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Concepts to Facilitate Very Large Blades

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Sandia National Laboratories (SNL) is developing concepts that will enable the utilization of longer blades that weigh less, are more efficient structurally and aerodynamically, and impart reduced loads to the system. Several of these concepts have been incorporated into subscale prototype blades. The description of these concepts and the results of prototype blade fabrication and testing are covered here.

I. Introduction

Sandia National Laboratories (SNL) is developing concepts that will enable the utilization of longer blades that weigh less, are more efficient structurally and aerodynamically, and impart reduced loads to the system. Several of these concepts have been incorporated into subscale prototype blades. The description of these concepts and the results of prototype blade fabrication and testing are covered here.

The SNL wind energy department focuses on producing innovations in blade technology. But, what is so important about blades? Blades are the only unique wind-turbine component, and they capture all of the energy and produce all of the system loads.

II. Growth Trends

Installed wind energy capacity both worldwide and in the U.S. has grown exponentially over the past few years. The U.S. demand for new turbines is up dramatically in large part due to the re-activation of the Production Tax Credit (PTC). The inflation-adjusted cost of energy (COE) for wind power has fallen dramatically as well. A large part of this drop has to do with the inherent efficiencies associated with larger turbines. The physical size has grown from an average of 100 kW in 1985 to over 1.5 MW today.

The top utility-scale manufacturers in 2004, GE Energy (U.S.), Gamesa (Spain), Enercon (Germany), and Vestas-NEG Micon (Denmark) (1) are typically in the 1-3 MW size range. But the current trend is a continuation of the increase in size of commercial turbines (2). Per BTM Consults (1), the following companies are planning to commercialize turbines in the 3-5 MW size range by 2007: GE, Siemens, REPower, Vestas, Nordex, Ecotecnia, Prokon Nord, ScanWind, and WINWinD.

One of the prime goals for larger blade developments is to keep blade weight growth under control. Gravity scales as the cube of the blade length and as turbines continue to become larger, eventually gravity loads become a constraining design factor. We can slow down this weight growth by becoming more efficient in design methodology. Figure 1 shows blade weight growth trends as a function of rotor diameter from commercial data and WindPACT preliminary designs (3). Here we can see trend lines of older commercial designs, newer commercial designs, and designs that have come out of the Department of Energy (DOE)-sponsored WindPACT studies (4) that incorporate new concepts. It is possible to lower the growth rate from an exponent of 3.0 to one of around 2.5. Figure 2 is a more recent but similar plot showing finer detail (5).

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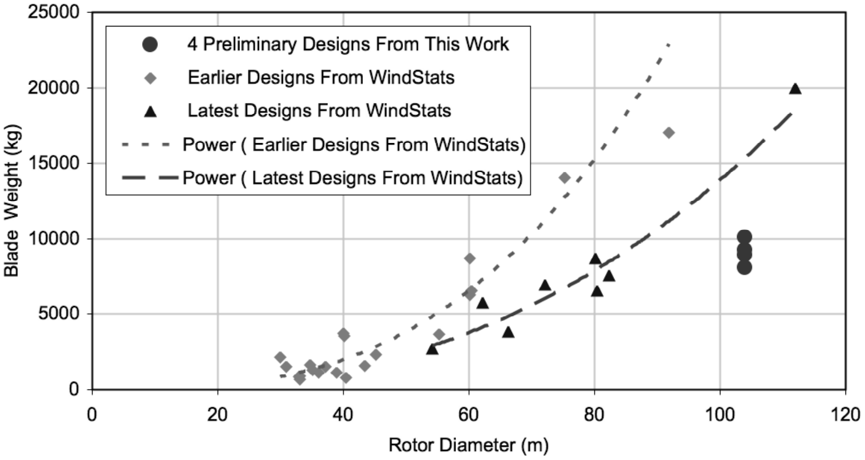


Fig. 1. Blade Weight vs. Rotor Diameter

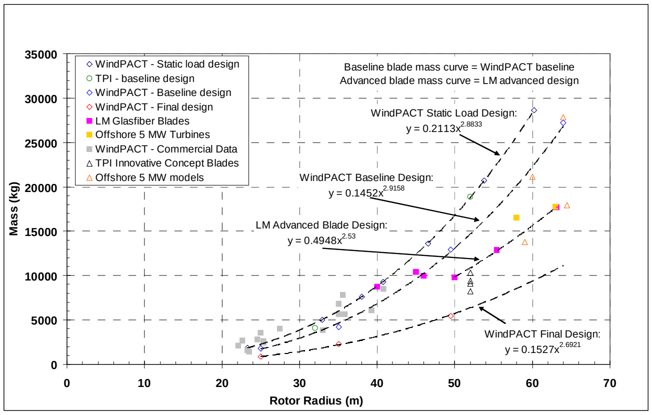


Fig. 2. Blade Mass vs. Rotor Radius

III. Advance Concepts

SNL is developing concepts that will enable the utilization of longer blades that weigh less, are more efficient structurally and aerodynamically, and impart reduced loads to the system. These concepts include those from the WindPACT studies (4). Several of these concepts have been incorporated into subscale prototype blades. (See Section IV) The prime areas we are working on and details of the concepts are detailed below:

1. Structural airfoils
    - Very thick
    - Flatbacks
2. Adaptive structures
    - Passive bend-twist coupling
    - Active devices
3. Manufacturing, materials, and fatigue
    - Less expensive, embedded blade attachment devices
    - Design details to minimize stress concentrations in ply drop regions
    - New materials for wind turbine blades
        - Carbon
        - Carbon-hybrid
        - S-glass
        - New material forms

4. More efficient blade designs
    - Integrated design (structure and aerodynamics considered simultaneously)
    - Slenderized blade geometries
5. Modeling and test loop
    - Validation of models with test data

A more detailed description of these five areas is included here.

1. Structural Airfoils. A BSDS (Blade System Design Studies) WindPACT contract with TPI (3) showed that very thick airfoils have a structural advantage in the in-board region of the blade, especially towards the root. As part of this study, new airfoils were created that were thicker and optimized for structural efficiency. These so-called "flatback" airfoils were developed (3) with the use of CFD and two-dimensional wind tunnel testing at UC Davis (part of the TPI design team). These are different from truncated airfoils, which change the basic aerodynamic properties, while flatback airfoils do not (they retain camber). Figure 3 shows the flatback airfoil TR-35-10 compared to the normal looking TR-35 baseline (3). The flatback airfoils are installed on 9-m BSDS prototype blades. (See Section IV) Figure 4 shows a CFD picture of airstreams over a flatback with trailing edge vortex shedding. The extra lift advantage of the flatback comes with an increase in drag. This extra drag will have to be measured; if it is larger than expected, it can be reduced with the use of trailing edge treatments.

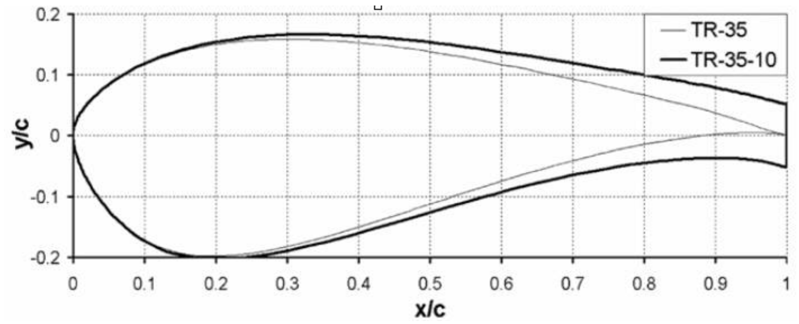


Fig. 3. Flatback Airfoil

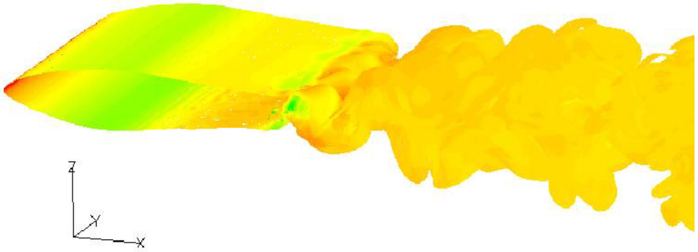
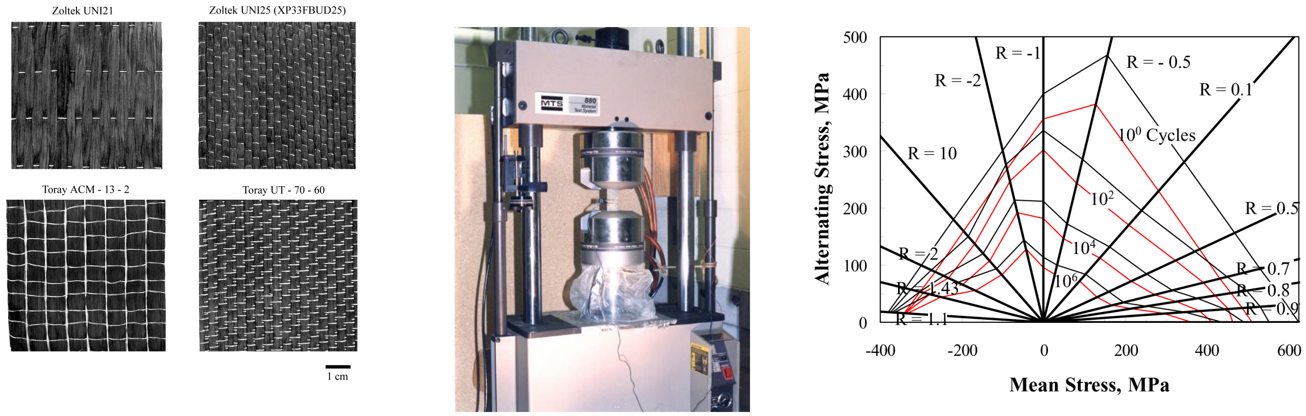


Fig. 4. CFD Plot Showing Flatback Trailing Edge Vortices

2. Adaptive Structures. Adaptive structures are those that are modified or tailored to obtain a desired response. In the case of wind turbines such tailoring can provide load alleviation (without detrimental effects on performance). Passive methods make these modifications in a passive way, primarily either by adjusting the material lay-up [such as off-axis fibers (6) – see Figure 5a] or by introducing geometric sweep, both of which allow the blade to be less torsionally stiff and increase bend-twist coupling. Active methods have been identified and will be applied to prototype blades in the future (7). Active devices have been around a while (such as ailerons on the Zond 750 – see Figure 5b), but have not been a good approach. Adaptive airfoils that can actually change shape (Figure 5c) are not ready for prime time and may not be a good solution for wind turbines. Microtabs are one solution that may be beneficial for turbine blades (Figure 5d). Here the microtabs are installed outboard in the trailing edge of the airfoil. Rapid deployment of the tabs can effectively modify the blade performance and/or reduce fatigue loads when used in conjunction with the primary control system.

Fig. 5a, 5b, 5c, 5d. Bend-twist Coupling, Aileron, Airfoils with Changing Shape, Microtabs

3. Manufacturing, Materials and Fatigue. We have been testing a variety of composite materials for many years in conjunction with Montana State University (MSU) and created the DOE/MSU Fatigue database (8). More recently to aid in goals of making blades lighter yet stronger, we have added to the traditional fiberglass type of materials and included testing of carbon and carbon-glass hybrids with resins including epoxy, vinyl ester and polyester. The fatigue tests characterize the material at a variety of R levels and cycle levels up to 10^8 with loading that includes both constant and variable amplitude. MSU and GEC are now testing structural details such as ply drops and transitions (9). Details of this recent work are shown in Appendix A. Figure 6a shows typical carbon materials such as those from Zoltec and Toray. Figure 6b shows the coupon fatigue testing machine at MSU. Figure 6c shows a typical full fatigue characterization of a composite material.



Figs. 6a, 6b, 6c. Typical Carbon Materials, Coupon Fatigue Testing at MSU
and Heavily Populated Fatigue Characterization

4. More Efficient Designs Blade designers are always looking for more efficient blade designs. The use of more slenderized geometries with stronger materials and an integrated design process that considers structural optimization in conjunction with good performing airfoils have been identified and used in recent research blade studies and in prototype blade fabrication (3). In the manufacturing arena, we have been encouraging the expansion of inexpensive, reliable ideas to attach blades to the hub. The BSDS prototype blades used embedded threaded rods, which fits this description.

5. Modeling and Test Loop To validate how well we are doing in estimating the influence of these concepts, we invoke a "model, design & fabricate" loop that provides information on how we are doing in our ability to model these complex structures. One cannot afford to build and test every concept, but validated modeling procedures can be used to confidently filter the concepts down to the most promising. (See Section IV)

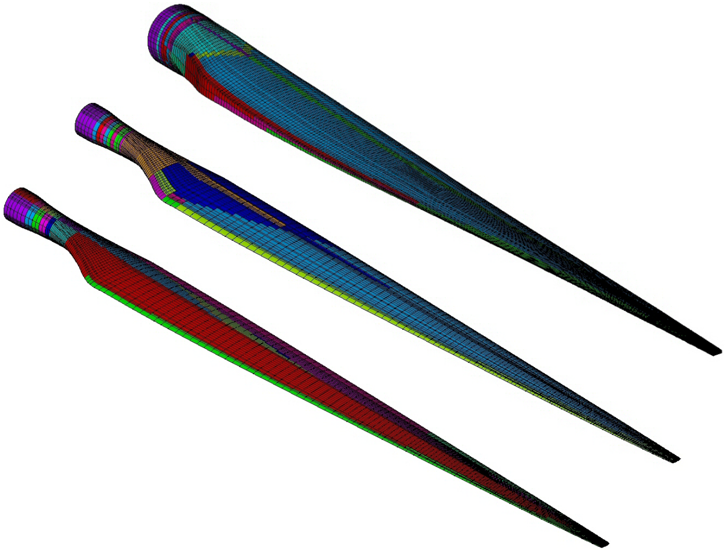


Fig. 7. NuMAD Finite Element Models of Prototype Blades

IV. New Prototypes

Innovations from the DOE R&D program are starting to show up in prototype blades. Under the carbon SBIR program, 3Tex has built a 9m prototype blade with their carbon-glass woven spar cap that is infused in place (10). GEC is producing a 29-meter carbon blade (11). In the Low Wind Speed Technology (LWST) project, a 28-m swept blade has been fabricated by Knight & Carver and will soon be tested in the laboratory and field (12).

In addition, Sandia has been developing several 9-m subscale blades that are scalable to utility-grade sizes and incorporate concepts identified as having a large impact on blade performance. These 9-m blades are the CX-100, TX-100 and the WindPACT BSDS. All three of these blades have been designed by TPI/Sandia design teams. TPI has completed the fabrication of seven blades for each set. The specifications are as follows:

- CX-100
    - 9-m long
    - carbon spar
    - glass skins and web
    - balsa core
    - constant thickness spar cap
- TX-100
    - 9-m long
    - constant thickness glass spar cap
    - carbon fibers in the skin at 20 degrees off of the zero axis
    - balsa core

- BSDS
    - 9-m long
    - flatback airfoils
    - constant thickness carbon spar cap
    - glass skins and web

Figure 8 shows each of these blades.

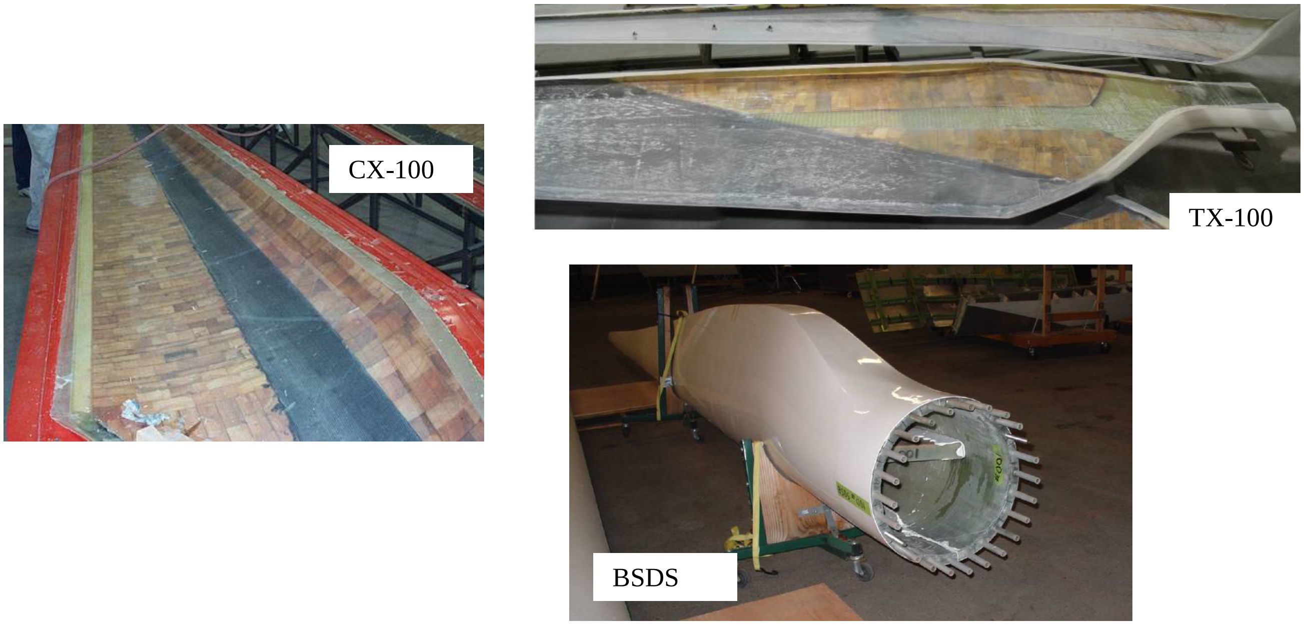


Fig. 8. CX-100, TX-100 and BSDS Prototype Blades

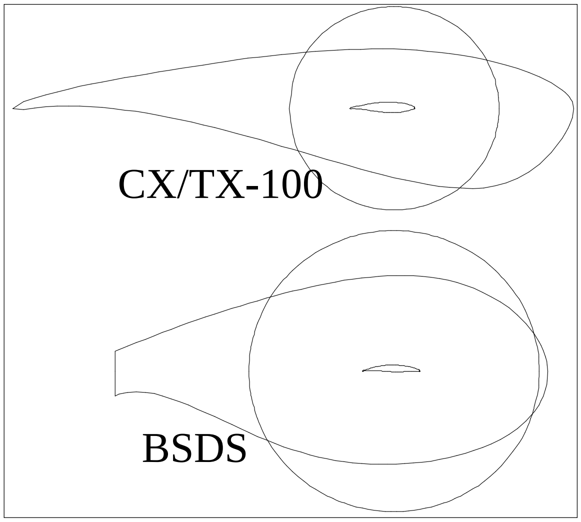


Fig. 9. Airfoils at Tip, Max Chord and Root for Prototype Blades

Figure 9 shows the un-rotated root, max-chord and tip airfoils for the 9m blades.

V. Testing of 9-m Prototype Blades

These 9-m prototype blades are undergoing a series of laboratory (13, 14) and field tests. The laboratory tests include modal, static and fatigue testing. Figure 10 shows a set-up for modal testing the CX-100 blade, and Figure 10 the resulting FRF (frequency response function) that provides a distribution of response (acceleration) versus frequency from which the natural frequencies of the blades can be derived. This test is repeated for all three prototype blades. The results are very consistent between blades from each set (13). This indicates a very consistent manufacturing process for material lay-up and thickness distribution.

Fig. 10. Modal Test Set-up

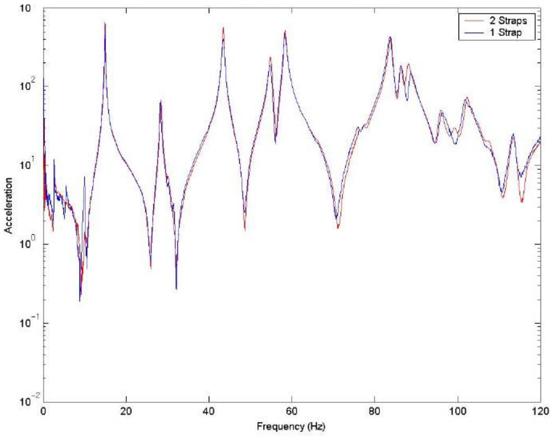


Fig. 11 FRF from Modal Test

Figure 12 and 13 show the static test set-ups for the CX-100 and TX-100 blades. The static load is imparted through a set of whiffle trees that simulate a flapwise loading distribution. In the case of the TX-100 the whiffle tree devices were modified to allow for blade twist to occur more readily to obtain an indication of the amount of bend-twist coupling achieved. Figure 14 is a strain vs. load plot for several sensors captured during the static test of a BSDS blade.

Fig. 12. CX-100 Static Testing

Fig. 13. TX-100 Static Testing

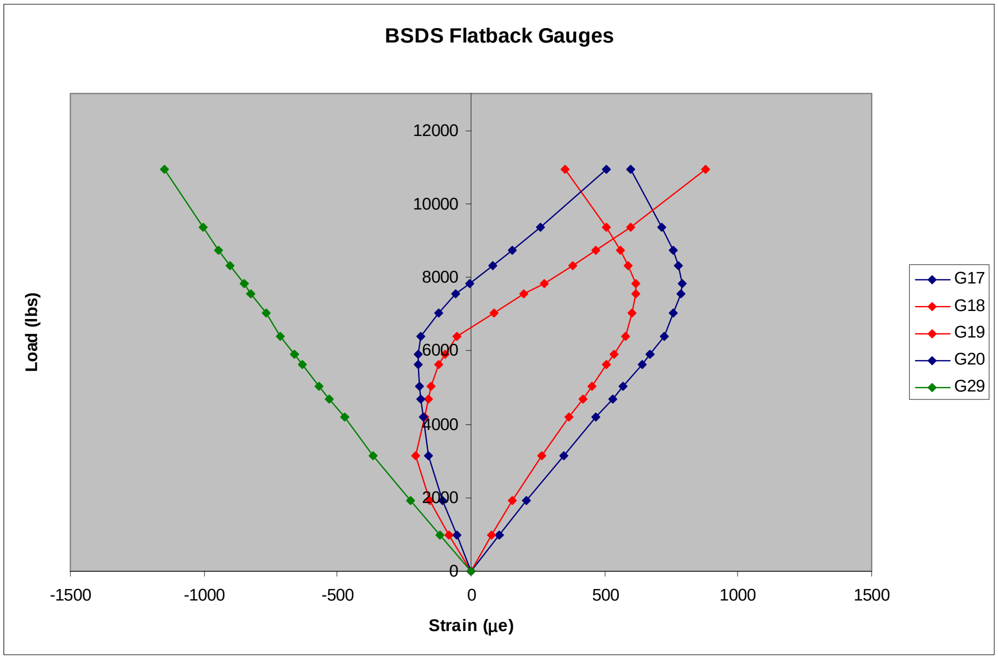


Fig. 14. Load vs. Strain for BSDS Static Test

Figure 15 shows a table of the static test results for all three prototype blades (13, 14). There are several interesting items to note here. The glass baseline blade (GX-100) weighed 450 pounds. The CX-100 blade weighs 383 lbs., the TX-100 361 lbs., and the BSDS only 289 lbs. Amazingly, the load at static failure was 115% of proof for the CX-100, 197% for the TX-100 and 310% for the BSDS. The addition of a carbon spar cap lowers the weight and strengthens a blade. The use of carbon in the skins (with a reduced glass spar) continues that trend. It is followed even more dramatically by the BSDS blade which has a carbon spar cap and thick flatback airfoils with a more slender overall planform and larger root diameter. Therefore, a combination of efficient design and carbon can have very good strength and weight results.

Property	**CX-100**	**TX-100**	**BSDS**
Weight (lb)	383	361	289
% of Design Load at Failure	115%	197%	310%
Root Failure Moment (kN-m)	128.6	121.4	203.9
Max. Carbon Tensile Strain at Failure (%)	0.31%	0.59%	0.81%
Max. Carbon Compressive Strain at Failure (%)	0.30%	0.73%	0.87%
Maximum Tip Displacement (m)	1.05	1.80	2.79

Fig. 15. Comparison of Results between Three 9-m Prototype Blades

VI. Test Validation Process.

All three sets of prototype blades will be flight tested on a Micon turbine located at USDA ARS, Bushland, TX (Figure 16). Field and laboratory data will be compared to FAST and NuMAD models as part of the Design/Fabricate/Model/Test Validation Loop. This will allow us to assess the impact of the innovations on the blades and estimate their impact on full scale utility blades. It also is an opportunity to validate material properties and modeling tools.

Fig. 16. Laboratory and Field Testing Results Help Validate Models

As mentioned earlier, under the DOE-sponsored LWST program, Knight and Carver is fabricating a 28-m swept blade that will produce the same loads but 15% more energy capture than the 25-m baseline with the same wind speed distribution (12). Figure 17 shows the initial mold fabrication for this blade.

Fig.17. Knight and Carver Swept Blade Mold

VII.   Summary

The following are the primary summary points from this paper.

- Efforts are underway at Sandia National Laboratories to create innovative concepts that reduce blade weight growth for larger blades.
- Laboratory results show advantages of carbon-hybrid blades.
- New airfoil designs allow for structural improvements.
- The CX-100 obtained a 10% weight reduction and 70% tip clearance reduction from the glass baseline (GX-100).
- The TX-100 twisted upon bending due solely to lay-up configuration and survived to 197% of design load.
- The BSDS (WindPACT) blade was 25% lighter than the CX-100 design, failed at 310% of design load, and had spar cap carbon material with very high compressive strain to failure.
- Future fatigue and field testing are expected to be completed in the next year to complete evaluation of all three prototype blades' performance.
- Advanced materials and aeroelastic tailoring likely will prove to be beneficial for future blade designs.
- Stress concentrations at ply drops can be reduced significantly by modifying edge configurations.

Appendix A. Material Testing – Ply Drops

As part of the Blade System Design Studies (BSDS) effort (3), a wind turbine blade material identification and testing effort has been performed. Part of this effort has focused on ply delaminations due to ply drops in the material (15).

Two styles of panels with ply drops were fabricated: drops with standard straight edges and drops with pinked edges as illustrated in Figure A1. The motivation for fabricating and testing the panels with the pinked ply drops was to reduce the stress concentration at the ply drop edge. Both the straight and pinked configurations were fabricated in prepreg and infused articles.

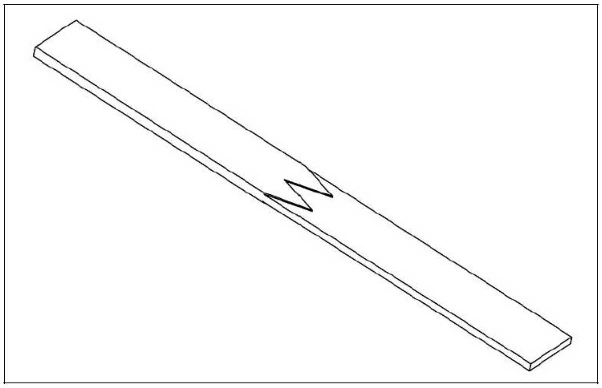


Figure A1. Pinked Ply Drop (outer plies not shown for clarity).

Asymmetries in the ply drop coupons due to manufacturing issues created challenges for obtaining reliable results in compression testing. Therefore, the majority of fatigue testing for the ply drop specimens was performed in tension (R=0.1). Ply drops were tested in both straight and pinked edge geometries. Figure A2 shows results for ply drop panels manufactured at Montana State University (MSU) using Grafil/Newport prepreg material (8). The data represent the number of cycles required to develop a delamination of 6.35 mm (0.25 inch). As indicated in the figure, for the straight ply drop (control) the strain level for 1E+6 cycle delamination is below 0.3%. The fatigue performance for the pinked coupon is greatly improved, with 1E+6 strain increased to above 0.5%.

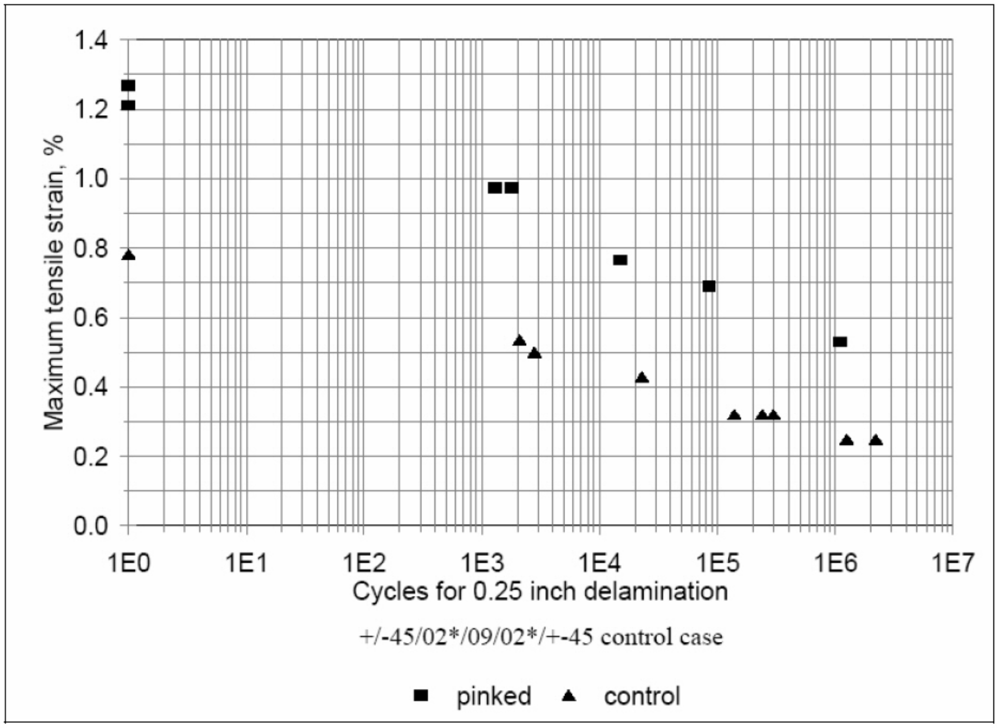


Figure A2. Cycles to delamination for carbon prepreg ply drops (R = 0.1).

Figure A3 and Figure A4 show results for infused ply drop panels manufactured at TPI using SAERTEX carbon-fiberglass triax fabric with both epoxy and vinyl ester (VE) resins, in both straight and pinked configurations. The trends for both epoxy and VE resins are quite similar. For the straight-edge configuration, the 1E+6 strain is about 0.3%, and only slightly higher for the epoxy resin that for VE. The improvement due to pinking is less than was seen for the prepreg materials, with 1E+6 strain values increase to about 0.4% for both epoxy and VE.

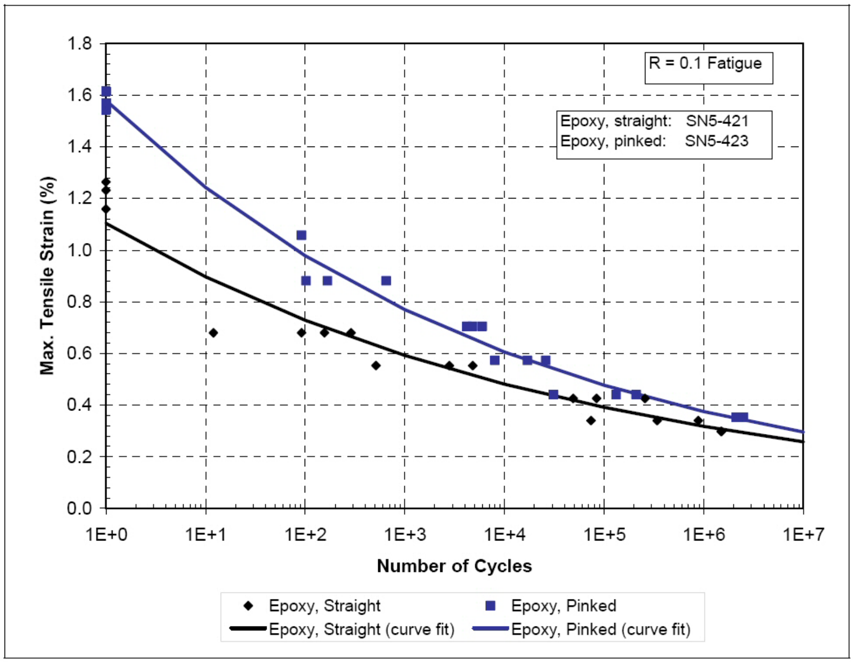


Figure A3. Tensile data for infused epoxy ply drops.

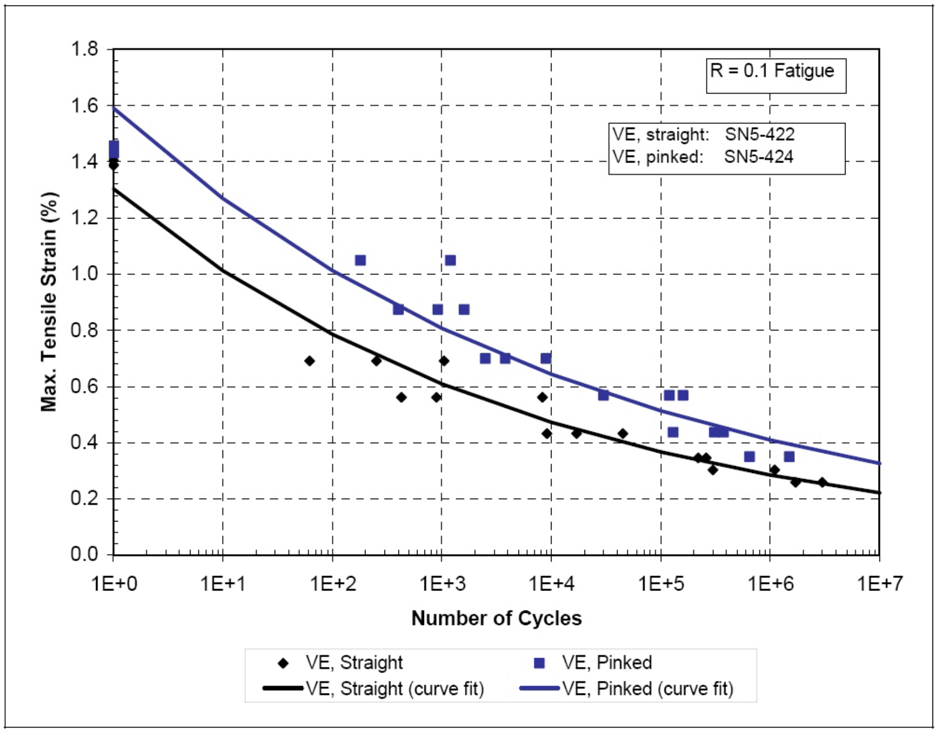


Figure A4. Tensile data for infused VE ply drops.

The relatively low fatigue performance for the infused ply drops with pinking may be partly due to the geometry of the ply drops and panels. Carbon fiber is difficult to cut, and Figure A5 shows that the accuracy of the pinking in the SAERTEX fabric was far from ideal. By contrast, the tacky nature of prepreg materials makes precise cutting much easier.

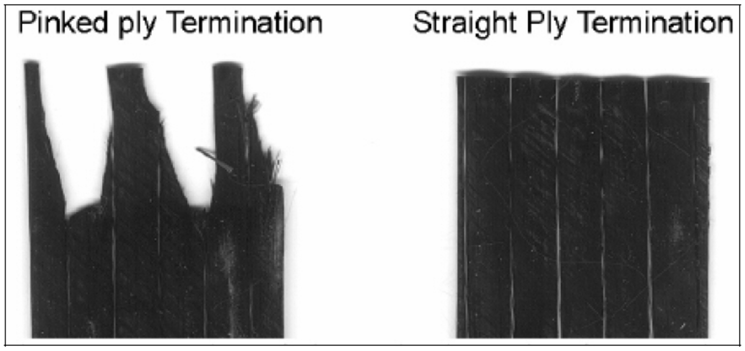


Figure A5. Face view of ply terminations.

For all fabric and resin styles, a ply drop with a straight edge resulted in lower fatigue performance than the same fabric and resin with a pinked ply drop. For prepreg laminate, the introduction of a pinked-ply drop edge nearly doubled the strain level for delamination at 1E+6 cycles. With the infused fabrics, the pinked edge showed far less benefit, with a strain improvement at 1E+6 cycles was only about 25%.

The relatively low fatigue performance for the infused ply drops with pinking may be partly due to the geometry of the ply drops and panels.

References

1. BTM Consult ApS, *Ten Year Review of the International Wind Power Industry 1995-2005*, Denmark.
2. Ashwill, T.D., "Some Recent Trends & Activities in Turbines and Blades," Sandia National Laboratories 2nd Wind Turbine Blade Workshop, www.sandia.gov/wind, April 2006.
3. TPI Composites, *Innovative Design Approaches for Large Wind Turbine Blades; Final Report*, SAND2004-0074, Sandia National Laboratories, Albuquerque, NM.
4. Ashwill, T.D., "Developments in Large Blades for Lower Cost Wind Turbines", AWEA 2004, Chicago, Illinois.
5. Hand, M., "Cost Prediction Tool for Onshore and Offshore Turbines", Sandia National Laboratories 2nd Wind Turbine Blade Workshop, www.sandia.gov/wind, April 2006.
6. Lobitz, D.W., Veers, P.S., Aeroelastic Behavior of Twist-Coupled HAWT Blades, *Proceedings of 1999 ASME Wind Energy Symposium*, Reno, NV.
7. Zayas, J., "Active Control Devices for Wind Turbine Blades," Sandia National Laboratories 2nd Wind Turbine Blade Workshop, www.sandia.gov/wind, April 2006.
8. Mandell, J.F., and D.D. Samborsky, *DOE/MSU Composite Material Fatigue Database: Test Methods, Materials, and Analysis*, SAND97-3002, Sandia National Laboratories, Albuquerque, NM.
9. Mandell, J.F., "Materials Testing: Thickness Tapering and Transitions," Sandia National Laboratories 2nd Wind Turbine Blade Workshop, www.sandia.gov/wind, April 2006.
10. Mohamed, M., "3D Woven Spar Cap and 9m Blade Development," Sandia National Laboratories 2nd Wind Turbine Blade Workshop, www.sandia.gov/wind, April 2006.
11. Griffin, D., "Demonstration of an Infused Carbon Fiber Spar in MW-Scale Blade," Sandia National Laboratories 2nd Wind Turbine Blade Workshop, www.sandia.gov/wind, April 2006.
12. Kanaby, G., "Swept 28-m Blade Design and Fabrication," Sandia National Laboratories 2nd Wind Turbine Blade Workshop, www.sandia.gov/wind, April 2006.
13. Paquette, J., "Lab Testing of SNL Subscale 9m Blades," Sandia National Laboratories 2nd Wind Turbine Blade Workshop, www.sandia.gov/wind, April 2006.
14. Paquette, J., van Dam, J. and Hughes, S., "Structural Testing of 9m Carbon Fiber Wind Turbine Research Blades," AIAA 2006, Reno, NV.
15. Griffin, D.A. and Roberts, D., *Blade System Design Studies Volume II: Final Project Report (draft)*, December 2006, Sandia National Laboratories, Albuquerque, NM.