Fatigue Testing of 9 m Carbon Fiber Wind Turbine Research Blades

Joshua Paquette
Sandia National Laboratories

Scott Hughes and Jeroen van Dam
National Renewable Energy Laboratory

Jay Johnson
Georgia Institute of Technology

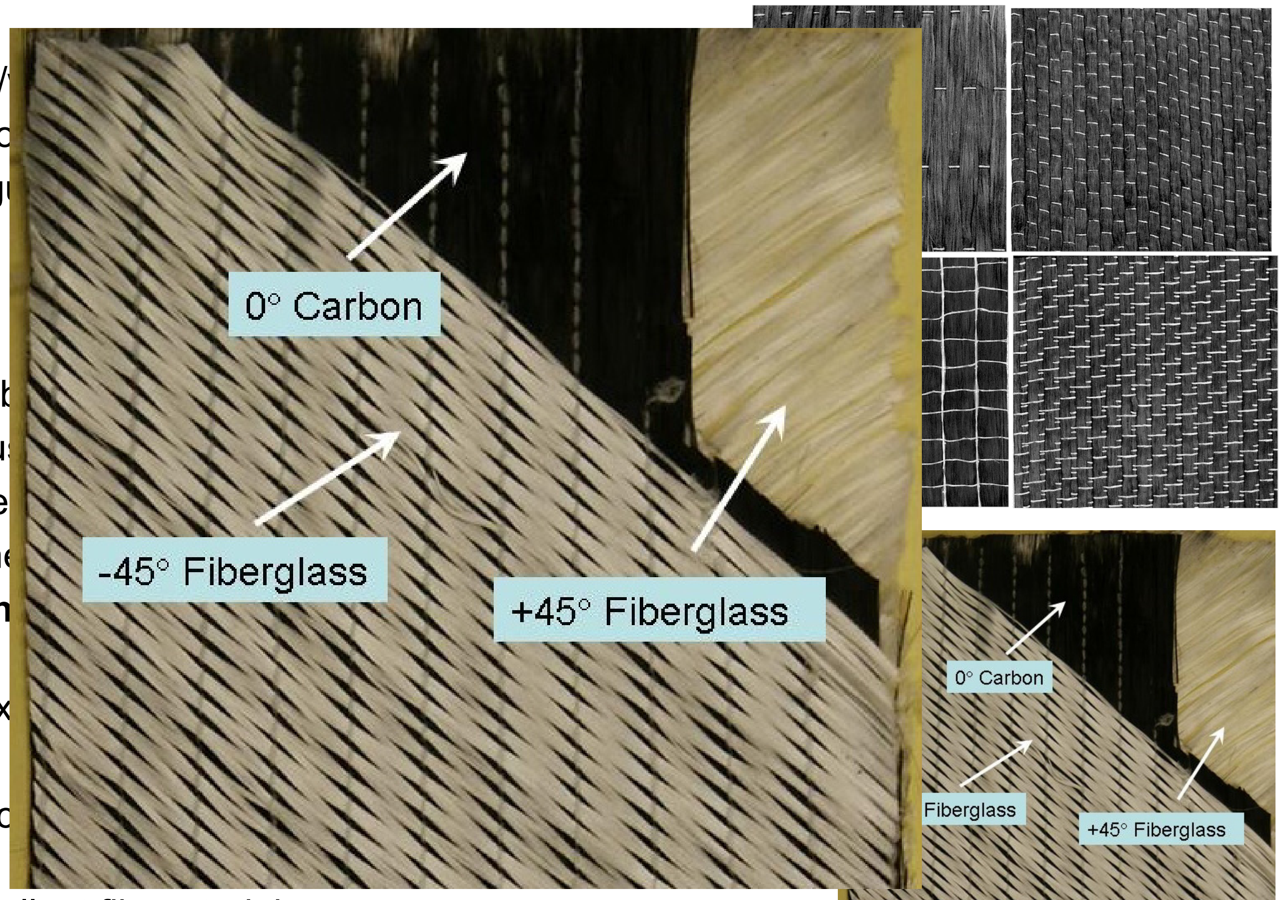
46th AIAA Aerospace Sciences Meeting and Exhibit
Reno, NV
January 10th, 2008

Background, Purpose, and Overview

- **Background**
  - SNL initiated a blade research program in 2002 to investigate the use of carbon in subscale 9 m blades
  - 7 CX-100 and 7 TX-100 blades were manufactured
  - Blades from each set have undergone modal and static tests
- **Purpose of Fatigue Tests**
  - Verify that blades met their design criteria
  - Investigate unique structural aspects of the blades
  - Examine the use of advanced sensors
- **Overview**
  - Carbon in blades
  - 9 m Blade Designs
  - Test Setup
  - Test Results
  - Conclusions

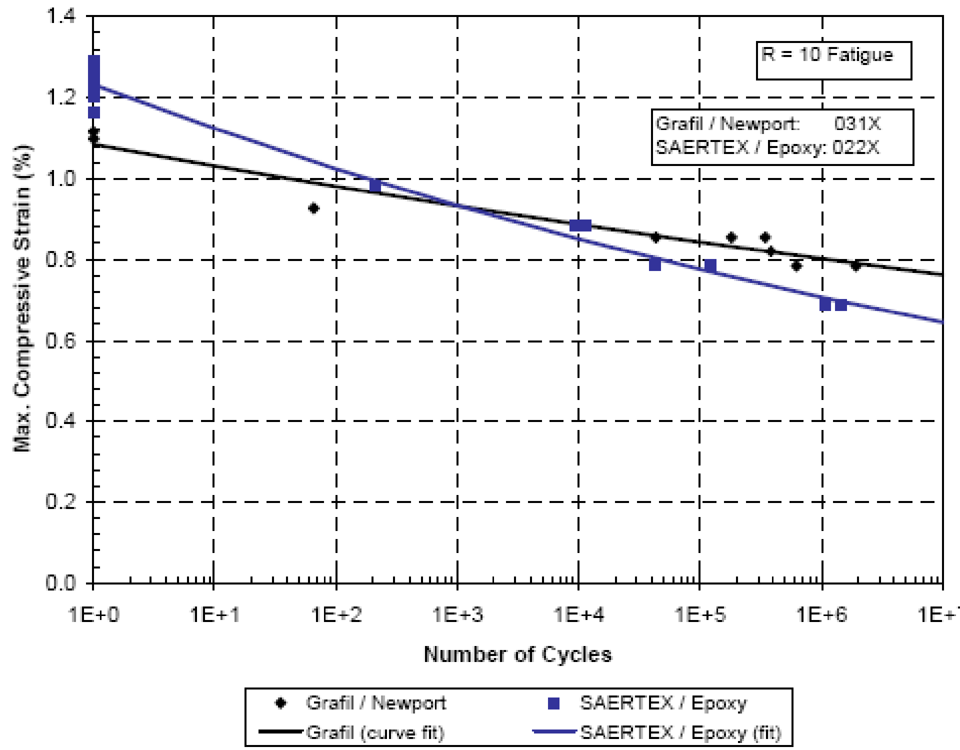
Carbon in Blades

- **Advantages:**
  - High stiffness/
  - Highly orthotro
  - Excellent fatig
    fibers
- **Disadvantages:**
  - Higher cost
  - Limited availab
  - Difficult to infu
  - Poor propertie
  - Possible stiffn
- **Potential solution**
  triax fabric
  - Relatively inex
  - Infusible
  - Dry fabric for c
    techniques
  - Maintains excellent fiber straightness



***Studies of carbon materials performed by and in collaboration with GEC and MSU**

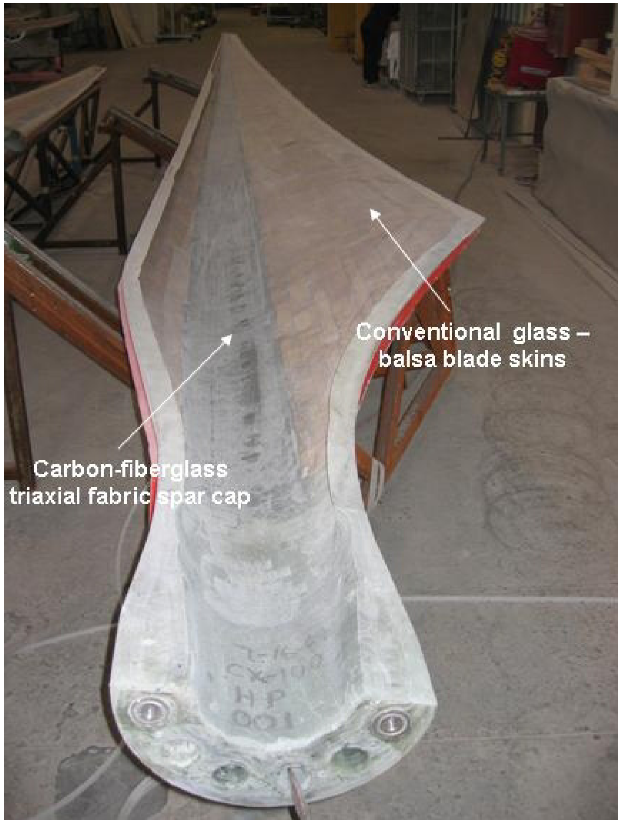
SAERTEX Carbon Tri-ax Fatigue Performance



Source: Montana State University

CX-100

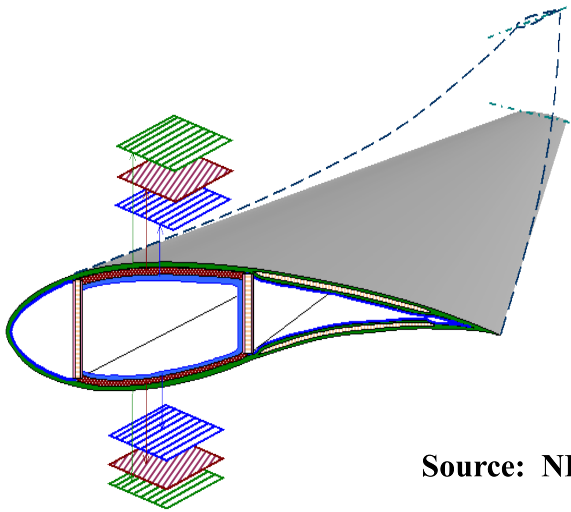
- **CX-100 (Carbon Experimental 100 kW)**
- **Manufactured using existing 9 m molds**
- **Based on ERS-100 blade with non-scalloped root**
- **Glass-Epoxy blade with full length carbon spar cap**



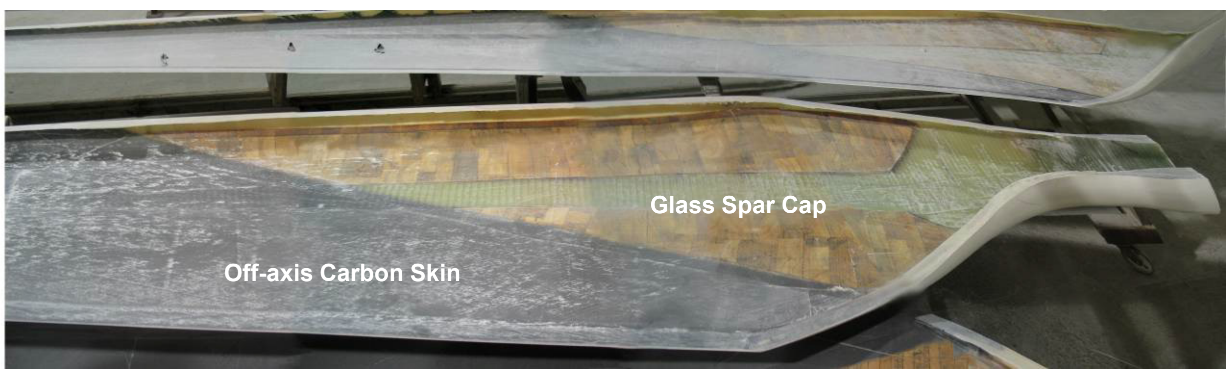
CX-100 Blade Skin

TX-100

- **TX-100 (Twist-Bend Coupled Experimental 100 kW)**
- **Identical geometry to CX-100**
- **Partial-length glass spar cap**
- **20° off-axis carbon in outboard (~>3.5 m) skins to produce material-induced, passive aerodynamic load alleviation**

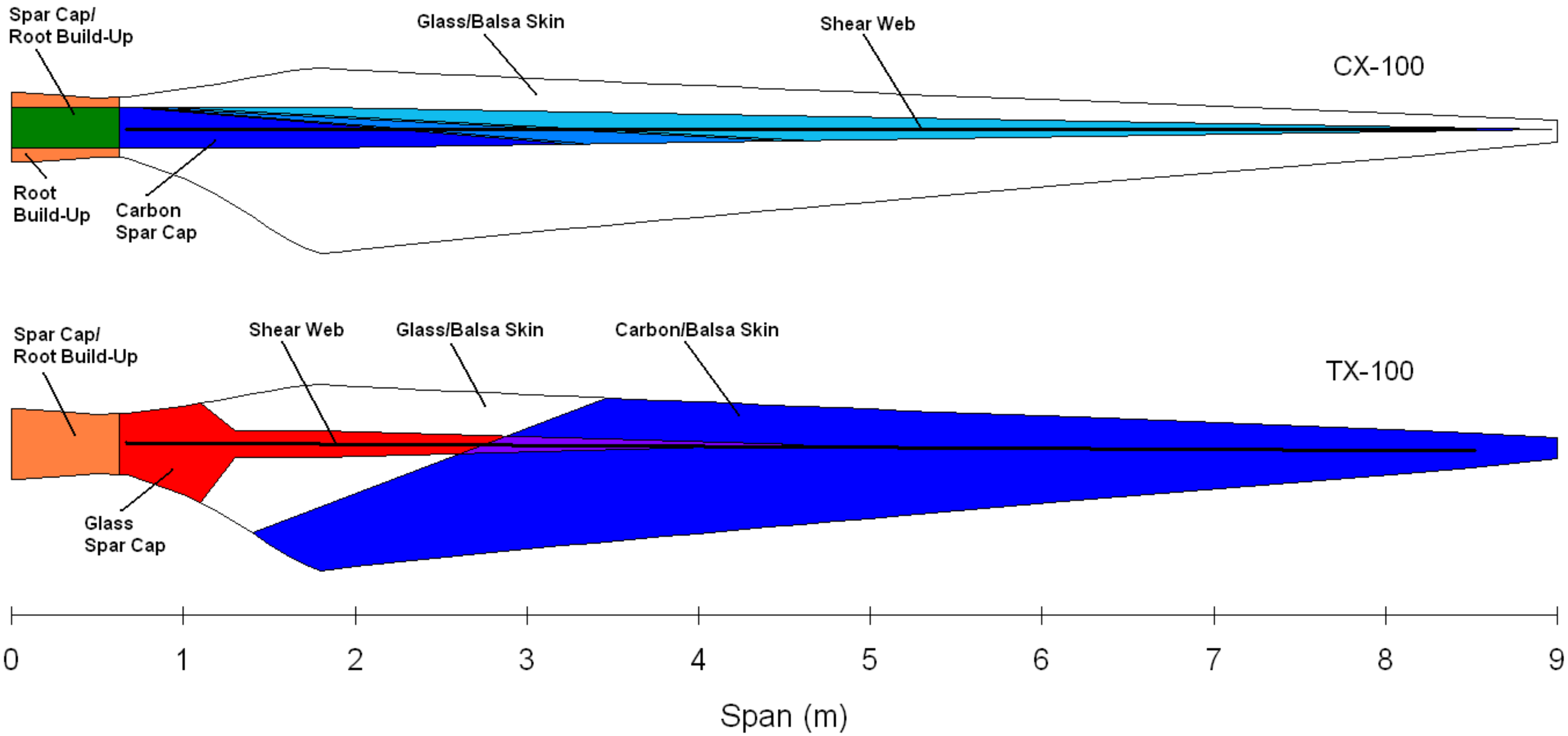


Material Induced Twist-Bend Coupling



TX-100 Blade Skin

9 m Blade designs



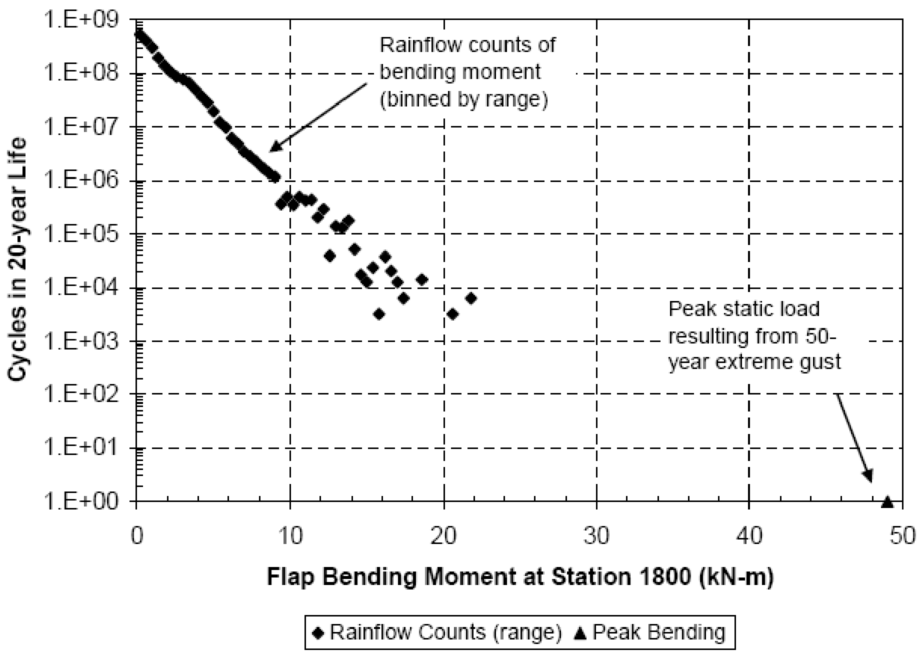
CX-100 (top) and TX-100 (bottom) Geometry and Major Laminate Regions

Fatigue Test Methodology

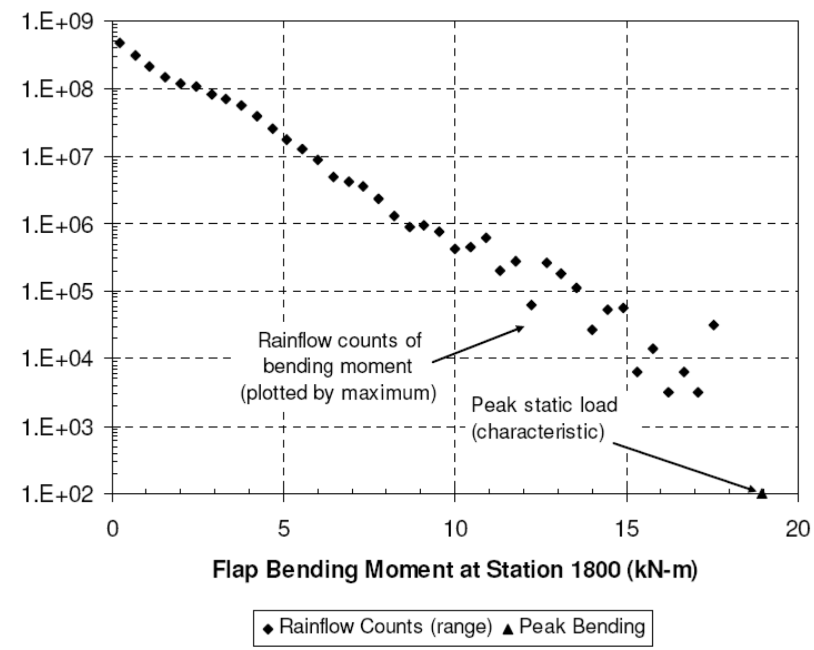
- **Test objective**
  - Demonstrate 20-year fatigue equivalent life
  - Complete test in 1-4 million cycles
- **Fatigue Equivalent Life Calculation Procedure**
  1. Perform system dynamics simulations
  2. Count fatigue cycles/second
  3. Extrapolate to 20-years
  4. Compute damage fraction using damage model along with material data, appropriate safety factors, and damage accumulation counting method

CX-100 and TX-100 Simulations

CX-100
(Static Driven Design)



TX-100
(Fatigue Driven Design)



Test Setup: CX-100

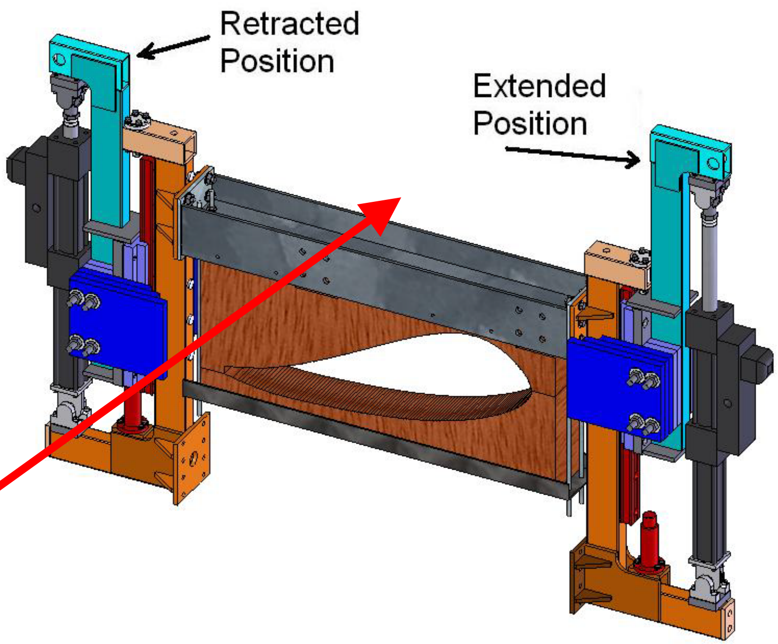
- **Fatigue analysis focused on carbon spar cap**
- **Slope parameter of 12 used (GL standards: 10 for glass, 14 for carbon)**
- **Single-axis flapwise point loading**
  - Hydraulic cylinder used to apply oscillating load at single point
  - Robust, simple setup
  - Only allows for target load matching in limited area
- **1.25-12.5 kN applied at saddle for 1M cycles, then increased by 10% every 500k cycles**
- **20-year fatigue equivalent life demonstrated in 6k cycles**

Test Setup: TX-100

- **Fatigue analysis focused on both glass and carbon areas**
- **Slope parameter of 10 used (for off-axis loading)**
- **Single-axis flapwise resonant loading**
  - Uses oscillating mass to excite natural frequencies of blade-mass system
  - Mean load adjusted by exciter and ballast masses
  - Amplitude adjusted by exciter displacement
  - Complicated setup required to produce correct shape and amplitude
  - Potentially allows for load matching for large portion of blade span
- **1M, 2M, and 4M cycle test loads calculated**
- **Test began with 4M load and then increased 10% beginning at 1M cycle count and repeating every 500k cycles**
- **Unable to increase at 2.5M cycles, load was held constant thereafter**
- **20-year fatigue equivalent life demonstrated at 2M cycles**

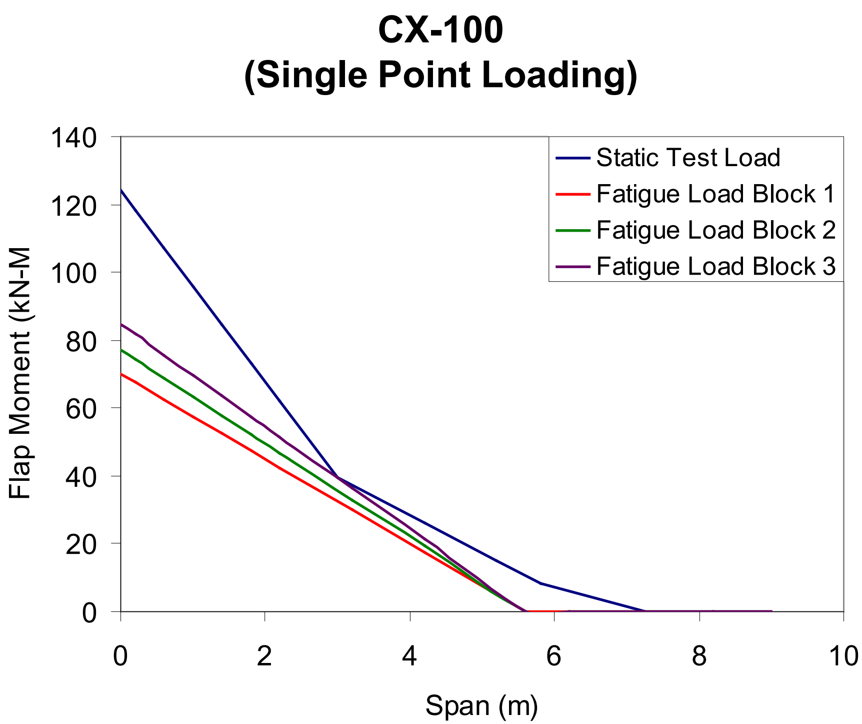
UREX

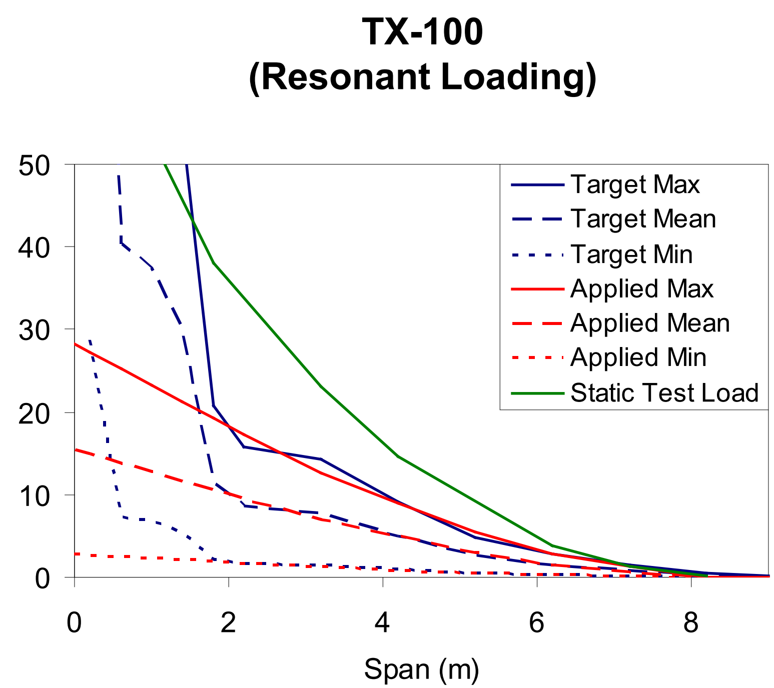
- **Developed specifically for the unique aspects of testing bend-twist coupled blades**
- **Pair of hydraulic actuators mounted to the blade through a ballast saddle**
- **Rotational inertia minimized compared to mounting actuator and resonant mass above the blade**
- **Possible to apply torsional loading by adjusting actuator phases**
- **Horizontally mounted cylinder can be used to excite edge movement**



UREX Schematic

Applied Loads





Fatigue Test Applied Loads

CX-100 Test Results

CX-100 Early in Fatigue Test

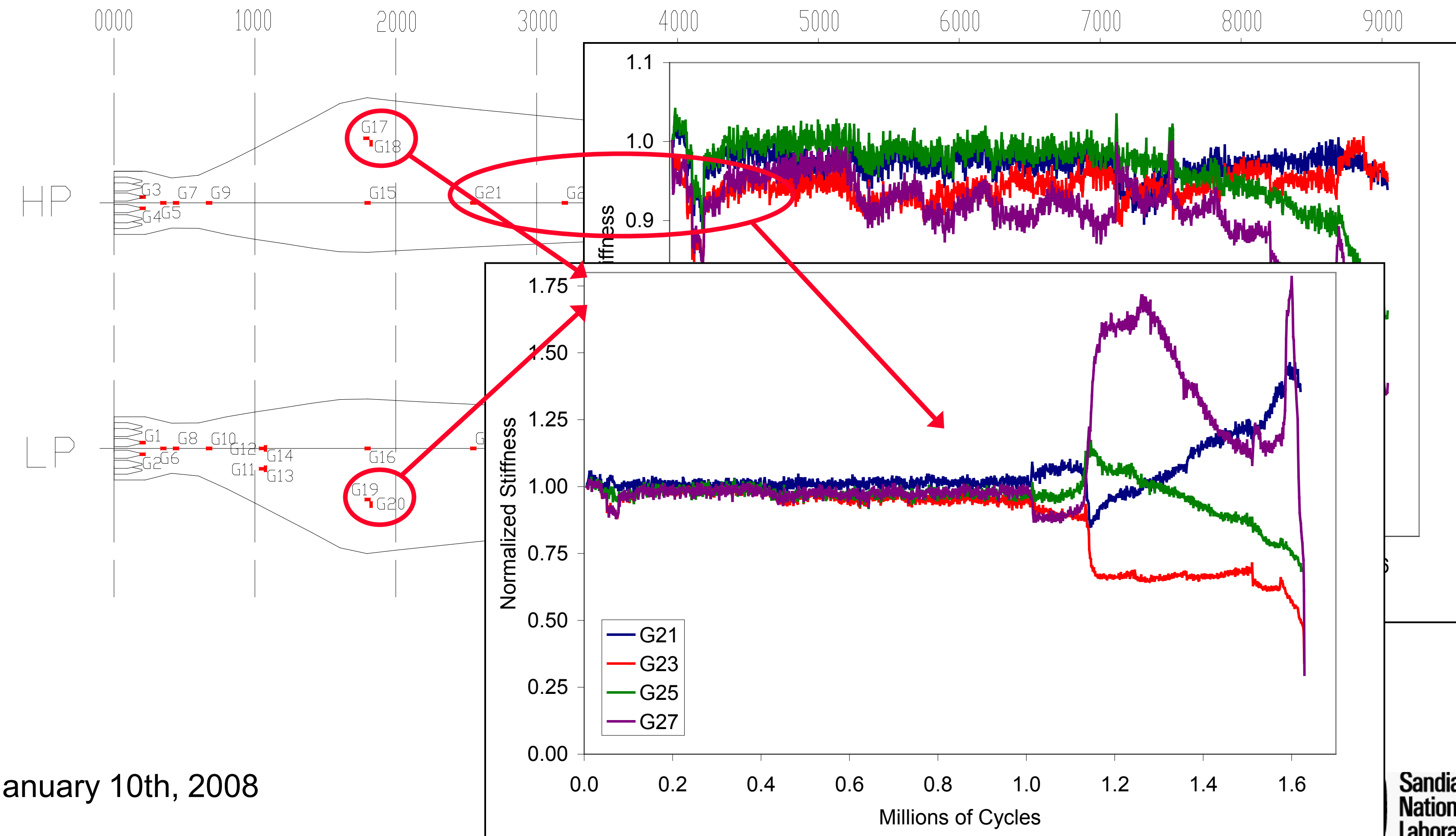
CX-100 Test Results

CX-100 Dimple (left) and Tip Movement (right) just before Failure

CX-100 Test Results

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

CX-100 Test Results

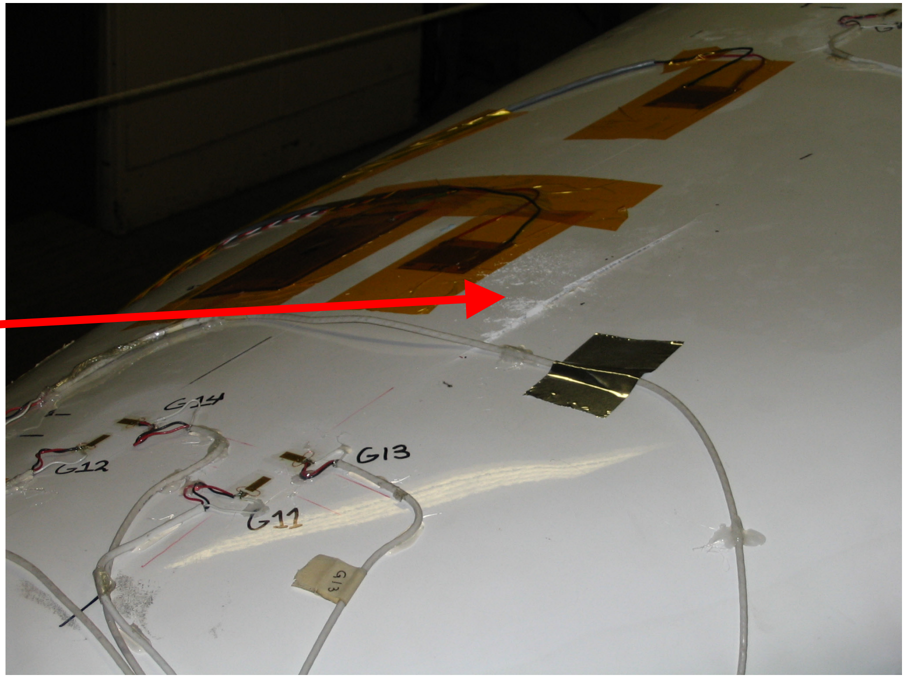


January 10th, 2008

Sandia National Laboratories

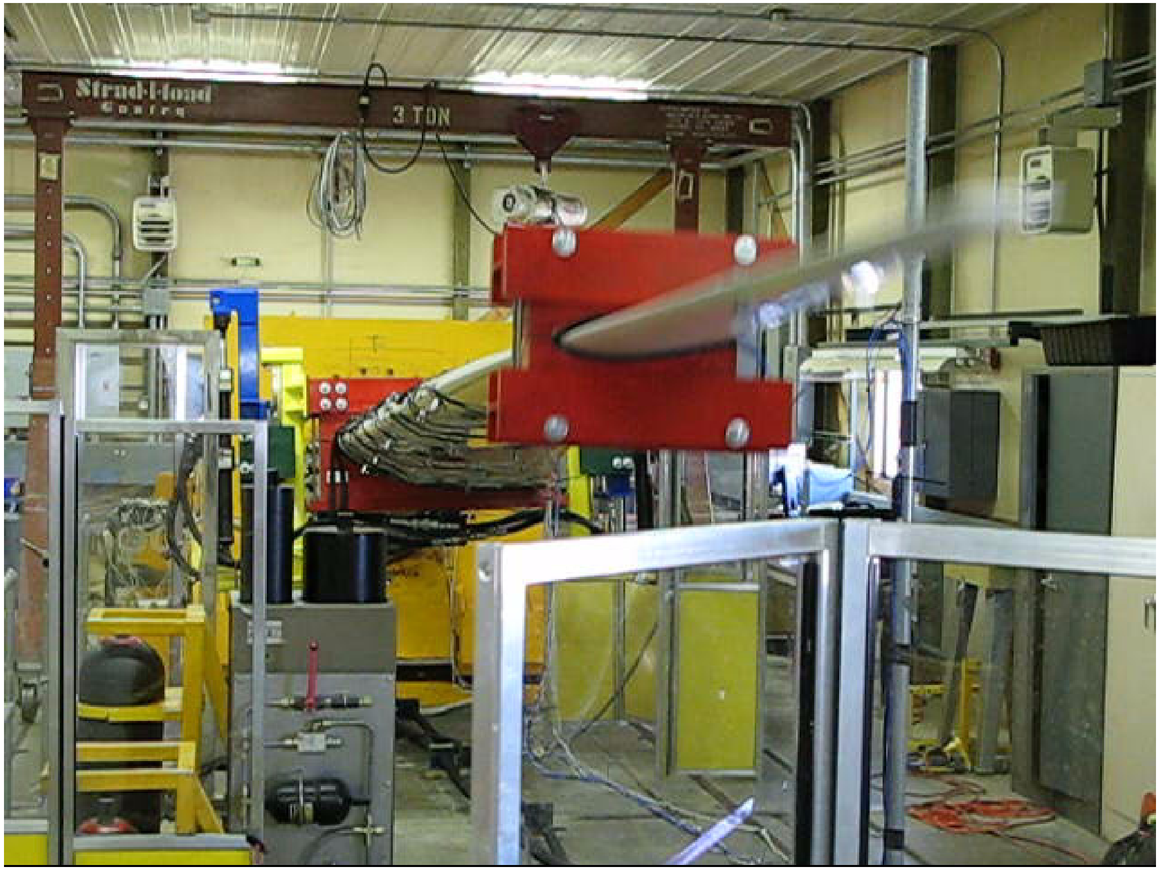
CX-100 Failure Mechanism

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



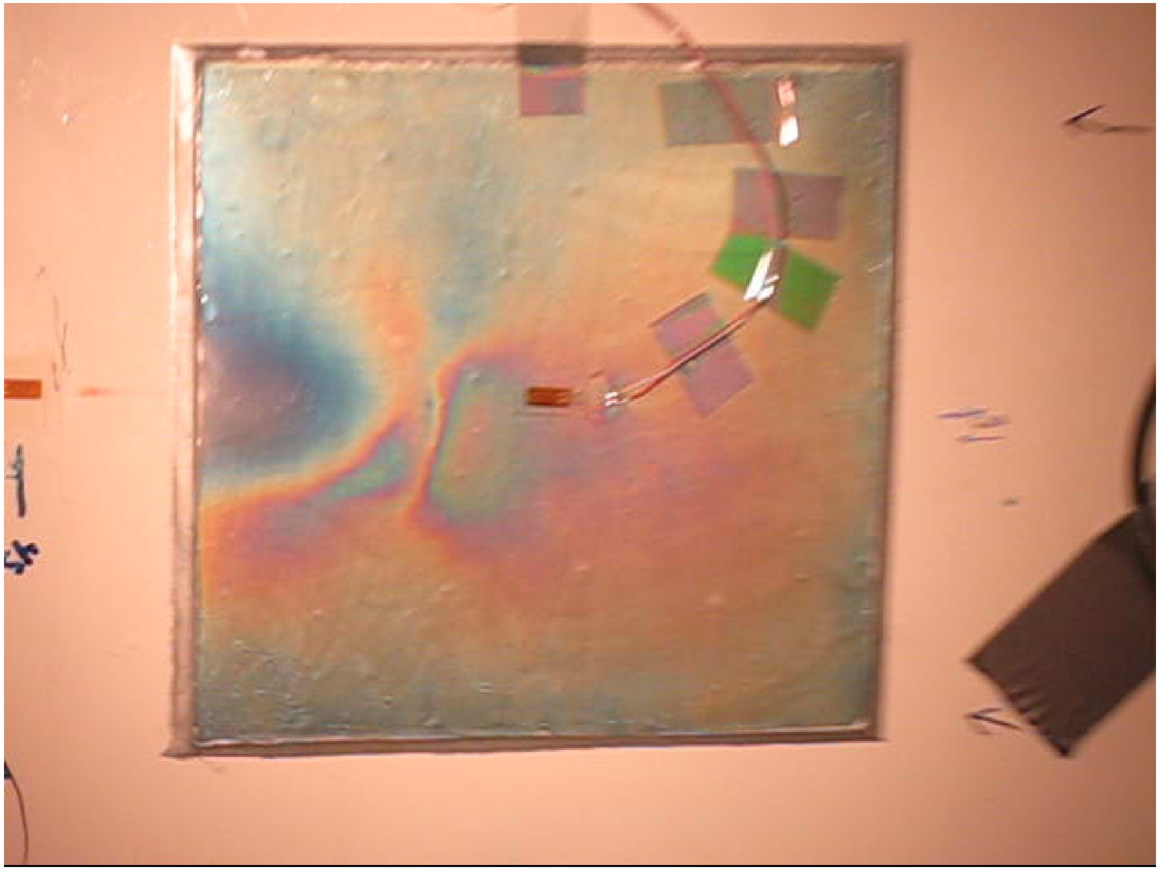
CX-100 Crack Growth

TX-100 Test Results



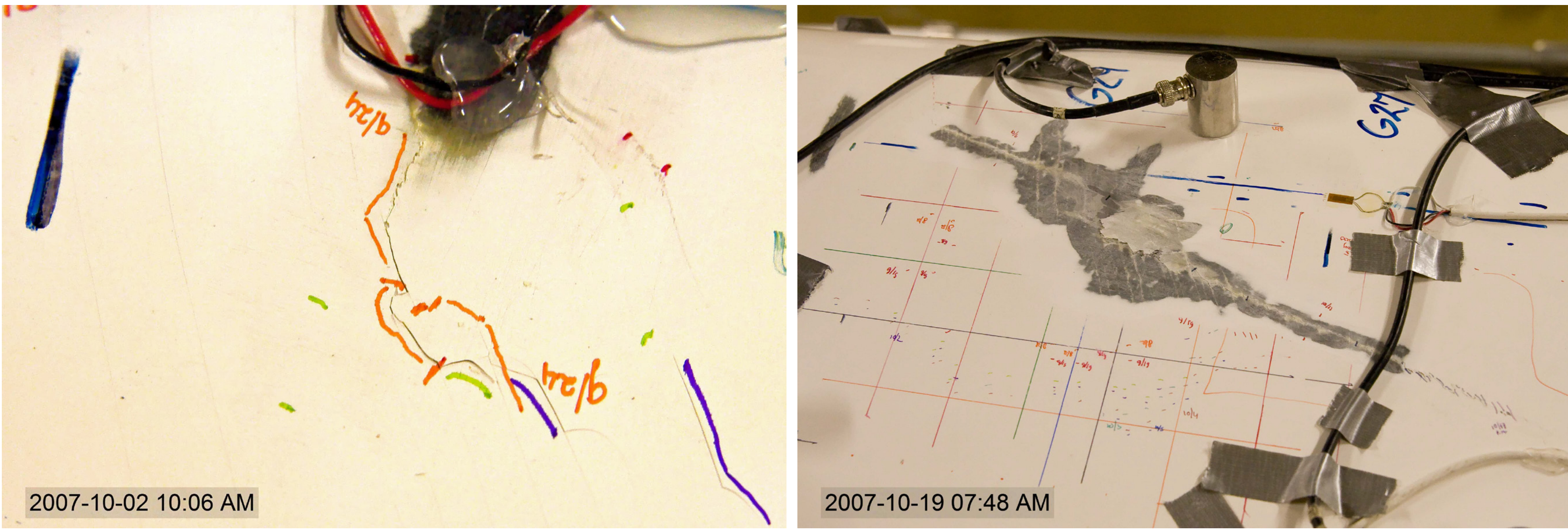
TX-100 Early in Fatigue Test

TX-100 Test Results

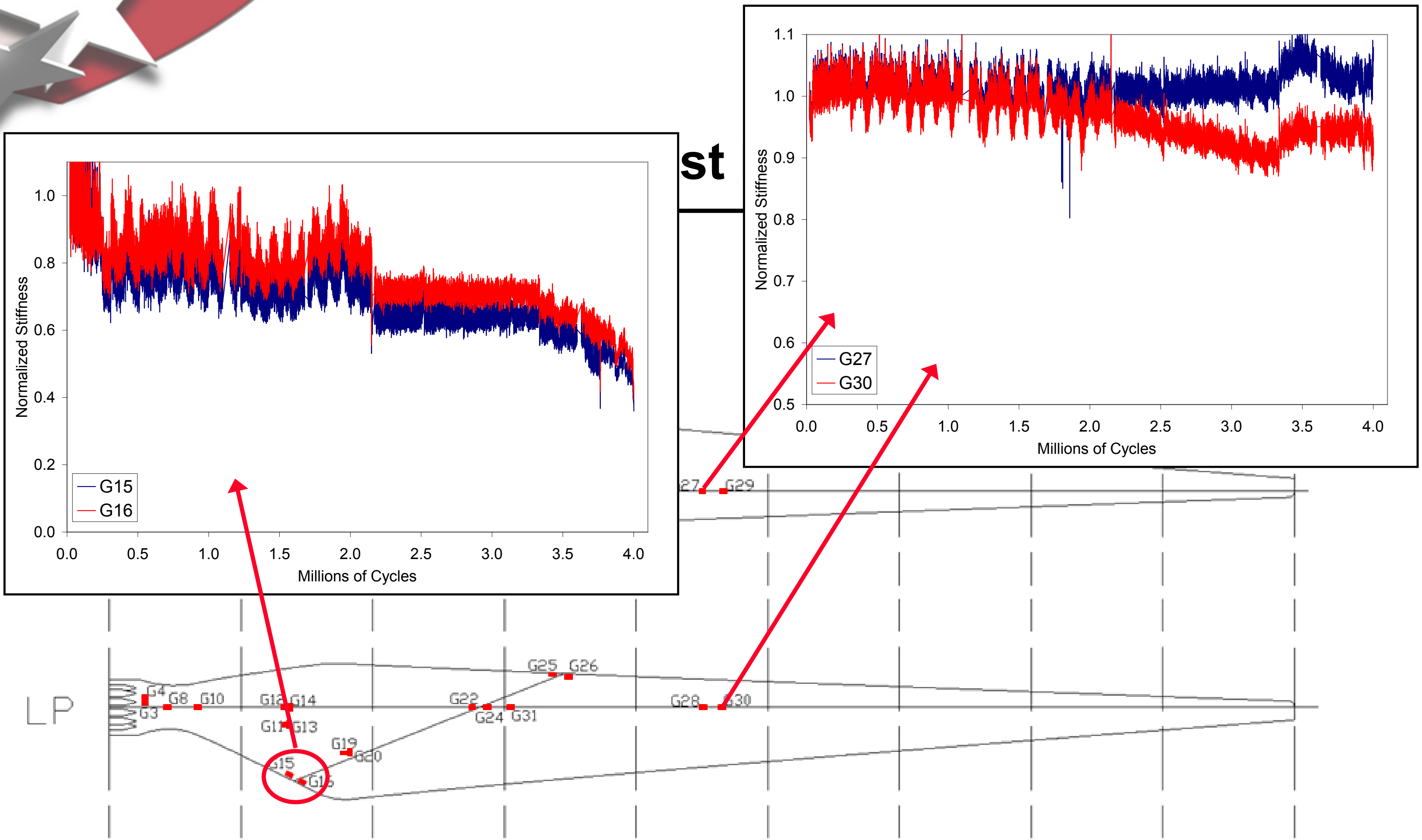


TX-100 Sparcap Tip Stress Contours

TX-100 Test Results



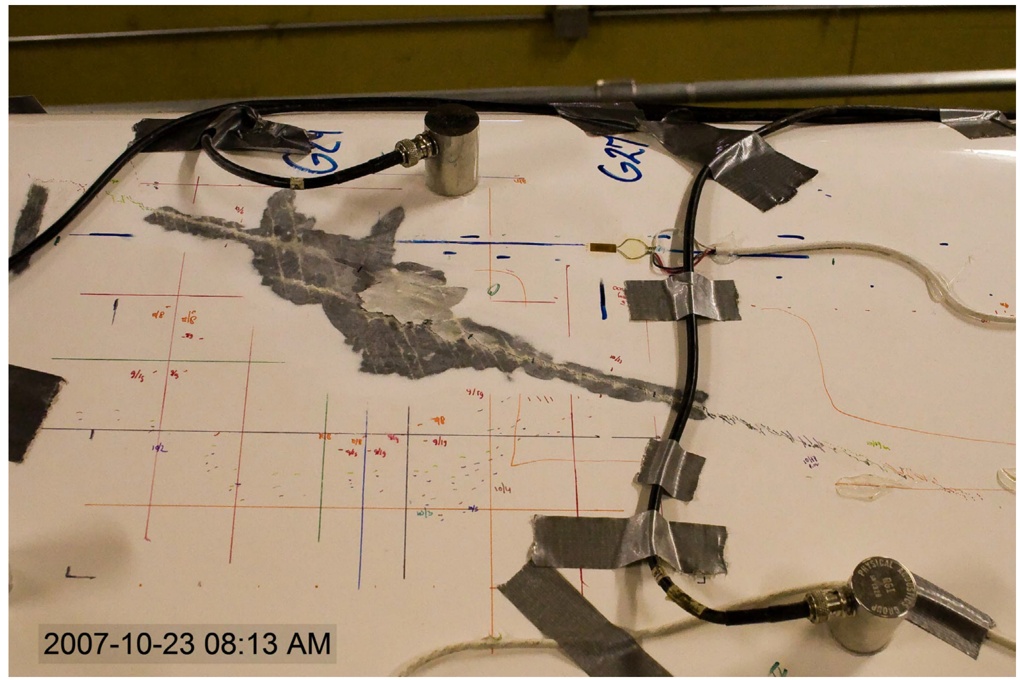
TX-100 Crack Growth Beginning (left) and Progression (right)



TX-100 Strain Gage Layout

TX-100 Failure Mechanism

- At 723k cycle count, crack began to grow just outboard of HP sparcap 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



TX-100 HP Crack Growth

Conclusions

- CX-100 failed 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 due to crack which grew from sparcap termination on HP surface along carbon fiber direction causing excessive tip rotation
- Infused carbon was effectively implemented in a CX-100 and TX-100 blade designs
- Both blades failed in carbon areas
- Blades failed due to damage in off-axis directions, showing the difficulty in using fiber-direction fatigue calculations

Acknowledgements

US Department of Energy

Mike Jenks, Jason Cotrell, and Dave Sims (NREL)

Dayton Griffin and Tim McCoy (GEC)

Mark Rumsey, Perry Jones, Wesley Johnson (SNL)

Mike Zuteck

Derek Berry (TPI)