

Blade Technology Innovations for Utility-Scale Turbines

Tom Ashwill
Wind Energy Department
Sandia National Laboratories*
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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.

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 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.

Figure 1 shows pictures of turbines from the top utility-scale manufacturers in 2004, GE Energy (U.S.), Gamesa (Spain), Enercon (Germany), and Vestas-NEG Micon (Denmark) (1). These turbines 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.

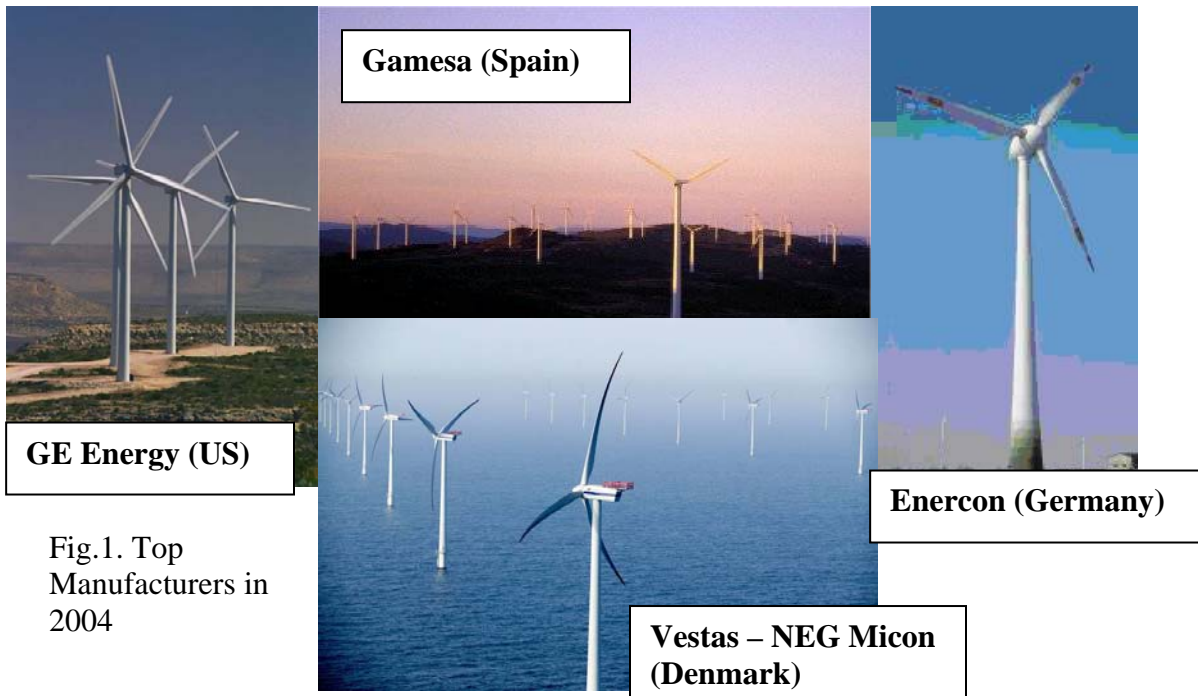


Fig.1. Top
Manufacturers in
2004

*Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin company, for the U.S. Department of Energy

We at the labs, both SNL and NREL (National Renewable Energy Laboratories), continue to perform research and development (R&D) in concert with industry to incorporate technology innovations that aid in reaching DOE goals of further COE reductions and increased reliability of turbine systems.

In the R&D framework and with emphasis on large utility-grade turbines, SNL's wind energy department focuses on producing innovations in blade technology (3). What is so important about blades? Blades are the only unique wind-turbine component; not only do they capture all of the energy but produce all of the system loads as well. In addition, DOE has recently identified blades and rotor as the areas that can provide up to 50% of the desired reductions in COE.

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 2 shows blade weight growth trends as a function of rotor radius from commercial data and WindPACT preliminary designs (4). Here we can see trend lines of older commercial designs, newer commercial designs, and designs that have come out of the DOE-sponsored WindPACT studies (5) that incorporate new concepts. It is possible to lower the growth rate from an exponent of 3.0 to one of around 2.5.

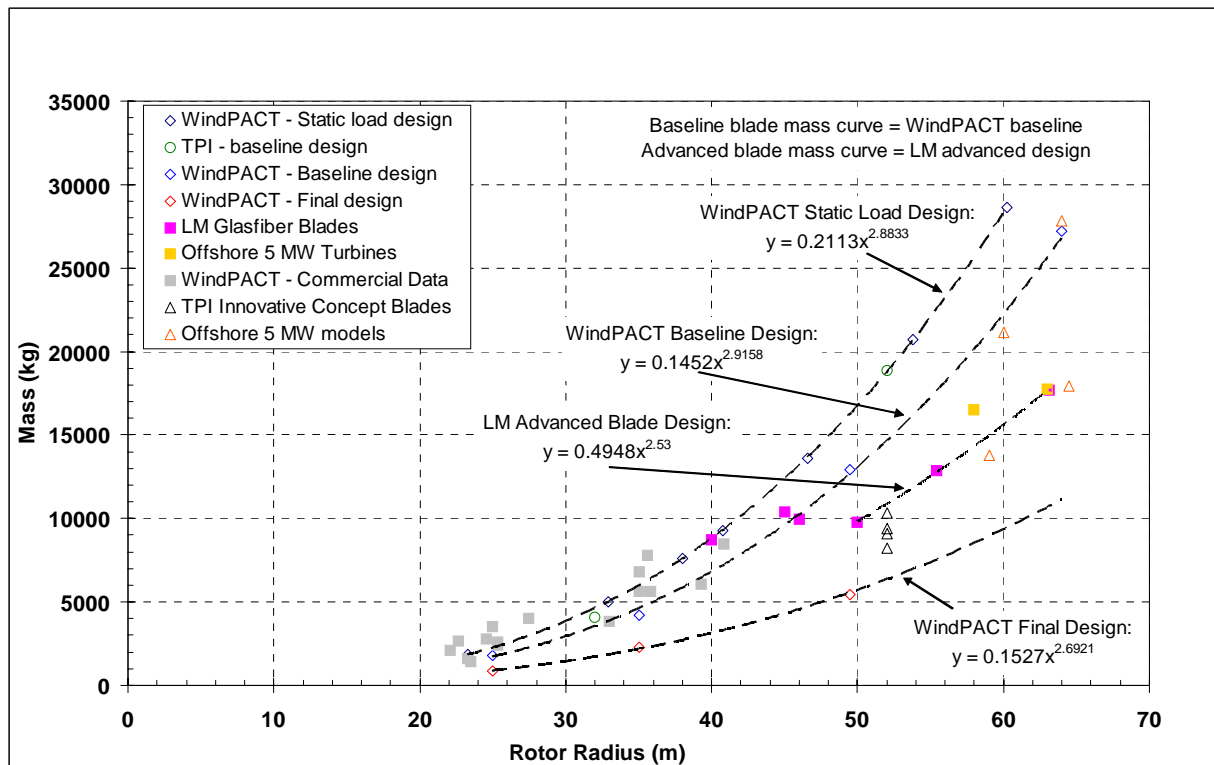


Fig. 2. Blade Mass vs. Rotor Radius

Advance Concepts. Sandia Labs 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 (5). Several of these concepts have been incorporated into subscale prototype blades. (See next section.) The prime areas we are working on and details of the concepts are shown below:

1. Structural airfoils
 - Very thick airfoils
 - Flatback airfoils
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 structure with aerodynamics
 - Slenderized blade geometries

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

1. Structural Airfoils. A BSDS (Blade System Design Studies) WindPACT contract with TPI (6) 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 (6) 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 (6). The flatback airfoils are installed on 9-m BSDS prototype blades. (See New Prototypes section.) 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.

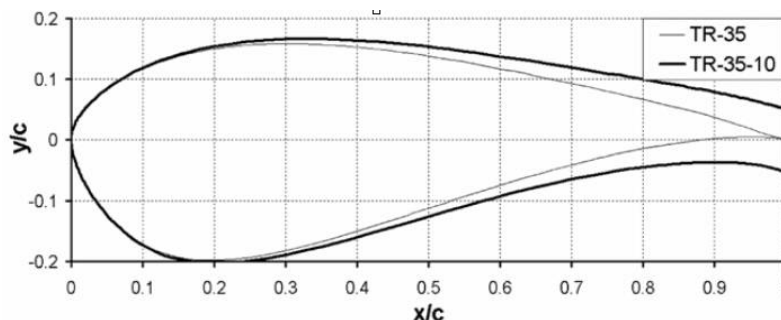


Fig. 3. Flatback Airfoil

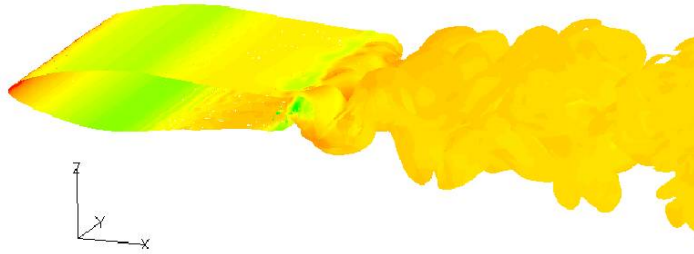


Fig. 4. CFD Plot Showing Flatback Trailing Edge Vortices

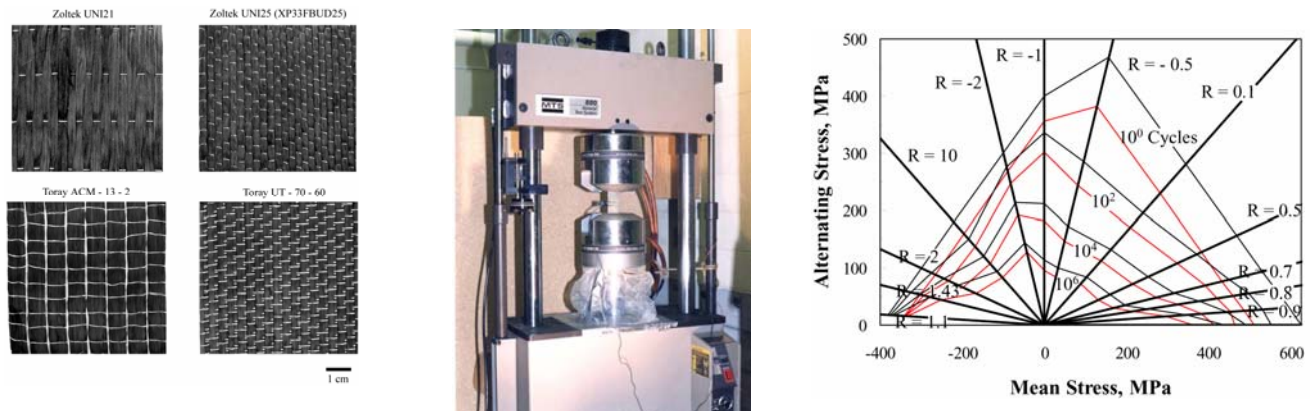
2. Adaptive Structures. Adaptive structures are those that are modified or tailored to obtain a desired response. In the case of wind turbines such tailoring can provide load alleviation (without detrimental effects on performance). Passive methods make these modifications in a passive way, primarily either by adjusting the material lay-up [such as off-axis fibers (7) – 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 (8). 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 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 at Montana State University and created the DOE/MSU Fatigue

database. (9) 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 (10). Figure 6a shows typical carbon materials such as those from Zoltek and Toray. Figure 6b shows the coupon fatigue testing machine at MSU. Figure 6c shows a typical full fatigue characterization of a composite material. 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.



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 (6).

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 (11). GEC is producing a 29-meter carbon blade (12). In the LWST (Low Wind Speed Technology) project two blades are being designed; a 34-m carbon blade by GE Wind under LWST Phase I (13) and a 28-m swept blade by Knight & Carver under LWST Phase II (14).

In addition, Sandia has been cultivating 9-m subscale blades that are scalable to utility-grade sizes and that incorporate concepts identified as potentially 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 7 shows each of these blades.

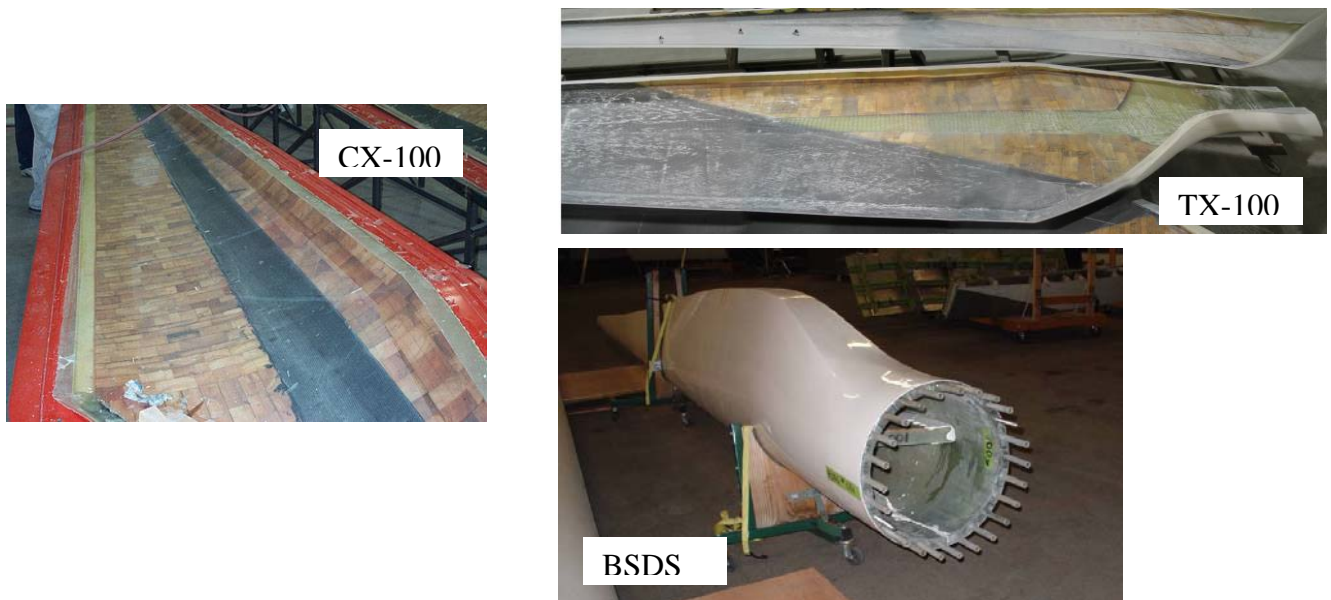


Fig. 7. CX-100, TX-100 and BSDS Prototype Blades

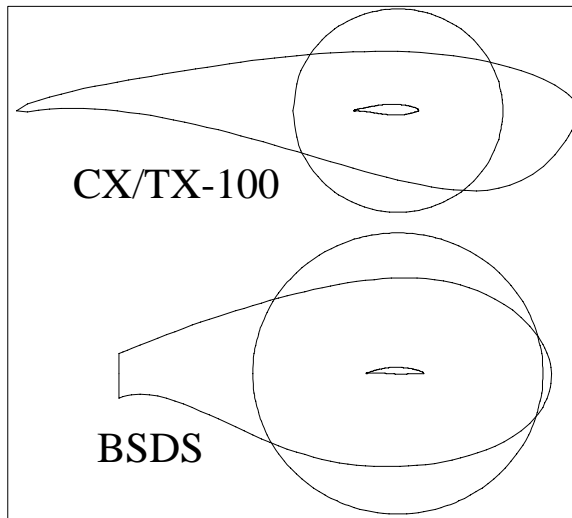


Fig. 8. Airfoils at Tip, Max Chord and Root for Prototype Blades

Figure 8 shows the root, max-chord and tip airfoils for the 9m blades.

Testing of 9-m Prototype Blades. These 9-m prototype blades are undergoing a series of laboratory (15) and field tests. The lab tests include modal, static and fatigue testing. Figure 9 shows a set-up to modal test 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. Figure 11 shows a comparison of the results of modal testing for two CX-100 and two TX-100 blades. From this table, it is clear that the results are very consistent between each blade from each set. This indicates a very consistent manufacturing process on material lay-up and thickness distribution.



Fig. 9. Modal Test Set-up

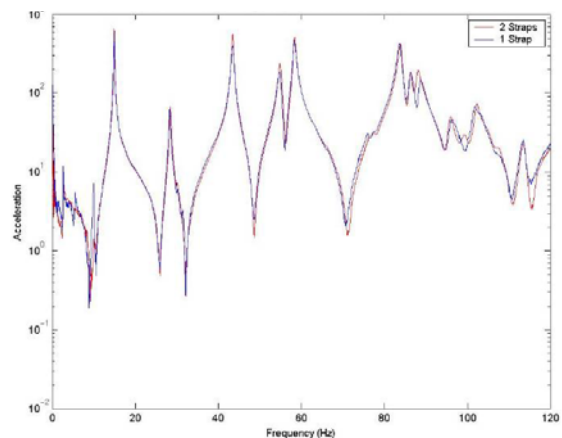


Fig. 10. FRF from Modal Test

Mode Description	CX-100 #002	CX 100 #006
	Frequency (Hz)	Frequency (Hz)
1st Flap	7.99	7.97
1st Edge	17.18	17.15
2nd Flap	20.35	20.24
3rd Flap	34.10	33.80
2nd Edge	44.38	44.87

Mode Description	TX-100 #002	TX 100 #006
	Frequency (Hz)	Frequency (Hz)
1st Flap	6.44	6.49
2nd Flap	15.16	15.14
1st Edge	25.00	25.25
3rd Flap	28.44	28.94
4th Flap	43.89	43.92

Fig. 11. Modal Frequencies for Two CX-100 and Two TX-100 Blades

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 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

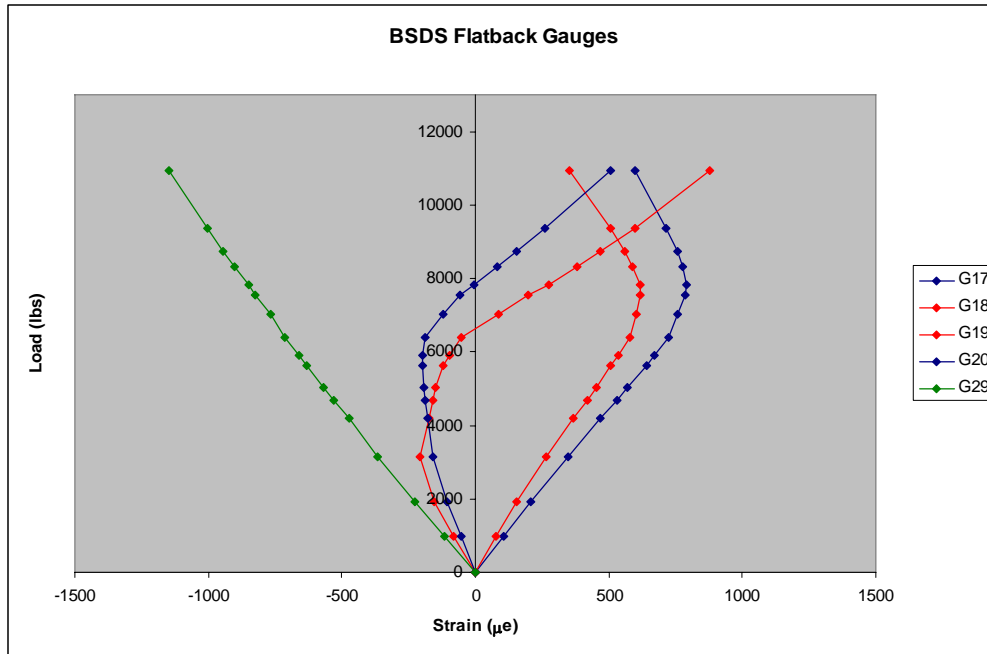


Fig. 14. Load vs. Strain for BSDS Static Test

Figure 15 shows a table of the static test results for all three prototype blades (15). 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 flatback airfoils with a more slender 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

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. Figure 17 shows the initial mold for this blade.



Fig.17. Knight and Carver Swept Blade Mold

Summary. The following are the primary summary points from this paper.

- Efforts are underway at Sandia National Laboratories to reduce blade weight growth for larger blades.
- Advanced materials and aeroelastic tailoring may prove to be beneficial for future blade designs.
- 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 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.

Where are we going next in blades? We plan to continue efforts to look for ways to achieve mass production savings, use less expensive and/or higher quality materials, and produce more efficient structural and aerodynamic designs. The NREL blade test facility has tested blades up to 45 m in length, but has reached its limit on blade length. Attempts are underway to facilitate the creation of a new, larger blade test facility. Other areas that require R&D are as follows:

- ❖ Sensors and active devices coupled to control system and condition monitoring
- ❖ Materials, blades, and components for offshore
 - Testing of materials in hot, wet conditions for marine environments
- ❖ Designs that maximize material usage
- ❖ Joints and segmented blades
- ❖ Lightning protection

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