Wind Turbine Blade Fatigue Analysis for Development of Predictive Life Models

Cooperative Research and Development Final Report

CRADA Number: CRD-17-00696

NREL Technical Contacts: Scott Hughes

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5000-77809
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Suggested Citation
Hughes, Scott. 2020. *Wind Turbine Blade Fatigue Analysis for Development of Predictive Life Models: Cooperative Research and Development Final Report, CRADA Number CRD-17-00696.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-77809. https://www.nrel.gov/docs/fy20osti/77809.pdf.

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National Renewable Energy Laboratory
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Golden, CO 80401
303-275-3000 • www.nrel.gov

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Report Date: September 2, 2020

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Sentient Science Corporation

CRADA Number: CRD-17-00696

CRADA Title:Wind Turbine Blade Fatigue Analysis for Development of Predictive Life Models

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Sponsoring DOE Program Office(s):
Office of Energy Efficiency and Renewable Energy, Wind Energy Technologies Office (WETO)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$ 125,000.00
TOTALS	$ 125,000.00

Executive Summary of CRADA Work:

This Small Business Voucher CRADA will focus on wind turbine blade fatigue analysis for development of predictive life models. The parties will cooperate to conduct structural validation fatigue testing that produces high quality data enabling validation of blade damage models with sensing technologies developed by Sentient.

Summary of Research Results:

Work conducted at NREL followed the CRADA Joint Work Statement. NREL performed a structural fatigue test of the Sentient 13 m blade. The fatigue test of the Sentient 13-meter blade was conducted at the National Renewable Energy Laboratory (NREL). The fatigue testing was performed in Building 254 at the National Wind Technology Center (NWTC), with cyclic (fatigue) testing occurring between 30 March and 27 July of 2018. Project partners included Sentient Science, Sandia National Laboratories, and Michigan State University.

The Sentient blade was a 13-m wind turbine blade produced by TPI Composites in Warren, RI. The blade design, laminate schedule, and manufacturing process was the same as the Sandia National Rotor Test Bed blade. Primary construction materials include fiberglass, balsa wood, and epoxy. The blade root bolt pattern was thirty M20 bolts on a 508-mm bolt circle. The nominal maximum chord of the blade was 1.473 m. The blade includes pre-bend in the flapwise, upwind direction.

The purpose of flapwise fatigue testing was to operate the fatigue test up to and including periods where the blade incurred damaged. Data collected during the fatigue test provided data for validation of blade damage models and comparisons with sensing systems provided by Sentient and Michigan State University. An optical Video Capture system was provided by Sentient and a Piezo-Floating-Gate Measurement system was installed and monitored by Michigan State University.

Structural fatigue testing was performed according to NREL's Quality Assurance Program. NREL is accredited by A2LA for blade testing in accordance with the IEC 61400-23 international standard that covers full-scale structural testing of wind turbine blades. A test plan was developed prior to testing to document the types of tests and the operation of each test type. A photograph of the blade test is shown in Figure 1.

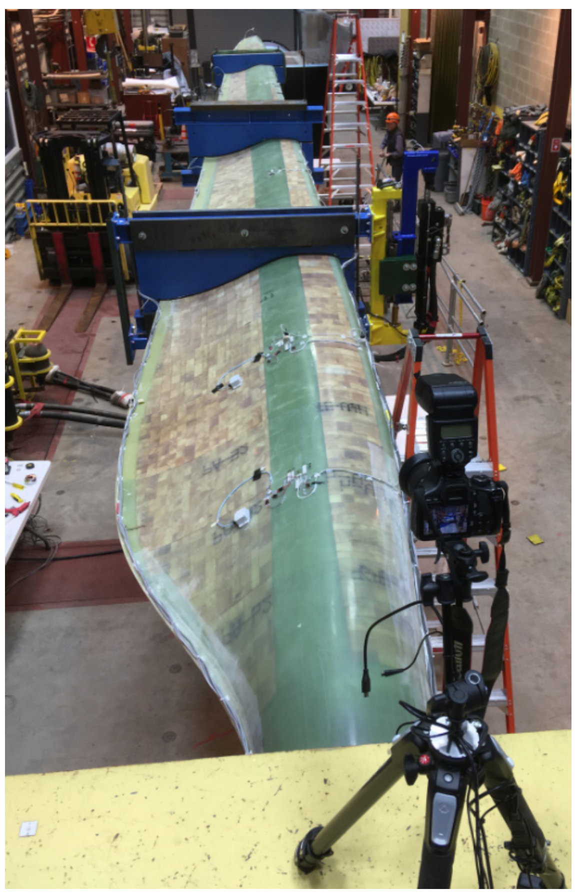

Figure 1. Sentient 13 m blade fatigue test

A series of property tests and a fatigue test were performed. Prior to structural testing, blade properties including mass and center of gravity were measured. Dynamic characterization of the blade was performed prior to, and during, structural fatigue testing by measuring low-order blade natural frequencies and structural damping Free-decay and modal impact methods were used to measure and calculate natural frequencies and damping of the test system. Dynamic characterization tests were performed periodically throughout the fatigue test, pausing fatigue cycling to measure frequencies and damping.

The target fatigue loading was based on a laboratory equivalent 1 million cycle load that simulated 20 years of in-field loading in the flapwise direction. Testing was performed using a resonant test system, cycling the blade at a test frequency near 1.6-hz (1.6 cycles per second). The resonant test system operates by linearly oscillating a mass via hydraulic actuators to excite the blade at the first flapwise mode and frequency. Static (slow) calibration loads were applied to the blade periodically to calibrate the blade mounted strain gages to bending moment equivalents. During dynamic fatigue testing, applied test moments were calculated from strain-to-moment-calibration curves.

The blade was instrumented with 20 strain gages, and 24 accelerometer channels. Strain gages were located in areas of the blade with relatively low strain reserves or positioned to indicate applied bending moment. Acceleration was measured in the flapwise and lead-lag direction at several blade stations from root to tip. Load cells and string potentiometers measured force and displacement during static calibration tests. These data were collected with the NREL EDAS data acquisition system. During fatigue testing, data were collected as peak-valley pairs indicating the maximum and minimum values for each test cycle. Data were also collected periodically as time series files, capturing waveform data at 100 to 200-Hz. In total about 90 GB of data were collected. Data systems provided by Sentient and Michigan State were maintained by NREL staff during testing, uploading to remote servers during fatigue testing.

Over 4.4 million fatigue test cycles were applied to the Sentient blade between 30 March and 27 July, 2018. The total run time of fatigue testing was approximately 800 hours. Fatigue testing was performed for 4.1 million cycles without significant changes in blade response that could indicate a functional failure of the blade. Damage was introduced to the blade by scoring the low-pressure surface spar cap at the 2.8 m station. This was performed to elicit a structural failure representative of a wave or other defect in the structural laminate. The blade fatigue test continued for another 400k cycles until damage progressed to the stage where the functional properties of the blade significantly changed. The damage at the 2.8 m station was noted to progress as damage deeper into the spar cap and surface cracks in the panels towards both the leading and trailing edges of the blade. This damage is shown in Figure 2. Changes in structural performance were most notably observed by a considerable drop in the test system's natural frequency. The test was stopped prior to a catastrophic failure of the blade to allow post-mortem inspection. After the blade fatigue test was completed the blade was sectioned into 7 spanwise sections. Several sections were sent to Sentient for post-mortem inspection.

Figure 2. Blade damage on low-pressure spar cap at the 2.8 m station

Figure 3 provides the damage equivalent load distribution applied to the blade from all of the fatigue cycles as compared to the target fatigue load. Damage equivalent loads are shown for the high pressure and low pressure surfaces. Figure 4 shows the percent damage equivalent load applied through fatigue testing relative to the 100 % equivalent load.

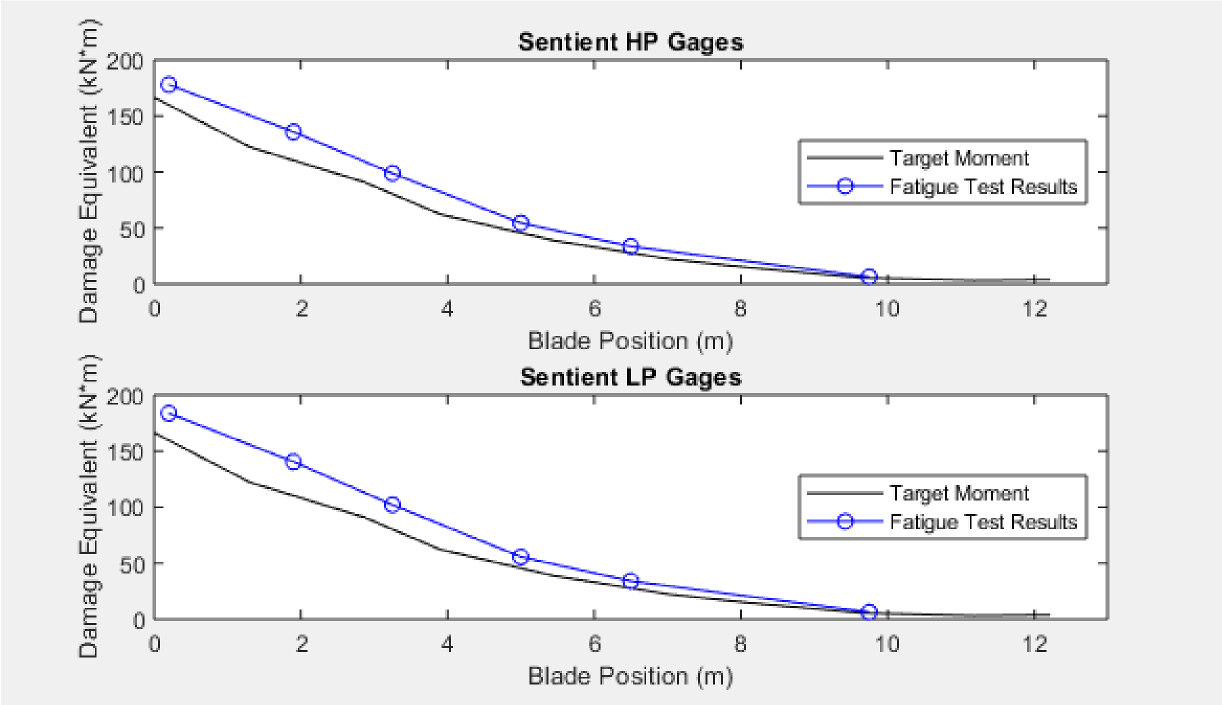

Figure 3. Target test and Applied DEL

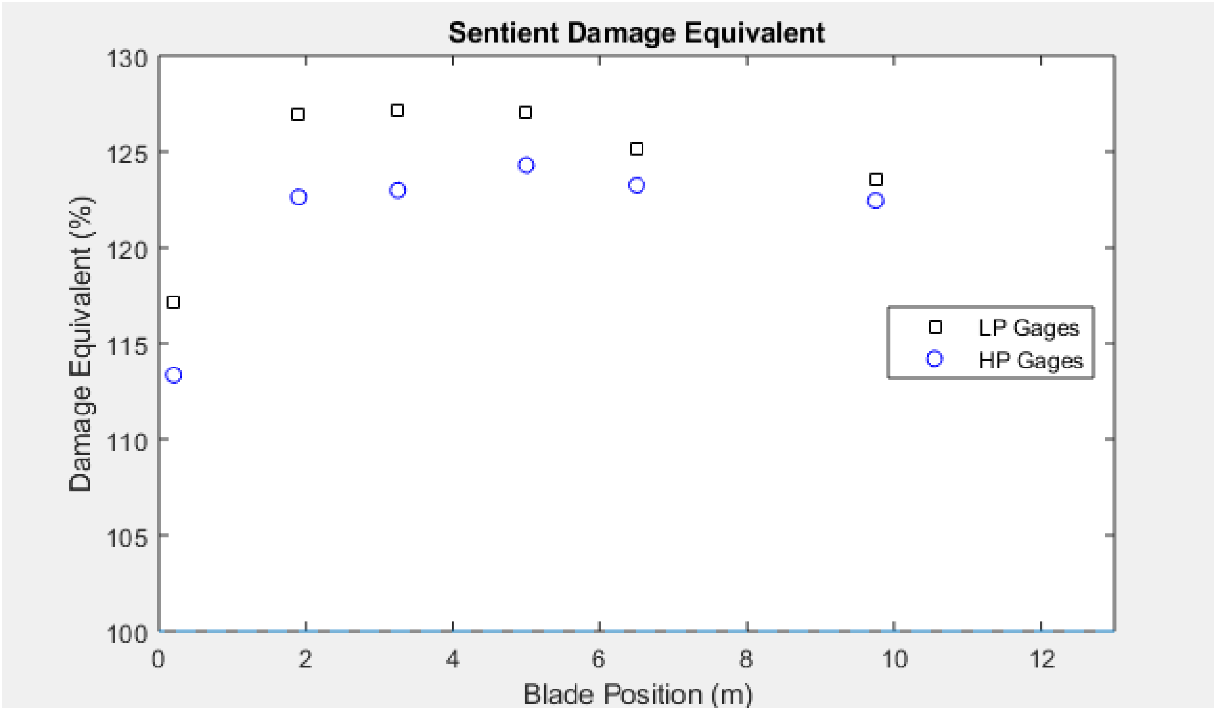

Figure 4. Applied DEL (% test plan target)

The test report was delivered to the project group on 13 December 2018. This test report documented the performance of the structural fatigue test. All data files and test photographs were transferred to a web-based data sharing site maintained by Sentient. The test report and data collected during the fatigue test were reviewed and validated by the project team. The final validation report including feedback from the project group was released on 26 April, 2019. This report conformed to reporting requirements of the IEC 61400-23 international standard on testing of wind turbine blades. The final report released to Sentient and Sandia National Laboratories was titled 'Laboratory Wind Turbine Blade Fatigue Testing of the Sentient 13-meter Wind Turbine Blade'. This report covered validated data including an uncertainty budget for measured and reported values.

The objectives and deliverables of **Task 1** (Task - Structural Testing; Deliverable – Test Report) of the CRADA Joint Work Statement were achieved through the performance of the fatigue tests and data and reporting distributed in December 2018. The objectives and deliverables of **Task 2** (Task - Data Validation; Deliverable – Data validation report) were achieved by completing the data validation report.

Subject Inventions Listing: None

ROI #: None