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Dynamic Stress-Strain on Turbine Blade using Digital Image Correlation Techniques
Part 1 – Static Load and Calibration

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ABSTRACT

Often times, wind turbine blades are subjected to static and dynamic testing to identify the performance levels that can be achieved for a particular configuration. These tests are a necessary part of the validation process. Typically, a variety of different static and dynamic measurements are made using a variety of different transducers. Typically, only a handful of strain gages are deployed to capture strain information.

Recent advances in digital image correlation (DIC) and dynamic photogrammetry (DP) have allowed new opportunities for blade inspection, structural health monitoring, and full-field vibration testing. The primary benefit to using DIC is that the measurement approach is not limited to identifying the displacement or strain at only a few discrete measurement locations, but instead makes full-field surface measurements possible. These techniques are currently being explored on several wind turbine blade applications and can provide a wealth of additional information that was previously unobtainable.

This paper, which is the first part of a two part paper, presents the static strain measurements and calibration of the system overall. The strain distribution along the length of the structure is compared to the finite element model. The data analysis is used to assure that the model is calibrated for the dynamic testing results; dynamic testing results are presented in the second part of this paper.

INTRODUCTION

As part of the certification process for wind turbine blades, static and dynamic tests are conducted to validate the structural configuration. Load tests are performed along with fatigue testing on the blades. Generally, the blades are instrumented with various measurement transducers and, in particular, many strain gages are generally included as part of the measurement system.

These strain gages are used to identify the stress and strain from the test. However, these gages are located at discrete points and information regarding the full-field distribution of the stress-strain is not available. Using digital image correlation (DIC) techniques, the full-field stress-strain can be obtained.

This work focuses on the use of DIC techniques to measure full-field stress and strain for both static and dynamic tests. Part 1 (this paper) focuses on the static testing and general calibration of the system. Part 2 focuses on the dynamic testing results. The test configuration is described and the results of conventional strain gages are compared to the DIC technique to show the advantages of the full-field approach.

In preparation for the testing of an actual wind turbine blade, a simple beam like structure was used for the validation of the test set up and methodology for the actual testing (see Fig. 1). The beam is very easy to characterize from both a test and model standpoint and the results provide more credibility for the proposed approach. (The actual testing of the Southwest Windpower turbine blade was underway at the time of this writing and the results will be presented in a future paper.) The test rig is described followed by the static testing performed prior to the dynamic tests; the dynamic testing results are presented in Part 2 of this paper.

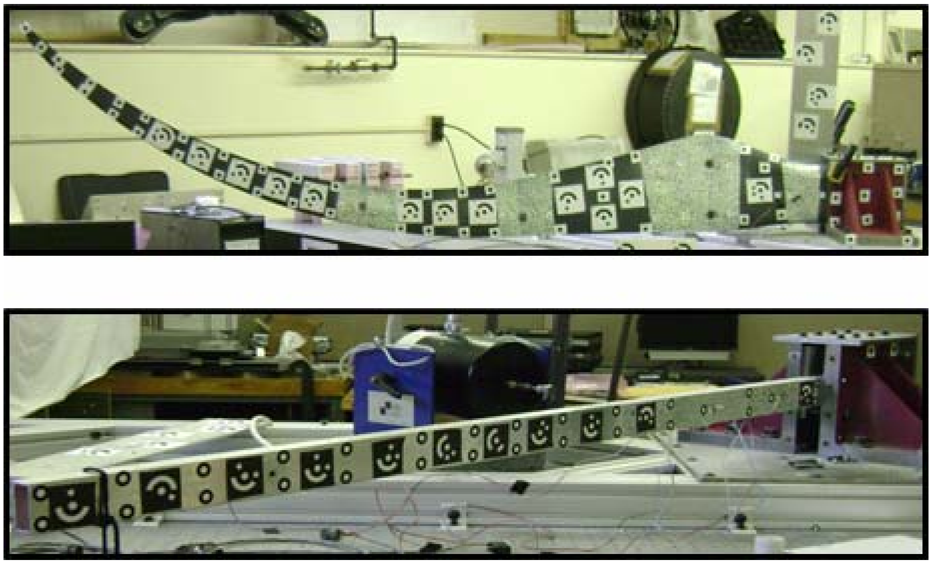

Figure 1. Test Setup for Turbine Blade (Top) and Aluminum Beam (Bottom)

TEST RIG FOR TESTING BLADES

To perform testing on the turbine blades, a test rig was designed, manufactured, and assembled [1]. During the design process, information on loading procedure and experimental requirements was based upon a test report from the National Renewable Energy Laboratory (NREL) [2]. An overview of the test setup is shown in Figure 2.

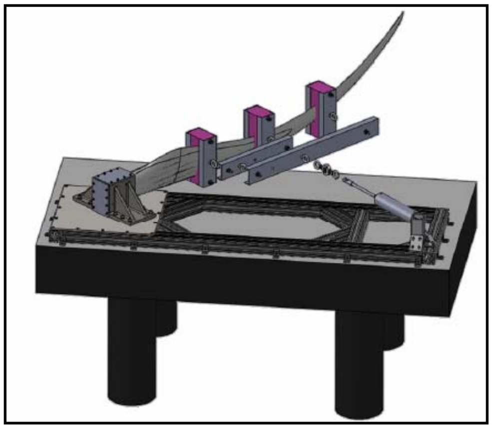

Figure 2. Test Rig Including the Mounting Fixture, Turbine Blade, Whiffle Tree, and Pneumatic Actuator

An optical table was chosen as the base of the test rig. To prevent transferring of forces generated by testing to the table, a frame was used to connect the fixture to the table. The frame was constructed with 3 in. by 3 in. aluminum extrusion beams. A 3/8 in. steel plate was bolted over a 2 ft by 2 ft area of the frame on which the fixture holding the blade was bolted. A CAD model of the frame is shown in Figure 3.

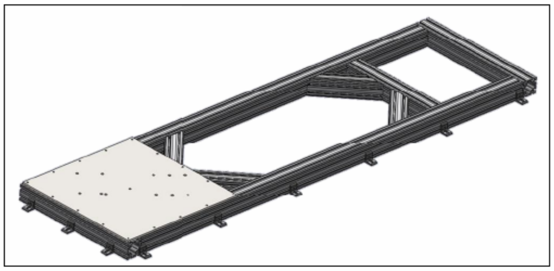

Figure 3. Frame Design

The fixture is designed to secure the root of the blade during testing and consists of two cast iron angle blocks, two shear plates, two spacer plates, and assorted hardware. The cast iron angle blocks clamp against the blade and secure the blade to the frame. The shear plates are used to increase torsional rigidity of the fixture. The aluminum spacer plates were used to adapt the face of the root, which has compression limiters and a triangular extrusion that interfere with clamping, to the face of the angle blocks. The fixture is shown in Figure 4.

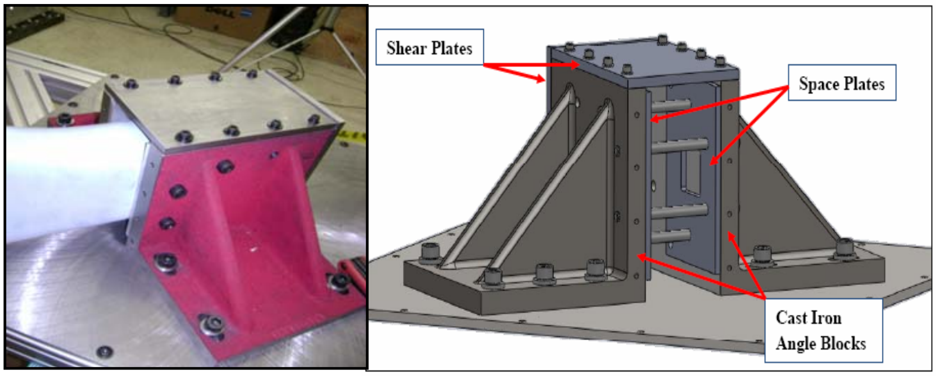

Figure 4. Fixture Realization and CAD Model

The load applied to the blade was distributed using a whiffle tree. The design of the whiffle tree was based on the NREL test report [2], but pink insulation foam was used for the saddles instead of machined delrin pieces. The whiffle tree is shown in Figure 5.

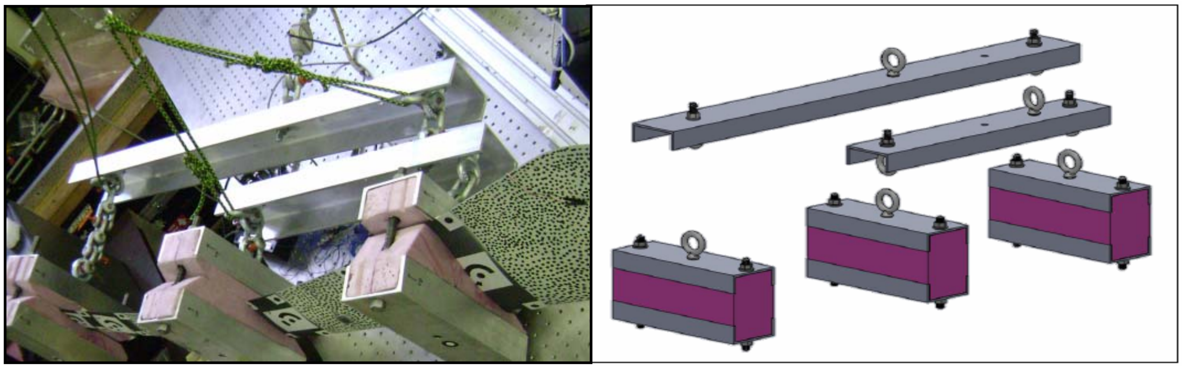

Figure 5. Whiffle tree

The designed loading mechanism consists of a 3 in. pneumatic (air) ram controlled by three precision air flow valves and fed by a small compressor. A controller was designed and manufactured to allow the load to be increased or decreased. This device permitted a user-controlled loading speed. The ram was mounted to the frame using a square post and a swiveling mounting bracket. The swiveling bracket allows the pneumatic ram to maintain a perpendicular pulling angle with respect to the whiffle tree. The air ram is connected to the whiffle tree with rope that has a force gage in the middle to measure the load. The pneumatic ram is shown in Figure 6.

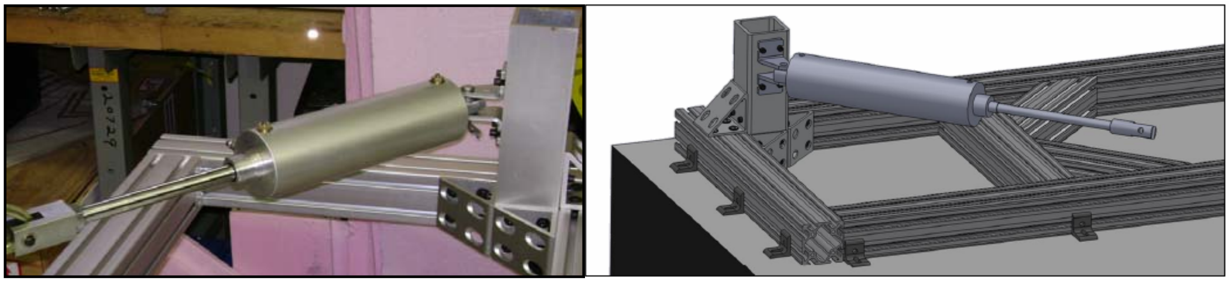

Figure 6. Pneumatic Ram Actuator used to Provide the Turbine Blade Loading

STRUCTURE DESCRIPTION

Testing and analysis was performed on a 5-ft long aluminum beam. The cross-section of the beam was a rectangular tube with dimensions of 1-in by 2-in and a thickness of 1/8-in. The beam was clamped in a fixture specifically designed for testing a wind turbine blade. The beam was used as a simplified structure for preliminary testing to validate the test set up and methodology for the actual testing. The beam is very easy to characterize from both a test and model standpoint and the results provide more credibility for the proposed approach. The test methods were designed for wind turbine blade applications and will be implemented on a wind turbine blade when the testing procedures and equipment are better understood and successfully performed on the beam.

TESTING PERFORMED

For validation and calibration of the system and finite element model, a static test was performed on the structure. The load was applied using the pneumatic ram described earlier. Incremental loads of 25 lbs were applied up to a 125 lb load. At each loading stage, data was taken using strain gages and DIC cameras, and the results were compared. A visual comparison of the finite element model to the DIC results when the structure was subjected to a 125 lb load, along with graphical strain comparisons of the strain gage results and DIC results, are shown in Figure 7.

The DIC data provides a full-field strain plot over the measured length of the beam. This plot shows a similar trend compared to the finite element model over the same field of the beam. To compare the results of the strain gages and the DIC data, the results from one measurement point of the speckle pattern located in the center of the strain gages was compared to the strain gage data, as shown in the plots of Figure 7. In addition to the strain gages and DIC results, an expected value of strain at those locations was calculated to ensure the results were reasonable. Although there was variance on the DIC data due to the proximity to the noise floor of the DIC measurement, the data is comparable to the strain gage results. Table 1 shows the coefficient of determination (R^2) values between the strain gage data and the DIC data (Note: Strain gage data for the location nearest the tip of the structure was not measured for runs 3 or 4, so an R^2 correlation was performed between the DIC data and the calculated strain). All the R^2 values are greater than 0.98, except in Run 3 in the data closer to the tip of the beam in which the DIC data were offset from the expected strain values. Overall, the results from the strain gage, model, and DIC compare very well. The acceptable correlation of data from a static test validates the testing approach and permits dynamic testing to be performed with confidence. The dynamic testing is presented in Part 2 of this paper.

Using DIC techniques to measure strain provides full-field strain results on a structure, that has a large advantage over conventional discrete strain measurement techniques. Because strain gages only measure discrete points, unexpected strain values due to defects in the structure would only be captured if a strain gage were placed at that precise location. However, current studies show that measuring strain along a structure using DIC techniques allows for the detection of defects due to changes in the full-field strain results. Additionally, using DIC permits measurements to be taken without the preparation time and wiring required when using strain gages.

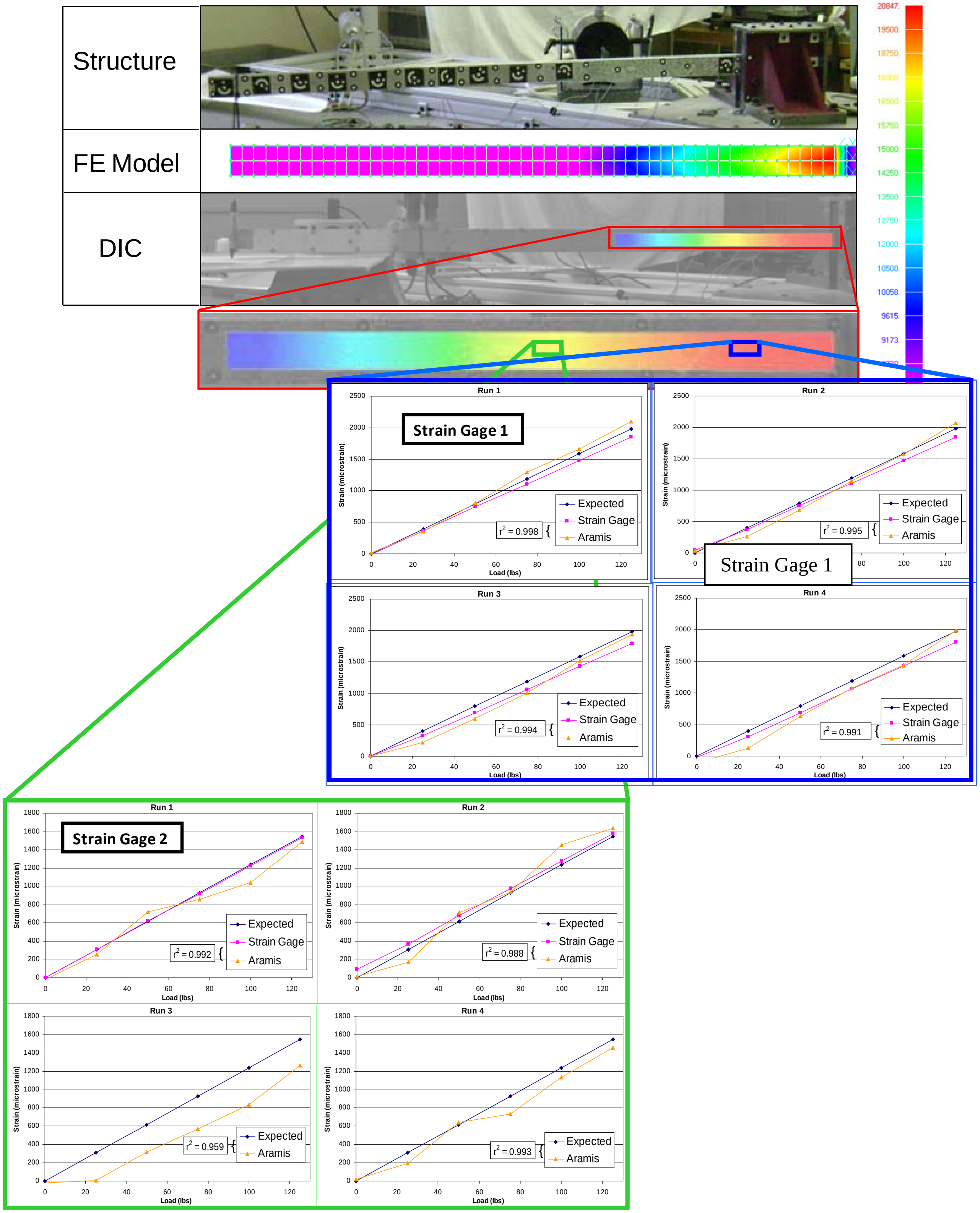

Figure 7. Comparison of the Full-field DIC Results and the Measurement from Two Strain Sensors

Table 1. Coefficient of Determination for Strain Gage and DIC Data

Run #	Strain Gage 1 (near base)	Strain Gage 2 (near tip)
1	0.998	0.993
2	0.995	0.988
3	0.994	0.959
4	0.991	0.993

CONCLUSION

Static and dynamic measurements for wind turbine blades are generally required for validation procedures. Digital image correlation has been used for making full-field surface measurements of displacement and strain in many applications and is currently being explored for measurement on turbine blades. For this work, in Part 1 of this paper, a static load test was performed on a cantilevered aluminum beam to validate the test setup and methodology for testing that will be performed for a turbine blade. Strain gages measured strain at discrete points on the structure while DIC measurement techniques were also employed to capture a full-field strain measurement. The DIC results and strain gage data compared very well; all strain measurements between the two techniques had R^2 correlation coefficients greater than 0.98, and the use of DIC for this application was validated. The full-field strain contour from the DIC measurement was also compared to a strain contour of the finite element model, and the contour plots exhibited the same trend along the length of the structure.

ACKNOWLEDEMENTS

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