape that results for a 1 m (39.4 in) bend depth with a sweep exponent of 4. The data blocks summarize the key results for the all-fiberglass blade and the three different lengths of carbon spar cap hybrid.

Maximum Edgewise Bend Depth (m) =	1.00	(1 or less)		Sweep Curve Exponent =	4	(2 or greater)
(ins) =	39.4			Unit Curve Depth =	0.47	(2 is circular arc)
				Deepest At =	63%	



	Weighted Twist* (deg)	Tip Twist (deg)	Max Shear (psi)
AllGlass	2.28	3.95	1974
Carbon75%->	2.48	4.70	1974
Carbon55%->	3.20	6.15	2364
Carbon35%->	4.03	7.30	2842

Notes: X axis is approximate blade pitch axis

Bend depth is the maximum offset of the leading edge relative to a straight line from the leading edge at the root to the leading edge at the tip

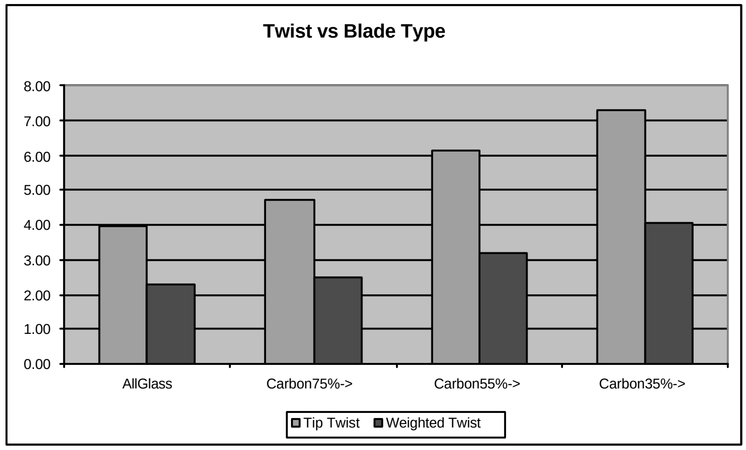
The tip is shown aft of the pitch axis by this same amount

* Segment twists weighted by fraction of disk area affected

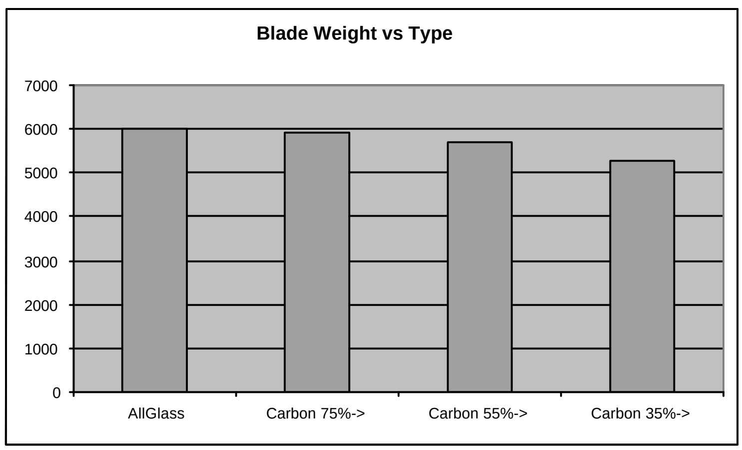
Additional Blade Property Comparisons

The tables and graphs below show the twist data, the blade shell weight (no root fitting weight was added), and carbon spar cap weights implied by the underlying blade section analysis. The figure below shows the airfoil structure (for both glass and carbon spar caps) at station 65% r/R.

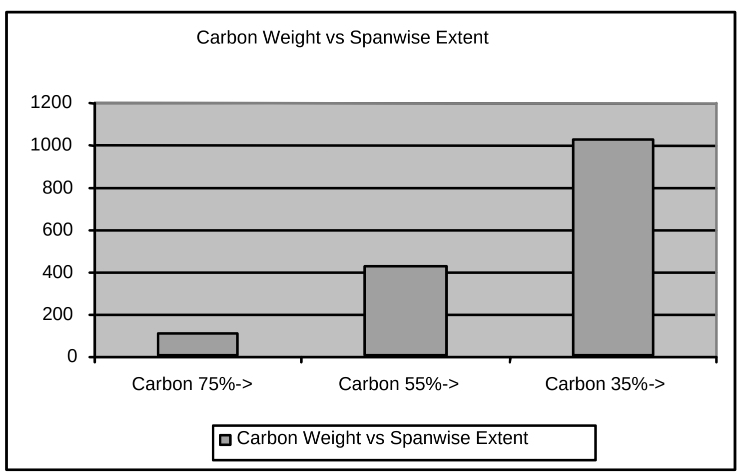
Blade Type	Tip Twist (deg.)	Weighted Twist (deg.)
AllGlass	3.95	2.28
Carbon75%->	4.70	2.48
Carbon55%->	6.15	3.20
Carbon35%->	7.30	4.03



Blade Type	Blade Weight (lbs)
AllGlass	6020
Carbon 75%->	5906
Carbon 55%->	5715
Carbon 35%->	5279

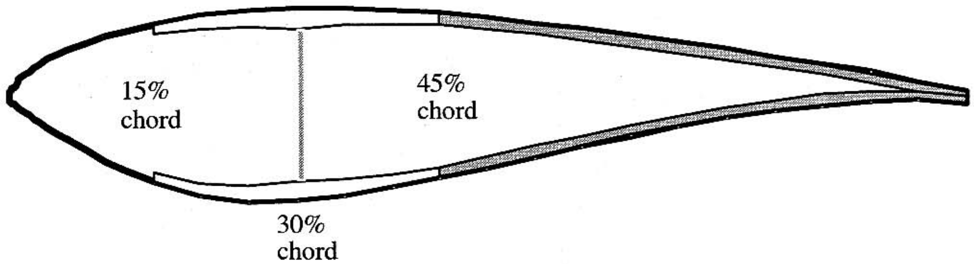


	Carbon to Tip (lbs)
Carbon 75%->	122
Carbon 55%->	432
Carbon 35%->	1035



Glass vs Carbon Spar Cap
Construction Comparison
at Station 65% r/R

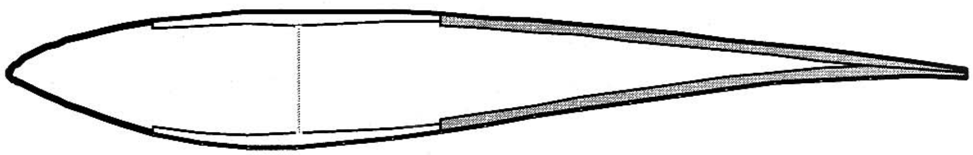
19.9% t/c with Glass Spar Caps



Nose Panels:
DB Glass Skins .036" Thick
Spar Cap Skins .022" Thick

Tail Panels:
Balsa Core 1% of Chord Thick
DB Glass Skins .036" Thick

14.1% t/c with Carbon Spar Caps



Spar Caps:
Center is 10% of Foil Thickness
Tapers to 1/2 Thickness at Edges
Extend from 15% to 45% Chord

Shear Webs:
Balsa Core 3% of Foil Thickness
DB Glass Skins .060" Thick
Centered at 30% of Chord

Further Discussion

Blade Structural Detailing

In order to enhance the twist response from a given level of sweep-induced, torsional moments, it is desirable that the sectional GJ product be no larger than necessary. Carbon fiber spar caps increased the twist response precisely because they made the torque tube smaller and less stiff. What may be less obvious are the other measures that were included in the design for the same purpose.

The tail panel construction is near the minimum considered reasonable for a 1MW blade; the DB glass skins are only 0.914 mm (0.036 in.) thick on either side of a balsa core. While a 0/90 fabric would be more flexible than a DB, it is not as suited to carrying the long-term torsional fatigue as DB, and also suffers crack initiation due to flatwise bending at much lower strains. However, it is possible that somewhat thinner skins, particularly on the inside of the panel, could be acceptable, if more twist response was needed. The twist-induced shear stresses are not a limitation; it is strictly the panel strength for handling and enduring maximum winds that is an issue. Note that thicker core could be used to compensate for thinner skins as long as they remain acceptable for handling. The balsa core has very low (rolling) shear stiffness in the direction that resists twist, so this is a promising path that could be further explored. The gains from fine-tuning this aspect of the design might be 10% or greater, significant though not dramatic.

An aspect of the design that is quite important and might be easily overlooked is that it has only a single shear web. This makes the structural spar composed of spar caps and shear web an “I” beam, with low resistance to torsion. As long as the tail panels are compliant, the overall torque tube will be relatively soft, in spite of the fact that the spar caps are quite stiff in shear. If double shear webs at the forward and aft edges of the spar caps had been used instead, they would cause the spar caps to become part of a tube whose torsional stiffness could be quite high if the shear webs were of robust construction. Double shear webs are quite common in large wind turbine blades, because they reduce panel free span and the tendency for panel buckling and create good resistance to torsional instability. However, if blade twist response is to be enhanced, then the single shear web concept, which has been quite successful in smaller blades, may need to be carried to much larger sizes due to its lower resulting torsional stiffness.

The purpose of these comments is to record the impact of these aspects of the design. Optimization must await further work that can consider these and other ways of obtaining necessary strength, while eliminating undesirable torsional stiffness.

Weighted Twist and Optimum Sweep Exponent

The first look at twist coupling considered tip twist as a comparative measure of design variations. However, it quickly became apparent that one might induce a lot of twist in the torsionally soft outer extremity of the blade and have rather limited effect overall. Certainly a degree of twist in the innermost 10% of the blade will have a lot more effect than a degree of twist in the outermost 10%, because the former case affects essentially the whole span of the blade. This leads to the concept of weighted twist, wherein the twist in a blade segment is weighted by the fraction of the total disk area it affects, in creating a net summation for assessment of induced twist effect.

Using weighted twist as the measure of twist effect, it was found that the glass spar cap blade had its optimum response with a sweep exponent near 4, whereas on the basis of tip twist, the maximum occurred near 7. A similar result was found for the carbon spar cap blade designs, although in that case the optimum exponent was higher, near 4.8 for the design using carbon from 35% outboard. To unify the results for presentation, a sweep exponent of 4 was chosen as a round number value that gave near optimal weighted twist for all the design variants.

Inverse Triangle Loading Assumption Limitations

To create a torque distribution along the blade due to the specified sweep profile, an inverse triangular loading distribution with zero loading at the blade root and maximum loading at the tip was used. This is a usual approximation to the loading near rated power, which is what the twist calculations are meant to represent. For modest amounts of induced twist, this remains a reasonable approximation. However, for a tip twist of 7°, about 2/3 of the section lift would be gone, and this approximation is clearly no longer accurate. It would not be unduly difficult to iterate the loading to reflect the induced twist, but that destroys the easily understood load distribution and replaces it with one that is different for each set of blade properties. To keep the results of this study on a basis where comparisons could be easily made and understood, it was decided to retain the same loading distribution for all twist calculations. Follow on work can investigate the effect of altered angles of attack on steady state twist, or likely of more value, the blade torsional properties presented herein could be incorporated into a more comprehensive evaluation of load and power response. For the present, the reader should be aware that the loading assumption does not reflect the effects of induced twist, primarily so that case-to-case comparisons can be made easily without correcting for different implied loading conditions.

Trailing Edge Centrifugal Tension

The aft sweep of the blade will clearly create added tension in the trailing edge of the blade due to centrifugal forces. This will be at its worst in the outer part of the blade where sweep angles are largest, centifugal acceleration is highest, and blade chord is shortest. At an assumed 20 rpm, the tip region of the blade will see about 14 gs of acceleration. The outer 10% of the fiberglass blade (which is heaviest) will weigh about 44 kg (97 lb) based on the blade section analysis. This gives a centrifugal force of 620 kg (1360 lb). If this force is assumed to act at 95% radius, its offset to the next blade segment centered at 85% is about 0.6 m (24 in) for a 1 m (39.4 in) bend depth, resulting in an edgewise moment of 3700 N-m (32,600 in-lb). From the 85% section analysis results, we find the edgewise moment capability at 3,750 μs is 4.1E+4 N-m (3.675E+5 in-lb). So the implied trailing edge strain from centrifugal force acting on the sweep is 3,750 * (3.26E4/3.675E5) = 330 μs. This calculation is a bit conservative, because the center of mass of the outermost blade segment will be inboard of 95% radius. Even so, the computed trailing edge strain is small. It is concluded that trailing edge stress is not a design limit for any reasonable degree of blade sweep, even with the lightly built tail panels assumed in the present work.

Curved Spar Cap Manufacturing Implications

A fundamental driver in investigating a sweep-twist blade option is to remove the need for off-axis carbon fiber in the spar caps, but this advantage does not come completely free of tradeoffs. Wide layers of fabric, while easily bent out of their plane, will resist the sort of in-plane bending that a swept spar cap implies. If some special provision to account for this is not made, the fiber on the inside of the curve will become wavy or kinked due to its excess length compared to the fiber on the outside of the curve. One solution would be to use a type of fabric with minimal in-plane shear resistance, so that the fibers could shear rather than wrinkle. Another approach is to compose the spar caps of narrow tapes or fiber bundles, which accomplish much the same thing. In large volume, one could imagine fabric or 3D weave custom formed with the required curve. This manufacturing implication does not appear to constitute a fundamental barrier to this kind of blade design, but the economics of this unconventional feature must be demonstrated.

Low Cost Bend-Twist Hybridization

In principle, there is nothing to stop structural bend-twist coupling from being used with sweep-twist coupling as described herein, except cost. Both methods have additional manufacturing costs associated with them, so the cost penalty of combining them would appear prohibitive, if either alone can do the job. However, there is one way a modest degree of bend-twist coupling could be combined with sweep-twist at modest added cost. This is via the use of a hybrid glass-carbon DB cloth for the blade shell skins. The aft panels are lightly built and quite compliant, and the single web "I" beam spar has low torsional resistance, so having one of the two 45° plies made of carbon would have highly leveraged effect in producing classic bend-twist response. It is beyond the scope of this work to do more than simply note that this possibility exists and may be worthy of follow-up, if dynamic analysis leads to the conclusion that combined sweep and bend twist coupling may have special benefits that warrant the additional complexities.

Conclusions

This initial study of blade planform curvature as a method to induce twist response indicates that a 1 m (39.4 in) bend depth on a 30m (98.4 ft) blade can produce substantial twist. With a bend exponent of 4, which produces more rapid edgewise bend in the outer blade, the all-fiberglass blade provided about 4 degrees of tip twist, whereas the same planform with carbon spar caps to reduce torsional stiffness (via lessened airfoil thickness) produced more than 7 degrees of tip twist. This assumes that blade thrust has an inverse triangle load distribution with zero thrust at the root and maximum thrust at the tip, with the total thrust being approximately that for 1MW steady state power production on a three-bladed wind turbine. Since a 10-degree angle of attack reduction would bring a typical wind turbine blade design to near zero lift, the potential to shed a large load from the outer rotor exists. This can reduce bending moments and power peaks, and thereby reduce fatigue. Alternatively, a larger and more energy productive rotor may be possible, which is a powerful path to lowered cost of energy. This is the lure of adaptive twist blades, and the magnitude of the twist response appears to make curved planform blades solid contenders in this category.

To maximize twist response, the blades must be built with relatively lower torsional stiffness. This favors a single shear web design, with tail panels that avoid excess structure to encourage enhanced twist response. The dynamic stability boundaries need further study to assure that significant operational limitations do not accrue to this reduced torsional stiffness. This must account for the phasing of the twist response, which appears to occur sooner than with classic bend-twist coupling, and may thereby stabilize certain dynamic motions. Further evaluation of the potential of this class of blades must also address the manufacturing implications of making spar caps that curve substantially in their own plane.

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Appendix A – Key Section Analysis Results

The purpose of the 10 following pages is simply to document the section analysis results for the both the fiberglass and carbon spar cap constructions. These are the values that resulted once the airfoil t/c was converged to the value that equaled the baseline flatwise stiffness, with spar caps whose center thickness was 10% of the overall airfoil thickness. The units are pounds and inches, and the limiting strengths shown are those for a critical fiber strain of 3,750 μs. Note that the procedure of thinning the airfoils at equal flatwise stiffness results in flatwise strength that exceeds the baseline values. Stations 15% and 25% were not modified from the baseline; thickness convergence was performed only at stations 45%, 65%, and 85%.

85% Station – Fiberglass Spar Caps @ 15.95% t/c

****
REPORT FOR STATION 85% 15.95%max WITH FOIL Sta85% 15.95%
****
Accuracy factor:0.20 Cut plane angle: 5.16 Me Axis Rotation Ang: 0.00

WEIGHT PER FOOT	FLATWISE EI	EDGEWISE EI	UPPER SURF FLATWISE MOMENT	FWD EDGE EDGEWISE MOMENT
18.941	4.639e+8	2.565e+9	5.530e+5	7.531e+5
CHORDWISE CG	**FLATWISE SHEAR CENTER**	**EDGEWISE SHEAR CENTER**	**UPPER SURF CRITICAL DISTANCE**	**FWD EDGE CRITICAL DISTANCE**
15.16	12.49	0.436	3.146	12.77
FLATWISE CG	**FLATWISE NEUTRAL AXIS**	**EDGEWISE NEUTRAL AXIS**	**LOWER SURF FLATWISE MOMENT**	**AFT EDGE EDGEWISE MOMENT**
0.499	0.491	12.77	5.674e+5	3.675e+5
ROTATIONAL MOMENT OF INERTIA	**AE PRODUCT**		**LOWER SURF CRITICAL DISTANCE**	**AFT EDGE CRITICAL DISTANCE**
1.551e+3	7.312e+7		3.066	26.17

LAYER SUMMARY DATA
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X LEFT	X RIGHT	LEFT THICKNESS	RIGHT THICKNESS	WEIGHT	EDGEWISE FORCE	FLATWISE FORCE
0.00	38.94	0.005	0.005	0.107	92	239
0.00	38.94	0.005	0.005	0.106	93	-237
0.00	38.94	0.015	0.015	0.437	605	1568
0.00	38.94	0.015	0.015	0.430	613	-1556
0.00	38.94	0.036	0.036	1.133	1840	4694
0.00	38.94	0.036	0.036	1.115	1862	-4659
0.00	19.47	0.024	0.024	0.382	-323	1865
0.00	19.47	0.024	0.024	0.373	-296	-1900
5.84	11.68	0.311	0.621	2.214	-7730	42478
5.84	11.68	0.311	0.621	2.207	-7722	-43698
11.68	17.52	0.621	0.311	2.202	3193	48664
11.68	17.52	0.621	0.311	2.200	3171	-47528
0.00	19.47	0.024	0.024	0.379	-318	1621
0.00	19.47	0.024	0.024	0.370	-292	-1653
17.52	35.05	0.389	0.389	0.506	228	257
17.52	35.05	0.389	0.389	0.504	226	-225
0.00	38.94	0.036	0.036	1.124	1844	3799
0.00	38.94	0.036	0.036	1.110	1872	-3763
0.00	38.94	0.035	0.035	0.694	452	909
0.00	38.94	0.035	0.035	0.686	459	-901
12.08	15.18	0.186	0.186	0.042	1	27
12.08	15.18	0.186	0.186	0.042	1	-26
12.08	15.18	0.120	0.120	0.289	65	1318
12.08	15.18	0.120	0.120	0.289	63	-1291
35.83	38.16	0.000	0.000	0.000	0	0
35.83	38.16	0.000	0.000	0.000	0	0

TORSIONAL CELL DATA
****

X LEFT	X RIGHT	DS OVER T	AREA
0.00	13.63	0.000061	32.997
13.63	36.99	0.000224	55.715
0.00	13.63	0.000058	21.350
13.63	36.99	0.000223	29.077

GJ PRODUCT IS 1.542e+8

****

85% Station – Carbon Spar Caps @ 11.49% t/c

****
REPORT FOR STATION 85% 11.49%carb WITH FOIL Sta85% 11.49%
****
Accuracy factor:0.20 Cut plane angle: 4.43 Me Axis Rotation Ang: 0.00

WEIGHT PER FOOT	FLATWISE EI	EDGEWISE EI	UPPER SURF FLATWISE MOMENT	FWD EDGE EDGEWISE MOMENT
15.086	4.635e+8	3.211e+9	7.668e+5	9.826e+5
CHORDWISE CG	**FLATWISE SHEAR CENTER**	**EDGEWISE SHEAR CENTER**	**UPPER SURF CRITICAL DISTANCE**	**FWD EDGE CRITICAL DISTANCE**
16.02	12.29	0.323	2.267	12.25
FLATWISE CG	**FLATWISE NEUTRAL AXIS**	**EDGEWISE NEUTRAL AXIS**	**LOWER SURF FLATWISE MOMENT**	**AFT EDGE EDGEWISE MOMENT**
0.360	0.353	12.25	7.876e+5	4.512e+5
ROTATIONAL MOMENT OF INERTIA	**AE PRODUCT**		**LOWER SURF CRITICAL DISTANCE**	**AFT EDGE CRITICAL DISTANCE**
1.380e+3	1.392e+8		2.207	26.69

LAYER SUMMARY DATA
****

X LEFT	X RIGHT	LEFT THICKNESS	RIGHT THICKNESS	WEIGHT	EDGEWISE FORCE	FLATWISE FORCE
0.00	38.94	0.005	0.005	0.106	98	237
0.00	38.94	0.005	0.005	0.105	98	-235
0.00	38.94	0.015	0.015	0.431	645	1556
0.00	38.94	0.015	0.015	0.428	650	-1543
0.00	38.94	0.036	0.036	1.118	1961	4637
0.00	38.94	0.036	0.036	1.109	1973	-4596
0.00	19.47	0.024	0.024	0.375	-249	1836
0.00	19.47	0.024	0.024	0.370	-235	-1868
5.84	11.68	0.224	0.447	1.317	-13899	89171
5.84	11.68	0.224	0.447	1.315	-13894	-91784
11.68	17.52	0.447	0.224	1.314	8931	102632
11.68	17.52	0.447	0.224	1.314	8904	-100117
0.00	19.47	0.024	0.024	0.373	-246	1589
0.00	19.47	0.024	0.024	0.368	-233	-1619
17.52	35.05	0.389	0.389	0.503	230	242
17.52	35.05	0.389	0.389	0.502	230	-210
0.00	38.94	0.036	0.036	1.111	1965	3541
0.00	38.94	0.036	0.036	1.105	1979	-3500
0.00	38.94	0.035	0.035	0.676	460	839
0.00	38.94	0.035	0.035	0.683	485	-829
12.51	14.75	0.134	0.134	0.022	1	14
12.51	14.75	0.134	0.134	0.022	1	-13
12.51	14.75	0.120	0.120	0.209	73	915
12.51	14.75	0.120	0.120	0.209	72	-895
35.83	38.16	0.000	0.000	0.000	0	0
35.83	38.16	0.000	0.000	0.000	0	0

TORSIONAL CELL DATA
****

X LEFT	X RIGHT	DS OVER T	AREA
0.00	13.63	0.000062	23.501
13.63	36.99	0.000225	38.912
0.00	13.63	0.000060	15.111
13.63	36.99	0.000224	19.698

GJ PRODUCT IS 7.527e+7

****

65% Station – Fiberglass Spar Caps @ 19.90% t/c

****
REPORT FOR STATION 65% 19.90%max WITH FOIL Sta65% 19.90%
****

Accuracy factor:0.20 Cut plane angle: 4.57 Me Axis Rotation Ang: 0.00

WEIGHT PER FOOT	FLATWISE EI	EDGEWISE EI	UPPER SURF FLATWISE MOMENT	FWD EDGE EDGEWISE MOMENT
42.445	4.741e+9	1.118e+10	3.105e+6	2.230e+6
CHORDWISE CG	**FLATWISE SHEAR CENTER**	**EDGEWISE SHEAR CENTER**	**UPPER SURF CRITICAL DISTANCE**	**FWD EDGE CRITICAL DISTANCE**
21.85	17.97	0.219	5.726	18.80
FLATWISE CG	**FLATWISE NEUTRAL AXIS**	**EDGEWISE NEUTRAL AXIS**	**LOWER SURF FLATWISE MOMENT**	**AFT EDGE EDGEWISE MOMENT**
-0.145	-0.298	18.80	2.920e+6	1.032e+6
ROTATIONAL MOMENT OF INERTIA	**AE PRODUCT**		**LOWER SURF CRITICAL DISTANCE**	**AFT EDGE CRITICAL DISTANCE**
6.939e+3	1.933e+8		6.089	40.65

LAYER SUMMARY DATA

****

X LEFT	X RIGHT	LEFT THICKNESS	RIGHT THICKNESS	WEIGHT	EDGEWISE FORCE	FLATWISE FORCE
0.00	59.45	0.005	0.005	0.164	146	370
0.00	59.45	0.005	0.005	0.165	146	-276
0.00	59.45	0.015	0.015	0.669	966	2435
0.00	59.45	0.015	0.015	0.672	965	-1814
0.00	59.45	0.036	0.036	1.734	2931	7336
0.00	59.45	0.036	0.036	1.743	2929	-5452
0.00	29.73	0.024	0.024	0.588	-432	2977
0.00	29.73	0.024	0.024	0.594	-427	-2845
8.92	17.83	0.591	1.183	6.394	-19266	129318
8.92	17.83	0.591	1.183	6.356	-19272	-138483
17.83	26.75	1.183	0.591	6.395	11749	134114
17.83	26.75	1.183	0.591	6.450	11669	-130552
0.00	29.73	0.024	0.024	0.583	-426	2616
0.00	29.73	0.024	0.024	0.584	-422	-2459
26.75	53.51	0.595	0.595	1.179	538	573
26.75	53.51	0.595	0.595	1.189	540	-266
0.00	59.45	0.036	0.036	1.722	2931	6204
0.00	59.45	0.036	0.036	1.729	2943	-4288
0.00	59.45	0.035	0.035	1.064	719	1502
0.00	59.45	0.035	0.035	1.069	722	-1033
17.85	23.77	0.355	0.355	0.152	6	95
17.85	23.77	0.355	0.355	0.152	6	-94
17.85	23.77	0.120	0.120	0.549	177	2465
17.85	23.77	0.120	0.120	0.550	163	-2441
54.69	58.26	0.000	0.000	0.000	0	0
54.69	58.26	0.000	0.000	0.000	0	0

TORSIONAL CELL DATA

****

X LEFT	X RIGHT	DS OVER T	AREA
0.00	20.81	0.000087	81.094
20.81	56.48	0.000340	116.161
0.00	20.81	0.000088	90.360
20.81	56.48	0.000337	80.582

GJ PRODUCT IS 7.900e+8

****

65% Station – Carbon Spar Caps @ 14.10% t/c

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REPORT FOR STATION 65% 14.10%carb WITH FOIL Sta65% 14.10%
****
Accuracy factor:0.20 Cut plane angle: 3.24 Me Axis Rotation Ang: 0.00

WEIGHT PER FOOT	FLATWISE EI	EDGEWISE EI	UPPER SURF FLATWISE MOMENT	FWD EDGE EDGEWISE MOMENT
31.196	4.737e+9	1.529e+10	4.361e+6	3.128e+6
CHORDWISE CG	**FLATWISE SHEAR CENTER**	**EDGEWISE SHEAR CENTER**	**UPPER SURF CRITICAL DISTANCE**	**FWD EDGE CRITICAL DISTANCE**
23.30	17.86	0.072	4.073	18.33
FLATWISE CG	**FLATWISE NEUTRAL AXIS**	**EDGEWISE NEUTRAL AXIS**	**LOWER SURF FLATWISE MOMENT**	**AFT EDGE EDGEWISE MOMENT**
-0.049	-0.228	18.33	4.134e+6	1.395e+6
ROTATIONAL MOMENT OF INERTIA	**AE PRODUCT**		**LOWER SURF CRITICAL DISTANCE**	**AFT EDGE CRITICAL DISTANCE**
5.798e+3	3.797e+8		4.296	41.12

LAYER SUMMARY DATA
****

X LEFT	X RIGHT	LEFT THICKNESS	RIGHT THICKNESS	WEIGHT	EDGEWISE FORCE	FLATWISE FORCE
0.00	59.45	0.005	0.005	0.162	152	371
0.00	59.45	0.005	0.005	0.162	153	-271
0.00	59.45	0.015	0.015	0.659	1006	2437
0.00	59.45	0.015	0.015	0.661	1007	-1777
0.00	59.45	0.036	0.036	1.710	3055	7321
0.00	59.45	0.036	0.036	1.714	3057	-5321
0.00	29.73	0.024	0.024	0.575	-350	2957
0.00	29.73	0.024	0.024	0.577	-346	-2780
8.92	17.83	0.419	0.838	3.756	-36259	271975
8.92	17.83	0.419	0.838	3.743	-36250	-289387
17.83	26.75	0.838	0.419	3.758	28263	282174
17.83	26.75	0.838	0.419	3.773	28179	-270757
0.00	29.73	0.024	0.024	0.572	-346	2599
0.00	29.73	0.024	0.024	0.572	-343	-2409
26.75	53.51	0.595	0.595	1.173	541	552
26.75	53.51	0.595	0.595	1.179	542	-235
0.00	59.45	0.036	0.036	1.701	3057	5955
0.00	59.45	0.036	0.036	1.706	3068	-3940
0.00	59.45	0.035	0.035	1.051	749	1435
0.00	59.45	0.035	0.035	1.054	752	-941
18.71	22.90	0.251	0.251	0.077	4	47
18.71	22.90	0.251	0.251	0.077	4	-46
18.71	22.90	0.120	0.120	0.392	155	1738
18.71	22.90	0.120	0.120	0.392	150	-1698
54.69	58.26	0.000	0.000	0.000	0	0
54.69	58.26	0.000	0.000	0.000	0	0

TORSIONAL CELL DATA
****

X LEFT	X RIGHT	DS OVER T	AREA
0.00	20.81	0.000086	57.108
20.81	56.48	0.000341	79.581
0.00	20.81	0.000087	63.896
20.81	56.48	0.000336	54.829

GJ PRODUCT IS 3.987e+8

****

45% Station – Fiberglass Spar Caps @ 21.91% t/c

****
REPORT FOR STATION 45% 21.91%max WITH FOIL Sta45% 21.91%
****
Accuracy factor:0.20 Cut plane angle: 8.75 Me Axis Rotation Ang: 0.00

WEIGHT PER FOOT	FLATWISE EI	EDGEWISE EI	UPPER SURF FLATWISE MOMENT	FWD EDGE EDGEWISE MOMENT
76.085	2.030e+10	3.385e+10	9.053e+6	5.038e+6
CHORDWISE CG	**FLATWISE SHEAR CENTER**	**EDGEWISE SHEAR CENTER**	**UPPER SURF CRITICAL DISTANCE**	**FWD EDGE CRITICAL DISTANCE**
29.05	23.84	0.103	8.407	25.19
FLATWISE CG	**FLATWISE NEUTRAL AXIS**	**EDGEWISE NEUTRAL AXIS**	**LOWER SURF FLATWISE MOMENT**	**AFT EDGE EDGEWISE MOMENT**
-0.510	-0.772	25.19	8.148e+6	2.274e+6
ROTATIONAL MOMENT OF INERTIA	**AE PRODUCT**		**LOWER SURF CRITICAL DISTANCE**	**AFT EDGE CRITICAL DISTANCE**
2.220e+4	3.792e+8		9.341	55.83

LAYER SUMMARY DATA
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X LEFT	X RIGHT	LEFT THICKNESS	RIGHT THICKNESS	WEIGHT	EDGEWISE FORCE	FLATWISE FORCE
0.00	81.02	0.005	0.005	0.224	204	503
0.00	81.02	0.005	0.005	0.231	195	-341
0.00	81.02	0.015	0.015	0.914	1350	3316
0.00	81.02	0.015	0.015	0.943	1288	-2244
0.00	81.02	0.036	0.036	2.369	4096	10011
0.00	81.02	0.036	0.036	2.446	3909	-6760
0.00	40.51	0.024	0.024	0.803	-551	3921
0.00	40.51	0.024	0.024	0.854	-658	-4088
12.15	24.31	0.887	1.774	13.095	-36566	249782
12.15	24.31	0.887	1.774	12.977	-36742	-288121
24.31	36.46	1.774	0.887	13.060	26402	264617
24.31	36.46	1.774	0.887	13.405	26245	-235085
0.00	40.51	0.024	0.024	0.797	-544	3447
0.00	40.51	0.024	0.024	0.844	-660	-3592
36.46	72.92	0.810	0.810	2.187	1006	1122
36.46	72.92	0.810	0.810	2.213	1011	-239
0.00	81.02	0.036	0.036	2.297	3984	8338
0.00	81.02	0.036	0.036	2.434	3918	-5332
0.00	81.02	0.035	0.035	1.406	966	2001
0.00	81.02	0.035	0.035	1.505	960	-1290
23.92	32.79	0.532	0.532	0.341	17	205
23.92	32.79	0.532	0.532	0.350	15	-187
74.54	79.40	0.000	0.000	0.000	0	0
74.54	79.40	0.000	0.000	0.000	0	0
79.02	81.02	0.810	0.810	0.253	100	12
79.02	81.02	0.810	0.810	0.135	54	5

TORSIONAL CELL DATA
****

X LEFT	X RIGHT	DS OVER T	AREA
0.00	28.36	0.000116	153.534
28.36	76.97	0.000458	235.032
0.00	28.36	0.000133	223.183
28.36	76.97	0.000465	136.326

GJ PRODUCT IS 2.465e+9

****

45% Station – Carbon Spar Caps @ 15.43% t/c

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REPORT FOR STATION 45% 15.43%carb WITH FOIL Sta45% 15.43%

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Accuracy factor:0.20 Cut plane angle: 6.17 Me Axis Rotation Ang: 0.00

WEIGHT PER FOOT	FLATWISE EI	EDGEWISE EI	UPPER SURF FLATWISE MOMENT	FWD EDGE EDGEWISE MOMENT
53.436	2.029e+10	4.830e+10	1.282e+7	7.322e+6
CHORDWISE CG	**FLATWISE SHEAR CENTER**	**EDGEWISE SHEAR CENTER**	**UPPER SURF CRITICAL DISTANCE**	**FWD EDGE CRITICAL DISTANCE**
30.42	23.76	-0.135	5.936	24.74
FLATWISE CG	**FLATWISE NEUTRAL AXIS**	**EDGEWISE NEUTRAL AXIS**	**LOWER SURF FLATWISE MOMENT**	**AFT EDGE EDGEWISE MOMENT**
-0.300	-0.558	24.74	1.159e+7	3.218e+6
ROTATIONAL MOMENT OF INERTIA	**AE PRODUCT**		**LOWER SURF CRITICAL DISTANCE**	**AFT EDGE CRITICAL DISTANCE**
1.650e+4	7.588e+8		6.565	56.28

LAYER SUMMARY DATA

****

X LEFT	X RIGHT	LEFT THICKNESS	RIGHT THICKNESS	WEIGHT	EDGEWISE FORCE	FLATWISE FORCE
0.00	81.02	0.005	0.005	0.221	210	502
0.00	81.02	0.005	0.005	0.225	205	-332
0.00	81.02	0.015	0.015	0.900	1389	3303
0.00	81.02	0.015	0.015	0.917	1355	-2180
0.00	81.02	0.036	0.036	2.334	4216	9956
0.00	81.02	0.036	0.036	2.378	4111	-6549
0.00	40.51	0.024	0.024	0.785	-458	3884
0.00	40.51	0.024	0.024	0.814	-520	-3969
12.15	24.31	0.625	1.250	7.644	-70446	521090
12.15	24.31	0.625	1.250	7.608	-70668	-600843
24.31	36.46	1.250	0.625	7.635	60219	553017
24.31	36.46	1.250	0.625	7.735	60089	-481338
0.00	40.51	0.024	0.024	0.782	-453	3417
0.00	40.51	0.024	0.024	0.809	-520	-3490
36.46	72.92	0.810	0.810	2.069	976	1021
36.46	72.92	0.810	0.810	2.191	1010	-190
0.00	81.02	0.036	0.036	1.955	3076	6933
0.00	81.02	0.036	0.036	2.371	4121	-4866
0.00	81.02	0.035	0.035	1.079	572	1507
0.00	81.02	0.035	0.035	1.465	1010	-1170
25.23	31.48	0.375	0.375	0.171	10	102
25.23	31.48	0.375	0.375	0.173	9	-91
25.23	31.48	0.120	0.120	0.584	249	2523
25.23	31.48	0.120	0.120	0.592	235	-2235
74.54	79.40	0.000	0.000	0.000	0	0
74.54	79.40	0.000	0.000	0.000	0	0

TORSIONAL CELL DATA

****

X LEFT	X RIGHT	DS OVER T	AREA
0.00	28.36	0.000113	107.416
28.36	76.97	0.000542	162.180
0.00	28.36	0.000123	157.045
28.36	76.97	0.000463	93.284

GJ PRODUCT IS 1.245e+9

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25% Station – Fiberglass Spar Caps @ 28% t/c

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        REPORT FOR STATION 25% 28%int WITH FOIL Sta25% 28%t/c
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Accuracy factor:0.20  Cut plane angle:12.12  Me Axis Rotation Ang: 0.00
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WEIGHT PER FOOT	FLATWISE EI	EDGEWISE EI	UPPER SURF FLATWISE MOMENT	FWD EDGE EDGEWISE MOMENT
95.002	6.846e+10	1.123e+11	1.861e+7	1.233e+7

CHORDWISE CG	FLATWISE SHEAR CENTER	EDGEWISE SHEAR CENTER	UPPER SURF CRITICAL DISTANCE	FWD EDGE CRITICAL DISTANCE
39.67	30.90	0.397	13.792	34.15

FLATWISE CG	FLATWISE NEUTRAL AXIS	EDGEWISE NEUTRAL AXIS	LOWER SURF FLATWISE MOMENT	AFT EDGE EDGEWISE MOMENT
-0.872	-1.321	34.15	1.651e+7	5.949e+6

ROTATIONAL MOMENT OF INERTIA	AE PRODUCT		LOWER SURF CRITICAL DISTANCE	AFT EDGE CRITICAL DISTANCE
6.172e+4	4.475e+8		15.552	70.81

LAYER SUMMARY DATA

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X LEFT	X RIGHT	LEFT THICKNESS	RIGHT THICKNESS	WEIGHT	EDGEWISE FORCE	FLATWISE FORCE
0.00	104.96	0.005	0.005	0.295	247	653
0.00	104.96	0.005	0.005	0.310	226	-447
0.00	104.96	0.015	0.015	1.203	1632	4302
0.00	104.96	0.015	0.015	1.265	1490	-2943
0.00	104.96	0.036	0.036	3.119	4953	13010
0.00	104.96	0.036	0.036	3.282	4522	-8887
0.00	52.48	0.024	0.024	1.065	-944	5078
0.00	52.48	0.024	0.024	1.173	-1191	-5479
15.74	31.49	0.774	1.548	14.883	-50530	292345
15.74	31.49	0.774	1.548	14.813	-50690	-340464
31.49	47.23	1.548	0.774	14.773	22629	308905
31.49	47.23	1.548	0.774	15.437	22783	-276571
0.00	52.48	0.024	0.024	1.057	-935	4738
0.00	52.48	0.024	0.024	1.163	-1195	-5116
47.23	94.46	1.050	1.050	3.348	1582	1700
47.23	94.46	1.050	1.050	3.761	1679	-385
0.00	104.96	0.036	0.036	2.828	4382	10524
0.00	104.96	0.036	0.036	3.273	4534	-7670
0.00	104.96	0.035	0.035	1.712	1043	2496
0.00	104.96	0.035	0.035	2.023	1111	-1865
29.39	44.08	0.882	0.882	0.936	30	619
29.39	44.08	0.882	0.882	0.977	26	-574
96.56	102.86	0.132	0.132	0.711	16422	3963
96.56	102.86	0.132	0.132	0.684	15833	2031
102.96	104.96	1.050	1.050	0.480	191	23
102.96	104.96	1.050	1.050	0.430	172	15

TORSIONAL CELL DATA

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X LEFT	X RIGHT	DS OVER T	AREA
0.00	36.74	0.000161	336.700
36.74	99.71	0.000591	505.593
0.00	36.74	0.000196	500.913
36.74	99.71	0.000576	291.312

GJ PRODUCT IS 8.605e+9

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15% Station – Fiberglass Spar Caps @ 42% t/c

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REPORT FOR STATION 15% 42%int WITH FOIL Sta15% 42%t/c
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Accuracy factor:0.30 Cut plane angle:17.39 Me Axis Rotation Ang: 0.00

WEIGHT PER FOOT	FLATWISE EI	EDGEWISE EI	UPPER SURF FLATWISE MOMENT	FWD EDGE EDGEWISE MOMENT
98.155	1.329e+11	1.401e+11	2.539e+7	1.564e+7

CHORDWISE CG	FLATWISE SHEAR CENTER	EDGEWISE SHEAR CENTER	UPPER SURF CRITICAL DISTANCE	FWD EDGE CRITICAL DISTANCE
37.39	34.17	-1.037	19.628	33.60

FLATWISE CG	FLATWISE NEUTRAL AXIS	EDGEWISE NEUTRAL AXIS	LOWER SURF FLATWISE MOMENT	AFT EDGE EDGEWISE MOMENT
-1.647	-2.033	33.60	2.485e+7	8.613e+6

ROTATIONAL MOMENT OF INERTIA	AE PRODUCT		LOWER SURF CRITICAL DISTANCE	AFT EDGE CRITICAL DISTANCE
7.320e+4	4.639e+8		20.056	61.01

LAYER SUMMARY DATA

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X LEFT	X RIGHT	LEFT THICKNESS	RIGHT THICKNESS	WEIGHT	EDGEWISE FORCE	FLATWISE FORCE
0.00	94.61	0.005	0.005	0.286	223	746
0.00	94.61	0.005	0.005	0.294	171	-596
0.00	94.61	0.015	0.015	1.165	1472	4919
0.00	94.61	0.015	0.015	1.199	1126	-3933
0.00	94.61	0.036	0.036	3.021	4465	14889
0.00	94.61	0.036	0.036	3.109	3418	-11899
0.00	47.31	0.024	0.024	1.007	-1324	4916
0.00	47.31	0.024	0.024	1.113	-1647	-5377
4.73	33.11	0.435	0.870	15.770	-86194	302311
4.73	33.11	0.435	0.870	16.308	-93310	-355653
33.11	61.50	0.870	0.435	15.017	74695	355036
33.11	61.50	0.870	0.435	15.517	77246	-311591
0.00	47.31	0.024	0.024	0.998	-1298	4685
0.00	47.31	0.024	0.024	1.098	-1619	-5101
61.50	85.15	0.946	0.946	1.710	974	1208
61.50	85.15	0.946	0.946	1.762	997	-538
0.00	94.61	0.036	0.036	2.988	4420	14131
0.00	94.61	0.036	0.036	3.080	3424	-11145
0.00	94.61	0.030	0.030	1.583	927	2957
0.00	94.61	0.030	0.030	1.632	719	-2331
23.18	43.05	1.190	1.190	1.721	-8	1282
23.18	43.05	1.190	1.190	1.712	-14	-1315
23.18	43.05	0.120	0.120	1.848	-49	10097
23.18	43.05	0.120	0.120	1.832	-126	-10331
87.04	92.72	0.037	0.037	0.266	6124	2710
87.04	92.72	0.037	0.037	0.192	4427	-183
92.61	94.61	0.950	0.950	1.122	442	78
92.61	94.61	0.950	0.950	0.807	319	27

TORSIONAL CELL DATA

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X LEFT	X RIGHT	DS OVER T	AREA
0.00	33.11	0.000105	387.578
33.11	89.88	0.000378	858.985
0.00	33.11	0.000134	576.833
33.11	89.88	0.000379	739.020

GJ PRODUCT IS 2.731e+10

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