This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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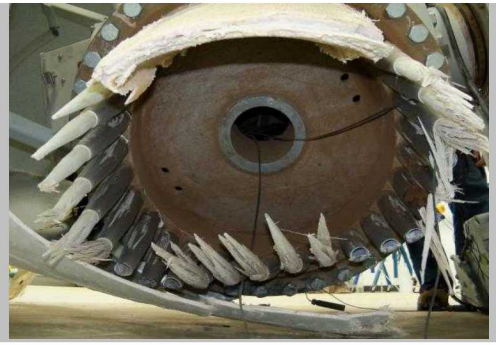

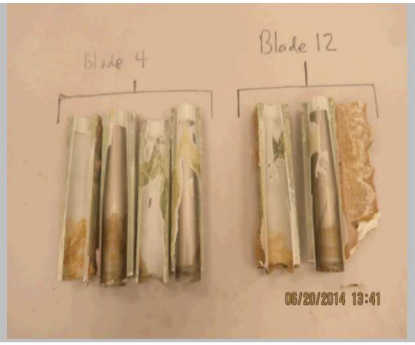

Characterization of Composite Wind Turbine Blades

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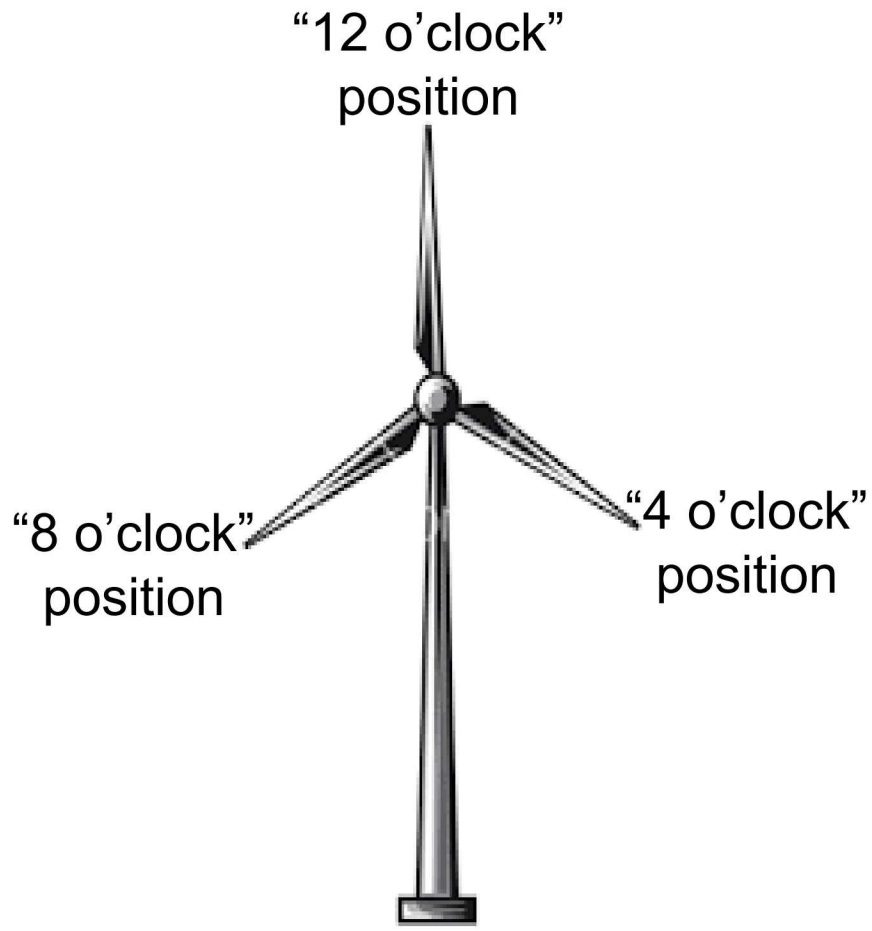
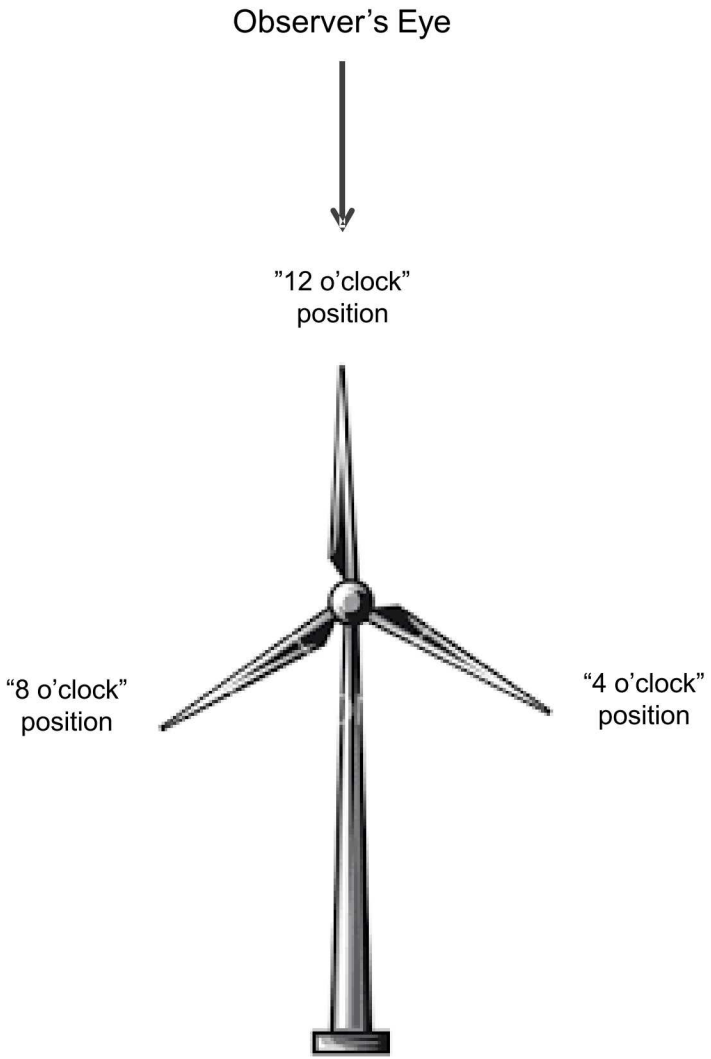
Wind Turbine Background

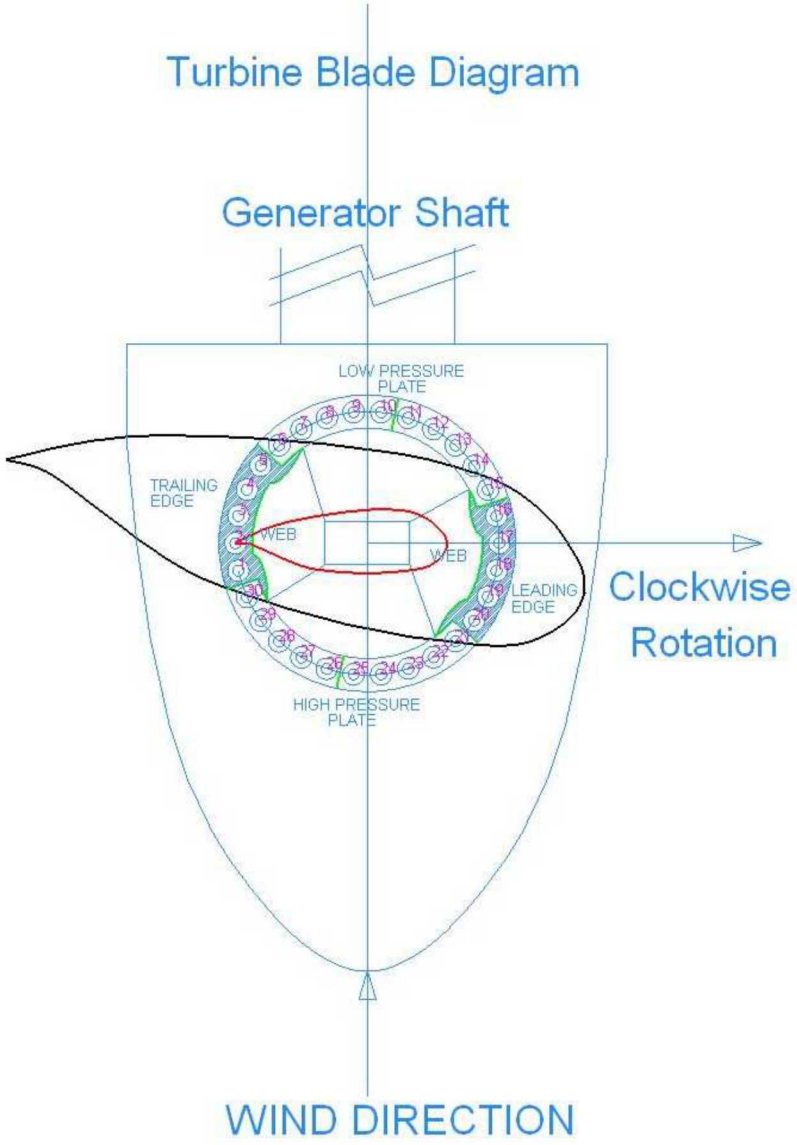
- In 2014, a wind turbine experienced an over speed condition (blades rotating faster than intended) resulting in the structural failure of the turbine.
- The turbine in question was a 3-bladed horizontal machine successfully used in industry for years.
- We describe here the results of our study of the composite turbine blades that were badly damaged during this incident.
  - Analysis of turbine blade remnants
  - Materials characterization
    - mechanical load testing
    - adhesive bond testing
    - thermal analysis
    - non-destructive inspection (NDI)

For clarity, the different blade positions (4, 8, 12) are defined by their clock positions



Wind Turbine Blade – Terms, Description

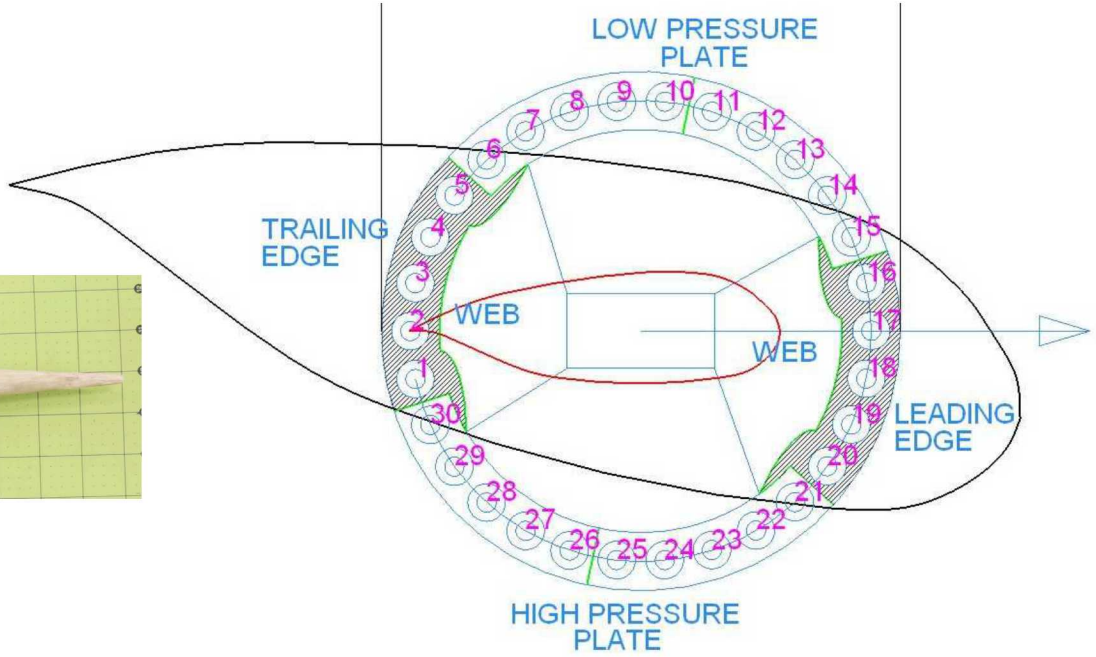




Attachment of Turbine Blades to Turbine

- The turbine used a bonded 30 carrot system to attach each blade to the slewing ring of the hub
  - 5 stainless steel (SS)/fiberglass carrots are bonded into curved wedge shaped fiberglass root inserts using a structural adhesive.
  - 6 root inserts in total are made for each blade.
  - These prebonded root inserts are co-molded into the fiberglass box beam that is made up of the Low Pressure Plate, High Pressure Plate, and Leading and Trailing Edge Webs.
  - The High Pressure and Low Pressure skins are molded separately and bonded to the box beam.

SS Root Carrot with Fiberglass Insert



Blade 4 Investigation: adhesive failure?

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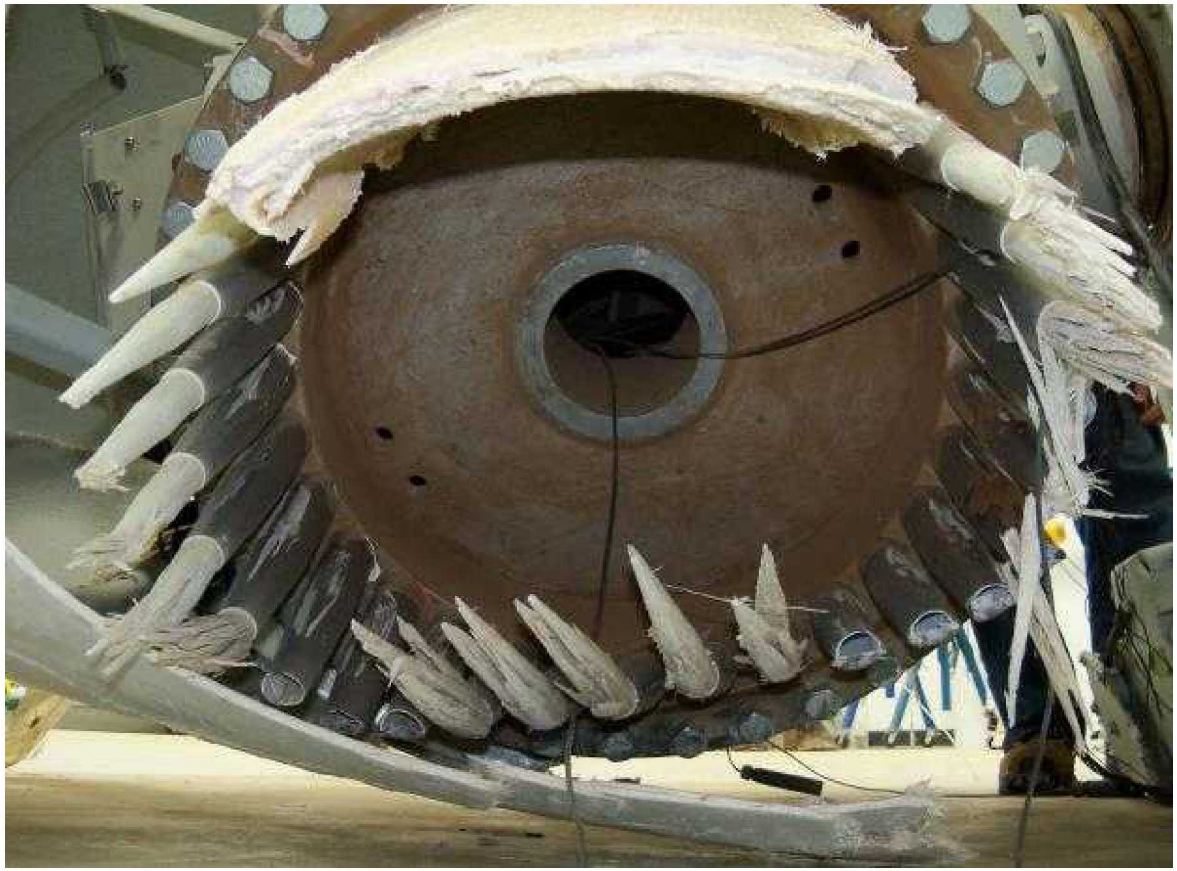
- The photo clearly shows all but 5 carrots of Blade 4 are exposed after the failure. This raised questions of a possible premature adhesive failure between the SS carrots and the fiberglass root inserts.

- Only the Trailing Edge Web root insert remains attached (seen at top of picture).
- Examination of the remaining 24 SS carrots shows little remaining adhesive.
- Some carrots show signs of surface contamination near the base of the carrot.
- Investigation focused initially on the remains of Blade 4 and the Trailing Edge Web Insert.



Blade 4 Investigation *(continued)*

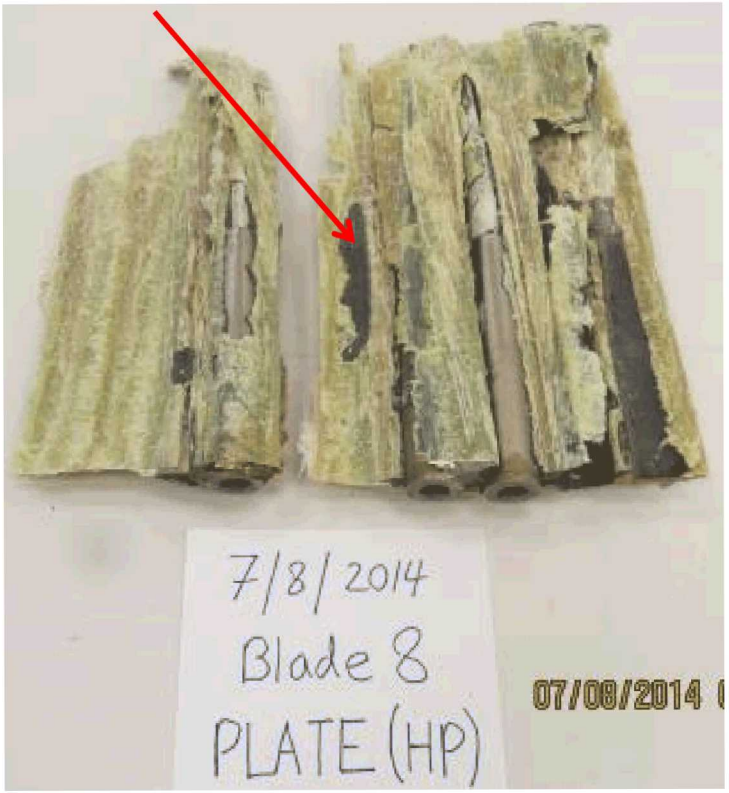
- Low Pressure Plate shows 9 empty carrot sockets (and 1 socket still containing the SS carrot).
- Carrot pockets 10, 12, 13, 14, and 15 still contain the fiberglass carrot inserts, while carrot pockets 7, 8, 9, and 11 are empty, with the fiberglass insert remaining bonded to the stainless steel carrots mounted on the hub.
- Both carrot wedge inserts are cracked about 100 mm down the bond line from the base.

Blade 4 Investigation *(continued)*

- Trailing Edge Web
  - Root carrot 1 is cut free from root insert.
  - Root carrot 1 is split open to inspect/evaluate adhesive bond, metal surface finish, *etc.*
  - Brown discoloration was further investigated.

Blade 8 Investigation

- Most of the root of Blade 8 is intact.
- Trailing Edge Web and part of the High Pressure (HP) Plate is damaged.
- We observed that the structural adhesive on Blade 8 looked different (grey in color) compared to that used on Blade 4 (white in color).



Blade 12 Investigation

- Blade 12 was the most intact of the 3 blades.
- The root section was intact and in one piece.
- In fact, the entire length of HP and LP Plates survived.
- Carrot 1 shows the same characteristic rust colored contamination at the base as the Carrots from Blade 4.
- Blade 12 has white adhesive.
- The main goal of our harvesting work was to collect adhesive samples for analysis.

Thermogravimetric Analysis (TGA) of white and grey adhesives

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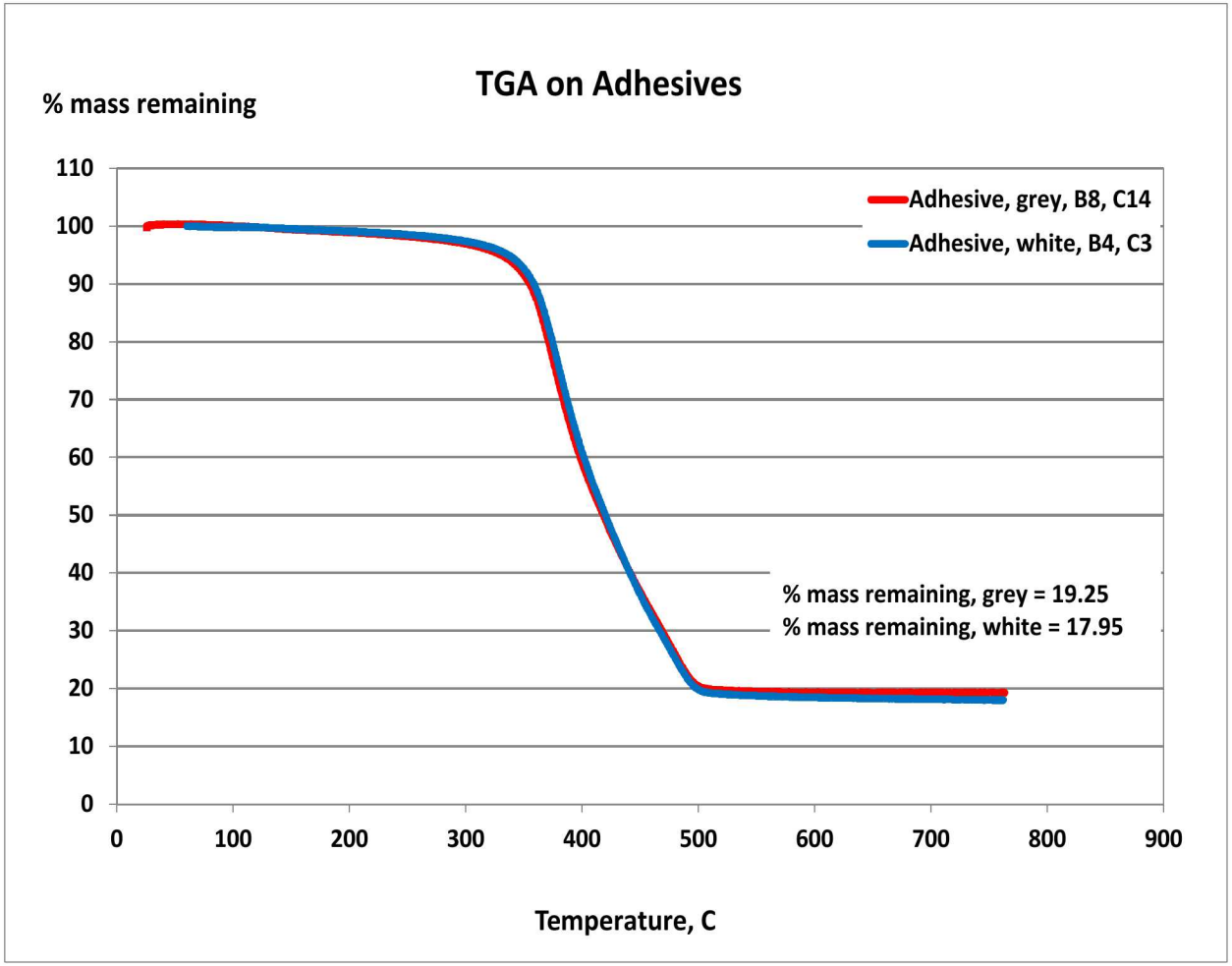
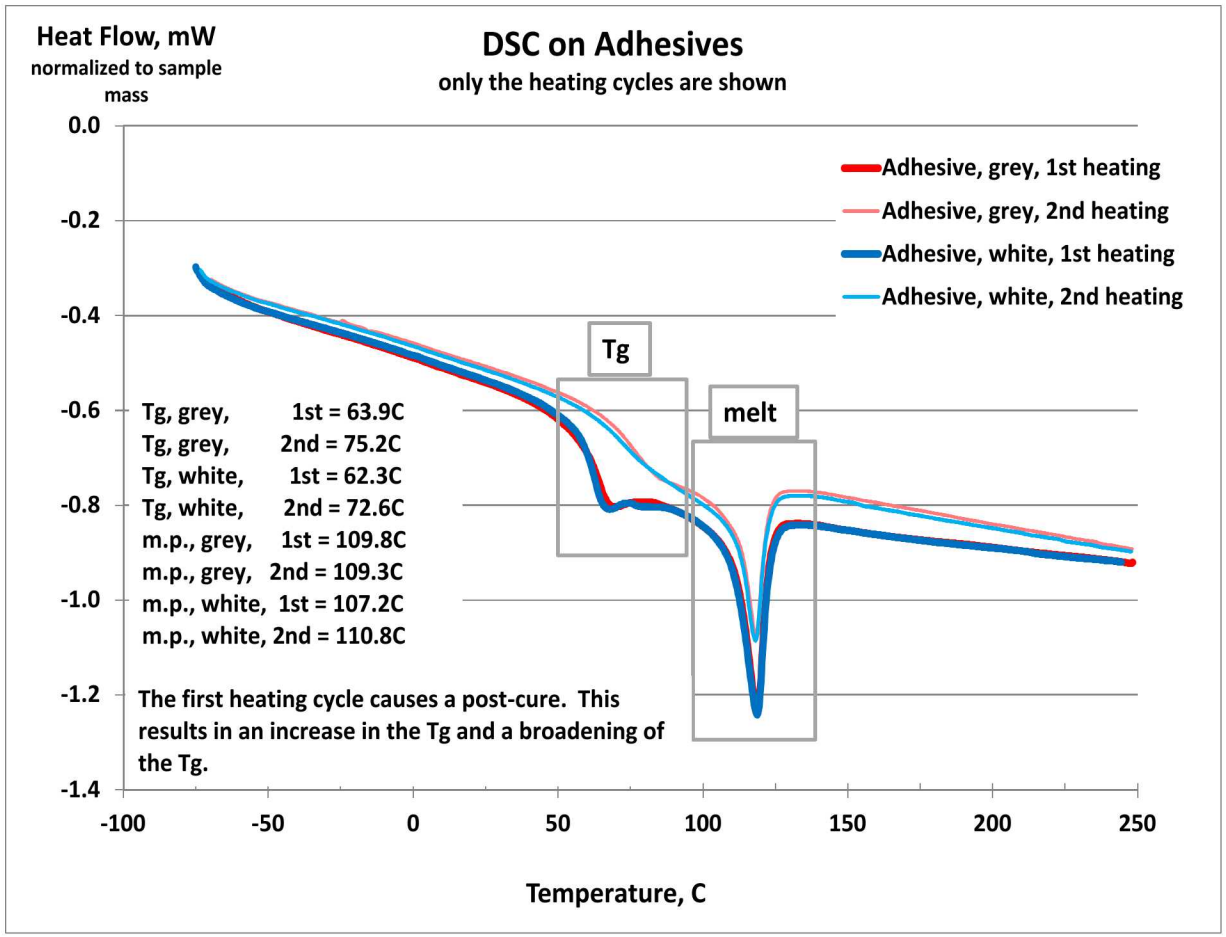
- The similarity in the final weight percent values (19% for grey adhesive, 18% for white adhesive) is indicative of similar non-volatile/non-thermally-degradable material content.



Differential Scanning Calorimetry (DSC) of white and grey adhesives

- Strong overlap between the DSC curves for the white and grey adhesives, including the similarity in the measured T_g values of 65 C and measured melt temperatures of approximately 120 C, indicate that the white and grey adhesives have very similar thermal properties.



Load to Fail Tests of white and grey adhesives

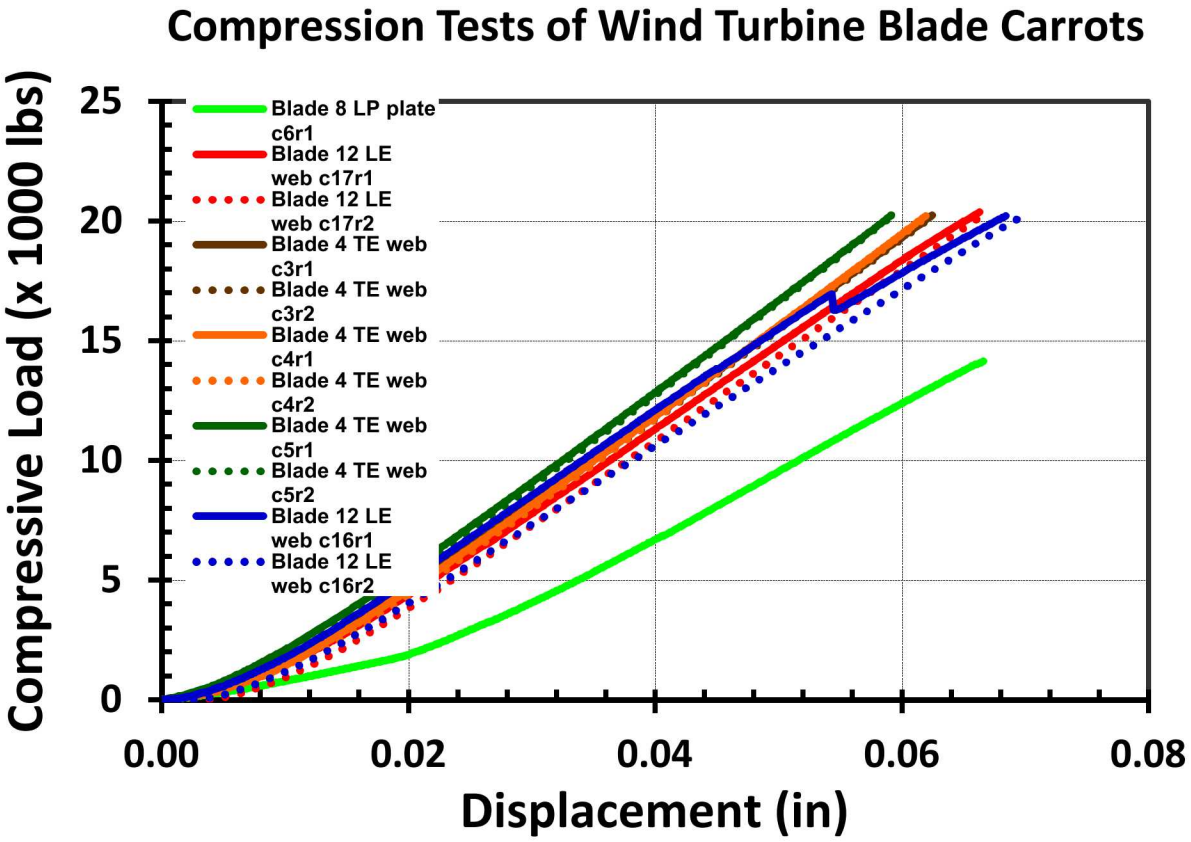
- We prepared samples to precise dimensions by cutting and polishing, and tailored them for measurement in a 3-point bend configuration. Each sample had a pre-measured thickness and width, both of which were used to take measurement data and to produce a calculated Young's modulus.
- The average Young's modulus was 2.28 GPa for the grey adhesive with a standard deviation of 0.23 GPa, while the white adhesive the Young's modulus average was 2.27 GPa with a standard deviation of 0.05 GPa. The Young's moduli for the two samples is identical within the statistical uncertainty of this analysis.

Source Blade	Source Carrot	Adhesive type	Length, mm (DMA rail)	Width, mm	Thickness, mm	Young's Modulus, GPa*	% strain at failure
8	14	grey	15	2.44	1.37	2.16	5.52
8	14	grey	15	2.46	1.30	2.61	4.70
8	8	grey	15	2.56	1.39	2.28	5.05
8	8	grey	15	2.52	1.73	2.08	n/a
4	3	white	15	2.36	1.43	2.31	4.63
12	16	white	15	2.44	1.31	2.24	3.86

*Young's Modulus calculated from within 1 to 2% strain region

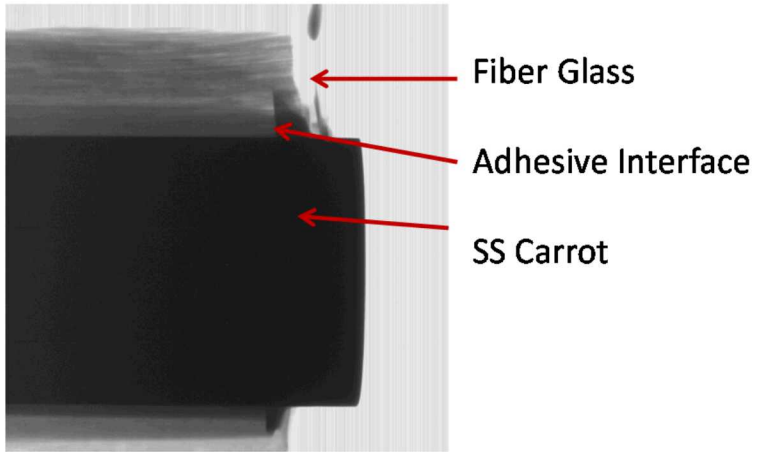
Mechanical Load Testing

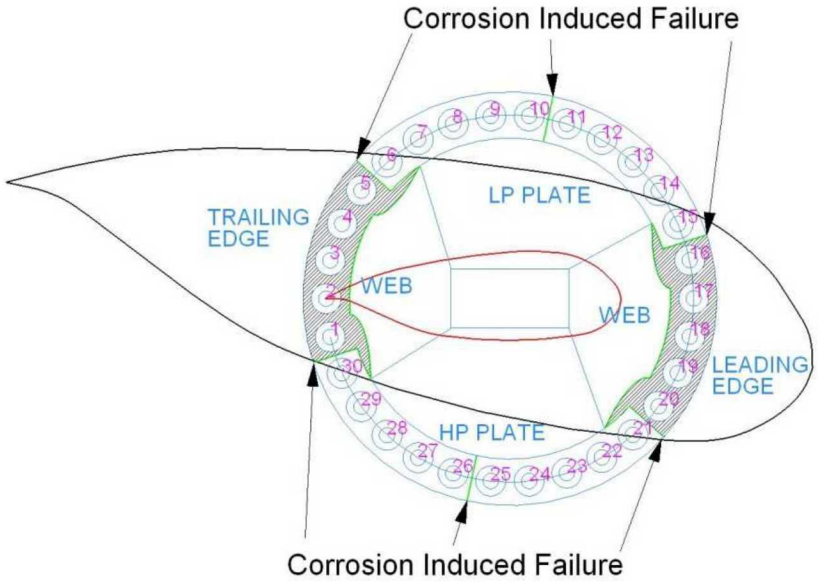
- All samples were loaded twice to 20,000 lbs (maximum output for our Instron load frame).
- A steel ring was used to isolate the SS root from the fiberglass and place the adhesive in shear mode.
- A lack of samples makes quantitative analysis difficult. However:
  - Results show that the low pressure side of Blade 8 (position 6, root number 1) failed during the first ramp to 20,000 lbs (neon green curve).
  - In total, 40 of 42 carrots tested passed this test!



Corrosion /NDI Investigation

- Brown discoloration is indicative of corrosion, per visual inspection by metallurgy/corrosion expert (Rob Sorenson, Sandia).
- Inspection under an optical microscope showed crack formation in the SS and metal flakes embedded into the adhesive after mechanical failure. Sorensen's hypothesis is that the prevailing aging mechanism is grain edge boundary corrosion of the SS.
- Given what we understand about the aging history of these blades (including long term service near an ocean), typical corrosion precursors (moisture, chloride) were certainly available to promote this aging/degradation of the stainless steel carrots.





Conclusions

- Grey and white adhesives appear equivalent based on thermal and mechanical characterization.
- Corrosion was clearly present on the interface carrots (those carrots that interface between a web and a plate). In this design, the interface carrots are:
  - Carrots 1 and 30
  - Carrots 5 and 6
  - Carrots 15 and 16
  - Carrots 20 and 21
- All 29 carrots from Blade 12 (the most intact of the 3 blades) were tested.
  - 28 passed the compressive load of 20,000 lbs administered twice.
  - 1 failed this test (Carrot 16, an interface carrot). The other 7 interface carrots all passed.
- For Blade 4 (which was badly damaged) and Blade 8:
  - 12 of the 13 carrots that were tested passed the compressive load of 20,000 lbs administered twice.
    - Exception: Carrot 6 on Blade 8 (an interface carrot).

- This turbine design (a bonded 30 carrot system which attaches each blade to the slewing ring of the hub) is strong (as evidenced by our mechanical tests). It is also known to be reliable, elegant, and easy to manufacture.