Background, Purpose, and Objective

- **Background**
  - SNL initiated a blade research program in 2002 to investigate the use of carbon in subscale 9 m blades
  - 7 blades manufactured from each of three designs: CX-100, TX-100, and BSDS

- **Purpose of Lab and Field Tests**
  - Verify that blades met their design criteria
  - Investigate unique structural aspects of the blades
  - Examine the use of advanced sensors

- **Overview**
  - 9 m Blade Design Concepts
  - Design Innovations: Inclusion of Carbon, Twist-Bend Coupling, Flatback Airfoils
  - Final 9m Designs
  - Testing: Static, Fatigue, Field
  - Conclusions
9 m Blade Design Concepts

- **CX-100 (Carbon Experimental 100 kW)**
  - Based on ERS-100 blade outboard and NW-100 root
  - Glass-Epoxy blade with full length carbon spar cap
- **TX-100 (Twist-Bend Coupled Experimental 100 kW)**
  - Based on ERS-100 blade outboard and NW-100 root
  - Glass-epoxy blade with terminating glass spar cap
  - 20° off-axis carbon in outboard (~>3.5 m) skins to produce material-induced, passive aerodynamic load alleviation
- **BSDS (Blade System Design Study)**
  - Advanced design featuring flat back airfoils, full-length constant thickness carbon spar cap, integrated root studs, high performance airfoils, and a large, thin root
Carbon in Blades

- Advantages:
  - High stiffness/weight ratio
  - Highly orthotropic
  - Excellent fatigue properties with straight fibers

- Disadvantages:
  - Higher cost
  - Limited availability
  - Difficult to infuse
  - Poor properties with wavy fibers
  - Possible stiffness mismatch issues

- Potential solution: SAERTEX glass/carbon triax fabric
  - Relatively inexpensive
  - Infusible
  - Dry fabric for conventional infusion techniques
  - Maintains excellent fiber straightness

Studies of carbon materials performed by and in collaboration with GEC and MSU
Skin Material-Based Twist Bend Coupling

- Couples tension/compression and shear strains in blade skins
- Produces passive aerodynamic load alleviation
- Requires orthotropic materials

Source: NREL

Material Induced Twist-Bend Coupling

TX-100 Blade Skin

2008 Wind Turbine Blade Workshop
May 12th, 2008
Flatback Airfoils

- Flatback airfoils created by the symmetric addition of thickness about the camber line
- Different from truncated airfoils which “chop” the trailing edge off and thus lose camber

Advantages
- Increased sectional area moment
- Reduced sensitivity to surface soiling compared with conventional thick airfoils

Disadvantages
- Increased drag
- Unknown and complex 3D flow
- Greater aero-acoustic emissions*

*Study of flatback airfoils performed in collaboration with UC Davis

Source: Tanner (1973)
9 m Blade Designs: Materials

- Carbon
- Glass
- Fiber Direction
- TX-100
- BSDDS
9 m Blade Designs: Geometry

- **Flatback**
- **Root**
- **Max-Chord**
- **Tip**
- **High Performance Airfoils**

Diagram showing the geometry of 9 m blade designs with labels for flatback, root, max-chord, and tip. Also includes a graph showing span in meters for BSDS, CX, TX, and TX-100.
Static Test Setup

- **PULLEY**
- **WIRE ROPE**
- **LOAD SADDLE**

Graph:
- **Desired Test Load**
- **Applied Test Load**

Axes:
- **Moment (kN-m)**
- **Blade Station (m)**

Diagram:
- **OVERHEAD CRANE**
- **LOAD CELL**
- **SPREADER BAR (2)**
- **TEST STAND**
- **TEST BLADE**
- **LOAD SADDLE**
Static Test Instrumentation

- String Potentiometers
- Acoustic Sensors
- Inclinometers
- Strain Gages
- String Potentiometers
Static Test Results: Spar Cap Strains

![Graph showing strain values for different blade stations and models.](image-url)
Static Test Results: TX-100 Twist

Blade #007

Blade #004

Rotations Measured at 44.0 kN-m Root Moment

67.7 kN-M Root Moment

116.9 kN-m Root Moment

TX-100 Blade #004
Test Results and Analysis: Aft Panel Strains

Note: 0% = HP Edge, 100% = LP Edge
Static Test Results: CX-100 AE Event Location

*Note: Energy defined as area under V-t curve.*
Static Test Results: BSDS AE Event Location

*Note: Energy defined as area under V-t curve.

Energy:
- <100
- 100-1000
- >1000

Static Test Results: BSDS AE Event Location
Static Test Results: AE Accumulation

![Energy vs Root Moment Graphs for BSDS, CX-100, TX-100, and BSDS](image_url)
Summary of 9 m Results

<table>
<thead>
<tr>
<th>Property</th>
<th>CX-100</th>
<th>TX-100</th>
<th>BSDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (lb)</td>
<td>383</td>
<td>361</td>
<td>289</td>
</tr>
<tr>
<td>% of Design Load at Failure</td>
<td>115%</td>
<td>197%</td>
<td>310%</td>
</tr>
<tr>
<td>Root Failure Moment (kN-m)</td>
<td>128.6</td>
<td>121.4</td>
<td>203.9</td>
</tr>
<tr>
<td>Max. Carbon Tensile Strain at Failure (%)</td>
<td>0.31%</td>
<td>0.59%</td>
<td>0.81%</td>
</tr>
<tr>
<td>Max. Carbon Compressive Strain at Failure (%)</td>
<td>0.30%</td>
<td>0.73%</td>
<td>0.87%</td>
</tr>
<tr>
<td>Maximum Tip Displacement (m)</td>
<td>1.05</td>
<td>1.8</td>
<td>2.79</td>
</tr>
</tbody>
</table>
CX-100 and TX-100 Fatigue Simulations

CX-100
(Static Driven Design)

TX-100
(Fatigue Driven Design)
Fatigue Loading

CX-100
(Single Point Loading)

TX-100
(Resonant Loading)
CX-100 Fatigue Test

(click image to play video)

CX-100 Early in Fatigue Test

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CX-100 Fatigue Test

CX-100 Dimple (left) and Tip Movement (right) at Failure
CX-100 Fatigue Failure Mechanism

- Dimple formed early during test around max chord
- Low pressure skin pushed outward aft of spar cap and inward forward of spar cap
- At 1.5M cycles, crack began to grow along spar cap/aft-panel intersection
- Crack resulted in greatly decreased stiffness in the area and cause severe edgewise movement

CX-100 Crack Growth
TX-100 Fatigue Test

TX-100 Early in Fatigue Test

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TX-100 Test Results

TX-100 Sparcap Tip Stress Contours

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May 12th, 2008
TX-100 Fatigue Failure Mechanism

- At 723k cycle count, crack began to grow just outboard of HP spar cap termination
- Cracks grew at 65° angle from blade axis until 2.4M cycles
- Crack then changed direction and grew along 20° direction corresponding to carbon fiber direction
- Growth of crack continued until 4M cycles when excessive torsional movement of the blade tip occurred
Site
6 m/s average wind speed at 10 m

Measurements
■ 40 Hz Data
■ Currently recording 47 channels
■ Inflow
  • Center and off-axis met towers, and nacelle
  • Wind speed and direction
■ Power
■ Loads
  • Tower, hub, and blade
■ Noise
ATLAS II (Accurate Time-Linked data Acquisition System)

- Built for Wind Turbine Applications
- Compact
- Continuous Operation (24/7)
- High Reliability
- Automated Acquisition and Archiving
- Lightning Protection on all Channels
- Wireless Data Acquisition and Programming

ATLAS II Ground (top) and Rotor (bottom) Units
CX-100 Field Test Results

- Wind Speed (m/s):
  - Hub Edge
  - Hub Flap

- Moment (kN-m):
  - Wind Speed (m/s)
  - Power (kW)
Conclusions

- Infused carbon was effectively implemented in 9m blade designs
- All blade designs survived static test loadings
- TX-100 blade displayed twist-bend coupling
- Strains of over 8000 me (tension and compression) measured in BSDS carbon spar cap
- BSDS flat back behaved well at and beyond test load
- Acoustic emissions monitoring detected locations of damage as well as blade failure loads
- CX-100 and TX-100 blades survived 20-year damage equivalent fatigue tests
- CX-100 failed in fatigue due to buckle formation near max-chord which caused a fracture between the sparcap and aft balsa panel leading to excessive edge movement
- TX-100 failed in fatigue due to crack which grew from sparcap termination on HP surface along carbon fiber direction causing excessive tip rotation
- Both blades failed in or near carbon areas
- Blades failed due to damage in off-axis directions, showing the difficulty in using simple, fiber-direction fatigue calculations
- Initial results show CX-100 performed as expected
Acknowledgements

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