**SANDIA REPORT**
SAND2012-9274
Unlimited Release
Printed October 2012

# A NuMAD Model of the Sandia TX-100 Blade

Brian R. Resor and Joshua Paquette

Prepared by
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**Abstract**

This report provides basic documentation of information used to create a TX-100 finite element model using NuMAD. The model is intended for use as a structural model. Use of this model for aerodynamic analyses is to be performed with caution. The TX-100 blade was designed to demonstrate the use of bend-twist coupled behavior for fatigue loads alleviation in a wind turbine blade. Refer to the References at the end of this report for full and in-depth information on the TX-100 blade project.

## ACKNOWLEDGMENTS

The authors thank the DOE Wind and Water Power Program for the support that was required to produce a blade model and blade modeling approach such as is documented in this report.

Acknowledgement of the teams who executed the Sandia blade programs of the early 2000's is needed. These are the experts who were involved in the design, manufacture, test and documentation of the CX-100, TX-100 and BSDS blade programs: Derek Berry and Steve Nolet of TPI Composites; Dayton Griffin of DNV; Mike Zuteck of MDZ Consulting; Case van Dam of UC-Davis; Kevin Jackson of Dynamic Design; Tom Ashwill, Dale Berg, Henry Dodd, Mark Rumsey, Herb Sutherland, Paul Veers, Jose Zayas of Sandia National Laboratories.

The authors thank Tyler Bushnell, Sandia National Laboratories engineering student employee, for his work in pulling together the references and documentation to produce this report.

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# NOMENCLATURE

| | |
|---|---|
| APDL | Ansys Parametric Dynamic Language |
| BPE | Beam Property Extraction tool |
| c | chord length |
| $c_{max}$ | maximum blade chord |
| FE | Finite Element |
| HP | High Pressure |
| L | blade Length |
| l/L | fractional spanwise location |
| LE | Leading Edge |
| LP | Low Pressure |
| NuMAD | Numerical Manufacturing and Design tool |
| TE | Trailing Edge |
| x/c | distance along airfoil chord |

# MODELING APPROACH

NuMAD[1] is a MATLAB[2]-based tool developed at Sandia to provide an intuitive interface for defining the outer geometry, shear web locations, materials and stacks, and stack placement in wind turbine blades. The output from NuMAD is a sequence of ANSYS[3] APDL commands used to create the finite element model in ANSYS. Once the model is created, various analyses are used to understand the strength and response of the blade to given loads.

The TX-100 and the CX-100 are the same shape. The CX-100 NuMAD model was used as a starting point for this TX-100 model. See Reference [4] for information on the CX-100 model.

The CX/TX model is based primarily on the intended design of the blade. Layup drawings are available as References [5,6,7]. Some material locations were obtained more accurately by actual measurements of a manufactured blade.

This model has not been calibrated to match blade test data. Due to possible small discrepancies in design versus manufacture, the model represents the intended blade design, but not necessarily the manufactured blade. For example, the weight of the blade model is computed to be lower than the actual blade weights.

The model described by this report is meant as a starting point for a validation project or as a tool that can be used for research and engineering studies of blades.

## Blade Geometry

The geometry of the blade is based on the ERS-100 blade. There were modifications to the root and the tip of the ERS-100 blade, but no major changes in airfoil shapes were made. The S821, S819, and S820 are used, respectively, for the inboard region (21% to 40%), 70%, and 95% radius[i].

Detailed information on the evolution of the CX-100 blade root and airfoils is found in Reference [8].

To validate the drawings, measurements were made on a TX-100 blade, and adjustments in the model were made to reflect the blade measurements.

[i] Coordinates for S-series airfoils are publicly available through the NREL NWTC webpage. Certain airfoils are patented and may be licensed through NREL. More information on patents and commercial licensing can be found at the following URL: http://wind.nrel.gov/airfoils/AirfoilLicensing.html

**Table 1: Baseline Planform Dimensions**

| Station (mm)[8] | l/L (%)[8] | Chord (m) [8] | Twist (deg) [8] | Chord length represented in model* |
|---|---|---|---|---|
| 200 | 9.4 | 0.356 | 29.6 | |
| 600 | 13.5 | 0.338 | 24.8 | |
| 1000 | 17.6 | 0.569 | 20.8 | |
| 1400 | 21.7 | 0.860 | 17.5 | 0.772 |
| 1800 | 25.8 | 1.033 | 14.7 | 1.035 |
| 2200 | 30.0 | 0.969 | 12.4 | |
| 3200 | 40.3 | 0.833 | 8.3 | |
| 4200 | 50.6 | 0.705 | 5.8 | |
| 5200 | 60.9 | 0.582 | 4.0 | X |
| 6200 | 71.2 | 0.463 | 2.7 | 0.4758 |
| 7200 | 81.5 | 0.346 | 1.4 | 0.3488 |
| 8200 | 91.8 | 0.232 | 0.4 | |
| 9000 | 100.0 | 0.120 | 0.0 | X |

*The chord length in the model largely matches the Baseline Planform Dimensions from Reference [8] for blade locations outboard of 25% span (indicated by X's). The chord length in the model differs slightly from the Baseline Planform Dimensions inboard of 25% span (indicated by as-modeled chord lengths). Blank table entries indicate discrete stations from the Baseline Planform Dimensions table that were not directly included in the blade model.

## Aerodynamic Center

Aerodynamic center at each station is assumed to be located at x/c=0.25 and 0.50 for airfoil shapes and for circular shapes, respectively. Values are interpolated in the transition between circular section and airfoil section.

## Normalized X-Offset

Normalized x-offset at each station is assumed to be x/c=0.32 and 0.50 for airfoil shapes and for circular shapes, respectively. Values are interpolated in the transition between circular section and airfoil section.

## Model Images

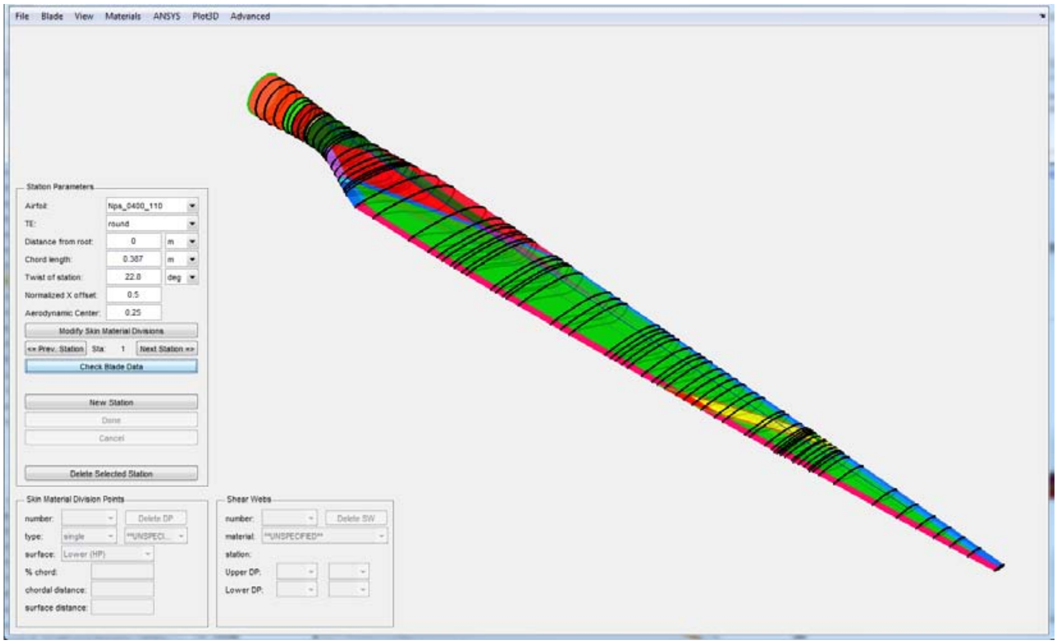



**Figure 1: TX-100 model as viewed in NuMAD v2.0.**

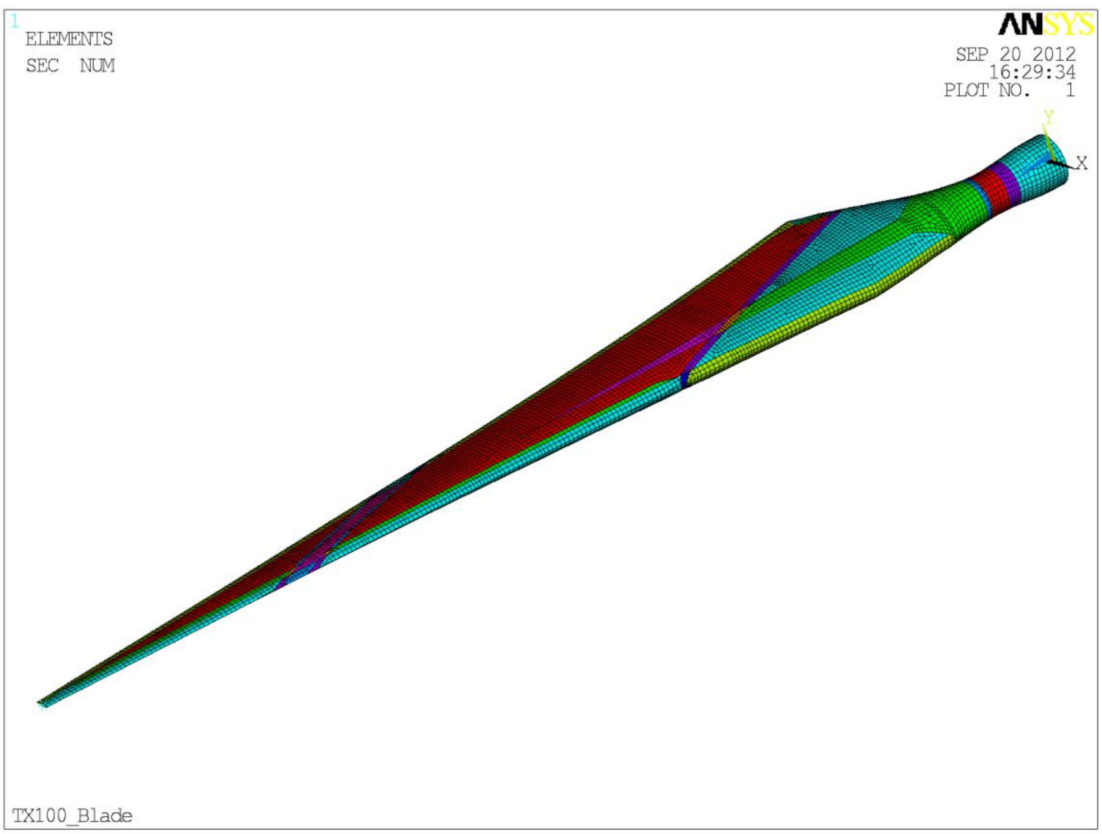



**Figure 2: TX-100 blade model in ANSYS.**

# MATERIALS

There are six materials used in the blade. Table 2 contains design values for each of these materials, which are reflected in the model.

**Table 2: Summary of material properties**

| | C260 | C520 | Seartax_ Carbon_ triax | DBM 1208 | DBM 1708 | Balsa | Gel Coat | 075oz_ Mat |
|---|---|---|---|---|---|---|---|---|
| **Ex (GPa)** | 37.30 | 37.30 | 73.85 | 9.58 | 9.58 | 0.120 | 3.44 | 7.58 |
| **Ey (GPa)** | 7.60 | 7.60 | 6.82 | 9.58 | 9.58 | 0.120 | 3.44 | 7.58 |
| **Gxy (GPa)** | 6.890 | 6.890 | 3.320 | 6.89 | 6.89 | 0.020 | 1.38 | 4.00 |
| **$v_{xy}$** | 0.31 | 0.31 | 0.25 | 0.39 | 0.39 | 0.3 | 0.3 | 0.3 |
| **P (g/cm3)** | 1.874 | 1.874 | 1.685 | 1.814 | 1.814 | 0.023 | 1.23 | 1.687 |
| **Ply Thickness** | 0.66 | 1.32 | .000625 | 0.00087 | 0.00038 | Varies | .00051 | .00033 |

There are twenty-five material composite defined by these six materials that define all areas of the model. Naming conventions are identified in Table 3.

**Table 3: Composite material naming conventions and definitions (excludes Root and Shear Web)**

| Layer Callout | Meaning | Specific Change |
|---|---|---|
| **(none)**<br>**Balsa**<br>**Spar** | (No core material)<br>Balsa Core<br>Spar Core | No core Material<br>Core is a 1/2' or 3/8’ balsa depending on location<br>Core is five layers of C520 spar material |
| **Lower**<br>**Upper** | Inboard of the 3/8’ balsa change<br>Outboard of the 3/8’ balsa change | Balsa is 1/2’ thick, additional DBM1708 layers<br>Balsa is 3/8’ m thick |
| **(none)**<br>**Strip** | (No strips of reinforcement)<br>DBM1708 LE or TE reinforcement | No additional DBM1708<br>Extra layers of DBM1708 |
| **(none)**<br>**Trans**<br>**Joint_1x**<br>**Joint_2x** | (No additional materials)<br>Transition from Lower to Upper<br>DBM1208 single layer region<br>DBM1208 double layer region | No additional materials<br>Extra layers of DBM1708<br>One layer of DBM1208 below the carbon layers<br>Two layers of DBM1208 sandwiching the carbon |

The hybrid triaxial fabric used in the layup drawings has been reproduced in the model as a layer of Seartax_Carbon_triax sandwiched between two thin (1.02 mm) layers of ±45° offset C520. This is done to reproduce similar qualities to the material used on the built blade.

Balsa thicknesses were compared with measurements on the real blade, and the measured thickness of balsa is used in the model. The difference is described in Table 4.

**Table 4: Balsa thickness adjustments to match measured thicknesses**

| Named thickness | Real thickness (reflected in model) |
|---|---|
| Balsa 1/2' | 9.525 mm |
| Balsa 3/8’ | 7.020 mm |

## Measured Material Properties

Mechanical tests were performed in order to determine the as-built mechanical material properties for the blade materials. The test-derived values have not been included in the model here, but the results of those tests are included in this report as Appendix A.

## Material Layup

Drawings for manufacture of this blade are available as References [5,6,7] of this report.

The model is based primarily on these drawings but is supplemented with actual measurements of a manufactured blade.

## Shear Web

The shear web has a very simple material layup that is shown in Table 5.

**Table 5: Shear Web Material Definition**

| Layer # | Material | Thickness |
|---|---|---|
| 1 | DBM1708 | 1.740 mm |
| 2 | Balsa | 9.000 mm |
| 3 | DBM1708 | 1.740 mm |

## Blade Root Hardware

Blade root hardware is not included in this model of the TX-100 blade.

## Blade Root

The material layup drawings call for the root to taper off from over forty layers to about eight. The layers come in blocks, so the model reflects three critical material changes during the taper, at 0.236 m, 0.326m, 0.498 m, and 0.638 m from root. These stations have simplified material layers that equals the summation of layer thicknesses in the actual blade.

## Angled Transition

The TX-100 blade features an angled material transition that runs at 20° across the blade. At this transition, the (so called) 1/2' balsa core changes to a 3/8’ balsa core. The layer of DBM1708 also changes to the hybrid carbon triaxial fabric, placed at 20° offset. The two inch transitional area has DBM1708 overlapping the carbon triaxial fabric, and has a 1/2' balsa core. The transitional area can be seen as the overlap of DBM1708 over the carbon layer in Figure 3.

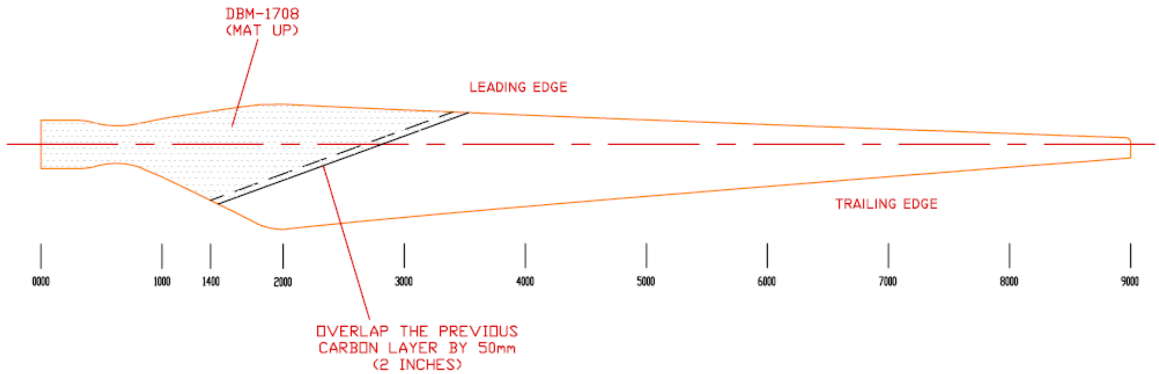



**Figure 3: The lower DBM1708 layer overlap marks the transitional area of the blade.**

## Spar Cap

The spar cap begins at the root, and continues through all of the root ply-drops before thinning, and then tapering off to a point at the station 4.611 m from the root. The diagram of the spar cap which was reported as being the 'as built' diagram was different from the actual measurements made on the blade sections, so the model reflects a spar cap that is the mean between the two. The shape and definitions of the spar cap used in the model can be seen in Figure 4.

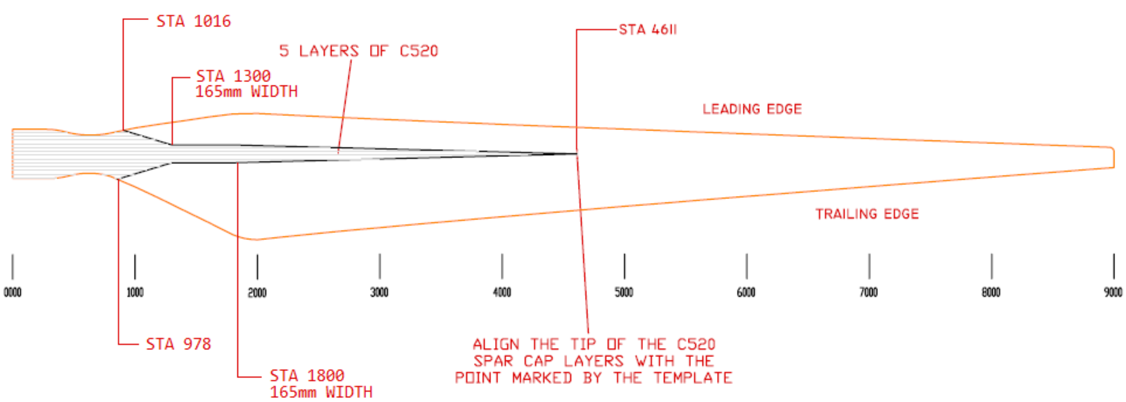



**Figure 4: The spar cap shape and size.**

## DBM1208 Butt Joint

There are two strips of DBM1208 that sandwich both layers of carbon triaxial fabric along a seam in the outboard sections of the blade. This seam is due to the thickness of the carbon fabric being 1270 mm, and not being able to cover the entire blade in one sweep. As seen in Figure 5, one layer is 4' and the other is 6', which creates two regions where only one layer exists (_1x), and one region where both layers overlap (_2x). These regions are reflected as accurately as possible in the model.

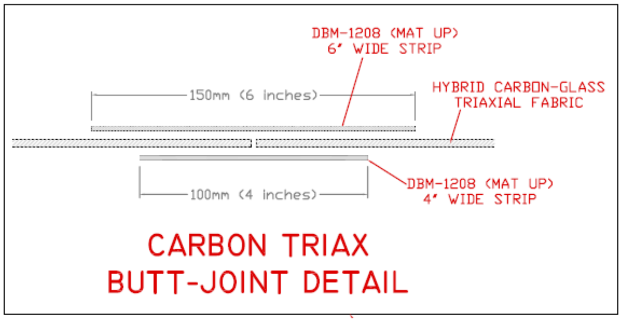



**Figure 5: Butt-Joint Detail**

## Defining Material Locations

Excel was used to manage algorithms for finding crucial material division points on the blade skin. First, the blade outline was plotted. Lines were then plotted to represent where material changes would occur, and the intersections of these lines would dictate where a new station would need to be made. Finally, each material division point was placed.

The downfall to this method is that in the TX-100 blade layup drawings have many definitions based on surface distance (i.e. where the leading and trailing edge balsa begins). This means that using the 'chord %' definition is a close approximation, and is off in a few spots, especially near the leading and trailing edges. To offset some of errors that occur due to the approximation, the model's leading edge uses measured surface distances, and are correct to drawing. This, however, required an iterative approach to solving material intersects, and may cause some uneven lines in the model.

## Leading Edge Alterations

The leading edge has some alterations to the material to avoid shell element errors in ANSYS. Leading edge material composites were renamed with a modifying tag: "_x10". The modification indicates that the 'strip' of DBM1708 in that composite was made ten times as strong, stiff, and dense, and one tenth the thickness. This modification has been done in small areas around the joints, and not the entire leading edge.

# BLADE MODEL ARCHIVE FILES

## NuMAD Project Files

The following files are located in the TX-100 blade model folder, *TX100_v1.0:*

### *TX100_v1.0.nmd*

The NuMAD blade model data file. This file is for use with NuMAD v2.0.

### *MatDBsi.txt*

The NuMAD material data file.

### *shell7.src*

Output from NuMAD. This file contains the APDL commands that are used directly in ANSYS to create the TX-100 shell element model using the command string "/INPUT,shell7,src" at the ANSYS command input.

### *zAirfoil.mac, zFlatback.mac, zSmoothe.mac*

These are ANSYS macro files that are required to execute the commands found in the *shell7.src* file. These macros must remain in the same folder as the shell7 file when the ANSYS input execution is performed.

## 'Airfoils' Folder

Following is a list of the airfoil shape files found in the TX-100 *airfoils* folder:

| | |
|---|---|
| CXTX_0450_110f.txt | CXTX_4600_110.txt |
| CXTX_0500_110f.txt | CXTX_4729_110.txt |
| CXTX_0570_110f.txt | CXTX_4800_110.txt |
| CXTX_0653_110f.txt | CXTX_4865_110.txt |
| CXTX_0667_110f.txt | CXTX_5024_110.txt |
| CXTX_0700_110f.txt | CXTX_5144_110.txt |
| CXTX_0800_110f.txt | CXTX_5200_110.txt |
| CXTX_0900_110f.txt | CXTX_5280_110.txt |
| CXTX_1200_110f.txt | CXTX_5410_110.txt |
| CXTX_1400_110f.txt | CXTX_5500_110.txt |
| CXTX_1600_110f.txt | CXTX_5600_110.txt |
| CXTX_1800_110f.txt | CXTX_5700_110.txt |
| CXTX_0400_110.txt | CXTX_5853_110.txt |
| CXTX_0978_110.txt | CXTX_5943_110.txt |
| CXTX_1016_110.txt | CXTX_6200_110.txt |
| CXTX_1054_110.txt | CXTX_6248_110.txt |
| CXTX_1300_110.txt | CXTX_6420_110.txt |
| CXTX_1471_110.txt | CXTX_6498_110.txt |
| CXTX_1536_110.txt | CXTX_6530_110.txt |
| CXTX_1568_110.txt | CXTX_6557_110.txt |
| CXTX_2000_110.txt | CXTX_6583_110.txt |
| CXTX_2400_110.txt | CXTX_6600_110.txt |
| CXTX_2618_110.txt | CXTX_6650_110.txt |
| CXTX_2719_110.txt | CXTX_6722_110.txt |
| CXTX_2780_110.txt | CXTX_6738_110.txt |
| CXTX_2870_110.txt | CXTX_6799_110.txt |
| CXTX_2915_110.txt | CXTX_6857_110.txt |
| CXTX_3000_110.txt | CXTX_6908_110.txt |
| CXTX_3050_110.txt | CXTX_6925_110.txt |
| CXTX_3400_110.txt | CXTX_6960_110.txt |
| CXTX_3499_110.txt | CXTX_7027_110.txt |
| CXTX_3632_110.txt | CXTX_7200_110.txt |
| CXTX_3800_110.txt | CXTX_7632_110.txt |
| CXTX_4000_110.txt | CXTX_7800_110.txt |
| CXTX_4110_110.txt | CXTX_8123_110.txt |
| CXTX_4207_110.txt | CXTX_8200_110.txt |

# EXAMPLE ANALYSES

Following are results from basic analyses. These results can be used as a baseline for comparison if the user needs to check the validity of their model against the original archive files.

## Mesh Size

The global element size (AESIZE setting in ANSYS) is set to 0.04 meters.

## Model Mass

The overall model mass is 129.12 kg, as calculated by ANSYS. The spanwise location of the blade center of mass is at 2.2443 meters.

Based on actual measurements of the first series of production blades[9], the weight of the average as-built TX-100 blade is 163.7 kg and the spanwise location of the blade center of mass is at 2.339 meters.

## Modal Analysis

A cantilevered modal analysis of the TX-100 ANSYS model is performed. The Block Lanczos solver is used to find six modes.

**Table 6: Results from an ANSYS modal analysis.**

| Mode | Frequency (Hz) | Shape |
|---|---|---|
| 1 | 2.54243 | 1st flapwise bending |
| 2 | 5.60683 | 1st edgewise bending |
| 3 | 7.16985 | 2nd flapwise bending |
| 4 | 13.4206 | 3rd flapwise bending |
| 5 | 20.5506 | 2nd edgewise bending |
| 6 | 23.5207 | 4th flapwise bending |

## Static Analysis

A cantilevered static analysis was performed on the TX-100 ANSYS model, using a flapwise (t-direction) 1000 N pull on the tip of the blade. Results were processed using the material coordinate system (RSYS,SOLU) and mid-thickness results (SHELL, MIDDLE). Shown is the elastic strain in the material x-direction, or blade spanwise direction. Maximum tip displacement computed with this analysis is 1.66051 meters.

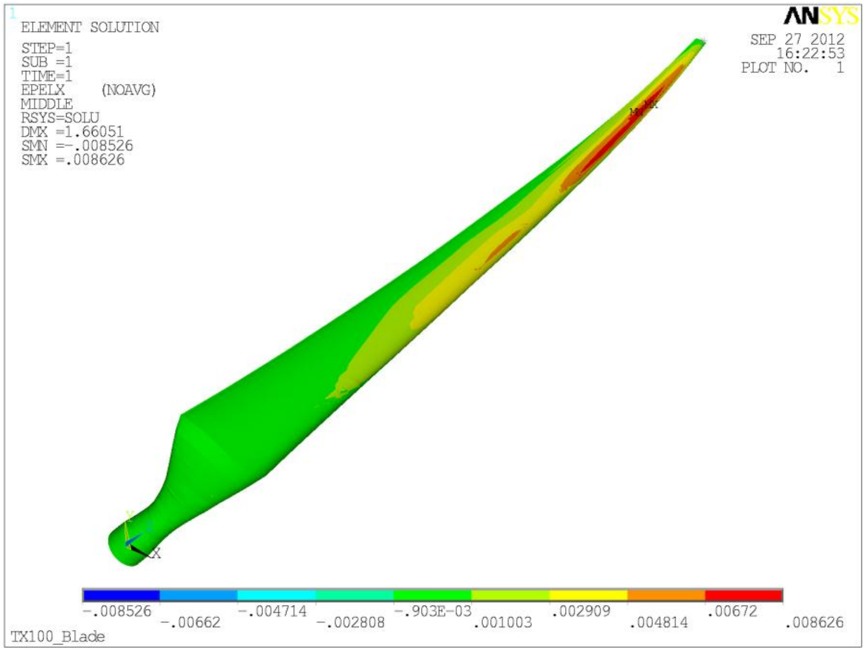
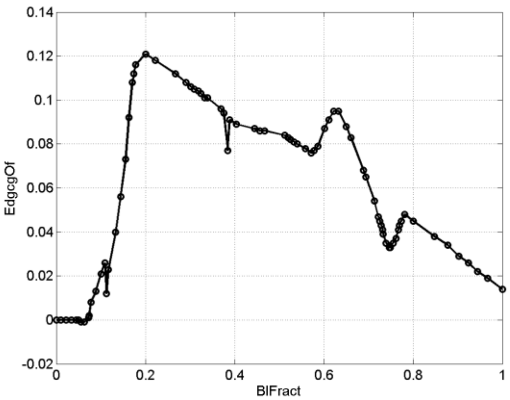
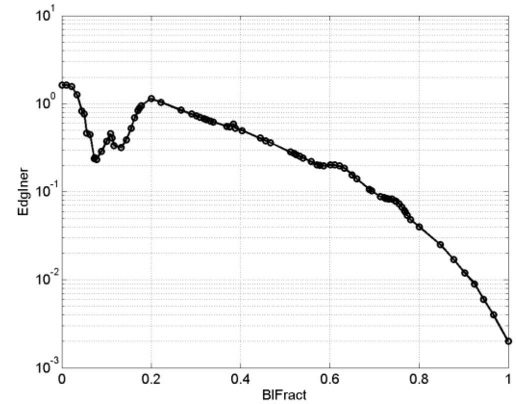


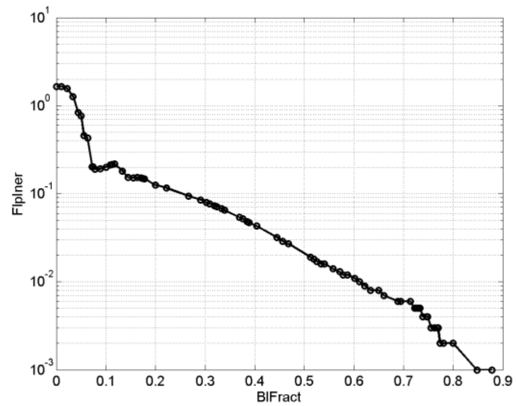

**Figure 6: A plot of the composite material x-direction strain resulting from a static analysis of the TX-100 blade; view of HP surface is shown.**

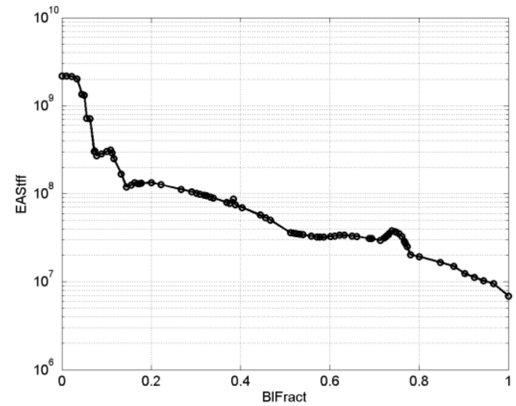
## PreComp Analysis

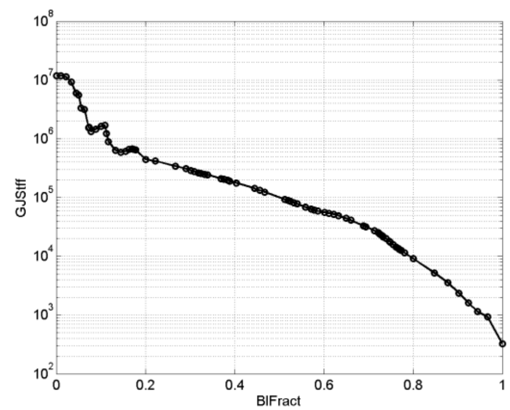
NuMAD v2.0 provides the capability to use PreComp[10] to compute sectional properties of the blade based on the information contained in the NuMAD blade model. Following are the results of those analyses:

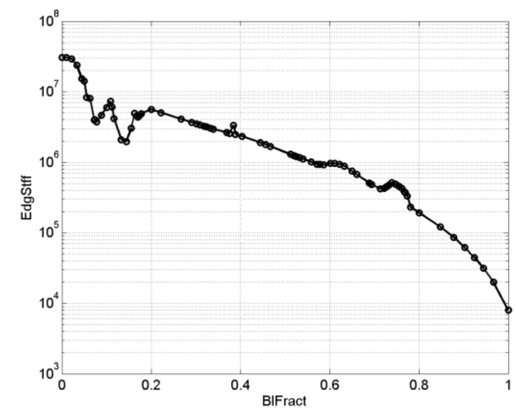


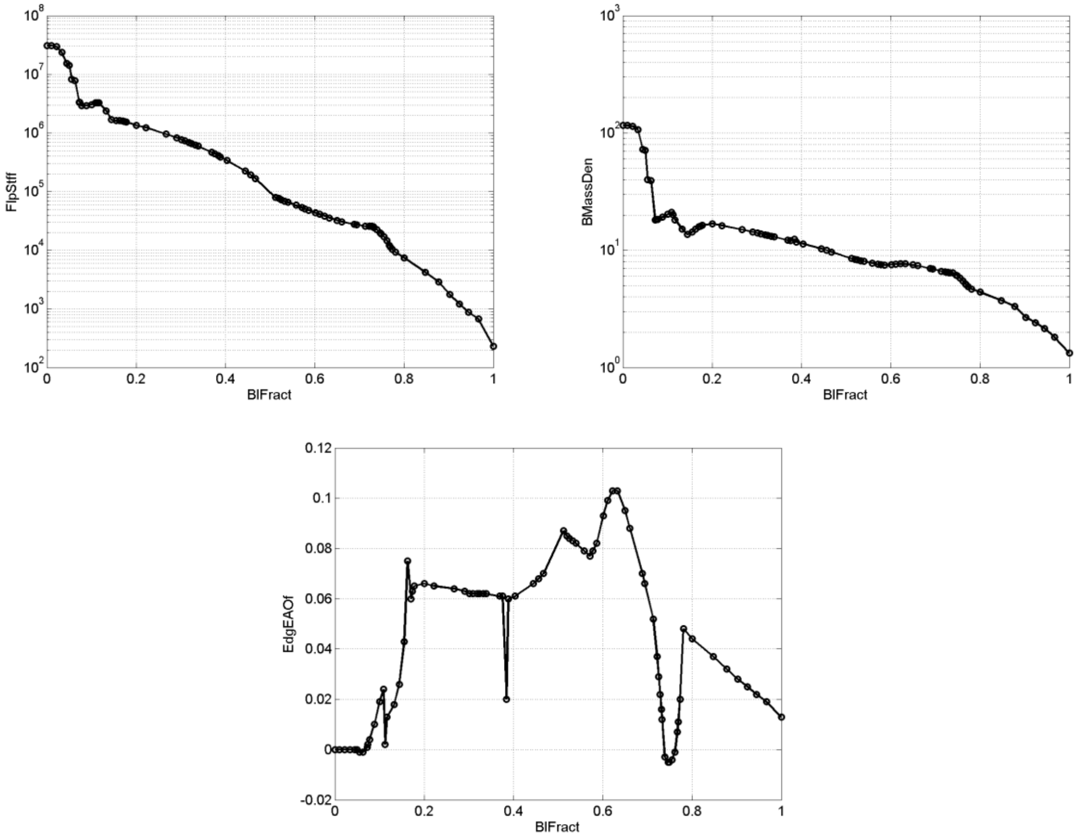
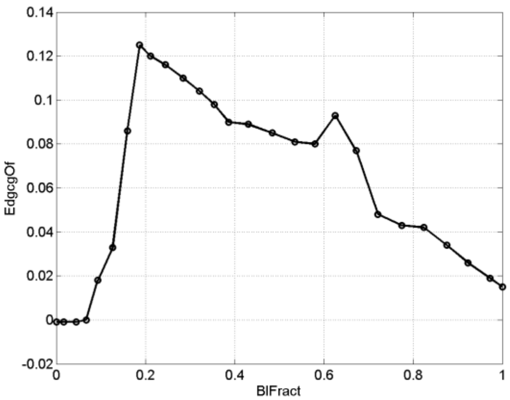
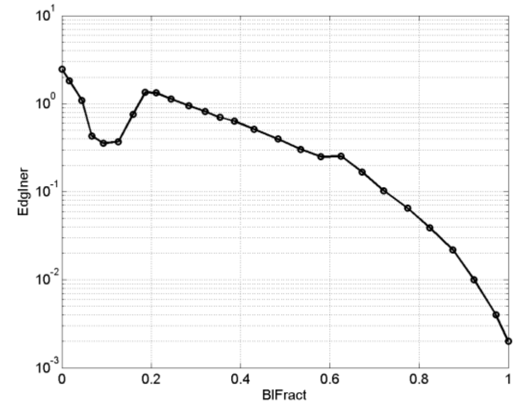


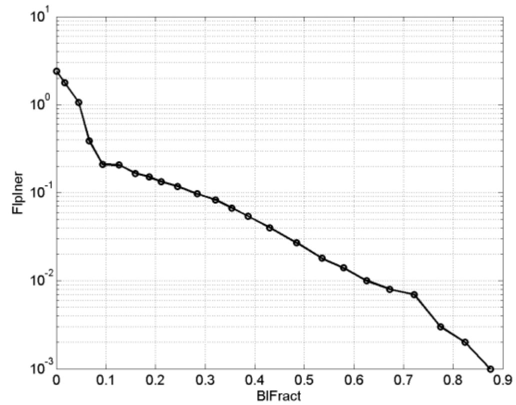

**Figure 7: Section properties computed using PreComp; parameters definitions are consistent with FAST blade input file inputs.**

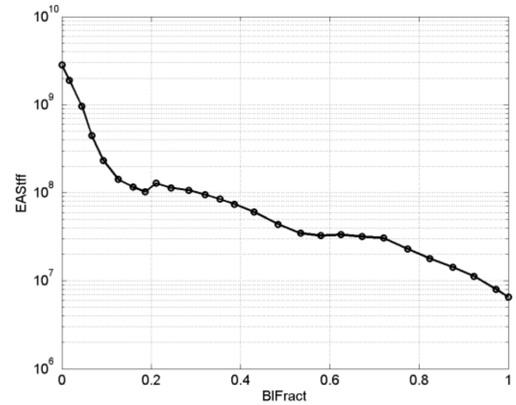
## BPE Analysis

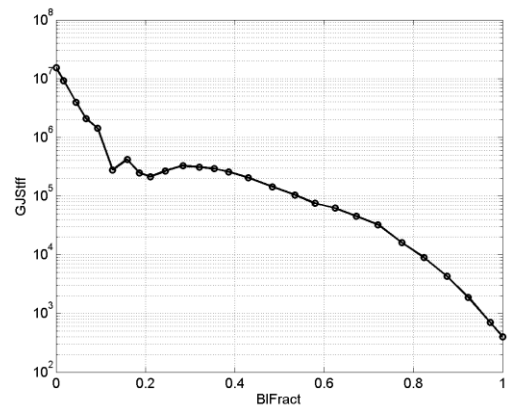
BPE is an approach used to compute equivalent section properties of the three-dimensional blade model using an inverse approach[11]. Following are the blade cross section property distributions computed using BPE:

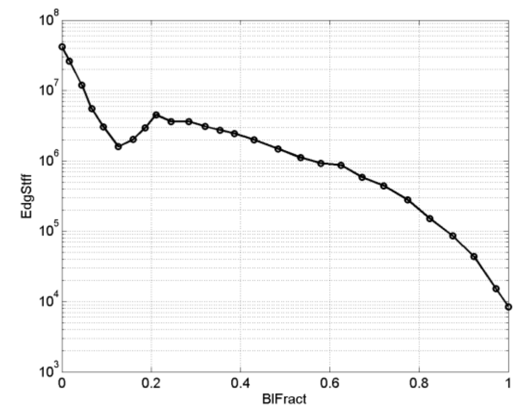


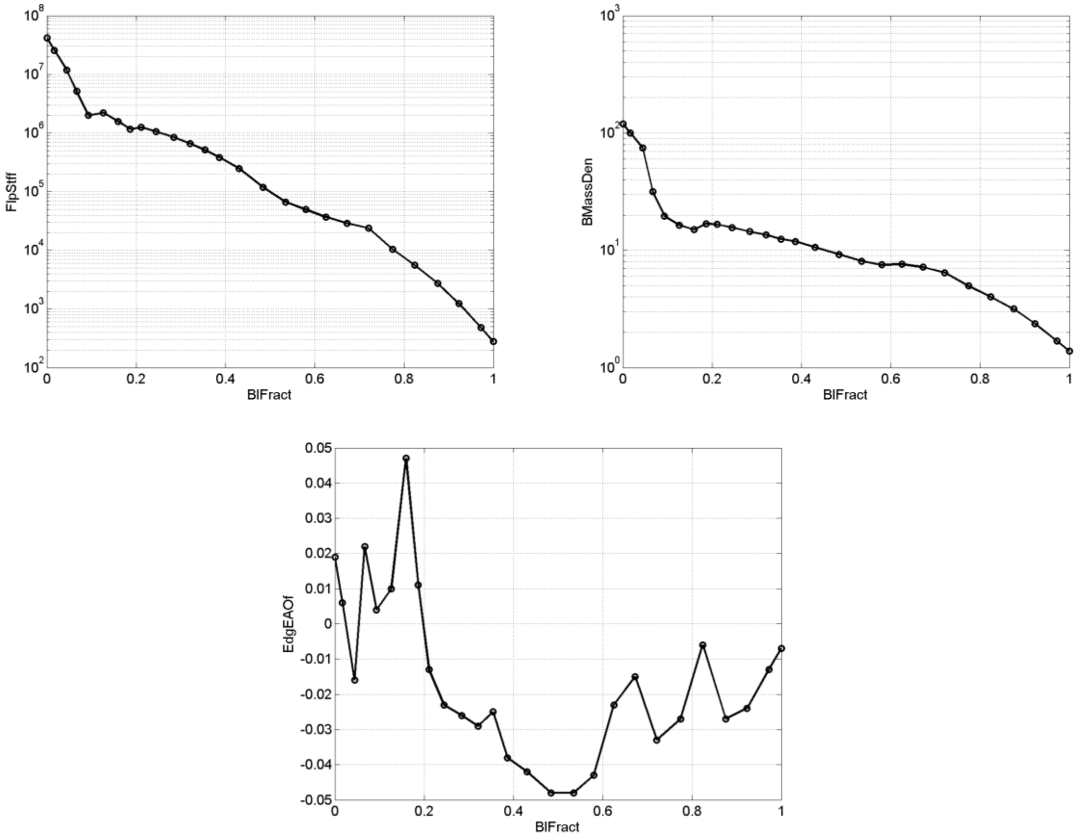



**Figure 8: Equivalent section properties computed using BPE; parameters definitions are consistent with FAST blade input file inputs.**

# ADDITIONAL TX-100 BLADE RESOURCES

Berry, Derek and Ashwill, T. “TX-100 Manufacturing Final Project Report.” Sandia Report SAND2007-6066. Printed November 2007.
http://prod.sandia.gov/techlib/access-control.cgi/2007/076066.pdf

D. Berry, T. Ashwill "Design of 9-Meter Carbon-Fiberglass Prototype Blades: CX-100 and TX-100" SAND07-0201
http://prod.sandia.gov/techlib/access-control.cgi/2007/070201.pdf

J.R. Zayas, P.L. Jones, A. Holman "CX-100 and TX-100 Blade Field Tests" SAND05-7454
http://prod.sandia.gov/techlib/access-control.cgi/2005/057454.pdf

J. Paquette, J. van Dam and S. Hughes. “Structural Testing of 9 m Carbon Fiber Wind Turbine Research Blades.” Conference Paper NREL/CP-500-40985. January 2007.
http://www.nrel.gov/wind/pdfs/40985.pdf

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# APPENDIX A:
# MEASUREMENT OF AS-BUILT BLADE MATERIAL PROPERTIES

Modern wind turbine blades are composed of composite materials. Normally, composite material properties are found either by micromechanics and laminate theory calculations, or from conducting experiments on samples made exclusively for testing purposes. However, wind turbine blades are commonly manufactured by resin transfer processes and thus, have some uncertainty associated with the material properties in their as-manufactured form. To address this problem, testing was conducted on samples that were cut directly from three, 9-meter wind turbine blades. The coupons were selected from different areas of the blade to allow for back-calculation of the properties of the individual materials contained within the samples. Mass and stiffness properties were then obtained by measuring and weighing the specimens and by conducting simple mechanical tests.

## Specimen Preparation

The specimen set consisted of 5-in. by 1-in. samples that were cut from different areas of the blades.  The locations were selected such that an adequate number of combinations of lamina would exist to solve for the unknown thickness, density, and elastic properties of each lamina.  The specimens were outfitted with bi-axial rosette strain gages bonded front and back.  Eight lay-up configurations in total were tested with three samples from each lay-up.  These configurations included both longitudinal and transverse fiber orientations for the mostly unidirectional materials, while quasi-isotropy was assumed for chopped and biaxial materials.  The samples were thoroughly measured and weighed for later geometry and density calculations.


**Figure 9:  Blade sections after removing samples.  From left to right: BSDS, TX-100 and CX-100 blades.**

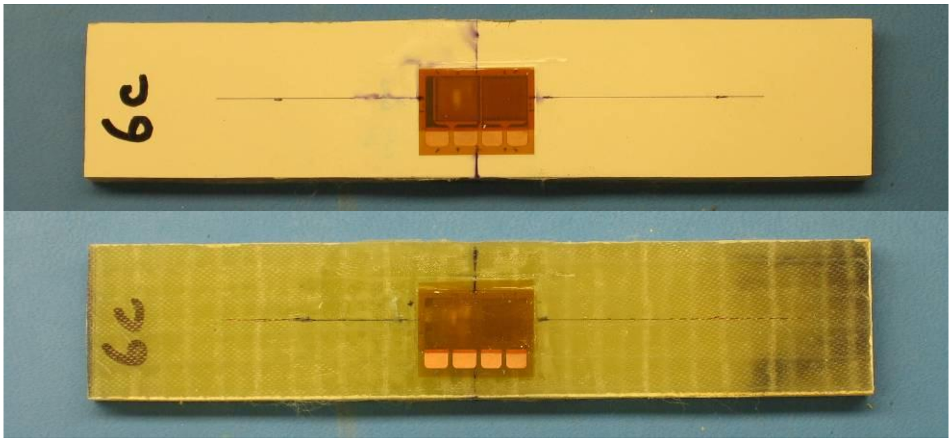


**Figure 10: Instrumented test coupons.**

## Mechanical Testing

Mechanical testing of the samples was conducted using both uniaxial and, in some cases, 3-point bending tests as some of the specimens had too much curvature to grip and test accurately with a uniaxial test. For the uniaxial tests, the grip length was 1-in. on each end, leaving 3-in. of gage section. The samples were cycled twice at 6 minutes per cycle, and were tested to 5000 micro-strain to determine a large range of stress-strain response while avoiding breakage. The data was collected at 2 Hz.

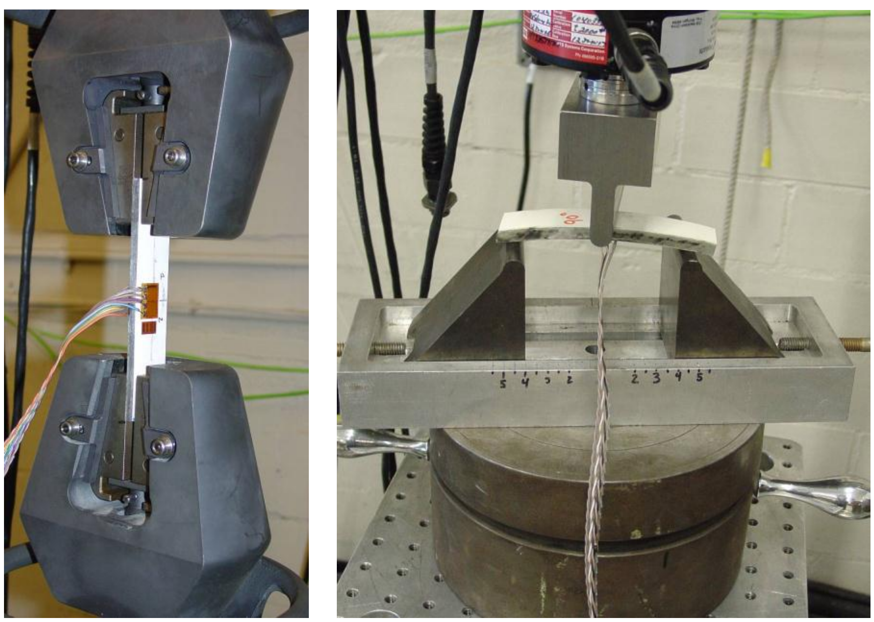

**Figure 11: Uniaxial (left) and 3-point bending (right) testing configurations.**

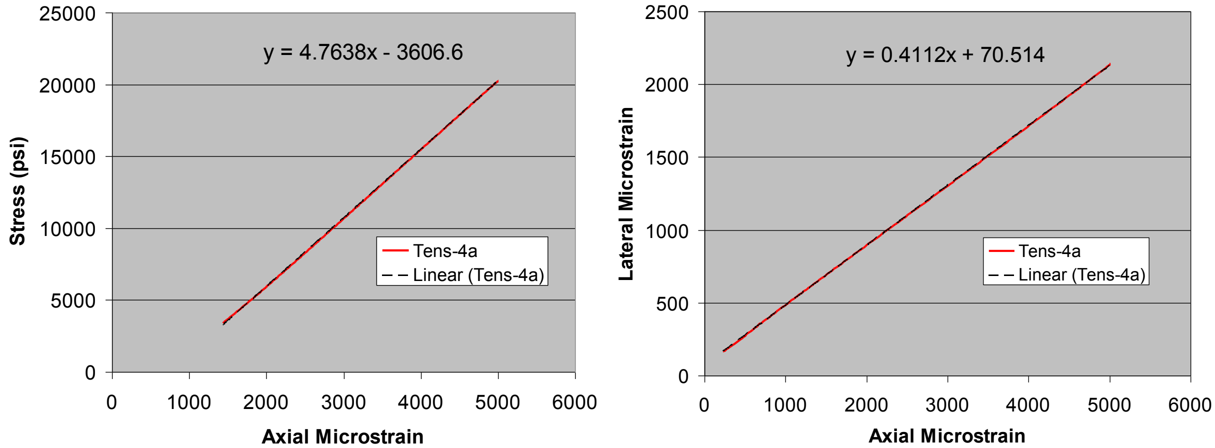


**Figure 12: Typical stress-strain results from test specimens.**

## Material Property Calculation

Classical Lamination Theory combined with experimental results was used to predict material properties, while data from various sources was used as check on calculations. The laminate thickness and weight of each specimen were measured directly. The results were then used to back-calculate lamina density and thickness using rule of mixtures. Calculation of elastic properties was conducted as follows.

The constitutive elastic stress-strain relationship for a lamina is given by

$$\{\sigma\} = [Q]\{\epsilon\}$$

where the rigidity $Q$ is given by

$$[Q] = \begin{bmatrix} E_{11}/\Delta & \upsilon_{12}E_{22}/\Delta & 0 \\ \upsilon_{12}E_{22}/\Delta & E_{22}/\Delta & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \quad \text{and} \quad \Delta = 1 - \upsilon_{12}^2 E_{22}/E_{11}$$

For lamina fiber angle θ relative to the laminate coordinate system, $Q$ can be transformed into the laminate coordinate system through

$$[\bar{Q}] = [T]^{-1}[Q][R][T][R]^{-1}$$

where

$$[T] = \begin{bmatrix} \cos^2(\theta) & \sin^2(\theta) & 2\cos(\theta)\sin(\theta) \\ \sin^2(\theta) & \cos^2(\theta) & -2\cos(\theta)\sin(\theta) \\ -\cos(\theta)\sin(\theta) & \cos(\theta)\sin(\theta) & \cos^2(\theta) - \sin^2(\theta) \end{bmatrix} \quad \text{and} \quad [R] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2 \end{bmatrix}$$

The laminate force-strain relationship is then given by

$$\begin{Bmatrix} N_{11} \\ N_{22} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{12} & A_{22} \end{bmatrix} \begin{Bmatrix} \epsilon_{11} \\ \epsilon_{22} \end{Bmatrix} \quad \text{and} \quad A_{ij} = \sum_{k=1}^{N} \left(\bar{Q}_{ij}\right)_k t_k$$

with layer thickness $t_k$.

Similarly, the laminate moment-curvature relationship is given by

$$\begin{Bmatrix} M_{11} \\ M_{22} \end{Bmatrix} = \begin{bmatrix} D_{11} & D_{12} \\ D_{12} & D_{22} \end{bmatrix} \begin{Bmatrix} \kappa_{11} \\ \kappa_{22} \end{Bmatrix} \quad \text{and} \quad D_{ij} = \sum_{k=1}^{N} \left(\bar{Q}_{ij}\right)_k \left(t_k \bar{z}_k^2 + \frac{t_k^3}{12}\right)$$

with layer thickness $t_k$ and distance from mid-laminate to mid-lamina $z_k$.

Using these relationships along with the lamina thickness calculations performed previously, the lamina elastic moduli and Poisson ratio can be back-calculated from the tensile and bending test results.

The resulting layer thickness, density, longitudinal and transverse elastic modulus, and Poisson ratio are shown in Table 1.

**Table 7: Calculated as-built material properties.**

| Material | Layer Thickness (mm) | Density (kg/m$^3$) | $E_{11}$ (GPa) | $E_{22}$ (GPa) | $\nu_{12}$ |
|---|---|---|---|---|---|
| GelCoat | 0.51 | 1235 | 4.96 | 4.96 | 0.006 |
| 3/4 oz Random Mat Glass* | 0.21 | 2058 | 15.15 | 15.15 | 0.590 |
| 6 oz Woven Glass* | 0.13 | 2076 | 42.22 | 42.20 | 0.857 |
| DBM-1208 ±45°Glass | 0.38 | 1659 | 12.42 | 12.41 | 0.202 |
| DBM-1708 ±45°Glass | 0.87 | 1659 | 11.12 | 11.12 | 0.612 |
| C-260 Unidirectional Glass | 0.57 | 1986 | 45.77 | 10.09 | 0.258 |
| C-520 Unidirectional Glass | 1.13 | 1986 | 45.77 | 10.09 | 0.302 |
| SAERTEX Carbon/Glass Triax | 0.81 | 1750 | 91.99 | 17.48 | 0.509 |
| *Due to very small amounts of this material in the samples tested, these results could have large errors. | | | | | |

Material thickness correlates well to predicted values. Material stiffness and density vary significantly from predicted values. Tested unidirectional carbon density is approximately 50% lower than the value used in current model. These variations in values would contribute significantly to results from model analyses and further work would be required to perform a full model calibration and validation exercise using these measured data.

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