NedWind 25 Blade Testing at NREL for the European Standards Measurement and Testing Program

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NREL

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1617 Cole Boulevard
Golden, Colorado 80401-3393

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1. Executive Summary

In the mid-90's the European Community initiated the Standards, Measurements, and Testing (SMT) program to harmonize testing and measurement procedures in several industries. Within the program, a project was carried out called the European Wind Turbine Testing Procedure Development (EWTTDP). The second part of that project, called Blade Test Methods and Techniques, included the United States and was devised to help blade-testing laboratories harmonize their testing methods. The project supported the need for comparison of the testing procedures used at the different laboratories, and, on this basis, supported the work of the International Electrotechnical Commission (IEC). Each of the individual laboratories benefited by having its procedures evaluated and accepted internationally, while they were able to observe, first hand, the methods used by others.

Three European Union member states and the United States participated in this project. The project was called SMT for short. Five laboratories were represented including RISØ (Denmark), the Center for Renewable Energy Sources (CRES--Greece), the Technical University of Delft (Netherlands), the Netherlands Energy Research Foundation (ECN), and the National Renewable Energy Laboratory (NREL--United States). CRES and NREL tested two blades while the other laboratories tested one blade. NREL, an invited member of this project voluntarily used internal funding from the U.S. Department of Energy.

The program objectives were:

- To make a reference database for different test methods, techniques, and results of static and fatigue testing of wind turbine blades used by different laboratories.
- To gain a greater collective understanding of the technical challenges of blade testing and to bring the international laboratories closer to a unified approach. As a result of this program, we anticipated that results from different laboratories will be shared and widely accepted.

SMT Program laboratories began by selecting a commercial blade model with good design records that could be released to the participating laboratories. They selected the Rotorline 12-meter and randomly chose blades from a sequential production series. The blades were weighed and identified at Rotorline at the time of manufacture. Each blade was marked at ECN to identify the position of common strain gauges. The laboratories were free to add additional measurement locations at their discretion.

The SMT project laboratories agreed on common prescribed static-tests to determine blade properties. Each laboratory was then required to perform a fatigue test on the blade. The laboratories were to independently determine fatigue test loads based on the design data, and then perform the tests using their "business as usual" practices. When possible, the laboratories agreed to follow the principles in IEC 61400-23 to reduce variability in the methods. NREL used the test load factors described in the draft IEC 61400-23 document to determine its test loads.

NREL's blades were designated by serial numbers #66 and #67. NREL performed all of the required measurements of the program. We performed identical mass property tests on both blades we received. We then determined eigenfrequencies by conducting modal tests for the flap and edge directions on both blades. NREL results showed very good agreement with those from the other laboratories, although modal results showed slightly lower frequencies associated with Blade #67. Torsional frequencies were much lower than predicted by Rotorline. However, this result was consistent with results from the other

laboratories. Damping was measured using a log decrement method, however NREL did not test at two temperatures as requested by the SMT program due to practical constraints in controlling laboratory temperature.

We also performed static-strength tests prior to and after the fatigue tests. The project laboratories agreed on common load magnitudes and a spanwise application location to perform strain verification tests on the blade. Several strain-gauge measurement locations were prescribed. Additional measurement locations were chosen by NREL. A total of 36 strain measurements and 2 bending bridges were used for each blade. For each blade test, the SMT project prescribed measurement of blade displacements at the load application point and at the tip.

Static test loads were taken from the NedWind 25 design extreme load cases. To determine the design loading, the extreme loads were multiplied by a design load factor of 1.5. The mandatory test load was taken to be 75% of this value. The load application point was at the 7.65-m spanwise location for both flap and edge loading. NREL elected to increase the load to 110% of the extreme loads to verify that the blade strains would maintain linearity throughout the fatigue test load range. No abnormal behavior or non-linearities were detected during the static testing. The highest strain in the flap-loading case was measured at 41% span at 40% chord.

We performed fatigue tests on both blades using NREL's servo-hydraulic system. One blade was tested using single-axis loading and the other using two-axis loading. Loads for both tests were generated using a damage-equivalent load model that was developed at NREL using the linear damage principles of Miner's Rule. Single-axis loads were constrained to a single load amplitude ratio and in-phase loading. Two-axis testing used an optimized load amplitude ratio for flap and edge components and a 90°-phase angle between them. The resulting peak single-axis loads were more severe than the two-axis loads and produced an earlier onset of damage, although the same cracks appeared for both tests. Most of the strain gauges showed higher strain on the single-axis test.

We conducted a post-fatigue static test on both blades to 100% of the design load prescribed. Results showed that both blades appeared to have stiffened between the pre- and post-fatigue tests. This result is unusual but might be explained by a drier ambient environment in Colorado than their original climate in the Netherlands. No unusual blade-to-blade variations were detected either globally or at individual strain measurement locations. However, we observed some local differences that were not explained by the strain-data analysis. A postmortem inspection was planned to identify possible anomalies in the construction but was not conducted due to time constraints on the program.

2. Introduction

2.1 *Background*

In the mid-90's the European Community initiated the Standards, Measurements, and Testing (SMT) program to harmonize testing and measurement procedures in several industries. Within the program, a project was carried out called the European Wind Turbine Testing Procedure Development (EWTTDP). The second part of that project, called Blade Test Methods and Techniques, was devised to help blade-testing laboratories harmonize their testing methods. Three European Union member states and the United States participated in this project. The project was called SMT for short. According to SMT documents, response to a survey initiated by the Strength and Fatigue of Large Wind Turbine Rotors Project (S&FAT) in Europe on the need for blade testing, showed that a majority of the European wind turbine and blade manufacturers believe that blade testing is a necessary part of wind turbine design [1]. This sentiment seems to be shared in the United States as well.

The standardization of blade testing was initiated in 1994 within the International Electrotechnical Committee (IEC) working group 8. The document, IEC 61400-23, was submitted for vote to the IEC TC88 technical committee as an IEC technical report and was accepted in May 2000. It was not developed as a standard because, at the time of its writing, the area of structural blade testing had not matured to a level where a prescriptive standard could be internationally adopted and accepted by a majority of countries.

2.2 *Standards Measurement and Testing Program Overview*

SMT Program laboratories began by selecting a commercial blade model with good design records that could be released to the participating laboratories. They selected blades from a series production and randomly assigned a blade to each laboratory. The Center for Renewable Energy Sources (CRES) and the National Renewable Energy Laboratory (NREL) agreed to test two blades while the other laboratories performed their tests on one blade. The blades were weighed at Rotorline at the time of manufacture. Each blade was also marked at the Netherlands Energy Research Foundation (ECN) to identify the position of common strain gauges. The laboratories were free to add additional measurement locations at their discretion.

The SMT project laboratories agreed on three tests that were to be conducted on each blade received.

1. Property tests, which included eigenfrequency measurements, weight, CG verification, and damping
2. A common set of prescribed static tests for strain verification
3. A fatigue test

The laboratories were to independently determine fatigue test loads based on the design data, and then perform the tests using their “business as usual” practices. When possible, the laboratories agreed to follow the principles in IEC 61400-23 to reduce variability in the methods. NREL used the test load factors described in the draft IEC 61400-23 document to determine its fatigue test loads.

2.3 NREL Blade Testing

NREL has been involved in blade testing since 1990 and has tested more than 75 wind turbine blades. Most of these tests were funded through the U.S. Department of Energy's (DOE's) turbine development projects. Because this work is proprietary in nature and is not usually available to the public, its development and dissemination of NREL testing methods have been inhibited. The SMT program gave NREL an opportunity to share its test results and methods amongst the project laboratories and with the wind industry at large. NREL currently has three blade test bays where blades as long as 34 meters can be fatigue or static tested [2].

2.4 Scope

This is the final report to be delivered to ECN under the Standards, Measurement, and Testing program. It covers all of the testing activities conducted by NREL under this program between 1997 and 2000.

2.5 Description of Program Objectives

The program objectives were:

- To make a reference database for different test methods, test techniques, and test results of static and fatigue testing of wind turbine blades being used by different laboratories.
- To gain a greater collective understanding of the technical challenges of blade testing and to bring the international laboratories closer to a unified approach. From this program, results from different laboratories may be shared and widely accepted.

3. Property Testing

3.1 Mass Properties

3.1.1 Objectives

All laboratories were to measure the weight and center of gravity (CG) of the blades. This data was needed to develop of blade structural and full-system dynamic models. The blade weights and CGs must also be verified so that the turbine manufacturer will have matched blade sets.

The blades received at NREL were weighed and adjusted for CG position at NedWind Heerhugowaard (later changed to Rotorline) and documented in a project document, "Jeroen 8" [3]. The blades were simultaneously weighed at the flange and at the 9.5-meter station. These weights and CGs are presented with the results in Table 3.5.

3.1.2 Test Method

NREL duplicated the method used by NedWind to determine weight and CG. Weight at the flange and at the 9.5-meter station were both measured during the lift. The 9.5-meter station was lifted with a strap

configured into a choker. The flange was lifted with a strap over a steel rod inserted into one of the flange holes. It was assumed that the flange lift was over the center of the flange, which was 70.8-mm thick.

Because of an oversight, we did not perform these mass property tests until the completion of the fatigue tests. The results include the effect of the strain gauges and lead wires, which we assumed to be negligible. Also, the tip (outboard 2-meters) for Blade #67 had been removed. We determined the weight of Blade #67 by adding the weight of the two parts. We determined the total blade CG by first determining the CG of the main blade section by weighing at the flange and at the 9.5-meter section as mentioned above. We then weighed the blade tip with a lower capacity load cell. We determined the tip CG by balancing it over a piece of angle iron. The total blade weight was the sum of the part weights (less material lost when cutting the blade, assumed to be negligible). The total CG was determined by adding the mass moment of inertia of the parts and dividing by the total weight (see Tables 3.2 to 3.4).

3.1.3 Instrumentation and Equipment

The blades were measured in NREL's Building 251 high bay. The blade was lifted at the flange with the 15-ton-capacity overhead crane. The weight was measured at this point with a 10,000-lb (4536-kg) capacity load cell (Transducer Techniques, model number SW0-10K, serial number 90132). The 9.5-m station was lifted with a 1-ton-capacity engine hoist. The weight was measured at this point with a 2000-lb (907-kg) capacity load cell (Transducer Techniques, model number SW0-2K, serial number 87158). The load cells were hooked up to NREL's Blade Structural Testing Real-Time Acquisition Interface Network (BSTRAIN) [4] for readout of the measurements.

The tip piece of Blade #67 was weighed with a 200-lb (91-kg) capacity load cell with external readout (Cardinal, model number HSDC-200, serial number 9407-35).

3.1.4 Results

Table 3.1 below lists the weight and CG data for Blade #66. Tables 3.2 to 3.4 list the data for Blade #67. Table 3.5 lists the compiled results along with the Rotorline data. The uncertainties in the NREL values are ± 6 kg and ± 0.02 meters. Note that the total weight matches within the experimental uncertainty. The CG values however, are 3% greater for the NREL measurements. Our first concern was that the strain-gauge installation (weight is estimated at less than one kilogram) effected the results. However, the NREL CG measurements matched those of the other laboratories [5], with the exception of ECN.

Table 3.1 Weight and CG Determination for Blade #66

Weight at Flange* (kg)	Weight at 9.5-m Span (kg)	Total Weight (kg)	Mass Moment about Flange (kg-m)	CG Distance from Flange (m)	CG Distance from Hub-Mating Surface (m)
513.9	242.7	756.6	2297	3.04	3.07

*Note that the flange center is 35.4 mm from the hub-mating surface.

Table 3.2 Weight and CG Determination for Blade #67-- Without Tip

Weight at Flange (kg)	Weight at 9.5-m span (kg)	Total Weight of Main Piece (kg)	Mass Moment about Flange (kg-m)	CG Distance from Flange (m)	CG Distance from Hub-Mating Surface (m)
519.8	205.9	725.7	1949	2.69	2.72

Table 3.3 Weight And CG Determination for Blade #67-- Tip Only

Tip Weight (kg)	CG Distance to Cut (m)	CG Distance from Hub-Mating Surface* (m)
31.6	1.03	10.99

*Note that the blade was cut at 9.96-meters.

Table 3.4 Total Weight and CG Determination for Blade #67

Total Weight (kg)	Mass Moment of Main Piece (kg-m)	Mass Moment of Tip (kg-m)	Total Mass Moment (kg-m)	CG Distance from Hub-Mating Surface (m)
757.3	1974	347	2321	3.07

Table 3.5 Blade Weight and CG

Blade Number	Rotorline Weight/CG (kg/meters)	NREL Weight/CG (kg/meters)
66	759.36/2.99	757/3.07
67	759.28/2.99	757/3.07

3.2 Eigenfrequency Determination

3.2.1 Eigenfrequency Determination Objectives

All of the laboratories were required to determine the first and second flap and edge blade frequencies and the first torsional frequency of the blades prior to static testing. The purpose was to determine the measurement scatter among the laboratories. This data could also be used as a boundary for the fatigue test frequency. Although not a specific objective of this program, this data could be used in the development of blade-structural and full-system dynamic models.

From [6] ("Jeroen 4") and [3] ("Jeroen 8"- included in Appendix F), the expected frequencies (blade cantilevered) are given. They are also summarized below in Table 3.6.

Table 3.6 Expected Eigenfrequencies

Mode	Blade Frequency (Hz)	Reference
First Flap	2.52	Jeroen 4
First Edge	4.0	Jeroen 4
Second Flap	7.8	Jeroen 4
Second Edge	26.1	Jeroen 4
First Torsion	37.5	Jeroen 8

3.2.2 Test Method

The eigenfrequencies were determined by measuring the frequency response function at various locations along the blade. Figure 3.1 shows a layout of the blade for the modal testing and the measurement positions used. Driving-point measurements (collocation of input and response) were made at position #9 (end of spar) and at position #5 (center of gravity) in the flap and edge directions. A modal survey was then conducted by impacting the blade at the survey test points and measuring the response at position #9. Based on a preliminary review of the data, we believe that position #9 was a node for the second flap frequency. We then changed the measurement position to #11.

To determine the first torsional frequency, a measurement was made taking the cross product of the flap response at positions #20 and #31 (leading edge and trailing edge at end of spar). The second blade (#67) was not extensively surveyed as the first blade. Driving-point measurements were only made at position #11 based on the first blade survey.

Figure 3.1 Blade modal sensor layout

3.2.3 Instrumentation and Equipment

The blades were connected to NREL's 1.35 million N-m (1 million ft-lb) capacity blade test stand with a custom adapter plate (see Appendix H for drawing). The blade was positioned with the tip chord perpendicular to horizontal, with the trailing edge down, and the pitch axis parallel to the floor. This was the same setup used in the edge static pulls. These tests were conducted in Building 252 (A-60) at the National Wind Technology Center (NWTC).

The accelerometers were mounted to the blade using the following procedure. At each measurement position, aluminum tape was applied to the curved surface of the blade. A small balsa square was sanded into a wedge and glued to the tape to provide a vertical surface for the accelerometer mount. Another layer of aluminum tape was applied over the wedge and the accelerometers were hot-glued to the wedge to orient the accelerometer's z-axis parallel to the ground. The accelerometer cable was then taped to the blade for strain relief.

Tables 3.7 to 3.10 below list the equipment used in the various aspects of the test.

Table 3.7 Equipment Used for Blade #66 Driving-Point Measurements

Device	Manufacturer	Model No.	Serial No.
Dynamic Signal Analyzer	Scientific Atlanta	SD380Z	719
Force Hammer	PCB	086C20	216
Three-axis Accelerometer	PCB	356A18	4152

Table 3.8 Equipment Used for Blade #66 Modal Survey

Device	Manufacturer	Model No.	Serial No.
Dynamic Signal Analyzer	Hewlett-Packard	HP3565S System	various
Force Hammer	PCB	086C20	216
Accelerometers	PCB	370A03	various

Table 3.9 Equipment Used for Blade #66 Torsion Measurements

Device	Manufacturer	Model No.	Serial No.
Dynamic Signal Analyzer	Scientific Atlanta	SD380	TBD
Force Hammer	PCB	086C20	216
Accelerometers	PCB	370A03	361, 362

Table 3.10 Equipment Used for Blade #67 Flap-Driving Measurements

Device	Manufacturer	Model No.	Serial No.
Dynamic Signal Analyzer	Scientific Atlanta	SD380Z	719
Force Hammer	PCB	086C20	216
Accelerometers	Kistler	8638B50	C106090, C106091

3.2.4 Analysis Method

The blade modes were determined by plotting the residuals of the frequency response functions (FRFs) that were measured during the modal survey. The residual at each location and for each direction (flap and edge) was determined with the Hewlett-Packard (HP) analyzer and noted in a table. Each residual was then divided by the maximum value along the blade. The residual plots for each frequency were then qualitatively analyzed to determine the blade modes. Figure 3.2 shows a plot of the first and second flap-bending modes. These residuals are from the spar location. The drop in the first flap mode could be due to a change in blade structure (no spar) at this location.

Figure 3.2 Blade #66 flap-bending-mode residual plot

The first torsion frequency for Blade #66 was determined by measuring the cross product of flap positions #20 and #31. The blade was excited in the flap direction at position #31. The torsion frequency was noted by a 180° phase shift at 25.875 Hz. This frequency was also evident in the flap driving point measurements. Figure 3.3 shows the cross product plot.

It was assumed that frequencies for Blade #67 would be similar, therefore only driving point measurements were made at position #11. Figure 3.4 shows the flap driving-point FRF for Blade #67. Figure 3.5 shows the edge driving-point FRF for Blade #67.

Figure 3.3 Blade #66 cross product of flap response at Positions #20 and #31 with flap excitation at Position #31

Figure 3.4 Blade #67 flap driving-point response at Point #11

Figure 3.5 Blade #67 Edge driving-point response at Point #11

3.2.5 Eigenfrequency Results

Table 3.11 below shows the results of the eigenfrequency tests. The resolution of the frequency measurement was 0.125 Hz. The expected frequencies are also listed, with only the first and second flap modes being predicted to within 4%. Amongst these modes was a coupled-flap/edge mode near 17 Hz for both blades.

Table 3.11 Eigenfrequency Results

Mode	Blade #66 Frequency (Hz)	Blade #67 Frequency (Hz)	Expected Frequency (Hz)	Average $\Delta\%$ from Expected
First Flap	2.500	2.500	2.52	0.8
First Edge	5.000	4.875	4.0	-19.0
Second Flap	8.250	7.875	7.8	-3.3
Second Edge	20.000	19.374	26.1	32.6
First Torsion	25.875	25.250	37.5	46.7

3.3 Damping

3.3.1 Damping Measurement Objectives

The laboratories were to measure the damping for the first flap and edge bending modes of the blade. This data, which is part of the modal properties of the blade, could be used with the eigenfrequency data to develop blade-structural and full-system dynamic models. The damping can be dependent on the temperature of the blade structure. Also, aerodynamic damping can contribute to the measurement depending on the deflection of the blade during excitation.

The SMT program requirements were to measure the damping with log decrement. Measurements at two different temperatures were also specified but this requirement was overlooked by NREL.

3.3.2 Test Method

NREL used a step-relaxation method to measure the blade damping. The blade was set up for the edge measurement as shown in Figure 4.1. For the flap measurement, the blade was rotated clockwise 90° in pitch from this position so that the tip chord was horizontal (high pressure side down) with the pitch axis remaining horizontal.

For initial deflecting the blade, 90 lb (41 kg) was suspended 11.5 m from the flanged mating surface with rope and tie-straps. The root strain gauge bending bridge was connected to a bridge power supply and storage oscilloscope. The oscilloscope was armed to collect approximately twenty cycles of data on the bridge signal. The tie-straps were cut to release the weight and the bridge signal was stored in the oscilloscope. Five trails were made for each measurement and the damping values were averaged.

The critical damping coefficient was determined by fitting a damped sine wave to the data, using a nonlinear regression program NLREG [7]. The damping is unit-less and is determined by fitting the following equation to the data [8]:

$$x(t) = Ae^{-\zeta\omega_n t} \sin(\omega_d t - \phi), \quad (3-1)$$

where:

- $x(t)$ = signal value at time t
- A = undamped amplitude
- ζ = damping factor
- ω_n = undamped natural frequency
- ϕ = phase angle

and,

$$\omega_d = \omega_n \sqrt{1 - \zeta^2}$$

The difference between ω_d and ω_n is a small quantity of second order. The curve fit was used to solve for the damping, ζ .

3.3.3 Instrumentation and Equipment

The bending-bridge gauges used for generating the time series are described in the static-testing Section 4.3.2. The bridge 08BFLAP was used for the flap measurements and bridge 08BLDLG was used for the edge measurement. The bridges were hooked up to a Measurements Group P-3500 digital strain indicator

with the output connected to a Tektronix THS710A digital-storage oscilloscope. The time series data was then downloaded to a PC using WaveStar software [9]. NLREG is then used to fit a damped sine wave to the data.

3.3.4 Damping Results

Figure 3.6 shows data for an edge step relaxation test for Blade #67. The damped sine curve parameters for this data are:

$$\begin{aligned} A &= 0.00393 \\ \zeta &= 0.0037 \\ \omega_d &= 30.8 \text{ radians/sec (4.90 Hz- compare to 4.875 Hz in Table 3.11)} \\ \phi &= 0.935 \text{ radians} \\ \text{offset} &= \text{negligible} \end{aligned}$$

Figure 3.6 Blade #67 edge step-relaxation test data

Figure 3.7 shows data for a flap step relaxation test for Blade #66. The damped sine-curve parameters for this data are:

$$\begin{aligned} A &= 0.00645 \\ \zeta &= 0.0038 \\ \omega_d &= 16.0 \text{ radians/sec (2.55 Hz- compare to 2.50 Hz in Table 3.11)} \\ \phi &= 0.012 \text{ radians} \\ \text{offset} &= -0.0017 \text{ volts} \end{aligned}$$

Figure 3.7 Blade #66 flap step-relaxation test data

Table 3.12 Damping Results

Mode	Blade #66 Damping	Test Temperature	Blade #67 Damping	Test Temperature
First Flap	0.0038 ± 0.0006	Not recorded	0.0044 ± 0.0008	22°C
First Edge	0.0042 ± 0.0002	27°C	0.0037 ± 0.0001	27°C

Table 3.12 lists the damping results. The values are the average of five measurements. The uncertainty, which includes random and systematic components, is within the 95% confidence limit. The systematic uncertainty for the measurements is for the curve fit output from NLREG. The random component is due to the variation in five measurements.

Because the energy released in the step relaxation contains all frequencies, all modes are excited in the blade. This creates a noisy signal that reduces the accuracy (error of 16% for the flap) of the damping curve fit. A better approach would be to excite the blade at the first mode frequency with an electrodynamic shaker and then remove the excitation and record the decaying signal.

4. Static Testing

4.1 *Static Testing-- Introduction*

The purpose of the static tests under the SMT program was to demonstrate that the individual laboratories could make the same measurements of strain, load, and deflection on different blades having the same characteristics and global properties. Blades were carefully selected and common strain-gauge locations were marked to assure uniformity. Under normal practice, this type of information is useful for validating structural models that predict stresses or strains on the blade, and to validate load-carrying capability and strength. Unfortunately, it was not possible under this program to perform a complete static-strength validation because of the requirement for most of the labs to incorporate all testing into a single blade. Therefore, the common test procedure prescribed did not include a test to failure.

At NREL we tried to meet the requirements of the program but also to try and produce a static test that was more representative of our common practice. We met the SMT requirement of loading to 75% of the extreme design load case. In addition, however, we added a step to increase the load to 110% in order to verify a minimum acceptable load for the fatigue test, which was expected to have cyclic test load peaks of nearly 100% of the design case. One of the reasons NREL agreed to purchase two blades was to demonstrate extreme-load-carrying capability. With two blades, we knew that an unexpected failure of one blade would not end the program.

Even though we were somewhat freed from a conservative static approach, the methods used in this program were not exactly consistent with the NREL recommendations or standard practices. Specifically, we believe the static-test procedure should include a test-to-failure on a blade to validate the strength and determine the design margins.

4.2 *Static-Test Method*

4.2.1 Static-Test Load

4.2.1.1 *NedWind Load Cases*

Static-test loads were derived from the load spectrum from NedWind in Appendix A. For the flapwise test, load case 93 was used. From [6], this was the case of the turbine parked at the extreme wind speed (52.2 m/s). For the edgewise test, load case 97 was used, which corresponds to a grid short circuit at 20 m/s. These load cases correspond to the maximum flapwise and edgewise moments respectively.

Rotorline performed a static test in 1992. The blade was loaded separately in flapwise and edgewise directions. The maximum flapwise bending moment came from load case 93. To apply the maximum bending moment, Rotorline applied a test load of 23000 N (5171 lb) at 7 meters from the blade flange. The edgewise test was performed with a load of 7150 N (1607 lb) at 7 meters from the blade flange. The maximum edgewise bending moment came from load case 97; however this value was not used. Table 4.1 shows the result of the Rotorline tests.

Table 4.1. Rotorline Static-Test Blade Deflections

Load (N)	Load Direction	Displacement at 7.65 m	Tip Displacement
23000	flapwise	150 mm	382 mm
7150	edgewise	20 mm	45 mm

4.2.1.2 NREL Loads

The loads prescribed by the SMT project were 75% of the extreme load cases moment at the flange (0.65 meter) multiplied by a partial safety factor of 1.5. The loads were to be applied at the same location as the Rotorline test at the 7.65-meter station.

In addition, NREL tested up to 110% of the extreme moments at the 0.2 m station (with 1.5 partial safety factor) to determine if there was adequate stability in the range of the expected fatigue-test loads.

The tare loads for the test were determined by the weight of the load saddle and the blade mass moment from the maximum chord position out to the load application point. The mass moment of this section was determined from “Alex 9” [10]. Table 4.2 shows the blade mass distribution. Adding the blade and saddle tare weight to the test loads would approximate zero bending at the maximum chord during the start of the test. The blade tare weight was 1980 N (445 lb). Table 4.3 shows the static-test loads used at NREL.

Table 4.2 Mass Distribution for Static-Test Blade Weight Tare [10]

Position (mm)	Mass Moment (N-mm)
7651	2.335E06
3151	11.243E06

Table 4.3 Static-Test Loads

Load Direction (load case)	Moment to Match at 0.65 m Flange (N-m)	SMT-Prescribed Load at 7.65 m	Moment to Match at 0.2 m (N-m)	NREL 110% Load at 7.65 m	Saddle Tare Weight	Total Tare Weight
edge (97)	92143.9	14809 N (3329 lb)	102865	22782 N (5122 lb)	1027 N (231 lb)	3007 N (676 lb)
flap (93)	153834	24723 N (5558 lb)	165036	36552 N (8218 lb)	912 N (205 lb)	2892 N (650 lb)

4.3 Instrumentation and Equipment

4.3.1 Load Apparatus

4.3.1.1 Test Stand

The test stand used for the static tests can be seen in Figure 4.1. This stand is one of the two stands at the NWTC with a 1.36 million N-m capacity (1 million ft-lb). The test-stand mounting face was set to perpendicular for the edgewise testing and was tilted back approximately 8° for the flapwise static tests. The tilt was necessary for the installation of the hydraulic actuator in the flapwise test.

An adapter plate was constructed of A-36, 102-mm (4-in.) steel plate. This plate was built to adapt the NedWind 753-mm (29.65-in.) bolt circle to the test stand 1219-mm (48-in.) bolt circle. A drawing of the adapter plate is in Appendix G. The adapter plate was mounted to the test stand with 1.25×7.00 UNC Grade 8 bolts torqued to 1360 N-m (1000 ft-lb). The blade was mounted to the adapter plate with M24×200 10.9 metric bolts torqued to 800 N-m (590 ft-lb). This was the blade-to-hub torque specified by NedWind [11].

Figure 4.1 NedWind 25 Blade Setup Edge Static-Loading Building 252 (A-60), NWTC

4.3.1.2 Load Saddles

Loads were introduced into the blade at the 7.65-m station with a load saddle. A drawing of the load saddle is shown in Appendix H. The saddle consists of a metal frame that can withstand the loads normal and parallel to the blade chord line. The metal frame compresses wood blocks with a cutout of the blade section. In between the wood and blade is a 76-mm (3-in.) wide strip of high durometer (80 shore-A) polyurethane. The polyurethane was molded directly to the blade section, which allowed the load to be spread around the blade section.

The saddle had a connection for the edge loading that pulled in the direction aligned with the blade section chord line. For the flap load, the load actuator was connected so that the load was normal to the blade section at 40% chord.

4.3.1.3 Load Cells

Table 4.4 below lists the information for the load cells used in the static tests.

Table 4.4 Load Cells Used for Static Pulls

Pull Direction	Manufacturer	Model No.	Serial No.	Capacity
Edge	Tri-Coastal Industries	TG 303	898	133,440 N (30,000 lb)
Flap	MTS®	661.20E-03	78892	97,856 N (22,000 lb)
Flap (blade 66 post-fatigue)	MTS®	661.20E-03	66265	97,856 N (22,000 lb)

4.3.1.4 Overhead Cranes

The 5-ton (44,480-N) overhead crane in Building 252 was used to apply the edge load, which was displayed on a large digital display for operator feedback. The crane can be seen in Figure 4.1. The crane winch is hydraulically powered and operated with hand valves in an adjacent control room. The crane has wheels that allow for free movement in the blade longitudinal direction.

For the post-fatigue edgewise static test on Blade #66, the 35-ton (311,360-N) overhead crane in Building 254 was used.

4.3.1.5 Servo-hydraulic System

Flap static-loads were applied with a hydraulic actuator controlled by an MTS® 458.14 servo-hydraulic system controller. The controller was operated with MTS® T/RAC software. A 762-mm (30-in.) stroke, 46,260 N (10,400-lb) capacity actuator was used to apply the loads. The controller was set to apply the load in a slow ramp and hold at load for 10 seconds.

For the post-fatigue flapwise static test on Blade #66, the same actuator was used but it was connected to an MTS® 497.13 Flex Test IIm System Controller.

4.3.1.6 Displacement Instrumentation

Table 4.5 lists the instrumentation used for measuring the displacement at the load application point (7.6 m). A string potentiometer was used to measure the edge load application point displacement. The

flap load application point displacement was measured using the load actuator's internal linear variable differential transformer (LVDT).

Table 4.5 Static-Pull Displacement Instrumentation--Load Application Point

Pull Direction	Type	Manufacturer	Model No.	Serial No.	Capacity
Edge	String Potentiometer	Patriot	P-40B(A56)	19540	1016 mm (40 in.)
Flap	LVDT	MTS®	247.11	0234238	762 mm (30 in.)

Tip displacement was measured for both flap and edge tests using linear retractable scales. The tip displacement scale readings were recorded by hand at the start of each load application and at the test load.

4.3.2 Strain Gauges

Common strain-gauge locations were prescribed by the SMT program and documented in “Jeroen 8” [3] and [12]. These locations were marked on the blades at ECN prior to shipment to the laboratories. The partners were to measure these common gauge locations according to procedures outlined in the SMT project plan [13].

Table 4.6 Common Strain-Gauge Locations

SMT Gauge	NREL Gauge	Blade #66 Radial*	Blade #67 Radial*	$\Delta\%$	Blade #66 Circumferential*	Blade #67 Circumferential*	$\Delta\%$
400E1	08BLDLG	0.393	0.408	3.8	0	0	0.0
400E2	08BLDLG	0.416	0.405	-2.6	0.981	0.993	1.2
400F1	08BFLAP	0.407	0.407	0.0	0.498	0.506	1.6
400F2	08BFLAP	0.403	0.407	1.0	1.463	1.484	1.4
1500S1	17S38UA	1.498	1.501	0.2	1.730	1.703	-1.6
1500P1	17S38LA	1.505	1.500	-0.3	0.740	0.696	-5.9
1500S0	17R62UA	1.488	1.486	-0.1	2.000	1.972	-1.4
1500P0	17R62LA	1.486	1.486	0.0	0.469	0.425	-9.4
1500S45	17R62UB	1.493	1.492	-0.1	1.995	1.968	-1.4
1500P45	17R62LB	1.492	1.492	0.0	0.474	0.430	-9.3
1500S90	17R62UC	1.497	1.497	0.0	1.991	1.962	-1.5
1500P90	17R62LC	1.469	1.497	1.9	0.478	0.435	-9.0
2500S1	25S26UA	2.498	2.503	0.2	1.907	1.899	-0.4
2500P1	25S26LA	2.506	2.500	-0.2	1.037	0.998	-3.8
2500S0	25R45UA	2.488	2.487	0.0	2.179	2.167	-0.6
2500P0	25R45LA	2.491	2.487	-0.2	0.766	0.726	-5.2
2500S45	25R45UB	2.492	2.490	-0.1	2.173	2.161	-0.6
2500P45	25R45LB	2.495	2.492	-0.1	0.722	0.730	1.1
2500S90	25R45UC	2.497	2.496	0.0	2.169	2.157	-0.6
2500P90	25R45LC	2.499	2.497	-0.1	0.776	0.736	-5.2

*Radial dimension is measured from flange mating surface, circumferential dimension is measured from trailing edge starting on pressure side. All dimensions are in meters [13].

The project partners were free to add additional measurement locations. In total, NREL applied 36 strain and 2 bending bridges to each blade. Tables 4.7 and 4.8 list the NREL gauge locations.

Gauges were placed at five blade span locations including the root. Gauges were placed at mid-panel fore and aft of the blade spar and along the spar. Three-axis rectangular rosette gauges were used on the compressive side mid-panels.

Tables 4.7 and 4.8 show the strain-gauge measurement locations for the edge and flap static tests respectively. Single element gauges were Measurements Group WK-09-250BF-10C. Measurements Group WK-09-250RD-10C were used for rectangular rosettes. Data sheets for these strain gauges are included in Appendix H.

Note that 08BLDLG and 08BFLAP were configured into active four-arm bending bridges. This was due to preliminary program information stating that these gauge locations would be used to measure bending. Later we found that the other laboratories were measuring the strain at these locations.

Table 4.7 Strain Gauge Setup for Edgewise Static Pulls

GAUGE NAME	SMT NAME	BIB BOX HOOK-UP	GAUGE CHANNEL	TYPE	DISTANCE FROM CENTER OF ROTATION	DISTANCE FROM ROOT PLANE	CHORD LENGTH	PERCENT SPAN	PERCENT CHORD	SURFACE	ORIENTATION
					mm	mm	mm				
08BLDLG	400E1/E2	1-1	4	BENDING	1050	400	TBD	8	N/A	LEAD-LAG	0°
08BFLAP	400F1/F2	1-2	5	BENDING	1050	400	TBD	8	N/A	FLAP	0°
17S38UA	1500S1	1-3	6	SINGLE	2150	1500	1060	17	38	UPPER	0°
17S38LA	1500P1	1-4	7	SINGLE	2150	1500	1060	17	38	LOWER	0°
17R62UA	1500S0	1-5	8	ROSETTE	2150	1500	1060	17	62	UPPER	0°
17R62UC	1500S90	1-6	9	ROSETTE	2150	1500	1060	17	62	UPPER	90°
17R62LA	1500P0	1-7	10	ROSETTE	2150	1500	1060	17	62	LOWER	0°
17R62LC	1500P90	1-8	11	ROSETTE	2150	1500	1060	17	62	LOWER	90°
25R20UA		2-1	12	ROSETTE	3150	2500	1385	25	20	UPPER	0°
17R62UB	1500S45	2-2	13	ROSETTE	2150	1500	1060	17	62	UPPER	45°
25S20LA		2-3	14	SINGLE	3150	2500	1385	25	20	LOWER	0°
25S26UA	2500S1	2-4	15	SINGLE	3150	2500	1385	25	26	UPPER	0°
25S26LA	2500P1	2-5	16	SINGLE	3150	2500	1385	25	26	LOWER	0°
25S40UA		2-6	17	SINGLE	3150	2500	1385	25	40	UPPER	0°
25S40LA		2-7	18	SINGLE	3150	2500	1385	25	40	LOWER	0°
25S70LA		2-8	19	SINGLE	3150	2500	1385	25	70	LOWER	0°
25R45UA	2500S0	3-1	20	ROSETTE	3150	2500	1385	25	45	UPPER	0°
25R45UC	2500S90	3-2	21	ROSETTE	3150	2500	1385	25	45	UPPER	90°
25R45LA	2500P0	3-3	22	ROSETTE	3150	2500	1385	25	45	LOWER	0°
25R45LC	2500P90	3-4	23	ROSETTE	3150	2500	1385	25	45	LOWER	90°
25R70UA		3-5	24	ROSETTE	3150	2500	1385	25	70	UPPER	0°
17R62LB	1500P45	3-6	25	ROSETTE	2150	1500	1060	17	62	LOWER	45°
31R20UA		3-7	26	ROSETTE	3900	3250	1317	31	20	UPPER	0°
25R45LB	2500P45	3-8	27	ROSETTE	3150	2500	1385	25	45	LOWER	45°
31S20LA		4-1	28	SINGLE	3900	3250	1317	31	20	LOWER	0°
31S40UA		4-2	29	SINGLE	3900	3250	1317	31	40	UPPER	0°
31S40LA		4-3	30	SINGLE	3900	3250	1317	31	40	LOWER	0°
31R70UA		4-4	31	ROSETTE	3900	3250	1317	31	70	UPPER	0°
25R45UB	2500S45	4-5	32	ROSETTE	3150	2500	1385	25	45	UPPER	45°
31S70LA		4-6	33	SINGLE	3900	3250	1317	31	70	LOWER	0°
41S40LA		4-7	34	SINGLE	5150	4500	1204	41	40	LOWER	0°
41S40UA		4-8	35	SINGLE	5150	4500	1204	41	40	UPPER	0°

REPLACES 31R20UC
REPLACES 31R70UC

REPLACES 25R70UC

REPLACES 25R20UC

GAUGES NOT USED FOR EDGEWISE TESTING

31R20UC	N/A	N/A	ROSETTE	3900	3250	1317	31	20	UPPER	90°
31R70UC	N/A	N/A	ROSETTE	3900	3250	1317	31	70	UPPER	90°
25R70UC	N/A	N/A	ROSETTE	3150	2500	1385	25	70	UPPER	90°
25R20UC	N/A	N/A	ROSETTE	3150	2500	1385	25	20	UPPER	90°

Using the following formula [14] we made an estimate of the strain at these locations:

$$e_0 = \frac{EK}{4}(\epsilon_1 - \epsilon_2 + \epsilon_3 - \epsilon_4) \quad (4-1)$$

which reduces to:

$$e_0 = \frac{EK}{4}\epsilon \quad (4-2)$$

this assumes that strain, ϵ , is equal in all four bridge arms.

e_0 = measured voltage

E = 3.333 VDC excitation voltage

K = 2.04, gauge factor for WK-09-250BF-10C.

Table 4.8 Strain Gauge Setup for Flapwise Static Pulls

GAUGE NAME	SMT NAME	BIB BOX HOOK-UP	GAUGE CHANNEL	TYPE	DISTANCE FROM CENTER OF ROTATION	DISTANCE FROM ROOT PLANE	CHORD LENGTH	PERCENT SPAN	PERCENT CHORD	SURFACE	ORIENTATION	
					mm	mm	mm					
08BLDLG	400E1/E2	1-1	4	BENDING	1050	400	TBD	8	N/A	LEAD-LAG	0°	
08BFLAP	400F1/F2	1-2	5	BENDING	1050	400	TBD	8	N/A	FLAP	0°	
17S38UA	1500S1	1-3	6	SINGLE	2150	1500	1060	17	38	UPPER	0°	
17S38LA	1500P1	1-4	7	SINGLE	2150	1500	1060	17	38	LOWER	0°	
17R62UA	1500S0	1-5	8	ROSETTE	2150	1500	1060	17	62	UPPER	0°	
17R62UC	1500S90	1-6	9	ROSETTE	2150	1500	1060	17	62	UPPER	90°	
17R62LA	1500P0	1-7	10	ROSETTE	2150	1500	1060	17	62	LOWER	0°	
17R62LC	1500P90	1-8	11	ROSETTE	2150	1500	1060	17	62	LOWER	90°	
25R20UA		2-1	12	ROSETTE	3150	2500	1385	25	20	UPPER	0°	
17R62UB	1500S45	2-2	13	ROSETTE	2150	1500	1060	17	62	UPPER	45°	
25S20LA		2-3	14	SINGLE	3150	2500	1385	25	20	LOWER	0°	
25S26UA	2500S1	2-4	15	SINGLE	3150	2500	1385	25	26	UPPER	0°	
25S26LA	2500P1	2-5	16	SINGLE	3150	2500	1385	25	26	LOWER	0°	
31R20UC		2-6	17	ROSETTE	3900	3250	1317	31	20	UPPER	90°	REPLACES 25S40UA
31R70UC		2-7	18	ROSETTE	3900	3250	1317	31	70	UPPER	90°	REPLACES 25S40LA
25S70LA		2-8	19	SINGLE	3150	2500	1385	25	70	LOWER	0°	
25R45UA	2500S0	3-1	20	ROSETTE	3150	2500	1385	25	45	UPPER	0°	
25R45UC	2500S90	3-2	21	ROSETTE	3150	2500	1385	25	45	UPPER	90°	
25R45LA	2500P0	3-3	22	ROSETTE	3150	2500	1385	25	45	LOWER	0°	
25R45LC	2500P90	3-4	23	ROSETTE	3150	2500	1385	25	45	LOWER	90°	
25R70UA		3-5	24	ROSETTE	3150	2500	1385	25	70	UPPER	0°	
17R62LB	1500P45	3-6	25	ROSETTE	2150	1500	1060	17	62	LOWER	45°	
31R20UA		3-7	26	ROSETTE	3900	3250	1317	31	20	UPPER	0°	
25R45LB	2500P45	3-8	27	ROSETTE	3150	2500	1385	25	45	LOWER	45°	
25R70UC		4-1	28	ROSETTE	3150	2500	1385	25	70	UPPER	90°	REPLACES 31S20LA
31S40UA		4-2	29	SINGLE	3900	3250	1317	31	40	UPPER	0°	
31S40LA		4-3	30	SINGLE	3900	3250	1317	31	40	LOWER	0°	
31R70UA		4-4	31	ROSETTE	3900	3250	1317	31	70	UPPER	0°	
25R45UB	2500S45	4-5	32	ROSETTE	3150	2500	1385	25	45	UPPER	45°	
25R20UC		4-6	33	ROSETTE	3150	2500	1385	25	20	UPPER	90°	REPLACES 31S70LA
41S40LA		4-7	34	SINGLE	5150	4500	1204	41	40	LOWER	0°	
41S40UA		4-8	35	SINGLE	5150	4500	1204	41	40	UPPER	0°	

GAUGES NOT USED FOR FLAPWISE TESTING											
31S70LA		N/A	N/A	SINGLE	3900	3250	1317	31	70	LOWER	0°
31S20LA		N/A	N/A	SINGLE	3900	3250	1317	31	20	LOWER	0°
25S40UA		N/A	N/A	SINGLE	3150	2500	1385	25	40	UPPER	0°
25S40LA		N/A	N/A	SINGLE	3150	2500	1385	25	40	LOWER	0°

4.3.3 Data Acquisition System

NREL's BSTRAIN was used for acquiring the static-test data. BSTRAIN is described in [15] and [4]. Figure 4.2 shows a schematic of the BSTRAIN system.

At the time of test planning the allowable number of channels measured during the static tests was limited to 36; therefore, different strain gauges were measured during the edge and flap tests, as shown in Tables 4.7 and 4.8 above.

The SCXI 1121 modules were configured with the low-pass frequency set at 4 Hz. The gain was 200 and the excitation was 3.333 VDC for the strain-gauge channels. The channel sampling-rate was set at 2 Hz.

Figure 4.2 Static Test Data Acquisition Schematic

4.3.4 Calibration

For the edgewise-static pulls, the load cell was calibrated by an off-site calibration facility. Prior to testing, the load cell was checked through the data acquisition system up to 2000 lb (8896 N) using a calibrated deadweight. The string potentiometer at the load application point was calibrated through the data acquisition system with a ruler over the full range. Factory-supplied strain-gauge factors were used for the strain data.

For the flapwise-static pulls, the load cell and actuator LVDT were calibrated through the control system by the MTS® representative prior to testing.

4.3.5 Static-Test Procedure

The static tests were conducted according to the following general procedures:

1. Mount blade to test stand in the proper orientation for the load.
2. Connect loading apparatus to blade.
3. Start data acquisition system.
4. Zero strain gauges at tare load.
5. Apply 75% design load to blade.
6. Hold for 10 seconds.
7. Return to tare load.
8. Apply 100% design load.
9. Hold for 10 seconds.
10. Return to tare load.
11. Apply 110% design load. (pre-fatigue only)
12. Hold for 10 seconds.
13. Return to tare loads.
14. Stop data acquisition.

4.4 Static-Test Results

4.4.1 Displacements

Displacements were measured at the load application point (7.65 m) and at the blade tip. Figures C.1 and C.2 in Appendix C show the data for edge test. Figures D.1 and D.2 in Appendix D show the data for flap test. The figures show the 75% and 110% load data for the static tests conducted prior to the fatigue tests. The 75% and 100% post-fatigue test data are also presented. Table 4.9 lists the results for the deflection at the 75% load point for pre- and post-fatigue tests. These data were interpolated from the 110% pre-fatigue test and the 100% post-fatigue test and were given to allow comparison with other laboratories. Note that the tip was removed for the fatigue test of Blade #67, so post-fatigue test tip deflection data were not available.

Table 4.9 Static Blade Deflections at SMT-Prescribed 75% Load

Pull Direction	Load	Position	#66 Pre-Fatigue (mm)	#66 Post-Fatigue (mm)	#67 Pre-Fatigue (mm)	#67 Post-Fatigue (mm)
Edgewise	14,809 N (3329 lb)	Load point (7.65 m)	46	48	48	51
Edgewise	14,809 N (3329 lb)	Tip (12.65 m)	94	98	102	N/A
Flapwise	24,723 N (5558 lb)	Load point (7.65 m)	192	188	191	187
Flapwise	24,723 N (5558 lb)	Tip (12.65 m)	504	497	502	N/A

These data show very slight differences in the deflection between the pre-fatigue and the post-fatigue static tests. Both of the edge tests show a very slight increase in displacement under the same load, indicating a drop in global stiffness. However, these differences are very small (less than 4 mm) and are within the uncertainty of the measurement system. The flap direction displacements showed a slight decrease in displacement under the prescribed 75% load. This is an unusual result because most blades

show a slight decrease in global stiffness after being subjected to fatigue loading. This increase in stiffness is also seen in the strain measurements, thus giving credence to its validity. This result is discussed later.

4.4.2 Strain Verification

Strain versus load data for the edgewise static-tests are presented in Appendix C. Data for the flapwise-static test are presented in Appendix D. Each page in the Appendix represents one gauge position. Pre-fatigue data is presented for each blade for the 75% and 110% load cases. Post-fatigue data are presented for each blade for the 75% and 100% load cases. Table 4.10 lists pre- and post-fatigue strain for the edgewise 75% and 100% loads. Table 4.11 lists the same for the flap test. These strain values were interpolated from the 110% load case data for the pre-fatigue test and from the 100% load case data from the post-fatigue test. The deflection data are also included in these tables.

One of the primary reasons NREL deviated from the SMT-prescribed load of 75% design and loaded up to 110%, was to determine the stable test load range that could be used for fatigue testing on the basis of linearity. The figures in the appendices show the linearity of each measurement location (except for off-axis "B" and "C" gauges) and show that even under the 110% load, there was no apparent danger of local buckling at these loads. This reassured us that fatigue loading at these levels could be achieved without inducing a buckling failure mode. This could not be determined from the 75% load tests. Moreover, under NREL's common practices, we would strongly have recommended a test to failure for at least one of the blades, preferably before the fatigue test, but certainly during the post-fatigue static test. This was not done to allow a uniform comparison among laboratories in the postmortem inspections. Unfortunately, these inspections were never done.

Figures 4.3 through 4.8 show various comparisons between the pre- and post-fatigue test strain-gauge data and comparisons between the two blades tested.

Generally, the differences between Blades #66 and #67 appeared to be random and could not be attributed to a significant difference in fabrication or testing technique without more extensive postmortem dissections. These results are shown best in Figures 4.7 and 4.8, which compare the flap and edge strains, respectively, at each strain measurement location for Blades #66 and #67 at the prescribed 75% static load for the SMT program. In a few locations, there appears to be very poor agreement between blades, particularly in the non-axial gauges. Gauge placement or low strain in the principal gauge direction can explain almost all of these differences. Most of the differences seemed to be characteristic of the blade itself and the differences did not appear to be altered by the fatigue test, with few exceptions. In other words, if the difference between blades existed before the fatigue test it was usually there after the fatigue test also, in about the same proportions. No distinguishable pattern was drawn from this data that would indicate a clear difference in manufacturing strength or blade properties. Any differences seem to average themselves out and did not affect the global property measurements.

Both of the blades' stiffness appeared to increase during fatigue testing. This phenomenon can be observed in Figures 4.3 through 4.6, which compare the static strains before and after the fatigue tests. These charts show reduced strain sensitivity in the post-fatigue static test as compared to the pre-fatigue static test, especially in the flap direction. For Blade #66 this effect was not noticeable in the edge direction but it was observed in Blade #67 in both flap and edge. This phenomenon is the opposite of the expected result, which would usually be a slight decline in blade stiffness over the course of a load-based fatigue test. This effect cannot be explained by load sensor error as we had originally thought. Both blades exhibited the same behavior but were tested at different times. Post static tests were conducted in different laboratories (Blade #66 in Building 254 and Blade #67 in Building 252). All of the pre-fatigue tests were conducted in Building 252. Load cell calibrations were double-checked to rule out sensor

errors. For Blade #66, the load cell used for the post-fatigue test was different than the one used for Blade #67, although the same result was observed. Additional evidence that suggests the effect was real is that the displacement sensors for both tests corroborate the strain data, with higher displacements following higher strain measurements in all cases (see Table 4.9).

One explanation for these results is that the blades may have stiffened slightly due to lower environmental humidity in Colorado. The blades originated in the Netherlands, where they may have absorbed ambient moisture for several years before being shipped to NREL. The strength gained due to the drying of the laminates in the Colorado climate may have been enough to offset and overshadow any stiffness losses encountered during the test.

Table 4.10 Edge Static-Test Strains

Measurement	SMT Nomenclature	Blade 66 pre- fatigue 75% loading	Blade 66 pre- fatigue 100% loading	Blade 66 post- fatigue 75% loading	Blade 66 post- fatigue 100% loading	Blade 67 pre- fatigue 75% loading	Blade 67 pre- fatigue 100% loading	Blade 67 post- fatigue 75% loading	Blade 67 post- fatigue 100% loading
Disp Load (mm)		46	66	48	66	48	68	51	71
Disp Tip (mm)		94	131	98	136	102	142	-	-
08BLDLG (μstrain)	400E1/2	439	619	452	633	433	610	431	607
08BFLAP (μstrain)	400F1/2	146	203	127	174	86	118	82	113
17S38UA (μstrain)	1500S1	-92	-125	-99	-136	-104	-142	-93	-128
17S38LA (μstrain)	1500P1	176	243	186	254	290	401	267	367
17R62UA (μstrain)	1500S0	402	568	391	544	394	558	392	551
17R62LA (μstrain)	1500P0	629	879	633	873	741	1042	737	1030
17R62UB (μstrain)	1500S45	29	45	29	43	38	59	36	54
17R62LB (μstrain)	1500P45	140	197	151	207	219	309	228	319
17R62UC (μstrain)	1500S90	-139	-191	-137	-187	-90	-120	-77	-103
17R62LC (μstrain)	1500P90	19	7	53	48	-16	-44	-50	-90
25R20UA (μstrain)		-507	-713	-518	-720	-559	-788	-545	-764
25S20LA (μstrain)		-104	-149	-91	-129	-166	-238	failed	failed
25S26UA (μstrain)	2500S1	-489	-689	-498	-691	-408	-560	-396	-554
25S26LA (μstrain)	2500P1	4	4	14	19	82	114	77	105
25S40UA (μstrain)		-21	-26	-30	-41	-42	-55	-38	-51
25S40LA (μstrain)		289	405	296	408	358	502	353	493
25R45UA (μstrain)	2500S0	119	172	110	153	99	145	102	145
25R45LA (μstrain)	2500P0	421	590	421	580	446	622	440	614
25R45UB (μstrain)	2500S45	-55	-76	-54	-76	-58	-84	-57	-81
25R45LB (μstrain)	2500P45	-1	9	4	13	-22	-19	-21	-18
25R45UC (μstrain)	2500S90	-112	-166	-111	-159	-105	-152	-98	-142
25R45LC (μstrain)	2500P90	-336	-461	-320	-430	-354	-475	-349	-472
25R70UA (μstrain)		371	539	382	541	408	578	404	573
25S70LA (μstrain)		674	949	672	931	637	900	633	890
31R20UA (μstrain)		-378	-532	-391	-542	-454	-631	-444	-621
31S20LA (μstrain)		-117	-169	-109	-152	-4	-11	-11	-17
31S40UA (μstrain)		-113	-156	-124	-172	-130	-175	failed	failed
31S40LA (μstrain)		202	284	209	290	312	434	297	417
31R70UA (μstrain)		512	722	500	691	445	624	445	624
31S70LA (μstrain)		532	777	545	777	663	947	669	959
41S40UA (μstrain)		-99	-135	-112	-154	-134	-184	-129	-177
41S40LA (μstrain)		154	219	164	227	189	261	179	249
Strain from bending bridges in BOLD are estimates based on 3.333 VDC excitation and 2.04 gauge factor.									

Table 4.11 Flap Static-Test Strains

Measurement	SMT Nomenclature	Blade 66 pre- fatigue 75% loading	Blade 66 pre- fatigue 100% loading	Blade 66 post- fatigue 75% loading	Blade 66 post- fatigue 100% loading	Blade 67 pre- fatigue 75% loading	Blade 67 pre- fatigue 100% loading	Blade 67 post- fatigue 75% loading	Blade 67 post- fatigue 100% loading
Disp Load (mm)		192	260	188	252	191	259	187	253
Disp Tip (mm)		504	678	497	669	502	675	-	-
08BLDLG (µstrain)	400E1/E2	91	131	101	140	32	51	25	38
08BFLAP (µstrain)	400F1/F2	946	1275	935	1256	963	1297	955	1278
17S38UA (µstrain)	1500S1	-1242	-1685	-1225	-1656	-1283	-1741	-1251	-1668
17S38LA (µstrain)	1500P1	1153	1554	1140	1531	1369	1841	1273	1703
17R62UA (µstrain)	1500S0	-1163	-1584	-1101	-1492	-1282	-1754	-1256	-1707
17R62LA (µstrain)	1500P0	975	1313	962	1320	970	1306	921	1237
17R62UB (µstrain)	1500S45	-386	-497	-354	-453	-515	-675	-493	-622
17R62LB (µstrain)	1500P45	453	619	430	617	461	634	453	622
17R62UC (µstrain)	1500S90	-117	-166	-114	-139	-264	-363	-241	-314
17R62LC (µstrain)	1500P90	94	143	80	154	123	177	104	132
25R20UA (µstrain)		-1724	-2369	-1692	-2314	-1400	-1941	-1350	-1859
25S20LA (µstrain)		1267	1710	1261	1722	1261	1701	failed	failed
25R20UC (µstrain)		-55	-181	-41	-155	70	9	61	4
25S26UA (µstrain)	2500S1	-588	-810	-2404	-3288	-302	-417	-1946	-2668
25S26LA (µstrain)	2500P1	1296	1747	1269	1704	1394	1881	1355	1818
25R45UA (µstrain)	2500S0	-1354	-1822	-1330	-1784	-1486	-1999	-1451	-1942
25R45LA (µstrain)	2500P0	1301	1751	1274	1712	1135	1528	1089	1439
25R45UB (µstrain)	2500S45	-700	-932	-677	-925	-724	-963	-694	-941
25R45LB (µstrain)	2500P45	519	715	501	692	400	566	392	548
25R45UC (µstrain)	2500S90	309	437	324	456	269	383	280	375
25R45LC (µstrain)	2500P90	-426	-546	-435	-558	-413	-525	-386	-510
25R70UA (µstrain)		-321	-418	-330	-399	-389	-512	-392	-512
25S70LA (µstrain)		506	686	476	671	365	501	330	430
25R70UC (µstrain)		472	633	422	585	418	562	394	544
31R20UA (µstrain)		-1307	-1772	-1299	-1781	-1468	-1984	-1421	-1911
31R20UC (µstrain)		307	341	300	336	311	349	failed	failed
31S40UA (µstrain)		-1849	-2510	-1833	-2478	-1771	-2400	failed	failed
31S40LA (µstrain)		1441	1945	1420	1910	1528	2073	1448	1930
31R70UA (µstrain)		-829	-1077	-804	-1046	-654	-849	-663	-853
31R70UC (µstrain)		268	287	283	327	290	374	284	384
41S40UA (µstrain)		-1939	-2641	-1925	-2641	-1840	-2503	-1824	-2499
41S40LA (µstrain)		1560	2163	1568	2140	1607	2170	1550	2089
Strain from bending bridges in BOLD are estimates based on 3.333 VDC excitation and 2.04 gauge factor.

Figure 4.3 Blade #66 flap static test pre- and post-fatigue test gauge comparison

Figure 4.4 Blade #66 edge static test pre- and post-fatigue test gauge comparison

Figure 4.5 Blade #67 flap static test pre- and post-fatigue test gauge comparison

Figure 4.6 Blade #67 edge static test pre- and post-fatigue test gauge comparison

Figure 4.7 Blades #66 and #67 comparison for SMT-prescribed 75% flap static tests

Figure 4.8 Blades #66 and #67 comparison for SMT-prescribed 75% edge static tests

4.4.3 Summary of Major Static-Test Observations

1. Blade #66 and Blade #67 appear to have some random differences but their global properties are very similar.
2. Pre- and post-fatigue data show a probable increase in blade stiffness due to possible laminate drying effects. This effect is most obvious in the flap direction.
3. The effect described in #2 above overshadowed any possible decline in global blade properties due to fatigue testing. Some local strain changes may have occurred but could not be fully evaluated for this test.
4. The SMT-prescribed static-test load (75% of ultimate) was insufficient to evaluate possible non-linearities for fatigue loading.
5. The SMT-prescribed static-test loading procedure was inadequate to evaluate extreme load behavior and did not allow the actual blade strength to be determined.

5. Fatigue Testing

5.1 Introduction

The methodology for conducting fatigue tests of wind turbine blades is inherently more complex than for static testing. The extreme static design loads can usually be applied to the test blade at near face value with a high level of confidence and without any complex manipulations. The fatigue load spectrum, however, must first be compressed and simplified, then applied to the blade within the constraints of the laboratory's hardware. As a result, fatigue-testing methodology has more variations among the laboratories and is less easily restricted to a single procedure. The SMT partners agreed that the “business as usual” practices for each laboratory should be followed to allow a wider range of methods to be examined.

For a particular fatigue test procedure, the methodology is determined by both the analytical technique used to synthesize the design loads, and the hardware constraints on the test lab. In practice, it is difficult to separate the two. A highly accurate damage model will not result in a representative test if the hardware cannot reproduce the loads. Similarly, an exceedingly versatile set of hydraulic equipment will not improve the test if the design loads are not properly reduced.

Previous fatigue tests performed at NREL have used the following test hardware arrangements:

1. Independent (sequential) fatigue tests of the flap and edge loads
2. Combined flap and edge fatigue test with blade pitched to a prescribed angle for the proper resultant load using a single hydraulic actuator
3. Two-axis test with separate flap and edge load inputs from separate hydraulic actuators

To compare methods 2 and 3 above, NREL elected to conduct both a single-axis test and a two-axis test on separate blades. The single-axis test is simple and easy to implement for strength verification and design strength checks. Method 1 is a subset of this type of testing. The two-axis test is more equipment-intensive but produces a better representation of the true operating conditions.

5.2 Design Data

5.2.1 Design Loads

To reduce some of the variability, the SMT program partners agreed to constrain the fatigue testing design load analysis to the original design assumptions used by Rotorline. Therefore, it was incumbent on the participants to resist temptations to apply further design enhancements while carrying out the test load development. Fatigue properties of the blade materials were given and were used to derive the equivalent damage of the load spectrum. The major constraint was that an S-N fatigue slope of $m = 10$ was used for all computations.

Load cases used by NedWind to design the blades were provided to the project partners to formulate fatigue test loads. The load cases are presented in Appendix A [16] and described in [6]. One hundred load cases were presented with the number of cycles for each case. For each load case the loads at ten spanwise sections were presented. Table 5.1 from file NW25.LBK below shows the spanwise positions. Table 5.2 shows an example listing of the range file (NW25.CSB). Radial force (F_z), edgewise moment (M_x), and flapwise moment (M_y) were given. These loads were aligned to the rotor plane with the tip

angle at zero [17]. Separate files of the maximum load (filename NW25.CMB) and load range (filename NW25.CSB) were presented for the load cases.

Table 5.1 Spanwise Positions for Load Cases (File name NW25.LKB)

Position Number	Radial Position from Rotor Center (m)	Description of Position
1	0.2	Weld in hub
2	0.6	Weld in hub
3	0.65	Blade flange
4	0.8	Pin-hole connection between flange and laminate
5	2.65	1 st aerodynamic cross section
6	3.9	2 nd aerodynamic cross section
7	5.15	3 rd
8	6.4	4 th
9	7.65	5 th
10	8.9	6 th

Table 5.2 Example Contents of File NW25.CSB, Range of Load Cases

No. of Load Cases		Position 1			Position 2			...	My10
		Fz1	Mx1	My1	Fz2	Mx2	My2		
No. of	3747660	25506.9	67645.61	37281.91	15847.83	57301.43	35460.76	...	3728.908
cycles	4145710	25506.9	72533.04	59440.37	15847.83	61977.53	56659.7	...	6738.19
	3699900	25506.9	74759.94	46726.85	15847.83	64126.9	44507.67	...	5060.531
	2759400	25506.9	73800.66	37519.26	15847.83	63223.22	35732.78	...	4019.418
	1746710	25506.9	72519.75	39519.11	15847.83	62025.46	37717.42	...	4766.019
	:	:	:	:	:	:	:	...	:
	20	25506.91	75214.84	107461	15847.83	65846.6	101730.1	...	9409.942

5.2.2 Design Strength and Test Load Factors

In the 1991 Rotorline analysis the primary equation used to determine the allowable number of cycles, N , was taken from [18] and properly stated in [19]. The equation, stated below, is a modified Goodman relation:

$$N = \left[\frac{\frac{UTS + |UCS|}{2 \times C1 \times C2 \times C3} - S_{mean} - \frac{UTS - |UCS|}{2 \times C1 \times C2 \times C3}}{S_{amp}} \right]^{10} \quad (5-1)$$

where,

C1, C2, C3 = material factors described below

S_{mean} = mean stress

S_{amp} = stress amplitude (one-half range)

UTS = ultimate tensile strength

UCS = ultimate compression strength.

The values for UTS, UCS, and E (modulus) were specified in [20] and taken from [10] and are listed in Table 5.3.

Table 5.3 NedWind Blade Material Properties

Laminate	UTS (MPa)	UCS (MPa)	Modulus E (N/mm ²)
Strength	372	260	24,500
Tail/Nose	87	76	7000

As part of the fatigue test load development, the test loading was modified to account for the various effects and uncertainties introduced by the test load analysis, by the test load methods, and by the lab conditions. The following test load factors were used to develop the test loading. The test load contains any relevant design load factors that were used in the original design. Each one is described below.

Design Load Partial Safety Factors--The design was apparently conducted under applicable Dutch codes in the 1992 time frame. As part of the design, a general fatigue load factor of 1.35 was applied to the design loads. For some sections, a larger factor of 1.5 was used, apparently for additional conservatism. NREL used the fatigue factors as applied by [18].

Stress Concentration Factors--Stress concentration factors (SCFs) were used in the design and applied to the design loads. It was assumed that the designer's intent was to account for various geometric transitions and complexities in the blade, which result in local stress amplifications. It was assumed that these stress risers were applied directly to the design loads, which in turn resulted in thicker blade sections in those areas. However, the geometric blade features that the SCFs were intended to account for are present in the actual blades, so the stress should already be higher in these regions. Therefore, it was not necessary to include the SCFs in the test load and they were ignored for this analysis.

Wind Farm Load Factor--A load factor was calculated to represent an allowable damage of only 0.66 (Miner's-rule fraction) on a 20-year life for turbines operating in a wind farm. This was a design requirement for the original blade and was included in the test. For an R ratio of -1.0 and assuming a slope of 10 on the S-N data, this load factor was 1.04 on the test load. It was appropriate to apply this to

the test load because the lower damage requirement was a direct result of higher loads resulting from wind farm operation.

Material Design Strength Factor--The general material factors are used in the design to adjust the material properties of the coupon samples (e.g., UTS [calcvall] on pg. 6 of Bernard 1 [18]) to the anticipated full-scale blade properties. These factors were used in the test equivalent damage analysis in the Goodman relation above as they were applied in the design. For fatigue, this factor was $V_{mf} = 1.5$, which is the product of C1, C2, and C3. For the test load calculation, these factors are to be applied again in the modified Goodman relation given in Equation 5-1, with the exception of C1 (the moisture absorption factor).

Environmental Effects--Because the test laboratory was at a lower temperature and humidity than the design conditions, the blade was stronger in the laboratory than it was operating under the most severe environmental conditions. The factor, C1, from the manufacturer's design data was given as 1.25. This factor was meant to account for these differences in moisture absorption between the test environment and the blade-operating environment. This effect was addressed in the test loads by not applying this factor to the Goodman relation in Equation 5-1 for the test load calculation, and determining the test equivalent damage based on a higher material strength. This resulted in a higher test load.

Errors in the Fatigue Formulation--A test load factor of 1.05 was used to account for errors in the fatigue formulation. This value was applied to remain consistent with IEC 61400-23 [21].

Blade-to-Blade Variations--A factor of 1.1 to cover blade-to-blade variations was applied in this test to account for possible variations in the as-built population if only one blade is tested. The application of this factor is not a standard practice at NREL; however, we have applied it to remain consistent with IEC 61400-23 [21] and the other laboratories.

NREL recognizes that uncertainty exists in the final manufactured population of blades; however, we do not believe that this issue is best addressed with an uncertainty factor on the blade test load that may drive up the turbine cost. We believe that this issue should be addressed in the design, by testing multiple blades if necessary, testing the blades to failure, and by postmortem evaluations to determine the relative quality of the test blade.

Tables 5.4 and 5.5 summarize the design and test load factors used.

Table 5.4 Fatigue Design Factor Summary

Parameter	Value	Description
Vbf	1.35	design load factor for sections 1-4 (0.2–0.8 m)
Vbf	1.5	design load factor for sections 5-10 (2.65 to 8.9 m)
C1	1.25	water consumption
C2	1.00	unidirectional/continuous
C3	1.20	general safety factor

Table 5.5 Fatigue Test Load Factor Summary

Parameter	Value	Description
C1a	1.00	water consumption-dry laboratory
C2a	1.00	unidirectional/continuous
C3a	1.20	general safety factor
γ_{eff}	1.05	error in fatigue formulation
γ_{sf}	1.1	blade-to-blade variation
γ_{wp}	1.04	wind park life reduction

5.3 Equivalent-Damage Analysis

5.3.1 Introduction

5.3.1.1 Conventional Methods

Conventional fatigue analyses used to determine equivalent test load are typically based on the blade structural design. These methods usually require a complex and time-consuming strength analysis, as well as a thorough understanding of the fatigue performance of the blade. Many errors can be propagated through this process. Most methods convert loads to stresses at several spanwise blade sections. Then, for measured or assumed S-N curves (applied stress versus allowable cycles to failure) of the laminate, Miner's Rule is applied to determine the design damage. Equivalent-damage test loads are then computed for given test load ratios and number of load cycles. These methods determine test loads by assuming that the behavior of the test article matches the design condition exactly. If the test blade is different than the design, then significant uncertainty is introduced. For example:

- The test blade cross-section geometry will not exactly match the drawing.
- Blade laminate material properties will deviate from coupon properties (e.g., resin versus fiber rich, ply drops, material handling, and workmanship).
- The critical area may be in a bolted or bonded joint or in a stress concentration region that will have a unique S-N curve.

As a result of these variations, the calculated damage to the test blade could be higher or lower than its actual value, and may disguise a problem where high damage is sustained. Moreover, considerable time is spent calculating and applying the various blade properties at each step of the analysis. This adds complexity to the problem and exposes the analysis to possible accounting errors. This effort may be necessary if the goal is to study the exact structural design of the wind turbine blade at every location and make quantitative comparisons with the design. Usually, however, the design details are not known well enough to perform these calculation without considerable guesswork, because the blade will usually fail in an area where material fatigue data is not precisely known or where stress concentrations alter the stress field in an unpredictable manner.

Blade test standards such as IEC 61400-23 attempt to compensate for these potential errors by applying significant test load factors to the equivalent damage test loads, such as errors in the fatigue formulation or blade-to-blade variations. However, the true uncertainty is largely unknown.

5.3.1.2 *NREL's Approach*

One of the goals of the SMT program at NREL was to simplify the fatigue test-load derivation process and minimize the potential errors in the analysis. It appeared that the most efficient and logical method would be to derive the fatigue test loads in a way analogous to the determination of ultimate-strength loads. The ultimate-strength loads are simply the maximum load case extracted from the load spectrum. The peak load in the spectrum is applied to the blade to verify adequate static strength. It is not necessary to know the blade geometry, material properties, or perform a complete stress analysis. The load is applied and the test is considered valid if it can survive the intended loads. The tested area is decided, by definition, based on which spanwise sections reached or exceeded the test bending moments.

For fatigue testing, the objectives should be the same. Each section of the blade that is tested to its equivalent design bending moment condition and survives has adequately demonstrated sufficient fatigue resistance. It is not necessary to evaluate the stresses at each point, especially if the calculations are limited to the parent composite material and uniform sections where blades rarely experience fatigue problems.

5.3.2 Simplified Load Spectrum Method

The goal of the simplified load spectrum method is to derive an equivalent damage fatigue test that is only dependent on the design-load spectrum. Using this method, the test loads are derived assuming the blade geometry and material fatigue properties are not accurately known. Then the test article is allowed to (and probably does) deviate from the intended design without affecting the test conditions.

This method remains strictly in the load domain; therefore, there is no conversion to stresses. So instead of an S-N curve there will be an M-N curve (applied moment vs. allowable cycles to failure) for the blade. The curve will be defined by the relationship,

$$M_a = M_u \times N^{(-1/m)} \quad (5-2)$$

where,

M_a	amplitude moment in one load cycle
M_u	ultimate moment of the blade
N	allowable cycles to failure
m	slope of the curve.

A blade's fatigue failure can occur in many locations by various modes (e.g., skin laminate failure in tension or local buckling, adhesive failure in shear or peel, or bolted-joint failure). Each failure mode could be characterized by a different M-N curve. A family of curves was defined to bound the potential M-N combinations for the test blade. A range of ultimate moments from $1.5 \times M_{\max}$ to $4.5 \times M_{\max}$ and a range of slopes from $m = 6$ to $m = 12$ were used. $M_{\max}$ is the maximum characteristic moment in the NedWind 25 load spectrum. The $1.5 \times M_{\max}$ was selected for the lower bound curve, which matched the 100% extreme static-test level and the extreme design-limit load. The 4.5 factor was arbitrarily selected for the higher bound to account for the possibility of conservative designs. Implicit in these boundaries is the assumption that the ultimate moment to cause blade failure is somewhere between 1.5 and 4.5 times the maximum load case experienced by the blade on the NedWind 25 turbine.

Figure 5.1 M-N curve family at $R_t = -1.0$

The range of slopes from 6 to 12 was supported by an extensive database of fiberglass laminates. Slopes approaching 6 were seen in poor performing fabrics and laminates, as well as in better-performing laminates with fabrication flaws such as resin- and fiber-rich areas, ply drops, and complex geometry. The family of M-N curves is shown in Figure 5.1.

Note that three levels of moments ($1.5 \times M_{\max}$, $3.0 \times M_{\max}$, and $4.5 \times M_{\max}$) were selected for this analysis, along with four M-N slopes ($m = 6$, $m = 8$, $m = 10$, and $m = 12$), giving a total of 12 curves. Using more curves to gain better resolution in the analysis was examined; however, it had very little effect on the results.

The damage associated with each curve can be calculated by applying Palmgren-Miner's Rule as follows:

$$\text{Damage} = \sum_{i=1}^j \frac{n_i}{N_i} \quad (5-3)$$

where,

- i load case number
- j total number of load cases
- n_i number of load cycles for case i
- N_i number of load cycles to failure for case i .

The family of M-N curves defined above are set at a load ratio of $R = -1.0$. The Goodman relationship was also assumed to be linear as far as the $R = -1.0$ line (vertical line showing zero mean moment in Figure 5.2). Because all but 1 of the 100 NedWind 25 load cases are on or to the right (positive mean load) of the $R = -1.0$ line, it was only necessary for us to model the right half of the Goodman diagram

(see Figure 5.2). The one case on the left side of the $R = -1.0$ line is a relatively low-damage case; modifying the method to account for this case had a negligible effect.

Figure 5.2 Goodman diagram and sample load case #1

For simplicity, we proceeded with the right half of the Goodman diagram model. When looking at different fatigue failure mechanisms, this linearized Goodman model combined with the M-N family of curves appears to be a good representation of the NedWind 25 design and load spectrum described in Equation 5-1. If the blade's fatigue failure were to occur in a fiberglass laminate, one would expect that the M-N curve and Goodman diagram of the blade would be best characterized by the laminate's S-N curve and Goodman diagram. A blade in bending will have skin laminates in both tension and compression. S-N curves for compressive failure in laminates tend to have a lower ultimate stress and a higher slope than their tensile counterpart [22]. The ratio of a tensile to a compressive ultimate stress can approach 2.0. This creates a wide range of laminate material properties, but they should be well bounded by the assumed M-N curves. The laminate compression curves may be most closely characterized by the $1.5 \times M_{\max}$, $m = 10 - 12$ curves, whereas the tension curves may better match the $4.5 \times M_{\max}$, $m = 6 - 10$ curves.

To support our linear Goodman model, another point should be made concerning the transition from a tensile to a compressive fatigue failure in a fiberglass laminate. At low cycles (typically below 1,000), the transition is somewhere between $R = 0.1$ and $R = -1.0$. At higher cycles, the transition is closer to $R = -1.0$ and may even trend towards $R = -2.0$ as the cycles increase [22]. This produces a nonlinear Goodman diagram. The impact of this was evaluated for the NedWind 25 spectrum. When this spectrum was plotted (see Figure 5.3) onto a normalized Goodman diagram for a similar laminate from the Montana State University (MSU)/DOE fatigue database, the linear representation appeared to be the best fit [22].

Figure 5.3 Normalized Goodman Diagram based on MSU/DOE database [22] and NedWind 25 load cases

The original NedWind 25 design analysis, using the Goodman relationship in Equation 5-1 (Figure 5.4), assumes linear-symmetric behavior about an offset to the right of the $R = -1.0$ line. This offset truncated the tensile failure line, creating lower peak amplitude at the tensile-to-compressive-fatigue-failure transition point. This relationship was compared with the simplified load spectrum-based method presented in this report. The difference in resulting damage between the SMT program's offset linear model and the $R = -1.0$ linear model was negligible (0.2%).

Figure 5.4 Rotorline analysis modified Goodman relation (Equation 5-1) with truncation of tensile failure line [19]

Most of the above discussion assumes that the failure occurs in the laminates where good coupon data can be collected. If the blade fatigue failure occurs in a structural detail such as a bonded or bolted joint, a Goodman relationship for the blade would be characterized by the Goodman relationship for that joint. Unfortunately, Goodman diagrams for joints are difficult to define because there is almost no joint fatigue data available and the number of test variables is greatly increased when compared to coupon testing. For lack of a better model, we considered our $R = -1.0$ linear Goodman relationship reasonable for characterizing joint failures.

The $R = -1.0$ linear Goodman relationship also simplifies the calculations and is easier to understand in this initial application of the method. However, this method can be applied to any nonlinear Goodman relationship by modifying the extrapolation routines that will now be discussed.

Because the load cases in the fatigue spectrum are at various load ratios, the equivalent damage will have to be extrapolated using a Goodman diagram. Each case in the load spectrum is defined with a moment amplitude, moment mean, and number of cycles. A sample load case is shown in Figure 5.2 and called load case 1.

The value for the amplitude mean when $R = -1.0$ ($M_{a1,R=-1}$), is extrapolated by setting the slopes on the Goodman diagram equal (see Figure 5.2).

$$\frac{M_{a1,R=-1}}{M_u} = \frac{M_{a1}}{M_u - M_{m1}} \quad (5-4)$$

Solving for $M_{a1,R=-1}$,

$$Ma_{1,R=-1} = \frac{MuMa_1}{Mu - Mm_1} \quad (5-5)$$

Plugging Equation 5-5 into Equation 5-2 and solving for the allowable number of cycles to failure for load case 1 gives,

$$N_1 = \left(\frac{(Mu - Mm_1)}{Ma_1} \right)^m \quad (5-6)$$

The damage from load case 1 is simply $D_1 = \frac{n_1}{N_1}$. Summing the damage from all the load cases will

give the total damage, $D_{total} = \sum_i \frac{n_i}{N_i}$.

To get the equivalent damage test load, the test conditions must be specified. Typically, this means the test load ratio, R_t (constant), and number of cycles, n_t . Because the total damage, D_t , R_t , and n_t are known, the test amplitude load and mean load can be calculated. This can be shown again with an example in Figure 5.5 below. For this case, it is assumed that the test load ratio is 0.1 and the test cycles are 3×10^6 .

The first step is to calculate the total number of allowable cycles to give the same total damage when the 3×10^6 test cycles are applied.

$$D_{total} = \frac{n_t}{N_t} \quad (5-7)$$

$$N_t = \frac{n_t}{D_{total}} \quad (5-8)$$

where,

n_t number of test cycles

N_t number of allowable cycles to failure at test loads.

Figure 5.5 Derivation of equivalent-damage test load

From Equation 5-2,

$$Ma_{t,R=-1} = Mu \times N_t^{(-1/m)} \quad (5-9)$$

Again setting the slopes equal,

$$\frac{Ma_{t,R=-1}}{Mu} = \frac{Ma_t}{Mu - Mm_t} \quad (5-10)$$

Defining the load ratio in terms of mean and amplitude moments,

$$R = \frac{M_{\min, \text{1cycle}}}{M_{\max, \text{1cycle}}} = \frac{Mm - Ma}{Mm + Ma} \quad (5-11)$$

$M_{\min, \text{1cycle}}$ Minimum moment in one load cycle
 $M_{\max, \text{1cycle}}$ Maximum moment in one load cycle

From Equation 5-11, the mean test moment is,

$$Mm_t = Ma_t \left(\frac{1+R_t}{1-R_t} \right) \quad (5-12)$$

Combining Equations 5-10 and 5-12 and solving for Ma_t .

$$Ma_t = \frac{Mu}{\frac{Mu}{Ma_{t,R=-1}} + \left(\frac{1+R_t}{1-R_t} \right)} \quad (5-13)$$

Plugging Equation 5-9 into 5-13 gives Ma_t in terms of N_t , Mu , and R_t .

$$Ma_t = \frac{Mu}{N_t^{1/m} + \frac{1+R_t}{1-R_t}} \quad (5-14)$$

Adding Equation 5-8 into 5-14 gives Ma_t in terms of D_{total} , n_t , Mu , and R_t .

$$Ma_t = \frac{Mu}{\left(\frac{n_t}{D_{total}} \right)^{(1/m)} + \frac{1+R_t}{1-R_t}} \quad (5-15)$$

The mean and the amplitude of the test load can now be calculated for any test load ratio, number of test cycles, and defined M-N curve using Equations 5-12 and 5-15.

The next step was to apply an interpolation routine to find the optimum test load ratio that minimized the sensitivity of the test loads to the family of M-N curves. A macro was written using Microsoft Excel's solver, which varied R_t to find the minimum range in maximum test loads ($Ma_t + Mm_t$). In other words, for any given R_t , there are 12 calculated test loads that correspond to the 12 M-N curves shown in Figure 5.1. The solver finds the R_t where the spread in the 12 test loads is at a minimum.

5.3.3 Application to NedWind 25 Blade

The above steps were done at blade stations 4--10 given in Table 5.1 for both flap and edge bending. Note that stations 1--3 are spanwise locations from the center of rotation to the root flange and are not relevant to this analysis.

To illustrate the method, the NedWind 25 load spectrum data are shown in Figures 5.6 and 5.7 at blade station 5 for both flap and edge moments. Blade station 5 is at 2.65 meters from the center of rotation. The 100 design load cases are presented as open, square symbols. Figures 5.6 and 5.7 also show the calculated equivalent-damage Goodman diagram curves for blade station 5 in flap and edge directions. There are 12 equivalent damage curves that correspond to the family of M-N curves for 3×10^6 test cycles. The Figure 5.5 example shows how each curve was generated. Because the NedWind 25 load spectrum was applied to 12 unique M-N curves, there were 12 different fatigue damage totals. So, each Goodman curve in Figures 5.6 and 5.7 shows the mean and amplitude test moments that will give the equivalent damage for the corresponding M-N curve at 3×10^6 test cycles. In other words, any point along each Goodman curve gives the same damage total for 3×10^6 test cycles as any other point on the same curve, but a different damage total from any point on any other curve.

Figure 5.6 Blade position #5 flap loads and equivalent test loads at $R_t = 0.081$

Figure 5.7 Blade position #5 edge loads and equivalent test loads at $R_t = 0.61$

Note the mean and amplitude moments in Figures 5.6 and 5.7 have again been normalized to the maximum moment in the load spectrum.

Figures 5.6 and 5.7 also show the optimized test load ratio (R_t) line. Graphically, this radial line intersects the 12 equivalent-damage test load curves at the point of minimum scatter. These intersections

are shown as closed-diamond symbols. These figures also show that there is clearly an optimum R_t where possible errors in S-N slopes are minimized. Conversely, it also shows how great the potential errors can be if R_t is arbitrarily selected. For example, if a non-optimum R_t was selected in Figure 5.6, at say $R = 0.5$, and the S-N curve was not accurately known, a very wide range of possible test loads will be given.

For the NedWind 25 spectrum, the scatter across the equivalent damage test loads at the R_t is especially tight in the flap direction. This indicates that at the optimum R_t of 0.081, the errors associated with choosing the wrong M-N slope are minimized. For the edge loads in Figure 5.7, the scatter is lowest at $R_t = -0.61$, but a wider scatter band is indicated. The figures also show that the optimized R_t approximately passes through the centroid of data points representing the load ratios of the individual load cases in the spectrum. Intuitively, it makes sense that the optimum R_t would correspond with the load spectrum data.

The final SMT program test loads at each station were taken from the maximum of the three remaining M-N curves corresponding to S-N slopes of $m = 10$ at the optimized R_t . To remain consistent with the original design, all the partners applied this constraint. Therefore, all the optimized R_t values were determined at an M-N slope of 10. In the flap direction, the difference in possible test loads was insignificant for the NedWind 25 load spectrum because the scatter was so close. For the edge loads, it can be seen from Figure 5.7 that if just the $m = 10$ curves are considered, the edge scatter significantly improves because the optimum R_t value shifts slightly to the right and any deviations with ultimate moment can also be ignored.

For the unconstrained case, when the full range of slopes are included, the greater scatter at the optimum R_t would suggest slightly higher edge moments, leaving the final loads open to some interpretation. The final load would depend on how conservative the test needed to be and how much confidence the designer had in the fatigue formulation. Because many wind turbine blades have structural details with unknown or poorly understood material properties, or structural details with poorly performing properties, the higher loads corresponding to $m = 6$ would be recommended.

Station 5 loads were chosen to illustrate the method in Figures 5.6 and 5.7 because it represents one of the most critical sections of the blade. However, the same analysis was performed for all relevant blade sections (Blade positions 4 through 10 from Table 5.1) to obtain the spanwise fatigue load distribution. These results are given in Section 5.5.3.

During the development of the single-axis test plan, this method had not been matured and tested sufficiently to apply to this test. It was used only for the two-axis loads. However, subsequent checks against the method that was used show nearly perfect agreement.

5.4 Single-axis Fatigue Test

5.4.1 Introduction

The single-axis test is the simplest and fastest of the fatigue test methods used at NREL. It requires a single actuator for testing both flap and edge directions at the same time. The disadvantages are the greater inaccuracy in matching the blade damage or operating load characteristics of the test to the design loads or theoretical design damage. Single-axis loading requires the flap and edge load components to be applied in-phase at a fixed load angle over the load cycle. These constraints result in a resultant load vector that can exceed the design stresses at certain locations around the blade section, while at other locations on the section the blade may be under-stressed. Single-axis testing also requires that the flap

and edge components be applied at the same load amplitude ratio (R_t), which prevents the flap and edge loads from being optimized for the design spectrum as described in Section 5.3.

5.4.2 Single-axis Test Description

Figure 5.8 shows a photo of the single-axis fatigue test in operation. The test blade for the single-axis test was Blade #67. NREL chose to reduce the design spectrum to 3 million constant-amplitude cycles with a load amplitude ratio (R_t) of -0.1. The test loads were developed by matching the damage caused by the 20-year design-load spectrum to the damage resulting for the test load for the design S-N slope of $m = 10$ for the composite material. Because the single-axis test constraints require that both load components be applied at the same R_t , an $R_t = -0.1$ was used.

Figure 5.8 Blade #67 Single-Axis Fatigue Test In NREL Building 252

5.4.3 Single-axis Fatigue Loads

The spreadsheet summarizing the single-axis fatigue test load is shown in Appendix B and is labeled “FatigueScott.xls.” A R_t of -0.1 was chosen for both axes. This R_t was chosen using a sensitivity analysis to the optimum value for the combined edge and flap axis. The sensitivity analysis varied the strain/load ratios and damage values to determine the R_t that resulted in the least variation in test loads. Figure 5.9 shows the maximum-damage equivalent edge (M_{xmax}) and flap (M_{ymax}) spanwise moment distribution from the FatigueScott.xls spreadsheet. We chose the load-application point at 8.65 m to best match the distribution of equivalent moments. The test load linear-moment distribution (load application at 8.65 m)

and the 100% static-test load (load application at 7.65 m) are shown for comparison. The edge load was chosen to match the moment (M_{xmax}) at point 4, the pinhole connection. This over-tested the majority of the blade span for edgewise loading. The flap load was chosen to match the moment (M_{ymax}) at point 5, the first true airfoil section. This position allowed the distribution to match region outboard of the root section and over-test the furthest inboard section where the most complex geometric changes are present.

Figure 5.9 Moment distribution of single-axis fatigue test including optimum damage-equivalent moments, fatigue-test moments, and 100% static-test moments

Table 5.6 lists the single-axis fatigue-test moments used for the flap and edge directions.

Table 5.6 Single-axis Fatigue-Test Moments

Load Direction	NW25.LKB Position to Match	DEL Moment (max.)	Test Load at 8.65 m	R_t
Edge	4 (0.8 m)	151615 Nm	19314 N	-0.10
Flap	5 (2.65 m)	140088 Nm	23348 N	same

The nomenclature to describe the resultant test load is presented in Figure 5.10. Typical for single-axis tests, there was initial concern that the high resultant forces from the combined in-phase loading might cause buckling in the suction side leading-edge panel. However, NREL became comfortable within the first few thousand cycles because non-linear behavior was not observed. The angle θ represents the tip chord angle for a vertical load application. The angle ψ represents the angle the resultant load makes with

respect to the tip chord. Figure 5.11 shows the test load, normalized to maximum resultant moment, over the fatigue cycle.

Figure 5.10 Resultant single-axis fatigue test load--looking at tip chord

Figure 5.11 Single-axis test normalized bending moment

Blade tare and fixture tare weights were also added. The tare weight of the blade mass from load application point (8.65 m) to the maximum chord position (3.15 m) was added to the fatigue-test load. This was done to force the bending moment at the maximum chord to zero for zero applied test load as in the static tests. Table 5.7 below shows the mass moment distribution. The mass moment at 8.65 m was

interpolated between the 8900-mm and 7651-mm positions. The blade tare weight was determined to be 1783 N (401 lb). Added to this was the fixture weight above the hydraulic actuator, including the blade saddle at 930 N (209 lb).

Table 5.7 Mass Distribution for Fatigue Test Weight Tare

Position (mm)	Mass Moment (N-mm)
8900	2.335E06
8650*	1.440E06*
7651	2.335E06
3151	11.243E06

*Interpolated

Source: [10]

The actuator was aligned such that the resultant load went through the elastic center of the chord, assumed at 40% in order to minimize the introduction of torsional moments.

The test load cycle frequency was fixed at 1.5 Hz; however, the controller was having trouble keeping up with the command signal because the blade tip was exhibiting its own independent vibration mode at this speed. We were also concerned about the possibility of the blade tip hitting the relatively low ceiling if an unstable control anomaly were encountered. We decided to cut off the outer two meters of the blade to remedy these concerns. With the tip removed, we were able to maintain 1.5 Hz with stable control.

5.4.4 Instrumentation and Equipment

5.4.4.1 Load Apparatus

5.4.4.1.1 Load Attachment

The load attachment for the single-axis fatigue test was made at the 8.65-meter station, and the tip chord angle was rotated to nominally achieve a tip chord angle of 40°. This angle was constrained by the 24-hole (15° increments) bolt pattern of the test stand adapter and the root flange pattern of the NedWind 25 blade, so that the angle at the load attachment was at 41.7°. With the difference in twist, this resulted in a tip chord angle of 45.8°. Therefore, the load actuator was tilted 5.8° from the vertical.

5.4.4.1.2 Load Saddle

The steel load saddle frame used for the static tests was also used for the fatigue tests. A separate wood insert sized for the airfoil at the 8.65-meter station was constructed for the fatigue tests. The load attachment was positioned such that the load actuator would act through the elastic axis (assumed at 40% chord) of the blade, thus minimizing torsional deflection. With the saddle thickness, and angle of the load saddle and hydraulic actuator taken into account, this placed the actuator attachment at 67% of chord on the lower edge of the saddle.

5.4.4.1.3 Test Stand and Root Fixing

The test stand was the same as the one used in the pre-fatigue static tests in Building 252. The tilt was set to the maximum value of 8.7°. Table 5.8 gives the torque specifications used for fastening the NedWind 25 blade to the test stand and for tightening the radial blade root sleeve bolts. The root sleeve attachment is shown in Figure 5.12.

Table 5.8 NedWind 25 Test Blade Torque Specifications

Bolted Connection	Fastener Designation	Property Class	Lubrication Specification	Torque Specification
Test Stand to Adapter Plate	M24	10.9	Anti-Seize	800 N-m
Adapter Plate to Blade Root	M24	10.9	Anti-Seize	800 N-m
Root Sleeve (radial bolts)	M24	As received	As received	300 N-m

Figure 5.12 Blade root detail

5.4.4.2 Hydraulic System

Test loads were controlled with an MTS® 458 analog servo-hydraulic controller and an MTS® T/RAC digital program controller. A 762-mm (30-in.) stroke, 46,260-N (10,400-lb) capacity actuator was used to apply the loads. This was the same actuator used in the static testing.

5.4.4.3 Strain Gauges

At the time of the single-axis test the data acquisition system was limited to 36 channels. The edge static-test gauge setup was used (see Table 4.7) because of a higher number of gauges near the leading and trailing edges. We felt that this gauge distribution was best for monitoring possible non-linear behavior near the leading edge.

5.4.4.4 Data Acquisition System

BSTRAIN was used for data acquisition. The data acquisition hardware setup for the single-axis fatigue setup was the same as the static tests, except that the input filter frequency was changed from 4 to 10 kHz. Data sampling frequency was set at 150 Hz. For fatigue testing, the data collection algorithm uses a custom peak-valley routine that preserves the sequence of the extrema, provides auto-zero strain-gauge function, and monitors blade stiffness at frequent intervals. This software is described fully in Reference [15].

5.4.4.5 *System Calibration*

Prior to testing, the MTS® representative calibrated the hydraulic-actuator load cell and LVDT to the MTS® system controller. Strain-gauge data acquisition calibrations were made through shunt calibrations; end-to-end reference voltage checks were also performed.

5.4.5 *Single-Axis Fatigue Results*

5.4.5.1 *Visual Damage*

NREL observed two areas of visual blade damage during the test. The first was a crack that developed at the polyurethane joint interface at the root flange assembly. The crack eventually propagated around the root circular section. Although this crack did not appear to have immediate structural significance, it would allow moisture intrusion in the field, resulting in a probable functional failure.

The second damaged area was a crack inboard of the maximum chord on the trailing edge. The crack began at approximately 205 cm from the root flange and extended outboard to 215 cm. This is the portion of the span where the blade transitions from an airfoil to a circular root section. The crack began forming at approximately 20,000 cycles and was very audible as it grew to about 100 mm in length over a short period of time. After that, the crack did not noticeably grow during the remainder of the test. This crack seemed to develop due to local stresses caused by the complex curvature of the high-pressure airfoil surface trying to straighten under positive load.

5.4.5.2 *Root Sleeve Bolt Tension*

Using a torque wrench, bolt pretension on the radial root bolts (see Figure 5.12) was checked under a schedule prescribed by the SMT project. The blade root bolts between the steel sleeve and GRP were torqued to 300 N-m and were checked after 0.2%, 2.0%, 20%, 40%, 60%, and 80% of the maximum number of cycles during the fatigue tests. In terms of the NREL test parameters of 3,000,000 cycles, these intervals equated to 6,000, 60,000, 600,000, 1,200,000, 1,800,000, and 2,400,000 cycles. Slight loosening was noted on one bolt (out of 21) at 2% and 20% test period checks. This bolt was located on the suction side by the trailing edge.

5.4.5.3 *Strain-Gauge Data*

5.4.5.3.1 *Analysis Methods*

Data files of 15,000 rows or 7500 cycles were acquired during the fatigue test. These individual channels were concatenated into a single file of approximately 6 million points (peak and valley) for the entire test. These data files included spurious points that surrounded test starts and stops along with points around the stiffness checks. These points were removed and the remaining data were reduced to approximately 10,000 points by averaging sequential blocks of 300 peaks and valleys. These data are presented in Appendix E for each channel. Two-axis data are also included in this appendix for comparison.

5.4.5.3.2 *Strain-Gauge Results*

Some strain-gauge channels failed during the test. See Figure E.16.2 in Appendix E for an example. In all cases, the replacement gauge failed again. NREL concluded this was due to locally high strains in the laminate and gauge grid-area and not a fatigue failure of the gauge caused by high blade strains. No visible signs of damage could be seen on the blade at these gauge locations.

Figure 5.13 shows the global stiffness of the blade over the test period. The global blade stiffness can be an indication of blade failure. As much as a 10% loss in stiffness has been observed in previous tests prior to failure [4]. No significant change in test stiffness was noted during the test. In fact, based on the static-test data for the pre- and post-fatigue tests, the blade's stiffness appeared to increase during the fatigue testing. This is not easy to observe from the data shown in Figure 5.13, but is more obvious in Figures 4.3 through 4.6, which show reduced strain sensitivity for most gauge locations in the post-fatigue static test as compared to the pre-fatigue static test, especially in the flap direction. For Blade #66, this effect was not noticeable in the edge direction but it was observed in Blade #67 in both flap and edge. This phenomenon could not be explained by load sensor error. Both blades exhibited the same behavior but were tested at different times and in different laboratories. Load cell calibrations were double-checked to rule out obvious sensor errors. For Blade #66, the load cell used for the post-fatigue test was different than the one used for Blade #67, yet the same result was observed. Additional evidence gleaned from the displacement plots also suggests that the stiffening effect was real. The displacement sensors for both tests show that for the same displacement, the strains were lowered in the post-fatigue test in all cases.

Figure 5.13 Blade #67 global stiffness data for single-axis fatigue test

One possible explanation is that the blades may have stiffened slightly due to lower environmental humidity in Colorado. The blades originated in the Netherlands, where they had the opportunity to absorb ambient moisture for several years before being shipped to NREL. The pre-fatigue static tests were done early in the program; however, the post-fatigue tests were not done for several months after. The strength gained due to the drying of the laminates in the Colorado climate may have been enough to offset and overshadow any stiffness losses encountered during the test.

5.4.5.4 Acoustic Emissions

Although this is not a standard practice for all blades tested, Sandia National Laboratories is often invited by NREL to perform nondestructive tests on certain blades if it is of mutual benefit to the laboratories and the blade client. An acoustic emissions test was conducted in parallel with the SMT fatigue and static testing of Blade #67 by researchers at Sandia [23]. Sensors placed along the blade measured high-frequency emissions that may be related to incipient blade damage during the test. Preliminary results

indicated high emissions around the observed root cracking and along the spar between stations 2500 and 4200 on the compressive surface. The trailing-edge crack was not detected because the sensors were not properly positioned to detect this damage. The spar damage will be verified if postmortem sectioning is conducted. A copy of the Sandia report for this work is attached in Appendix G.

5.5 Two-axis Fatigue Test

5.5.1 Two-axis Test Introduction

Two-axis testing is more complicated than single-axis testing because it requires considerably more equipment and a more complicated control strategy [2]. However, the test loading and the resulting damage are more realistic for at least two reasons. First, the load ratio R_t , described in Section 5.3, can be uniquely prescribed for each load axis. Second, the phase angle between flap and edge loads can be prescribed to match field conditions. Thus, the load angle given in Figure 5.16 varies over a load cycle as it would under normal operation. Two-axis testing is faster than testing edge and flap separately, and it is similar in required time to a single-axis, combined-load test.

5.5.2 Two-axis Test Description

NREL developed a two-axis testing capability in 1997. Figure 5.14 and 5.15 show the two-axis load configuration used to test Blade #66. Figure 5.15 is a line drawing of the test hardware. NREL reduced the design spectrum to three million constant-amplitude cycles for the two-axis test, thus enabling a better direct comparison to the single-axis test loads and results. The test loads were developed by matching the 20-year design load spectrum (100 load cases) to the damage resulting from the test load for the design S-N slope of $m = 10$ for the composite material. The load amplitude ratios, R_t , were chosen to be at their optimum values of 0.081 and -0.61 for flap and edge, respectively. The phase angle between flap and edge load components was chosen to be 90° , with the positive edge (leading edge in compression) lagging the positive flap load (high-pressure surface in tension).

5.5.3 Two-axis Fatigue Loads

The simplified load spectrum method described in Section 5.3.2 was applied to the NedWind 25 blade at blade positions 4 through 10 from Table 5.1. These distributions are shown in Figures 5.16 and 5.17, with the solid-diamond symbols representing each blade position. For reference, position 4 is the furthest to the left. They also show the single-point linear distributions of fatigue loading applied to the blade during the test at NREL. For all cases the loads were applied to the blade at the 8.65-m station using hydraulic actuators. The linear distributions were chosen to best match the optimized distributions under the following constraints. The test loads are listed in Table 5.9.

Table 5.9 Two-Axis Fatigue-Test Moments

Load Direction	NW25.LKB Position to Match	DEL Moment to Match (max.)	Test Load at 8.65 m	R-Ratio (R_t)
Edge	4 (0.8 m)	115,000 Nm	14,648 N	-0.55
Flap	5 (2.65 m)	159,740 Nm	26,623 N	0.062

Figure 5.14 Blade #66 two-axis fatigue test in NREL Building 254

Figure 5.15 Two-axis fatigue hardware schematic

Figure 5.16 Optimized and applied flap bending test loads for $m = 10$

Figure 5.17 Optimized and applied edge bending test loads for $m = 10$

To minimize flap displacements during the test, the load introduction point was moved inboard from the best load station, which would have been at least 1 meter further outboard from the 8.65 station. The 8.65 station still allowed the equivalent-damage flap loads to be matched or exceeded over a majority of the in-board blade stations, where most of the fatigue damage was expected.

Because both flap and edge loads had to be applied at the same station, the spanwise position of the loading could not be optimized for both flap and edge directions. Therefore, we decided to allow the edge loads to drift further from the optimized target values, while prioritizing fit of the flap loads to the optimized distribution. As shown in Figure 5.17, this problem was addressed using a conservative approach, forcing the single-point edge test loads to pass through position 4 at the root flange. This ensured that all positions from position 4 (0.8 m from center of rotation [COR]) out to almost position 9 (7.65 m from COR) were tested at or above the design condition in edge.

Another concern was that the test load apparatus could only apply the loads at one test load ratio for the entire span, although each position had a unique R_t value. We found that the variations in R_t values were small enough that if these differences could be introduced into the M_{min} values they would not significantly alter the damage and could therefore be ignored. Based on this, the applied loads were used for the optimized R_t values for position 5 (2.65 m from COR).

Figure 5.18 shows the two-axis fatigue loading for a single load cycle. The flap and edge components are shown individually. The resultant load is also shown as the heavy solid line. The vertical axis is normalized against the peak-resultant single-axis test moment shown in Figure 5.9. Because of the 90° phase angle in the two-axis loads, the peak-resultant load and the peak-flap load component do not differ very much. Also note that the two-axis peak resultant loads are approximately 10% lower than the peak single-axis loads.

Figure 5.18 Two-axis bending moment normalized to single axis test moment

Another major difference between the two-axis test is the direction of the load during the load cycle. For the two-axis test, the load angle is continually varying while single-axis load angle is fixed. This difference is described in more detail in Section 6.

5.5.4 Instrumentation and Equipment

5.5.4.1 *Load Apparatus*

5.5.4.1.1 Load Attachment

The load attachment for the two-axis fatigue test was made at the 8.65-meter station, and the tip chord angle was rotated for a horizontal orientation.

5.5.4.1.2 Load Saddle

The load saddle used for the two-axis test was the same used in the single-axis test, except that hardware was added for attaching the edge push-rod and restraining backlash between the blade and the saddle hardware. The flap attachment was made at the 40% chord position.

5.5.4.1.3 Test stand

The test stand used for the two-axis fatigue test was similar to the one used in the single-axis test. This stand usually resides in the NREL Building 251 High Bay but was moved to Building 254 where it was used for this test. The test stand moment capacity is 1.36 million N-m (1 million ft-lb). The test stand tilt was set at 7.4° with the blade angled upward.

5.5.4.1.4 Hydraulic Actuators

The actuator used for the flap direction was the same as the one used for the single-axis test. The edge actuator used was MTS® model number 247.21 (serial number 151977) with a 20-in. (508-mm) and 28,000-lb (124,544-N) load capacity. The load cell used in the edge direction was a 22,000-lb (97,856 N) capacity, model number 661.20E-03 (serial number 78893). The load cell used in the flap direction also had a 22,000-lb (97,856-N) capacity, model number 661.20E-03 (serial number 66265).

5.5.4.2 *Strain Gauges*

Prior to the two-axis fatigue test, the BSTRAIN channel capacity was increased to 48. Therefore, all strain-gauge signals on the blade were acquired for the two-axis fatigue test.

5.5.4.3 *Data Acquisition System*

In order to run two-axis tests, an additional LabVIEW-based program 2ACD (2-Axis Control Determination) was written to create corrected displacement profiles for the digital closed loop servo-hydraulic controller. The primary function of this program is to compensate for the cross-coupling effect. Blade tests are conducted using displacement control for dynamic stability [2]. 2ACD receives user inputs of loads and a phase angle to create a displacement control profile for the servo-hydraulic controller. User inputs include the maximum and minimum flap and edge loads, and the phase relation between the flap and edge peaks. Test geometry is also an input to the program. The program, which has control of the test via the servo-hydraulic controller, cycles the blade at a reduced rate (typically 0.1 Hz) in order to minimize dynamic effects. Starting with initial guesses for load maxima and phase angle, the

program cycles the blade for three cycles, then averages both the recorded load maxima and phase angle. Next, the control program compares the maxima with the desired loads and phases, and uses proportional gains to obtain new-time load and phase control parameters. This process is iterated until the load and phase angle converges within a specified tolerance. The program then creates displacement profiles for both the flap and edge actuators. During actual testing, the servo-hydraulic controller controls the blade, using the displacement profiles created by 2ACD. The test operator runs this program periodically throughout the test, creating new displacement parameters to account for changing stiffness of the blade.

As part of BSTRAIN, global stiffness values for both flap and edge are recorded. Stiffness monitoring is a method to determine the health of a blade under test where large changes in global stiffness can indicate a failure in progress. At regular increments during the test (typically once per hour), the blade is cycled at a reduced frequency to obtain stiffness values and to zero strain gauge scaling factors to compensate for gauge drift. A reduced frequency is used to remove dynamic effects. For single-axis testing, determining blade stiffness was straightforward, recording and calculating the stiffness as the load range divided by the displacement range. Two-axis testing requires BSTRAIN to account for the cross-coupling effect when calculating the blade stiffness. BSTRAIN had to be modified to calculate flap and edge stiffness independently.

An auto-zero function is included in BSTRAIN. After the blade has been cycled at a reduced frequency, the actuators are positioned at zero-load while BSTRAIN updates the gauge scaling constants to indicate zero strain. Unfortunately, following the testing, it was discovered that the auto-zero function was not performing properly during the two-axis test and that, therefore, the test data has a greater amount of scatter than the single-axis results.

5.5.4.4 *System Calibration*

An MTS® representative calibrated the load cells and LVDTs for both the flap and edge actuators on site prior to testing.

5.5.5 Two-axis Fatigue Results

5.5.5.1 *Visual Damage*

NREL ran the two-axis test at 1.25 Hz. Above this frequency it was more difficult to maintain continuous smooth loading. The trailing edge crack at 205 cm, developed during the single-axis test, was first observed in the two-axis test between 420,000 and 440,000 cycles. This is more than one order of magnitude beyond the cycle count when it was first observed on the single-axis test. Note that for an S-N curve slope of 10, a 10% reduction in stress results in an order of magnitude increase in allowable cycles [24]. Therefore, we believe that the delayed onset of damage in this region is most likely due to the higher loading experienced by the single-axis test.

The same polyurethane root bond crack described for the single-axis test was also fully developed during the two-axis test, but it was more difficult to quantify the stages of growth in relation to the number of cycles.

5.5.5.2 *Root Sleeve Tension*

No loss of radial bolt torque was observed at scheduled checks during the two-axis test. This was a slightly better result than the single-axis test, which found one bolt had lost its pre-load and needed to be retightened.

5.5.5.3 *Strain-Gauge Data*

5.5.5.3.1 Analysis Methods

As with the single-axis test, data files of 15,000 cycles were acquired during the two-axis fatigue test. These individual channels were concatenated into a single file of approximately six million points (peak and valley) for the entire test. Spurious points that surrounded test starts and stops along with points around the stiffness checks were removed. The temperature of the hydraulic-oil reservoir was also acquired during the two-axis test. The temperature cycle of the hydraulic oil had a period of approximately 800 cycles with a range of $\pm 4^{\circ}\text{C}$. Due to the cooling system cycle, the fatigue-test data were averaged over each temperature cycle to reduce the number of points. The fatigue test data are presented in Appendix E.

5.5.5.3.2 Strain Gauge Results

At 824,307 cycles, NREL discovered that the load phasing was incorrect, with edge leading (instead of lagging) flap by 90° . This was corrected immediately. It is difficult to assess the impact this error may have had on NREL's results; however, the strain-gauge (peak/valley) responses showed little change when the phase angle was corrected. Therefore, NREL did not feel that the final results were significantly affected by this error.

No strain-gauge failures occurred during the two-axis fatigue test. Also, no measurable loss of blade stiffness was observed in the two-axis test, which is the same result as that received from the single-axis test. Figure 5.19 shows the horizontal and vertical blade stiffness for the two-axis test. No significant change in stiffness can be determined from this plot; Figures 4.3 through 4.6 reveal, however, that an apparent blade stiffening occurred in the post-fatigue static test when compared to the pre-fatigue static test, especially in the flap direction.

Figure 5.19 Blade #66 stiffness data from the two-axis fatigue test

5.5.5.4 *Acoustic Emissions*

Acoustic emission testing was not performed on Blade #66.

6. Comparison of Two-axis and Single-axis Tests

NREL has used both single-axis and two-axis fatigue testing in its laboratories. Each type has demonstrated certain merits; however, there has never been a significant effort directed at quantifying the technical differences. Most single-axis tests were performed at NREL before the capability was available to do two-axis testing. Although the effort involved in two-axis testing was significantly greater, analytically, the two-axis results showed a better representation of true loading conditions. However, there are times when single-axis testing might still be the more appropriate method to use.

We conducted two blade fatigue tests consecutively on two different NedWind 25 blades. The first test used a single-axis (Blade #67) test load, combining the flap and edge equivalent-damage test loads into a single resultant load. The optimum load ratios, R_t , were computed to be 0.081 for the flap direction and -0.61 for the edge direction. However, because a single actuator applied the loads, the value R_t for both components had to be the same. Therefore, a compromise of -0.1 was chosen. This slightly favored the flap direction, which was the dominant direction for fatigue damage. In addition, the phase angle between the two load components is fixed at zero degrees, requiring the loads to reach their maximum and minimum values at the same time. As a result of the single-axis test load constraints, the peak loads tend to be higher (see Figure 6-1). Also, because the actuator is fixed on both ends, the load angle between the blade and the actuator is fixed throughout the load cycle (see Figure 6-2). This tends to concentrate the loading on the fibers furthest from the neutral axis. At these outer fibers the blade section is usually over-tested.

The second test used a two-axis (Blade #66) load method, which allowed the individual load components for flap and edge to be applied independently at the optimum R_t of 0.081 for flap and -0.61 for edge, at a predetermined phase angle of 90° . The introduction of the phase angle causes the flap and edge peaks to occur at different times, which lowers the magnitude of the resultant peaks as compared to the single-axis loads. The load angle, however, is continuously varying through the load cycle that tends to stress a greater portion of the blade cross section at any given spanwise position.

The single-axis test showed visible blade damage in several areas but no catastrophic failures. The two-axis test results showed the same visible damage as the single-axis test; however, the onset of the damage was delayed by more than an order of magnitude in cycles. This was probably due to the higher in-phase loading for the single-axis test. Correspondence with the laboratory at CRES indicated that the same visual damage seen at NREL was also seen at CRES.

Figure 6.1 Comparison of resultant fatigue load cycle for single- and two-axis tests

Figure 6.2 Comparison of resultant fatigue load angles for single- and two axis tests

Table 6-1 gives direct comparisons of the numerical strain values from Blades #66 and #67 under each blade's respective loading. Comparison of the columns of numbers allows each strain-gauge location to be compared on the basis of severity of strain amplitude. These comparisons are difficult, however, because the damage at a particular location is dependent on the mean and the range of the load cycle. To make the evaluation of strain severity easier, an additional calculation was performed at each location to compute cycles-to-failure, N , at each location. Using Equation 5-1, the cycles-to-failure calculation was made with the following parameters:

$$N = \left\{ \frac{\frac{UTS + |UCS|}{2 \times C1 \times C2 \times C3} - \left| S_{mean} - \frac{UTS - |UCS|}{2 \times C1 \times C2 \times C3} \right|}{S_{amp}} \right\}^{10} \quad (5-1)$$

where,

- $C1, C2, C3$ = material factors equal to one
- S_{mean} = $E\epsilon_{mean}$
- S_{amp} = $E\epsilon_{amp}$
- E = modulus 24500 N/mm² from Table 5.2-3
- ϵ_{mean} = mean strain from Table 6-1
- ϵ_{amp} = strain amplitude from Table 6-1
- UTS = 372 MPa from Table 5.2-3
- UCS = 260 MPa from Table 5.2-3

This equation is the same relation used by Rotorline during the design of the blade.

These data are shown in the three columns on the far right of Table 6.1; the percent difference, using the Blade #66 data as a reference, is plotted in Figure 6.3. From this comparison, we conclude that the single-axis test loading produced the highest damage rate for this test at almost all strain-gauge locations.

Table 6.1 Comparison of Fatigue Test Data

	SMT Name	Gauge No. for 66	Gauge No. for 67	Peak for 66	Peak for 67	Valley for 66	Valley for 67	Alternating for 66	Alternating for 67	Mean for 66	Mean for 67	R-ratio (min/max) for 66	R-ratio (min/max) for 67	Blade #66-N	Blade #67-N	Percent Difference based on 66
Flap Load		1	-	26327	-	9302	-	8512.5	-	17814.5	-	0.35	-	-	-	
Flap LVDT		2	-	365	-	14	-	175.5	-	189.5	-	0.04	-	-	-	
Edge Load		3	-	-11338	-	10305	-	10821.5	-	-516.5	-	-1.10	-	-	-	
Edge LVDT		4	-	136	-	5	-	65.5	-	70.5	-	0.04	-	-	-	
Load		-	5	-	28454	-	4252	-	12101	-	16353	-	0.15	-	-	
LVDT		-	6	-	435	-	15	-	210	-	225	-	0.03	-	-	
08BLDLG	400E1/2	7	7	487	625	-320	-75	403.5	350	83.5	275	-0.66	-0.12	1.71E+14	8.48E+14	395.3
08BFLAP	400F1/2	8	8	1151	1026	54	-154	548.5	590	602.5	436	0.05	-0.15	1.28E+13	5.30E+12	-58.5
17S38UA	1500S1	9	9	-1636	-1654	-112	227	762	940.5	-874	-713.5	14.61	-7.29	1.16E+11	1.67E+10	-85.6
17S38LA	1500P1	10	10	1513	1917	98	-264	707.5	1090.5	805.5	826.5	0.06	-0.14	1.20E+12	1.61E+10	-98.7
17R62UA	1500S0	11	11	-1560	-1017	8	208	784	612.5	-776	-404.5	-195.00	-4.89	9.66E+10	1.65E+12	1610.4
17R62LA	1500P0	12	12	1492	2100	-99	-300	795.5	1200	696.5	900	-0.07	-0.14	3.37E+11	6.60E+09	-98.0
17R62UB	1500S45	13	13	-472	-617	-25	102	223.5	359.5	-248.5	-257.5	18.88	-6.05	4.60E+16	3.93E+14	-99.1
17R62LB	1500P45	14	14	655	935	12	-109	321.5	522	333.5	413	0.02	-0.12	2.09E+15	1.77E+13	-99.2
17R62UC	1500S90	15	15	-406	-409	23	62	214.5	235.5	-191.5	-173.5	-17.65	-6.60	7.32E+16	2.93E+16	-60.0
17R62LC	1500P90	16	16	362	125	-59	-39	210.5	82	151.5	43	-0.16	-0.31	1.22E+17	1.37E+21	1122908.1
25R20UA		17	17	-2415	-2580	-112	285	1151.5	1432.5	-1263.5	-1147.5	21.56	-9.05	1.24E+09	1.59E+08	-87.3
25S20LA		18	18	1678	1340	96	-260	791	800	887	540	0.06	-0.19	4.22E+11	2.77E+11	-34.3
25R20UC		19	-	-161	-	88	-	124.5	-	-36.5	-	-1.83	-	1.96E+19	-	-
25S26UA	2500S1	20	20	-3327	-3160	-217	350	1555	1755	-1772	-1405	15.33	-9.03	3.53E+07	1.58E+07	-55.2
25S26LA	2500P1	21	21	1695	1828	108	-245	793.5	1036.5	901.5	791.5	0.06	-0.13	4.14E+11	2.60E+10	-93.7
25S40UA		22	22	-2037	-2119	-142	286	947.5	1202.5	-1089.5	-916.5	14.35	-7.41	1.05E+10	1.16E+09	-89.0
25S40LA		23	23	1865	2067	123	-267	871	1167	994	900	0.07	-0.13	1.76E+11	8.73E+09	-95.1
25R45UA	2500S0	24	24	-1746	-1698	-108	246	819	972	-927	-726	16.17	-6.90	5.35E+10	1.18E+10	-77.8
25R45LA	2500P0	25	25	1777	1995	76	-254	850.5	1124.5	926.5	870.5	0.04	-0.13	2.11E+11	1.23E+10	-94.2
25R45UB	2500S45	26	26	-912	-1022	-66	139	423	580.5	-489	-441.5	13.82	-7.35	6.16E+13	2.73E+12	-95.6
25R45LB	2500P45	27	27	705	632	45	-57	330	344.5	375	287.5	0.06	-0.09	1.67E+15	1.01E+15	-39.9
25R45UC	2500S90	28	28	459	193	-11	-48	235	120.5	224	72.5	-0.02	-0.25	4.35E+16	3.00E+19	69029.2
25R45LC	2500P90	29	29	-630	-807	105	145	367.5	476	-262.5	-331	-6.00	-5.57	3.14E+14	2.21E+13	-93.0
25R70UA		30	30	-509	160	161	-67	335	113.5	-174	46.5	-3.16	-0.42	8.63E+14	5.33E+19	6183983.1
25S70LA		31	31	1042	1360	-363	-157	702.5	758.5	339.5	601.5	-0.35	-0.12	8.48E+11	4.99E+11	-41.2
25R70UC		32	-	644	-	-79	-	361.5	-	282.5	-	-0.12	-	6.18E+14	-	-
31R20UA		33	33	-1907	-2540	-87	310	910	1425	-997	-1115	21.92	-8.19	1.73E+10	1.73E+08	-99.0
31S20LA		34	34	1885	1902	105	-254	890	1078	995	824	0.06	-0.13	1.42E+11	1.81E+10	-87.3
31R20UC		35	-	339	-	20	-	159.5	-	179.5	-	0.06	-	2.01E+18	-	-
31S40UA		36	36	-2546	-2430	-174	310	1186	1370	-1360	-1060	14.63	-7.84	8.35E+08	2.72E+08	-67.5
31S40LA		37	37	1978	2377	132	-293	923	1335	1055	1042	0.07	-0.12	1.04E+11	2.57E+09	-97.5
31R70UA		38	38	-1297	-331	119	186	708	258.5	-589	-72.5	-10.90	-1.78	3.23E+11	1.27E+16	3925849.2
31S70LA		39	39	1270	2006	-101	-203	685.5	1104.5	584.5	901.5	-0.08	-0.10	1.35E+12	1.52E+10	-98.9
31R70UC		40	-	390	-	-2	-	196	-	194	-	-0.01	-	2.60E+17	-	-
41S40UA		41	41	-2990	-2880	-194	403	1398	1641.5	-1592	-1238.5	15.41	-7.15	1.25E+08	3.69E+07	-70.5
41S40LA		42	42	2414	2590	160	-380	1127	1485	1287	1105	0.07	-0.15	1.72E+10	9.35E+08	-94.6

On Blade #66, a few locations on the upper surface at approximately 60% to 70% chord did produce higher damage for the two-axis test, because the neutral axis is fixed during the single-axis loading and passed through this location. For the two-axis loading, the load angle is continuously varying, as is the neutral axis, so no location experiences zero strain. Also, a couple of locations showed higher damage in the transverse strain direction for the two-axis test. The majority of locations showed significantly shorter life for the single-axis test, with many locations over an order of magnitude lower life. Some locations exhibited as much as 99% change in life as a direct result of using the single-axis loading.

Figure 6.3 Calculated difference in allowable cycles between Blade #66 (two-axis test) and Blade #67 (single-axis test) at each strain-gauge measurement location

7. Blade Postmortem

The blades were preserved for further inspection, validation, and possible postmortem sectioning. Unfortunately, the program ended because of lack of EU funding and this portion of the project was never done.

8. Summary and Conclusions

Under the SMT Program, five international blade-testing laboratories participated in testing 12-meter NedWind 25 wind turbine blades taken from a sequential production series at Rotorline. The purpose was to observe techniques used by different laboratories to help develop a common set of procedures for testing wind turbine blades. NREL participated as an invited partner and

tested two blades, identified as Blades #66 and #67. Static tests and fatigue tests were conducted on both blades. Identical static tests were conducted on both blades. Tests included property measurements and static-strength tests based on the NedWind 25 extreme-load cases. Static tests were repeated after the fatigue testing to determine the effect of fatigue loading on the static properties. The key observations from static testing are:

1. Blade #66 and Blade #67 had some random differences but their global properties were very similar.
2. Pre- and post-fatigue static-test data show a probable increase in blade stiffness, possibly caused by laminate drying effects. This effect is most obvious in the flap direction.
3. The effect described in #2 above overshadowed any possible decline in global blade properties resulting from fatigue testing. Some local strain changes may have occurred but could not be fully evaluated for this test.
4. The SMT-prescribed static-test load of 75% of the extreme design load was too low to evaluate possible non-linearities for fatigue loading.
5. The SMT-prescribed static-test loading procedure was inadequate to evaluate extreme-load behavior and did not allow the actual blade strength to be determined because the blade was not broken.

Two different methods were used for the fatigue tests. One blade was fatigue tested using single-axis loading and the other was conducted using two-axis loading. All labs used a common set of design loads containing 100 load cases to develop the fatigue-test loads. A new method of analysis was developed at NREL to convert design loads to a damage-equivalent spectrum while staying in the load domain. The new method simplifies the conventional damage evaluation techniques but will require further validation. Some of the key fatigue test observations are:

1. The load-domain damage analysis method described illustrates how minimizing scatter optimizes the load amplitude ratio, R_t , of the test loading.
2. The differences in the damage equivalent test load calculated for the two-axis and single-axis tests highlight the need to accurately determine the phase relationships between the edge and flap loads in the design.
3. Using identical design load conditions, the test loads for the two fatigue tests were significantly different and resulted in significant differences in the test outcome.
4. Phase angle uncertainty in the design data and in the test methodology led to large errors in the test blade damage.
5. Single-axis test loading was more severe than in the two-axis test using the NedWind 25 blade design loads.
6. Single-axis and two-axis tests produced virtually the same visual damage on the exterior of the blade. The onset of the trailing-edge crack was over an order of magnitude sooner for the single-axis test.
7. Single-axis test loading was less representative of true operational loading because: (a) the load amplitude ratio was not optimized for either flap or edge conditions, (b) the phase angle was forced to be 0° , causing the peak loading to be 10% higher, and (c) the load angle was fixed at 50° and did not vary during the load cycle.
8. The NedWind 25 blade sustained the test loading without loss of global properties; however, two non-structural cracks formed that could have adverse consequences due to environmental degradation if neglected.
9. Communications with other laboratories suggest that NREL's results are similar to the results produced in the other laboratories [25].

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10. References

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11. Appendices

Appendix A -- Fatigue Design Load Matrix

Appendix B -- Equivalent-Damage Spreadsheets

Appendix C -- Edgewise Static Data

Appendix D -- Flapwise Static Data

Appendix E -- Fatigue Data

Appendix F -- Correspondence

SMT [21] Pre-load in bolts

Jeroen 8

SMT [98] CRES strain-gauge locations

SMT [100] Nomenclature for common gauges

SMT [25] Radial position, pull direction, etc.

SMT [47] Data sets

Appendix G -- Acoustic Emissions Report

Appendix H -- Drawings and Calibration Records

Adapter plate

Load saddle

Strain-gauge data sheets

Appendix A

Fatigue Design Load Matrix

Energieonderzoek Centrum Nederland
Netherlands Energy Research Foundation ECN

ECN SOLAR & WIND ENERGY

FACSIMILE MESSAGE

TO : Martin Winther Jensen, Pantells Vionis, Don van Delft, Scott Larwood
FAX : +45 42 37 29 65, +30 1 6039905, 015 2782308, +1 303 384 7055
REF : load spectrum NW25 rotorblade/7.4262.01.02.20
FROM : Jeroen van Dam
PHONE : +31 224 564277
FAX : +31 224 563214
CC : Bernard Bulder
PAGES : 2
DATE : 10 February 1998

MESSAGE:

Dear colleagues,

LOADSPECTRUM

We have received information on the loadspectrum of the NW25 rotorblade. The load spectrum is described by three files. These files can be downloaded from the directory \pub\de\bulder on the ECN ftp-server: FTP.ECN.NL.

NW25.LKB gives ten positions for which the loads have been calculated. The ten positions are:

Radial position [m] from rotor centre	Description of position
0.2	weld in hub
0.6	weld in hub
0.65	Flange of the blade
0.8	Pin-hole connection between flange and laminate
2.65	1st aerodynamic cross section
3.9	2nd aerodynamic cross section
5.15	3rd
6.4	4th
7.65	5th
8.9	6th

The file NW25.CSB and NW25.CMB describe the ranges and means of three load components for the ten positions for all hundred load cases. The loads are given without

*If you did not receive all pages or find that they are illegible,
please contact the above mentioned phone number*

Postbus 1, 1755 ZG Petten
Westerduinweg 3, 1755 LE Petten
Telefoon: (0224) 564949 Fax: (0224) 564480
WWW: <http://www.ecn.nl/>

PO Box 1, 1755 ZG Petten, The Netherlands
Westerduinweg 3, 1755 LE Petten, The Netherlands
Phone: +31 224 564949 Fax: +31 224 564480
WWW: <http://www.ecn.nl/>

- 2 -

any load factor. In the first column of these files the number of cycles for each loadcase is given. A small part of NW25.CSB is given below.

Explanation of contents of file NW25.CSB

No. of load cases		position 1			position 2				My10
		Fz1	Mx1	My1	Fz2	Mx2	My2		
No. of	3747600	25506.9	67645.61	37281.91	15847.83	57301.43	35460.76		3728.908
cycles	4145710	25506.9	72533.04	59440.37	15847.83	61977.53	58859.7		8738.19
	3699900	25506.9	74759.94	48726.85	15847.83	64126.9	44507.67		5060.531
	2759400	25506.9	73800.66	37519.26	15847.83	63223.22	35732.78		4019.418
	1746710	25506.9	72519.75	39519.11	15847.83	62025.46	37717.42		4766.019
	:	:	:	:	:	:	:		:
	20	25506.91	75214.84	107461	15847.83	65846.6	101730.1		9409.942

The three files should give enough information for a test spectrum.

Yours sincerely,

Jeroen van Dam

Author: Jeroen van Dam [SMTP:vandam@ecn.nl] at SMTP
Date: 2/24/98 4:03 AM
Priority: Normal
TO: Scott Larwood at NREL
'C: bulder@ecn.nl [SMTP:bulder@ecn.nl] at SMTP
Subject: answers w.r.t. NW25

Scott,

Here are the answers to your questions, sorry for my late reply.

1. Is NW25.CSB the range of the loads? *RANGE*
2. Is NW25.CMB the mean loads? *MAXIMUM*

No, in my fax I incorrectly mentioned that the means and ranges are in these two files. Comparing the numbers in the files and Table I1 and I2 of "Jeroen 4" gives that NW25.CMB contains the maximum loads and NW25.CSB contains the load ranges. ✓

3. What are the units for the forces and moments?

Again comparing the files with Table I1 gives that the forces are in [N] and the moments are in [Nm]. ✓

4. What is the reference axis for Fz, Mx, and My and how do these compare to the forces and moments in appendix H of "Jeroen 4"?

Fz is comparable with "FR kracht radiaal" which means that it is the radial force component.

My is comparable with "MT moment tangential", being the flatwise moment
'x' is comparable with "MA moment axiaal", being the edgewise moment.

Although these last two of these load components do not match one on one, this probably has to do with different dates of the simulations.

5. Why do these load spectrum exclude the other 2 forces and 1 moment in appendix H of "Jeroen 4"?

Only these three load components were taken into account for the strength and fatigue calculations. This was done to save some calculation time. ✓

6. Why are the radial positions in NW25.LKB differ from those analyzed in appendix H of "Jeroen 4"?

The simulations were run before it was known which crosssections were critical. Afterwards the cross sections which were of interest were interpolated, these data are in the files on the FTP-site. The cross sections given in the files are more or less the same as the cross sections which were calculated on fatigue in "Bernard 1".

7. What do the filenames for the aerodynamic profiles mean?

The filename can be read as follows : "r10.65" gives the contour at 10.65 meter from the rotor centre. This is 10 meter from the blade flange.

8. What is the format for the aerodynamic profile files?

As far as I can see in the first column is the coordinate along the chord in [mm], in the second column the distance of the blade surface perpendicular to the chord is given also in [mm].

Regards,

Author: Scott Larwood at NREL
Date: 2/19/98 9:29 AM
Priority: Normal
TO: vandam@ecn.nl at SMTP
Subject: NW25 Information

Greetings Jeroen,

I would like some clarification on the NW25 files from the FTP site:

1. Is NW25.CSB the range of the loads?
2. Is NW25.CMB the mean loads?
3. What are the units for the forces and moments?
4. What is the reference axis for F_z , M_x , and M_y and how do these compare to the forces and moments in appendix H of "Jeroen 4"?
5. Why do these load spectrum exclude the other 2 forces and 1 moment in appendix H of "Jeroen 4"?
6. Why are the radial positions in NW25.LKB differ from those analyzed in appendix H of "Jeroen 4"?
7. What do the filenames for the aerodynamic profiles mean?
8. What is the format for the aerodynamic profile files?

Scott Larwood

MAXIMUM

NW25.CMB

No. of load cases	100	position 1		position 2		position 3		position 4		position 5		position 6		position 7		position 8		position 9		position 10					
No. of cycles		Fz1	My1	Fz2	My2	Fz3	My3	Fz4	My4	Fz5	My5	Fz6	My6	Fz7	My7	Fz8	My8	Fz9	My9	Fz10	My10				
134747600	72702	326003.3	52306.1	64091.3	30710.2	49541.7	63015	30048.6	49196.1	61975.1	29155.4	48253.6	49150	18140.1	36629.3	42148.1	12489.0	29063	35969.1	58023.2	3398.13	10397.5	16807.1	1089.402	6007.59
14545710	72702	42798.7	81031.5	64091.3	37181	76561.7	63015	30478.8	76453	61975.1	29155.4	48253.6	49150	22905.2	37361.7	42148.1	11528.1	4575.5	35969.1	58023.2	3398.13	10397.5	16807.1	2546.447	9532.51
3599000	72702	4859.6	8252.7	64091.3	42743.3	8252.7	63015	42013	8175.6	61975.1	40890.5	8943.3	49150	4558.5	42013	42148.1	15268	4558.5	35969.1	58023.2	3398.13	10397.5	16807.1	1361.745	10048.2
2755040	72702	52023.3	90640.6	64091.3	45975.9	96102.6	63015	45219.9	95535.3	61975.1	44039	83927.8	49150	29475.6	64102	42148.1	21447.7	51064.4	35969.1	58023.2	3398.13	10397.5	16807.1	3507.36	10456.2
1746710	72702	54417.5	96698.9	64091.3	48268.6	91913.4	63015	47501.2	91315.2	61975.1	46282.9	89615.2	49150	31257.6	68647.7	42148.1	22921.2	54668.1	35969.1	58023.2	3398.13	10397.5	16807.1	3815.538	11398.5
945721	72702	55324.9	96122.9	64091.3	49136.6	91310.7	63015	48363.1	90709.2	61975.1	47131.1	88998.9	49150	31936.3	67905.1	42148.1	23499.7	54669.6	35969.1	58023.2	3398.13	10397.5	16807.1	4041.125	11362.9
439683	72702	55224.1	94452.7	64091.3	49025.4	89616.9	63015	48250.5	89012.4	61975.1	47017.4	87294.1	49150	31808.4	66101.7	42148.1	23369.8	52292.3	35969.1	58023.2	3398.13	10397.5	16807.1	4017.408	10710.2
260171	72702	54920.9	95724.6	64091.3	48725.5	90732.1	63015	47951.1	91018	61975.1	46719.9	88322.5	49150	31535.3	66434.3	42148.1	23115.8	52231.2	35969.1	58023.2	3398.13	10397.5	16807.1	3905.844	10649.5
1499060	72702	36883.3	55504.7	64091.3	31641.6	52591.4	63015	30087.9	52227.2	61975.1	29369.2	51228.9	49150	16749.6	38916.4	42148.1	12956.6	30891.8	35969.1	58023.2	3398.13	10397.5	16807.1	1102.032	6384.94
1658280	72702	40408.4	83250.9	64091.3	38369	79074.3	63015	37659	78552.2	61975.1	36617.9	77080.3	49150	23777.9	58525.7	42148.1	16911	47002.5	35969.1	58023.2	3398.13	10397.5	16807.1	1767.68	9975.05
1479960	72702	49891.5	88475.1	64091.3	43751.5	94035.1	63015	43009	83480.2	61975.1	41867.9	81909.5	49150	27794.3	62265.6	42148.1	20097.2	49805.8	35969.1	58023.2	3398.13	10397.5	16807.1	2569.391	9758.97
1103760	72702	52945.4	92492.3	64091.3	48685.8	87853.8	63015	46956.8	87295.8	61975.1	44899	85648.8	49150	32296.3	67145.8	42148.1	21934	52165.5	35969.1	58023.2	3398.13	10397.5	16807.1	3577.119	10528.4
696964	72702	49459.9	97361.6	64091.3	48794.1	92537.7	63015	48022.8	91934.8	61975.1	46795.9	90220.3	49150	31654.9	69075.2	42148.1	23259.9	55189.3	35969.1	58023.2	3398.13	10397.5	16807.1	3577.119	10528.4
378289	72702	55454.6	95935.1	64091.3	49260.1	91098.8	63015	48485.8	90424.6	61975.1	47251.5	88774.8	49150	32028.2	67568.9	42148.1	23701.4	53705.4	35969.1	58023.2	3398.13	10397.5	16807.1	3734.06	11986.7
175873	72702	55361.7	95610.7	64091.3	49156.2	90685.7	63015	48380.6	90070.1	61975.1	47144.9	88163.8	49150	31905.1	66713.7	42148.1	23446.1	52651.2	35969.1	58023.2	3398.13	10397.5	16807.1	3906.574	11498.6
104068	72702	55078.1	97778.2	64091.3	48875.1	92647	63015	48099.8	92005.6	61975.1	46865.7	90178.1	49150	31645.8	67638.7	42148.1	23202.9	53034.7	35969.1	58023.2	3398.13	10397.5	16807.1	4057.044	11865.7
749531	72702	37760.5	58557.7	64091.3	32373.3	55502.4	63015	31706.6	55120.5	61975.1	30780.4	54069	49150	19357.4	41100	42148.1	13431.2	32638.6	35969.1	58023.2	3398.13	10397.5	16807.1	4032.107	10693.9
829142	72702	45240.6	85368.2	64091.3	39502.3	81089.7	63015	38785	80554.9	61975.1	37721.8	79044.7	49150	24609.6	60419.5	42148.1	17562.6	48182.6	35969.1	58023.2	3398.13	10397.5	16807.1	3920.444	10719.1
739980	72702	50694.9	89991.5	64091.3	47407.6	85479.7	63015	43959.2	84915.7	61975.1	42800.3	83181.8	49150	28507.7	63613.9	42148.1	20652.2	50687.3	35969.1	58023.2	3398.13	10397.5	16807.1	1994.865	6747.49
551879	72702	53601.1	93404	64091.3	47478.7	88741.2	63015	46720.1	88158.3	61975.1	45513.6	86504	49150	30533.6	66100.8	42148.1	22381.8	52697.5	35969.1	58023.2	3398.13	10397.5	16807.1	3350.704	10327.4
343432	72702	55585.2	97696.9	64091.3	49089.3	92477.8	63015	48309.4	92241.4	61975.1	47078	90516.8	49150	31890.3	6945.8	42148.1	23449.8	52698.9	35969.1	58023.2	3398.13	10397.5	16807.1	3694.617	10808.2
189144	72702	55569	95752.4	64091.3	49368	90901.9	63015	48593	90243.3	61975.1	47356.6	88555.9	49150	32107.9	67248.2	42148.1	23335	53328.2	35969.1	58023.2	3398.13	10397.5	16807.1	3777.735	11558.1
87936.6	72702	55493.8	97091.3	64091.3	49281.9	92062.4	63015	48505.5	91438.3	61975.1	47267.4	89643.1	49150	31998	67558	42148.1	23519.4	53196.8	35969.1	58023.2	3398.13	10397.5	16807.1	4069.167	11010.3
52034.2	72702	55229.4	100115	64091.3	49019.1	94829.4	63015	48242.8	94168.7	61975.1	47006	92283.3	49150	31752.1	69030.3	42148.1	23286.8	53977.6	35969.1	58023.2	3398.13	10397.5	16807.1	4069.167	11010.3
843223	72702	37601.7	58005	64091.3	32288.4	54975.4	63015	31556.8	54196.7	61975.1	30633.6	53564.8	49150	19247.4	40704.6	42148.1	13345.3	32222.3	35969.1	58023.2	3398.13	10397.5	16807.1	3936.805	10787.2
932785	72702	55024.7	94984.8	64091.3	39297.1	80724.8	63015	35851.1	80192.3	61975.1	37522	78689.1	49150	24459	60149.3	42148.1	17444.7	47969	35969.1	58023.2	3398.13	10397.5	16807.1	3936.805	10787.2
832478	72702	50513.2	89717	64091.3	44534.5	85218.1	63015	43787.1	84655.8	61975.1	42631.5	83063	49150	28378.5	63419.1	42148.1	20559.9	50503.1	35969.1	58023.2	3398.13	10397.5	16807.1	3936.805	10787.2
620864	72702	53490	93265.7	64091.3	47378.3	88609.7	63015	46614.3	88027.8	61975.1	45409.6	86376	49150	30551.3	66004.8	42148.1	23226.6	52611.3	35969.1	58023.2	3398.13	10397.5	16807.1	3936.805	10787.2
393010	72702	55210.8	97637.8	64091.3	49030.1	92791.7	63015	46257.5	92185.9	61975.1	47026.9	90463.1	49150	31849.5	69214	42148.1	23415.4	52709.9	35969.1	58023.2	3398.13	10397.5	16807.1	4069.167	11010.3
212781	72702	55474.4	95767.3	64091.3	49348.4	90912.3	63015	48573.6	90305.4	61975.1	47337.6	89548.9	49150	32296.3	71543.5	42148.1	23754.8	56762.9	35969.1	58023.2	3398.13	10397.5	16807.1	4069.167	11010.3
99828.6	72702	55459.9	96787.5	64091.3	49259.1	91779.2	63015	48482.8	91153.2	61975.1	47245.2	89370.2	49150	31981.1	67380.4	42148.1	23506.1	53078.8	35969.1	58023.2	3398.13	10397.5	16807.1	4069.167	11010.3
58538.4	72702	55202	95691.8	64091.3	48993	94434.2	63015	48216.9	93777	61975.1	46980.6	91902.1	49150	31732.8	68778.3	42148.1	23271.6	53086.8	35969.1	58023.2	3398.13	10397.5	16807.1	4069.167	11010.3
377289	72702	39109.6	63253.1	64091.3	33660.7	59979.5	63015	32979.6	59570.3	61975.1	32028.1	58436.9	49150	20292.3	44458.3	42148.1	14161.1	35325.1	35969.1	58023.2	3398.13	10397.5	16807.1	4069.167	11010.3
331114	72702	47074.2	88624.6	64091.3	41245.4	84189.3	63015	40516.7	83543.9	61975.1	39419.5	82066	49150	25888.7	62715.8	42148.1	18564.9	49997.7	35969.1	58023.2	3398.13	10397.5	16807.1	4069.167	11010.3
332991	72702	51825.9	92195.6	64091.3	45788.4	87586.8	63015	45033.8	87010.7	61975.1	43856.1	85376.7	49150	29311.7	65223.9	42148.1	21329.5	51969.8	35969.1	58023.2	3398.13	10397.5	16807.1	4069.167	11010.3
248346	72702	54544.7	94579.1	64091.3	48385.8	98857.5	63015	47619	98267.4	61975.1	46397.6	87591	49150	31333.8	68193.6	42148.1	23278.8	53334.8	35969.1	58023.2	3398.13	10397.5	16807.1	4069.167	11010.3
157204	72702	55576	97935.6	64091.3	49378.9	92948.5	63015	48605.3	92337.6	61975.1	47368.9	90599.4	49150	32120	69161.4	42148.1	23320.6	52611.3	35969.1	58023.2	3398.13	10397.5	16807.1	4069.167	11010.3
85114.9	72702	55744.2	97245.3	64091.3	49348.4	90912.3	63015	48573.6	90305.4	61975.1	47337.6	89548.9	49150	32296.3	71543.5	42148.1	23754.8	56762.9	35969.1	58023.2	3398.13	10397.5	16807.1	4069.167	11010.3
39571.5	72702	55598.3	97696.9	64091.3	49089.3	92477.8	63015	48309.4	92241.4</																

NW25.CMB

No. of load cases	100	position 1			position 2			position 3			position 4			position 5			position 6			position 7			position 8			position 9			position 10		
		Fz1	Mx1	My1	Fz2	Mx2	My2	Fz3	Mx3	My3	Fz4	Mx4	My4	Fz5	Mx5	My5	Fz6	Mx6	My6	Fz7	Mx7	My7	Fz8	Mx8	My8	Fz9	Mx9	My9	Fz10	Mx10	My10
19030700	72702	53794.5	91448.1	64091.3	47670.1	86889.6	63015	46904.5	86319.8	61975.1	45696.5	84704.6	49150	30797.1	64783.7	42148.1	22549.8	51706.3	35969.1	16230.7	39493.7	29528.4	11021	28405.5	23081.9	6874.22	18724.7	16807.1	3760.547	10789.9	
8847730	72702	54619.5	92017.2	64091.3	48448.3	87398.7	63015	47676.9	86821.4	61975.1	46454	85184.6	49150	31372.4	64997.6	42148.1	23015.4	51773	35969.1	16606.3	39473.5	29528.4	11319.3	28356.9	23081.9	7100.13	18681.7	16807.1	3907.354	10757.8	
5235420	72702	54172.2	91610.1	64091.3	48007.7	86962.9	63015	47237.1	86382	61975.1	46017.5	84736	49150	30975.6	64435.1	42148.1	22653.9	51184.2	35969.1	16298.9	38956.4	29528.4	11077.3	27979.9	23081.9	6923.34	18476	16807.1	3798.261	10702.9	
32140000	69888	29925.8	19795.9	61484.8	24988.5	18596.8	60434.4	24371.3	18446.9	59494.6	23616.2	18091.7	47904	14302.6	13710.4	41557	9666.12	10953.7	35789.3	6626.27	8473.09	29591.8	4303.45	6245.84	23265	2585.5	4313.05	17020.3	1373.643	2681.2	
2316000	69888	50760.5	106801	61484.8	45120.1	101396	60434.4	44415	100721	59494.6	43302.8	98788.5	47904	29585.4	74956.5	41557	21883.3	59469.1	35789.3	15851.7	45127.6	29591.8	10815.8	32211.9	23265	6775.93	21086.7	17020.3	3724.171	12081.2	
377000	12753.8	36347.1	112812	7924.21	30938.8	106162	7320.52	30262.8	105331	7085.92	29331	102933	4192.64	17839.2	73359.3	2955.27	11951.4	55046.9	2274.18	8012.29	39570.5	1705.75	5074.87	26810.9	1231.43	2963.31	16693	835.633	1524.621	9120.16	
120000	12879.4	38084.8	3291.8	8041.97	33127.2	2833.4	7437.29	32507.5	2776.1	7201.15	31597.8	2698.63	4288.75	20378.7	1743.26	3040.14	14397.9	1243.34	2347.87	10090.2	886.904	1767.06	6886.77	599.85	1279.88	4084.88	374.921	871.217	2196.132	206.593	
1	12753.8	41081.7	165036	7924.21	35309.3	155079	7320.52	34587.8	153634	7085.92	33519.5	150196	4192.64	20433.6	105328	2955.27	13506.8	77826.4	2274.18	8913.37	55075.9	1705.75	5550.64	36745.5	1231.43	3182.98	22539.2	835.633	1607.091	12141.6	
1	69888	54106.8	143667	61484.8	47838.4	135744	60434.4	47056	134754	59494.6	45814.2	131879	47904	30498.8	98419.3	41557	22056.4	74098.5	35789.3	15680.5	54617.2	29591.8	10524	37983.6	23265	6498.59	24291.1	17020.3	3524.627	13632.3	
1	69888	54761.2	133247	61484.8	49014.3	126320	60434.4	48296	125454	59494.6	47098.8	122953	47904	32227.6	92098.6	41557	23813.8	72305.4	35789.3	17184.8	54389.6	29591.8	11684.2	38532	23265	7302.21	25062.6	17020.3	4004.632	14286.1	
1	17720.7	59833.2	30814.4	12488.7	52507.9	28668.3	12362.4	51988.4	28434.7	11983.4	50430.1	27733.8	7308.95	31210	19088.6	5876.64	22475.9	14012.1	4650.34	15543.1	9850.23	3580.98	10155.9	6530.4	2639.16	6111.08	3981.04	1815.05	3233.39	2129.2	
1	69888	102865	81625.2	61484.8	93335.1	77426.7	60434.4	82143.9	76901.9	59494.6	89914.3	75423.3	47904	62416.1	57187.1	41557	46611.2	45443	35789.3	33919.1	34677.3	29591.8	23273.5	24960.1	23265	14685	16506.3	17020.3	8137.78	9568.34	
500	69888	49746.6	80181.8	61484.8	43835.5	76117.7	60434.4	43096.6	75609.7	59494.6	41976.2	74180.1	47904	28158.3	56548.7	41557	20576.3	45117.9	35789.3	14802.2	34518.4	29591.8	10033.6	24877	23265	6248.8	16443.1	17020.3	3415.462	9500.31	
500	13599	68318.2	4858.05	8716.16	62892.9	4331.45	8105.8	62214.7	4265.62	7859.86	60726.2	4162.22	4826.53	42368.7	2886.93	3507.88	31261.2	2175.53	2749.27	22166.3	1612.89	2098.04	14829.1	1129.54	1539.51	9121.31	727.882	1060.82	4925.552	411.486	
20	12753.8	43012.9	6171.77	7924.23	38726	5573.77	7320.54	38190.1	5499.02	7085.95	37132.1	5368.87	4192.66	24083.6	3763.7	2955.28	16558.8	2832.97	2274.19	10959.8	2067.37	1705.76	6858.31	1413.68	1231.43	3955.72	883.832	835.634	2010.045	482.617	

RANGE NW25.CSB

No. of load cases	position 1		position 2		position 3		position 4		position 5		position 6		position 7		position 8		position 9		position 10											
	Fz1	Mx1	Fz2	Mx2	Fz3	Mx3	Fz4	Mx4	Fz5	Mx5	Fz6	Mx6	Fz7	Mx7	Fz8	Mx8	Fz9	Mx9	Fz10	Mx10										
No. of cycles																														
3747660	25506.9	67465.6	37281.9	15847.8	57301.4	35460.8	14640.5	56008.4	35233.1	14171.3	54312.9	34550.4	8384.81	33401.2	25130.3	5910.11	22805.9	20567.8	4548	15699.3	15357.1	3411.2	10240.2	10726.3	2462.62	6171.72	6808.6	1671.09	3279.098	3728.91
4145710	25506.9	72533.3	54460.4	15847.8	61977.5	56569.7	14640.5	60568.1	56312.1	14171.3	58877.2	55269.8	8384.81	36912.9	42415	5910.11	25606.9	33866.8	4548	17826.3	25726.5	3411.2	11762.6	18319	2462.62	7175.36	11908.3	1671.09	3862.771	6738.19
3699900	25506.9	74759.9	49726.9	15847.8	64126.9	44507.7	14640.5	62797.8	44230.3	14171.3	60963.2	43398.6	8384.81	36929.9	33140.6	5910.11	26927.9	26325.5	4548	18900.8	19884.4	3411.2	12526.9	14049	2462.62	7665.92	14071.0	1671.09	4136.003	5063.53
2759400	25506.9	73800.7	37519.3	15847.8	63223.2	35732.8	14640.5	61901	35509.5	14171.3	61008.9	34639.9	8384.81	38005.3	26581.6	5910.11	26571.9	21086.4	4548	18598.2	15873.1	3411.2	12307.7	11167.1	2462.62	7510.01	17175.3	1671.09	4033.052	4019.42
1746710	25506.9	72519.8	39519.1	15847.8	62025.5	37171.4	14640.5	60713.7	37492.2	14171.3	59857.2	36817.4	8384.81	37233.3	28494.5	5910.11	26581.9	22973.6	4548	18294.4	17171.7	3411.2	12145.9	12793.9	2462.62	7423.1	6390.09	1671.09	3986.881	4766.02
9457210	25506.9	70804	33070	15847.8	60198.3	31492.1	14640.5	58897.6	31294.9	14171.3	57172.7	30703.5	8384.81	36898.8	23409.7	5910.11	25039.9	18661.1	4548	17623.7	14355.8	3411.2	11781.2	10480.6	2462.62	7275.78	7017.79	1671.09	3954.403	4087.71
439683	25506.9	68222.1	25859.7	15847.8	57892.6	24574.6	14640.5	56501.4	24401.4	14171.3	54910.6	23894.2	8384.81	34057.3	17584.6	5910.11	23498.1	14446	4548	15405.3	9995.45	3411.2	10903	7095.74	2462.62	6726.45	4654.84	1671.09	3658.041	2576.95
260171	25506.9	58892	22609.2	15847.8	55635	22212.3	14640.5	54354.1	22037.7	14171.3	52695.6	21519.1	8384.81	32240.9	15122	5910.11	21952	11447.4	4548	15132	7797.51	3411.2	10903	7095.74	2462.62	6005.85	3725.46	1671.09	3222.913	2246.64
1493960	25506.9	69052.1	43666.3	15847.8	68363.8	41546.6	14640.5	67335	41281.6	14171.3	55121.8	40466.9	8384.81	34372.5	30688.8	5910.11	23562.1	24196	4548	16261	18129	3411.2	10634.1	12710.1	2462.62	6425.81	8104.02	1671.09	3422.404	4458.46
1658280	25506.9	74511.6	66070.8	15847.8	63857.2	42976	14640.5	62525.4	42589.1	14171.3	60707.4	41429	8384.81	38285.5	47121.2	5910.11	26678.3	37599.1	4548	18620.9	28651.5	3411.2	12314.9	20330.9	2462.62	7525.72	13204.2	1671.09	4055.883	7452.46
1479590	25506.9	77452.8	54028	15847.8	66887.9	51467.9	14640.5	65342.3	51147.9	14171.3	63478.2	50188.4	8384.81	40487.8	38353.9	5910.11	28478.8	30486	4548	19003.8	23040.6	3411.2	13299.1	16294.2	2462.62	8162.51	10504.2	1671.09	4415.762	5895.56
1103760	25506.9	76705.5	42865.1	15847.8	65990.5	40848.4	14640.5	64651.1	40539.3	14171.3	62806.9	39630.4	8384.81	40062.8	30415.1	5910.11	28201.3	24152.7	4548	18233.3	18211.1	3411.2	13162.1	18227.9	2462.62	8049.27	8327.79	1671.09	4328.63	4604.28
698684	25506.9	75013.6	43428.6	15847.8	64402	41433.1	14640.5	63075.6	41183.7	14171.3	61270.6	40436.2	8384.81	39009	31216.9	5910.11	27468.8	25109.3	4548	19370.5	19314.9	3411.2	12914.3	13933	2462.62	7924.71	9136.55	1671.09	4271.379	5193.3
738289	25506.9	72514.7	35600.8	15847.8	62018.9	33870.2	14640.5	60707	33653.9	14171.3	59848.3	33005.3	8384.81	37257.9	25005.4	5910.11	26117.5	19799.6	4548	18428.5	15099	3411.2	12341.1	10917.5	2462.62	7631.15	7239.55	1671.09	4150.395	4811.16
175873	25506.9	69829.5	30055.2	15847.8	59428.7	28452.5	14640.5	58128.6	28525.2	14171.3	56411.1	27633.3	8384.81	36227.9	20267.5	5910.11	24462.2	15562.9	4548	17131.3	11537.1	3411.2	11413.7	8162.3	2462.62	7047.94	5314.04	1671.09	3842.816	3018.99
104068	25506.9	67270.5	27376.5	15847.8	56963.5	25758.3	14640.5	56575.2	25556	14171.3	53994.2	24954.4	8384.81	33262.2	17534.8	5910.11	22788.8	12917.6	4548	15792.9	9231.85	3411.2	10396	6429.85	2462.62	6330.92	4264.91	1671.09	3403.565	2549.06
932785	25506.9	76057.5	71250.9	15847.8	65325.7	67910.6	14640.5	63984.3	67493.1	14171.3	62137.3	62421	8384.81	41673.8	43394	5910.11	27633.3	27681.1	4548	18456.6	280.4	3411.2	11021.2	14604.7	2462.62	6575.68	8342	1671.09	3563.584	5157.13
829142	25506.9	76399.2	72396.1	15847.8	65650.4	69001.5	14640.5	64306.8	68577.3	14171.3	64253.4	67304.8	8384.81	39595	51611	5910.11	27900.5	41169.3	4548	19378.9	31265.9	3411.2	12941.8	12250.3	2462.62	7859.96	14440.5	1671.09	4240.11	8133.87
739890	25506.9	80021.9	60933.2	15847.8	69131.1	58108	14640.5	67769.7	57747.3	14171.3	65868.5	56665.8	8384.81	42285.9	43327.4	5910.11	28789.9	34455.1	4548	21056	26051.6	3411.2	14035.8	18436.1	2462.62	8536.27	11901	1671.09	4682.652	6692.18
551879	25506.9	79285	49866.7	15847.8	68445	47617.5	14640.5	67090	47321.4	14171.3	65199.4	46433.3	8384.81	41881.5	34281.1	5910.11	28944.6	28201.7	4548	20916.4	21310.7	3411.2	13942.1	15064.9	2462.62	8557.3	9714.91	1671.09	4617.85	5454.04
349342	25506.9	77573.6	47778.8	15847.8	66838.2	45562.9	14640.5	64596.3	45285.9	14171.3	63644.9	44455.7	8384.81	40810.7	34217.1	5910.11	28684.7	27445.6	4548	20485.5	21057.9	3411.2	13684.7	15167.8	2462.62	8432.71	9948.9	1671.09	4564.835	5662.29
189144	25506.9	74374.1	38085.7	15847.8	63790.3	36205	14640.5	62467.3	35969.9	14171.3	60675.6	35264.9	8384.81	38577.8	26570.4	5910.11	27162.2	20914.2	4548	19207	15824	3411.2	12881.4	11340.8	2462.62	7973.13	7451.68	1671.09	4338.42	4268.31
87936.6	25506.9	71737.2	34454.2	15847.8	61247.8	32612.9	14640.5	59363.6	32382.7	14171.3	58185.8	31694.3	8384.81	36592.5	23204.8	5910.11	25765.7	17782.8	4548	17948.1	13121	3411.2	11982.8	9218.05	2462.62	7407.58	5958.39	1671.09	4039.895	3362.71
52034.2	25506.9	69006	32879.4	15847.8	58622	30968.5	14640.5	57324.1	30729.7	14171.3	56411.1	27633.3	8384.81	34526	21244.5	5910.11	23181.4	15755.2	4548	16576.7	11039.1	3411.2	10947.3	7837.57	2462.62	6677.93	5125.27	1671.09	3592.268	3004.48
443223	25506.9	70181.8	48655.5	15847.8	59709.5	46302.8	14640.5	58400.5	46008.5	14171.3	56565.9	45126.3	8384.81	35129.9	34246.7	5910.11	24619.8	27040.3	4548	16712.7	20296.2	3411.2	12021	14621.7	2462.62	6530.44	9117.86	1671.09	3584.024	5030.64
832785	25506.9	76057.5	71250.9	15847.8	65325.7	67910.6	14640.5	63984.3	67493.1	14171.3	62137.3	62421	8384.81	41673.8	43394	5910.11	27633.3	27681.1	4548	18456.6	280.4	3411.2	11021.2	14604.7	2462.62	6575.68	8342	1671.09	3563.584	5157.13
832478	25506.9	75567.5	57312.1	15847.8	66688.7	56905.7	14640.5	67330.2	56562.4	14171.3	64247.5	55493	8384.81	41960.4	42426.8	5910.11	29531.1	33736.6	4548	20865.5	25506.4	3411.2	13802.4	18049.3	2462.62	8550.49	11549.1	1671.09	4634.327	5547.94
620864	25506.9	78824.8	48633.1	15847.8	68007	46327.3	14640.5	66554.7	46039.1	14171.3	64772.4	45174.8	8384.81	41557.1	34514.9	5910.11	29387.6	27430.2	4548	20721	20719.8	3411.2	13802.1	1637.6	2462.62	8465.53	9431.62	1671.09	4564.399	5290.21
393010	25506.9	77110	46991.1	15847.8	66397.1	44815.1	14640.5	65058	44543.1	14171.3	63215	43727.9	8384.81	40484.5	33673.9	5910.11	28637.5	27022.6	4548	20523.3	20742.3	3411.2	13545.2	14944.2	2462.62	8340.73	9801.82	1671.09	4511.701	5578.19
212787	25506.9	74016.7	37562.3	15847.8	63449.9	35712.2	14640.5	62129.1	35481	14171.3	60343.8	34787.5	8384.81	38324.9	26234.8	5910.11	26962.4	20670.7	4548	19058.1	15560.7	3411.2	12778	11240.8	2462.62	7907.72	7377.76	1671.09	4302.434	4243.77
98928.6	25506.9	71356.3	33610.9	15847.8	60884.8	31815.8	14640.5	59575.9	31591.4	14171.3	57831.8	30920.4	8384.81	36321.9	22644.3	5910.11	25319.5	17361.8	4548	17788.4	12824.4	3411.2	11872	9023.26	2462.62	7337.42	5840.24	1671.09	4001.328	3298.91
58538.4	25506.9	68691.8	31893	15847.8	58321.7	30025.2	14640.5	57025.5	29792.9	14171.3	55320.9	29101.3	8384.81	34297.2	20527.7	5910.11	23628	15214.4	4548	16434.7	10926.6	3411.2	10847.5	7582.67	2462.62	6615.1	4969.48	1671.09		

NW25.CSB

No. of load cases	position 1			position 2			position 3			position 4			position 5			position 6			position 7			position 8			position 9			position 10		
	Fz1	Mx1	My1	Fz2	Mx2	My2	Fz3	Mx3	My3	Fz4	Mx4	My4	Fz5	Mx5	My5	Fz6	Mx6	My6	Fz7	Mx7	My7	Fz8	Mx8	My8	Fz9	Mx9	My9	Fz10	Mx10	My10
19030700	25506.9	65879	25490	15847.8	55675.9	24284.7	14640.5	54400.5	24134	14171.3	52751.6	23682.3	8384.81	32414.4	18111.7	5910.11	22176.4	14455	4548	15361	11082.1	3411.2	10106.7	8031.95	2462.62	6151.96	5330.1	1671.09	3302.689	3077.73
8847730	25506.9	65110.5	22191.3	15847.8	54913.8	21087.6	14640.5	53639.2	20949.8	14171.3	51998.2	20537.9	8384.81	31758.8	15459.8	5910.11	21601.3	12172.5	4548	14885.5	9216.78	3411.2	9749.61	6608.52	2462.62	5927.46	4341.65	1671.09	3190.548	2487.08
5235420	25506.9	63950.3	19275.4	15847.8	53787.3	18256.8	14640.5	52516.9	18129.5	14171.3	50889.9	17752.7	8384.81	30823.4	13105.7	5910.11	20786.1	10170.2	4548	14194.7	7671.27	3411.2	9187.08	5578.27	2462.62	5494.79	3813.75	1671.09	2904.251	2325.73
32140000	25506.9	59706.5	5690.79	15847.8	49853.4	5347.47	14640.4	48621.8	5304.55	14171.3	47119.5	5175.81	8384.8	28591.8	3587.95	5910.11	19372	2585.02	4548	13320.3	1734.06	3411.19	8678.66	1073.03	2462.62	5227.33	617.277	1671.09	2779.757	336.039
2316000	25506.9	63525.1	53595.1	15847.8	53830.3	60900.8	14640.4	52618.5	50564	14171.3	51081.6	49553.7	8384.8	32126.6	37092.7	5910.11	22435.3	29044.8	4548	15775.3	21711.9	3411.19	10506.1	15246	2462.62	6459.84	9808.7	1671.09	3500.656	5519.9
377000	25506.9	61052.4	114455	15847.8	51111.4	107708	14640.4	49868.8	106895	14171.3	48333.6	104432	8384.8	29399.3	74427.8	5910.11	19930.8	55948.7	4548	13679.1	40146.9	3411.2	8886.97	27201.4	2462.62	5331.87	16936.1	1671.09	2821.354	9253.01
120000	25506.9	67994.5	3948.66	15847.8	58478.5	3722.54	14640.5	57289	3694.27	14171.3	55619.4	3609.47	8384.8	35027.9	2563.66	5910.11	24274.8	1913.61	4548	16779.1	1364.49	3411.2	10972.6	915.34	2462.62	6619.89	563.233	1671.09	3518.733	303.86
1	25506.9	59611.6	167440	15847.8	49764.7	157338	14640.4	48533.8	158075	14171.3	47033.9	152384	8384.8	28534.6	105862	5910.11	19332.6	78960.1	4548	13295.5	55878.1	3411.2	8664.4	37280.7	2462.62	5219.57	22867.5	1671.09	2775.515	12318.5
1	69888	60841	145759	61484.8	50913.7	137721	60434.4	49672.8	136717	59494.6	48284.3	133800	47904	31159.2	97823.8	41557	22195.7	75177.8	35789.3	15782.4	55412.8	29591.8	10592.3	23265	6540.82	24644.9	17020.3	3547.527	13830.9	
1	69888	66943	135188	61484.8	67397	128160	60434.4	56203.8	127282	59494.6	54597.9	124744	47904	34791.9	93440.2	41557	24410.9	73358.6	35789.3	17325.2	55181.9	29591.8	11760.1	39093.2	23265	7349.56	25427.7	17020.3	4030.65	14494.2
1	35440.3	115838	31263.2	24976.3	101477	29085.9	24723.6	100474	28848.8	23965.6	97465.5	28137.8	14616.9	60362.8	19367.7	11752.4	43666.4	14216.2	9299.88	30336.7	9993.71	7161.3	19913.9	6625.52	5277.78	12037.8	4039.03	3629.7	6397.784	2160.22
1	69888	103533	82814.2	61484.8	93941.5	78554.5	60434.4	92742.6	78022	69494.6	90498.5	76521.9	47904	62821.6	58020.1	41557	46914.1	46105	35789.3	34139.5	35182.4	29591.8	23424.7	25323.7	23265	14780.4	16745.7	17020.3	8190.652	9697.57
500	25506.9	59611.6	13234.5	15847.8	49764.7	12607.2	14640.4	48533.8	12528.8	14171.3	47033.9	12293.5	8384.8	28534.6	9392.14	5910.11	19332.6	7536.61	4548	13295.5	5829.74	3411.19	8664.4	4256.93	2462.62	5221.6	2840.89	1671.09	2790.477	1642.67
500	25506.9	120609	11852	15847.8	110490	11220	14640.5	109226	11141	14171.3	106523	10904	8384.8	73196.2	7981.12	5910.11	53251.4	6083.59	4548	37249.7	4406.35	3411.2	24592.6	3003.21	2462.62	14935	1876.91	1671.09	7968.041	1026.96
20	25506.9	75214.8	107461	15847.8	65846.6	101730	14640.4	64675.6	101014	14171.3	62800.7	98864.6	8384.8	39677	72359.2	5910.11	27100.9	55166.3	4548	18171.4	39996.6	3411.2	11534.1	27315.9	2462.62	6758.71	17125.3	1671.09	3493.467	9409.94

Appendix B

Equivalent-Damage Spreadsheets

Vbf_1_4 = 1.35 design load factor sections 1 to 4

Vmf = 1.50

UTS_str = 372.0 strength laminate ultimate tensile

UCS_str = 260.0 strength laminate ultimate compressive

Vbf_5_10 = 1.5 design load factor sections 5 to 10

UTS_t_n = 87.0 tail/nose ultimate tensile

UCS_t_n = 76.0 tail/nose ultimate compressive

Design Material Factors

C1 = 1.25

C2 = 1.00

C3 = 1.20

m = 10

Test Material Factors

C1a = 1.00

C2a = 1.00

C3a = 1.20

Test Load Factors $\gamma_{ef} = 1.05$ $\gamma_{sf} = 1.1$ $\gamma_{wp} = 1.04$

		Sum n
NW25csb	Range	4.28E+08
NW25cmb	Maximum	4.28E+08

DEL (Damage Equivalent Loads)									
			kMx = strain/N-m		kMy = strain/N-m				
	kFx	Sum n/N		kMx	Sum n/N		kMy	Sum n/N	
Fx1	1.1448E-03	9.99E-01	Mx1	1.5964E-04	1.00E+00	My1	6.8404E-04	1.00E+00	
Fx2	1.3881E-03	1.00E+00	Mx2	1.8829E-04	1.00E+00	My2	7.2479E-04	1.00E+00	
Fx3	1.4192E-03	1.00E+00	Mx3	1.9255E-04	1.00E+00	My3	7.3016E-04	9.99E-01	
Fx4	1.4448E-03	1.00E+00	Mx4	1.9849E-04	1.00E+00	My4	7.4634E-04	9.99E-01	
Fx5	1.6653E-03	1.00E+00	Mx5	2.8695E-04	1.00E+00	My5	9.1855E-04	1.00E+00	
Fx6	1.9558E-03	1.00E+00	Mx6	4.1330E-04	1.00E+00	My6	1.1839E-03	1.00E+00	
Fx7	2.2991E-03	1.00E+00	Mx7	5.9108E-04	1.00E+00	My7	1.5830E-03	1.00E+00	
Fx8	2.8076E-03	1.00E+00	Mx8	8.9084E-04	1.00E+00	My8	2.2394E-03	1.00E+00	
Fx9	3.5990E-03	1.00E+00	Mx9	1.4521E-03	1.00E+00	My9	3.4529E-03	1.00E+00	
Fx10	4.9510E-03	1.00E+00	Mx10	2.6844E-03	1.00E+00	My10	6.1043E-03	1.00E+00	

Define Test Fatigue Load

N = 3.00E+06 test cycles

radial and flap loads (Fx, My strength laminate)

damage = 1.00

Sm_str = 48.2 Assume mean stress

Sa_str = 58.9 test alternating stress from S/N curve

R = -0.10 test ratio of min/max

Smax_str = 128.7 test max stress

Smin_str = -12.9 test min stress

edge loads (Mx tail/nose laminate)

damage = 1.00

Sm_t_n = 11.3

Sa_t_n = 13.8

R = -0.10

Smax_t_n = 30.1

Smin_t_n = -3.0

*optimum R ratio
for combined*

TEST LOADS

FXmax (Nm)		FXmin (Nm)	MXmax (Nm)		MXmin (Nm)	MYmax (Nm)		MYmin (Nm)	Radius(m)
Fx1	112400.9	-11238.4	Mx1	188513.3	-18855.2	My1	188114.6	-18808.6	0.2
Fx2	92703.4	-9268.9	Mx2	159827.9	-15986.1	My2	177538.3	-17751.1	0.6
Fx3	90668.4	-9065.5	Mx3	156288.1	-15632.1	My3	176232.6	-17620.6	0.65
Fx4	89061.0	-8904.7	Mx4	151615.4	-15164.7	My4	172411.7	-17238.5	0.8
Fx5	77270.1	-7725.8	Mx5	104873.6	-10489.5	My5	140087.8	-14006.6	2.65
Fx6	65792.8	-6578.3	Mx6	72813.3	-7282.8	My6	108686.2	-10867.0	3.9
Fx7	55969.3	-5596.1	Mx7	50912.4	-5092.3	My7	81288.2	-8127.6	5.15
Fx8	45832.0	-4582.5	Mx8	33781.0	-3378.8	My8	57462.2	-5745.3	6.4
Fx9	35753.4	-3574.8	Mx9	20723.7	-2072.8	My9	37266.3	-3726.1	7.65
Fx10	25990.3	-2598.6	Mx10	11210.4	-1121.3	My10	21079.8	-2107.7	8.9

Extreme Load - Load Case 93 x 1.5

	R	Flap-Extr.	Load (N)
My1	0.2	247554.0	33,229
	7.65	0	

Extreme Load - Load Case 97 x 1.5

	R	Edge-Extr.	Load (N)
Mx1	0.2	154298.0	20711
	7.65	0	

Test Load

match Mx4max and My5max

	R	Flap-Ult	Load (N)
My1	0.2	197290.4	23,348
	8.65	0	

	R	Edge-Ult	Load (N)
Mx1	0.2	163203.9	19,314
	8.65	0	

Appendix C

Edgewise Static Data

Figure C.2.1. Displacement at Tip, Edge Static Test, Blade #66, Pre-Fatigue

Figure C.2.3. Displacement at Tip, Edge Static Test, Blade #67, Pre-Fatigue

Figure C.2.2. Displacement at Tip, Edge Static Test, Blade #66, Post-Fatigue

Blade #67 tip removed for fatigue test

Figure C.5.1. 17S38UA (1500S1), Edge Static Test, Blade #66, Pre-Fatigue

Figure C.5.3. 17S38UA (1500S1), Edge Static Test, Blade #67, Pre-Fatigue

Figure C.5.2. 17S38UA (1500S1), Edge Static Test, Blade #66, Post-Fatigue

Figure C.5.4. 17S38UA (1500S1), Edge Static Test, Blade #67, Post-Fatigue

Figure C.7.1. 17R62UA (1500S0), Edge Static Test, Blade #66, Pre-Fatigue

Figure C.7.3. 17R62UA (1500S0), Edge Static Test, Blade #67, Pre-Fatigue

Figure C.7.2. 17R62UA (1500S0), Edge Static Test, Blade #66, Post-Fatigue

Figure C.7.4. 17R62UA (1500S0), Edge Static Test, Blade #67, Post-Fatigue

Blade #67 gauge failed

Figure C.23.1. 25R45UC (2500S90), Edge Static Test, Blade #66, Pre-Fatigue

Figure C.23.3. 25R45UC (2500S90), Edge Static Test, Blade #67, Pre-Fatigue

Figure C.23.2. 25R45UC (2500S90), Edge Static Test, Blade #66, Post-Fatigue

Figure C.23.4. 25R45UC (2500S90), Edge Static Test, Blade #67, Post-Fatigue

Figure C.24.1. 25R45LC (2500P90), Edge Static Test, Blade #66, Pre-Fatigue

Figure C.24.3. 25R45LC (2500P90), Edge Static Test, Blade #67, Pre-Fatigue

Figure C.24.2. 25R45LC (2500P90), Edge Static Test, Blade #66, Post-Fatigue

Figure C.24.4. 25R45LC (2500P90), Edge Static Test, Blade #67, Post-Fatigue

Figure C.28.1. 31S20LA, Edge Static Test, Blade #66, Pre-Fatigue

Figure C.28.3. 31S20LA, Edge Static Test, Blade #67, Pre-Fatigue

Figure C.28.2. 31S20LA, Edge Static Test, Blade #66, Post-Fatigue

Figure C.28.4. 31S20LA, Edge Static Test, Blade #67, Post-Fatigue

Blade #67 gauge failed

Figure C.33.1. 41S40UA, Edge Static Test, Blade #66, Pre-Fatigue

Figure C.33.3. 41S40UA, Edge Static Test, Blade #67, Pre-Fatigue

Figure C.33.2. 41S40UA, Edge Static Test, Blade #66, Post-Fatigue

Figure C.33.4. 41S40UA, Edge Static Test, Blade #67, Post-Fatigue

Appendix D

Flapwise Static Data

Figure D.2.1. Displacement at Tip, Flap Static Test, Blade #66, Pre-Fatigue

Figure D.2.3. Displacement at Tip, Flap Static Test, Blade #67, Pre-Fatigue

Figure D.2.2. Displacement at Tip, Flap Static Test, Blade #66, Post-Fatigue

Blade #67 tip removed for fatigue test

Blade #67 Gauge Failed

Figure D.21.1. 25R45LB (2500P45), Flap Static Test, Blade #66, Pre-Fatigue

Figure D.21.3. 25R45LB (2500P45), Flap Static Test, Blade #67, Pre-Fatigue

Figure D.21.2. 25R45LB (2500P45), Flap Static Test, Blade #66, Post-Fatigue

Figure D.21.4. 25R45LB (2500P45), Flap Static Test, Blade #67, Post-Fatigue

Blade #67 Gauge Failed

Blade #67 Gauge Failed

Appendix E

Fatigue Data

Figure E.1. Flap Load @ 8.65 m, Blade #66
Two-Axis Fatigue Test

Figure E.2. Flap LVDT @ 8.65 m, Blade #66
Two-Axis Fatigue Test

Figure E.3. Edge Load @ 8.65 m, Blade #66
Two-Axis Fatigue Test

Figure E.4. Edge LVDT @ 8.65 m, Blade #66
Two-Axis Fatigue Test

Figure E.5. Actuator Load @ 8.65 m, Blade #67
Single-Axis Fatigue Test

Figure E.6. Actuator LVDT @ 8.65 m, Blade #67
Single-Axis Fatigue Test

Figure E.7.1. 08BLDLG (400E1/2) Blade #66
Two-Axis Fatigue Test

Figure E.7.2. 08BLDLG (400E1/2) Blade #67
Single-Axis Fatigue Test

Gauge not measured during Blade #67 test.

Gauge not measured during Blade #67 test.

Gauge not measured during Blade #67 test.

Gauge not measured during Blade #67 test.

Appendix F

Correspondence

SMT [21] Pre-load in bolts

Jeroen 8

SMT [98] CRES strain-gauge locations

SMT [100] Nomenclature for common gauges

SMT [25] Radial position, pull direction, etc.

SMT [47] Data sets

Larwood, Scott

From: Jeroen van Dam [vandam@ecn.nl]
ant: Tuesday, May 26, 1998 7:19 AM
To: smt-2-l@ecn.nl
Subject: [21] pre-load in bolts

NedWind provided the following data:

The torque they use is 800 Nm giving a preload of 220kN for the M24 10.9 bolts.

Thus a preload of 220 kN has to be used by all laboratories for the bolts connecting the blade flange to the test rig.

Jeroen van Dam

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Direct line: +31 224 564277
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Our ref. : JvD/mb 98-471/7.4262.01.02.20
Subject : Jeroen 8 revision 2

Petten, 18 May 1998

Dear colleagues,

I herewith send you a copy of the Jeroen 8 document revision 2.

Yours sincerely,

bla MBrake (secr.)

Jeroen van Dam
ECN Solar & Wind Energy
Experiments & Assessment

Encl.

Working document of the EWTPD project
Subtask 2: Blade Test Methods and Techniques

"Jeroen8"

Jeroen van Dam
ECN, Petten
15 May 1998

JEROEN8.SMT
Revision: 2

Replaces: "Handout for the third meeting of the EWTPD project" dd March 18, 1998

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TESTS TO BE PERFORMED WITHIN THE EWTPD-PROJECT, SUBTASK 2	3
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BLADE NUMBERS.....	8
EXPLANATION OF TERMS IN DESIGN DOCUMENTATION	9

Tests to be performed within the EWTTPD-project, Subtask 2

Used information:

- European Wind Turbine Testing Procedure Developments, Annex I: project Programme
- Minutes of the second subtask 2 meeting
- "Eigenfrequentie metingen aan een NW-25 Rotorblad bij Nedwind te Heerhugowaard d.d. 23 oktober 1992"
- "Technische notitie bladtest NW25", T. Dobbe, 20-11-92

The last two documents describe eigenfrequency measurements and the derivation of the loads used for a blade bending test. The documents are both written in Dutch. During the blade bending tests deflections were only measured at the load application point and at the tip.

Mass

The mass of the blade has to be determined, a rough indication of the mass distribution is obtained by measuring the centre of gravity.

Eigenfrequencies

Five eigenfrequencies have to be measured:

The first two bending frequencies in the directions perpendicular and parallel to the tip chord.

The first torsional eigenfrequency.

From the test report :

- First torsional eigen-frequency: 37.5 Hz

Damping

Besides the eigenfrequencies also damping has to be measured. This has to be done for different tip deflections to distinguish the aerodynamic and structural damping. Since structural damping is dependent of temperature the eigenfrequencies will be determined at two temperature levels.

The damping is defined as:

$$\zeta = \frac{1}{2\pi n} \ln \frac{x_1}{x_{n+1}}$$

Strain distribution

Rotorline has performed a static test in 1992. The blade was loaded in flapwise and lead-legwise direction separately. The maximum flapwise bending moment came from loadcase 93. To apply the maximum bending moment Rotorline has applied a test load of 23000 N at 7m meter from the blade flange. The edgewise bending test was performed with a load of 7150 N at seven meters from the blade root. The maximum edgewise bending moment came from loadcase 97, but this value has not been used.

From the test report:

Calculated deflections when loads are applied at 7 meter from the blade flange:

load [N]	load direction	displacement at 7 [m]	tip displacement
23000	flap	150 mm	382 mm
7150	lead lag	20 mm	45 mm

As agreed upon during the third meeting the loading of the blade should go up to 75% of the limit load. The flap wise and lead-leg loads shall be applied seperately.

From the maximum loads in the file NW25.cmb bending moment distribution lines have been constructed. These deviate from the lines used by Rotorline. Keeping the load application point the same as for the Rotorline test (thus 7.65 meter from the rotorcentre), the test load giving the same bending moment at the blade flange can be calculated. Multiplying this with a load factor of 1.5 for the limit load and 0.75 for the 75% level gives the following loads:

14809 N in lead leg direction

24723 N in flapwise direction

The bending moment distribution of the most severe load cases are given in Figure 1 and 2. The test load is also depicted in these graphs.

Figure 1: Flapwise bending moment distribution for the most severe load cases and the test load.

Figure 2: Lead-leg bending moment distribution for the most severe load cases and the test load.

At least the deflection of the tip and the load application point should be recorded.

The most critical section for buckling during the test is the tail between $R=2.65$ and $R=3.15$ meter from the blade root.

Static test

For the static test no special procedures are prescribed.

Fatigue test

For the fatigue test no special procedures have to be prescribed. Business as usual is the starting point.

Post mortum

For the post mortum tests it should be known which areas are of interest for investigation. At least the laminate thickness of the root section should be checked. Other areas of interest are expected to follow from the strain distribution test, static test and fatigue test.

Strain gage markings made on the blade

The blades have been marked with the lines as depicted in Figure 3. These lines are drawn on both sides of the blade. The lines at 1000, 1500, 2000 and 2500 mm from the blade flange are perpendicular to the pitch axis. From the pitch-line intersection lines are applied with a distance of 200 mm.

Figure 3: Blade markings

Common strain gages

Instead of prescribing what type of strain gages should be placed at which position, for a limited number of places on the blade the sort of information to be measured is prescribed. In this way every partner is free to use the type of strain gage and bridge configuration which is preferred by the laboratory.

All locations at both sides of the blade.

1. The bending moment parallel and perpendicular to the blade tip should be measured at 400 mm from the blade flange. Markers are placed on the blade giving these locations.
2. At the cross-sections 1500mm and 2500 mm from the flange on both sides of the blade:
 - A rosette should be placed at 2500mm from the blade flange at 80 mm from the beam towards the tail. At least the strain in direction of the pitch axis should be measured.
 - The strain parallel to the pitch axis should be measured 190 mm from the beam towards the nose

All together this comes to a total of 20 strain gages.

Figure 4: Locations of common strain gages (dimensions in mm).

Suggestion for the table of contents for the measurement reports.

Each test laboratory

- Objective
- Test plan
 - Test rig
 - Test plan
 - Measurement plan
- Blade property tests:
 - Mass distribution
 - Test method
 - Test equipment
 - Results (mass, center of gravity)
 - Eigenfrequencies
 - Test method
 - Test equipment
 - Results (frequencies, damping)
 - Strain distribution:
 - Test loads
 - Test equipment
 - Results (loads, deflections, strains)
- Fatigue test:
 - Test loads (how derived, which areas are tested)
 - Test equipment
 - Results (loads, deflections, strains, damage)
- Static test
- Post Mortum test
- Conclusions

Final report

- Objectives
- Description of blade
- Description of design loads
- Abstract of main characteristics / results of separate tests
- Comparison of: test loads, test result,....
- Recommendations

Blade numbers

Setnr. /Bladenr.	Laboratory
22 / 65	ECN p/a TU Delft
22 / 66	NREL, USA
22 / 67	NREL, USA
24 / 71	CRES, Greece
24 / 72	CRES, Greece
24 / 73	TU Delft
27 / 81	Risø, Denmark

The blade properties of each blade, like mass, centre of gravity and balance mass as determined by Rotorline can be found on the three pages included.

setnummer	set number
Balanceergegevens	balancing data
Prod nr.	Production number
blad nr.	blade number within the set
The mass of the blade and centre of gravity were determined by weighing with two loadcells, one at the flange and one at L=9.5 meter.	
F1 flens (kg)	mass measured at the flange
F2 L= 9.5 (kg)	mass measured at L=9.5
F totaal	the total weighth
stat mom (kgm)	statical moment
Zp (m)	centre of gravity in meters from flange

The last four columns are of the balanced blade.

corr. stat. mom.	the statical moment after balancing
balanceer massa(kg) max 9.5	balancing mass, this mass may maximally be 9.5 kg
One blade in the set does not get extra mass this is indicated with:"geen balan. massa"	
corr. Zp (m)	the centre of gravity after balancing
Eind massa	blade mass plus balancing mass

Geometrische gegevens geometrical data

Columns:

1. "L=": gives a radial position in meters.
2. "gemeten": gives a measured value in mm from which the local angle is calculated.
3. "wrongafw.": the difference between the theoretical angle and the actual angle.
4. "nominaal": gives the theoretical angle.
5. "werkelijk": gives the measured angle.
6. Indicates whether or not the measured difference is within the limits.

Grootste wrongvershil in rotorset:

Per radial position the largest deviation between the measured angles in a rotorblade set is given. This difference may maximally be 0.5°

Geometrie-overzicht: this is a plot with the measured local twist angles for the three blades

Location of balance weighth:

Explanation of terms in design documentation

Jeroen5: "Laminaatopbouw Nedwind 25m/250"

80 in cilindrische deel	80 in the cylindrical part
achterkast	part between the beam and the trailing edge
detail	detail
doorsnede	cross-section
glasbreedte	glasswidth
idem	the same
"inklemming" sterktebaan met afstroomzijde	clamping of the strength layer by the trailing edge
	laminate
laag	layer
malrand	edge of the mould
nominaal	nominal
schaal	scale
staart laminaat	tail laminate
tiplaminaat	tip laminate
tot 15 in de tip	till 15 in the tip
type glas	type of glass
versch.	decrease
verscherving	decrease
Verscherving sterktebaan complex (schematisch excl. "inklemming" neus en staartlaminaat), decrease of laminate of the complex strengthlayers (schematic, meaning excluding the overlap of nose and tail laminate)	
Verschuivingsrichting staartlaminaat	shift direction of the tail laminate
vullaminaat	fill laminate

Jeroen6: "Glasoverzicht", J.M.P. Leeuwenberg, 20-04-93

aan	the layer is located in the leading edge
aanstroomzijde	leading edge
achterk.	rear section
af	the layer is located in the trailing edge
afstroomzijde	trailing edge
afdeklaminaat	cover laminate
anti krimpstroken	anti shrink layers
bladwortel	blade root
breed mm	width [mm]
Complex	layer existing of three layers: 100gr mat, 2*150gr +/-45° and 1134gr 0° UD.
csm	chopped strands mats.
drukzijde	pressure side
einde comp.	?
flens	flange
geknipt dd	cut on date
gelam. dd / gelamin. dd	laminated on date
Glasoverzicht	overview of used glass layers
glastype	glass type
hijspuntversterking	hoist point reinforcement
impregnator	This layer is put in the mould by a crane to position the fiber direction carefully.

indien geen prefab-paneel	in case of no prefab panel
kopse kanten	head/front side
laagnummer	layer number
laminaatopbouw	laminate structure
lang mm	length [mm]
legsel	similar to rov+/-45°(702) in "Bernard1". It consists of one 100 grams mat, 301 grams +45° and 301 grams -45°
lijmhoeken	glueing angles
neus	nose
opmerking	remark
positie	position
registratielijst	registration list
sjabloon	model
sterktebaan	strength laminate
stroken	?
tip	tip
trekzijde	tensile side
uit snijlijn	from secant ?
vanaf	from
verlijming	bonding
vullaminaat	"fill laminate"
wissel rol	change role
zelfkant	

In the column "glastype" the number mentioned before the "/" is the amount of grams per square meter.

page 10:

- 1) layer 1 mat 225/10 is only applied there where the gelcoat has also been applied. Thus not on the bonding areas
- 2) layer 12&14 are in the tip on the trailing edge 500 mm from the cutting edge to prevent too large a thickness.
- 4) Put the the fill laminate in the blade root until a smooth surface is formed. It may be adjusted in width
- 5) If in this column the remark 2X is made the layer has to be applied twice and it is laminated as mat 450/45° on the foam panel. The layers connect per set of 4 with a distance of 100 mm.

Bernard1: "Strength calculations of the NW25 rotorblade design"

Page A1

Blad lengte	blade length
kegelhoek	cone angle
tilthoek	tilt angle
geprojecteerd oppervlak	projected surface (per blade)
bladmateriaal	blade material
gewicht van een compleet rotorblad	weight of a complete rotorblade
ligging van zwaartepunt tov bladwortel	centre of gravity with respect to the blade root

Page A2

koorde verloop (lineair)	chord distribution (linear)
smalste koorde (excl. afr)	smallest chord (excl. curving)
breedte	chord length
radiale positie	radial position

profiel dikte
 wrong verloop
 totale twist hoek
 bladvoet
 wanddikte
 bevestiging
 bouten
 aantal
 steekcirkel
 aerodynamisch profiel serie(s)

profile thickness
 twist distribution
 tip twist angle
 blade root
 wallthickness
 connection
 bolts
 number
 pitch diameter
 aerodynamic profile series

Page A8: huidlaminaat
 Page A9: bevestigingsbouten
 Page A33: Massa verdeling
 Page 35: lijntraagheid

skin laminate
 connection bolts
 mass distribution
 products of inertia

Page A37 through A54

Gives a copy of the first volume of the design report of the bladeroot. Below a very brief summary is given of some parts of the report. The bladeroot calculations have been performed by Polymarin. Some additional figures and tables are included which is not included in the "Bernard1" report.

1. General:

Contains no information of importance to the project

2. Structure

Here it is described how the blade root is constructed: A pin/hole joint clamped between two steel flanges. The outer flange segmented in three parts.

3. Geometry

Here some geometrical factors are calculated:

width/diameter, edge/diameter and side/diameter. The ' means that the 21 bolts of the pin/hole connection have been considered instead of the 24 in the blade hub connection.

4. Materials and material properties

4.1 Materials

Flanges are made of nodular cast steel GGG40.3

The laminate in the root is glassfiber reinforced polyester consisting of 40% +/-45°, 50% UD fibers and 10% randomly oriented fibers.

The bolts are quality 8.8 made of 42CrMo4

4.2 material properties

4.2.1 GGG40.3 according to DIN 1693

For extremes: sigma allowable: 166 MPa. Fatigue strength is taken from Roloff/Matek giving a stress interval of 258MPa at a mean stress of 63 MPa with a survival probability of 90%. Assuming a normal distribution, the correction factor for 97.5% is 0.85.

4.2.2. GVP

Two UTS's are given one based on a research project on fatigue: 240 MPa and one based on data from NedWind giving a value of 346 MPa for statical loads and 189 MPa for dynamical loads.

4.2.3 Bolts

The bolt quality 8.8 gives $\sigma_{0.2} = 640$ MPa and a tensile stress of 800 MPa. The calculation value for extremes is 426MPa. For the calculation value for fatigue values have been taken from Roloff/Matek.

5. Loads

No extra information

6. Calculation method

First stress in the laminate is calculated. Multiplying with $(w/d)'$ gives the average plain stress in the laminate near the bolts.

The force will go partly to the flanges by friction through the bolts. For the load distribution a FEM-calculation is made.

The stresses in the steel flanges have been calculated by multiplying the stresses with (w/d) for the undisturbed cross section and $(w/(w-d))'f_c$ for the material between the bolts. Also a stress concentration for the curvature near the hub/blade connection is calculated. In case this stress concentration factor (f_{sp}) is larger than the $(w/(w-d))'f_c$ this is the most critical location.

7. Load transfer by friction

A friction coefficient of 0.12 is assumed. With a pre-stress of 15MPa this gives a stress reduction for the GVP of 17.5 MPa and 14.5 MPa for the GGG.

8. Dimensioning

8.1 GVP

The stress in the laminate has been calculated with a program called MEP. The averaged plain stress just above the hole of the bolts is critical. This stress has been derived by multiplying the stress in the laminate with $(w/d)'$ and decreasing it with the 17.5MPa for friction.

8.1.1. Fatigue damage

The fatigue damage has been calculated in two ways:

- 1) using UTS = 240 MPa and the fatigue formulation: $S = UTS - B \cdot \log N$ giving a damage of 0.64
- 2) using UTS and UCS of 189 MPa and using the Goodman relation, giving a damage of 0.51

8.1.2 Static calculation

The maximum stress is caused by load case 93 giving a stress of 82.1 MPa.

8.2 GGG

For the calculations it has been assumed that the outer flange carries maximally 76% of the loads and the inner flange carries maximally 50% of the loads.

8.2.1. Fatigue calculations

8.2.1.1 Material between the bolts

For the inner flange: $(w/(w-d))'f_c = 4.36$ and f_{sp} is 4.08

For the outer flange: $(w/(w-d))'f_c = 4.05$ and f_{sp} is 4.08

The fatigue calculations have been performed according to NEN 2063 which is standard for welding. This standard uses the S-n curve given in figure 2. $\Delta\sigma_k$ is taken from the Smith diagram in figure 3, which is for $N=1 \cdot 10^6$ cycles. $\Delta\sigma_k$ is calculated to be 101 MPa. This gives a damage of 0.015 for the outer flange and 0.085 for the inner flange.

The maximum stress range in the outer flange is 105 MPa and in the inner flange 116 MPa both caused by load case 77.

8.2.1.2 Material above the bolts.

Maximum stress in the outer flange : 79MPa ; maximum stress in the inner flange 66 MPa both caused by load case 72.

8.2.2. Static calculations

8.2.2.1 Material between the bolts (table 8)

Outerflange: 112 MPa; inner flange 126 MPa both caused by load case 93.

8.2.2.2. Material above the bolts (table 7)

outer flange: 90 MPa; inner flange 78 MPa due to load case 93.

8.3 bolts

Here the stresses in the bolts have been calculated showing that the bolts are strong enough.

Figuur 1. Wrijvingsoppervlak pasboutverbinding.
Friction surface glass/steel bolt connection

Figuur 2. $\Delta\sigma$ -N lijn

	F_{ax}	M_{top}	M_{edge}	no cycles
Belastinggeval	F_c [N]	M_{klap} [Nmm]	M_{zwaai} [Nmm]	n [-]
1 min	0.76E+05	0.20E+08	-0.40E+08	0.37E+07
1 max	0.98E+05	0.64E+08	0.45E+08	0.37E+07
2 min	0.76E+05	0.27E+08	-0.38E+08	0.41E+07
2 max	0.98E+05	0.10E+09	0.54E+08	0.41E+07
3 min	0.76E+05	0.51E+08	-0.33E+08	0.37E+07
3 max	0.98E+05	0.11E+09	0.61E+08	0.37E+07
4 min	0.76E+05	0.68E+08	-0.28E+08	0.28E+07
4 max	0.98E+05	0.11E+09	0.66E+08	0.28E+07
5 min	0.76E+05	0.73E+08	-0.23E+08	0.17E+07
5 max	0.98E+05	0.12E+09	0.69E+08	0.17E+07
6 min	0.76E+05	0.80E+08	-0.19E+08	0.95E+06
6 max	0.98E+05	0.12E+09	0.70E+08	0.95E+06
7 min	0.76E+05	0.87E+08	-0.17E+08	0.44E+06
7 max	0.98E+05	0.12E+09	0.70E+08	0.44E+06
8 min	0.76E+05	0.91E+08	-0.14E+08	0.26E+06
8 max	0.98E+05	0.12E+09	0.70E+08	0.26E+06
9 min	0.76E+05	0.16E+08	-0.41E+08	0.15E+07
9 max	0.98E+05	0.68E+08	0.46E+08	0.15E+07
10min	0.76E+05	0.22E+08	-0.39E+08	0.17E+07
10max	0.98E+05	0.10E+09	0.56E+08	0.17E+07
11min	0.76E+05	0.43E+08	-0.35E+08	0.15E+07
11max	0.98E+05	0.11E+09	0.63E+08	0.15E+07
12min	0.76E+05	0.63E+08	-0.30E+08	0.11E+07
12max	0.98E+05	0.12E+09	0.67E+08	0.11E+07
13min	0.76E+05	0.69E+08	-0.25E+08	0.70E+06
13max	0.98E+05	0.12E+09	0.70E+08	0.70E+06
14min	0.76E+05	0.76E+08	-0.22E+08	0.38E+06
14max	0.98E+05	0.12E+09	0.70E+08	0.38E+06
15min	0.76E+05	0.83E+08	-0.18E+08	0.18E+06
15max	0.98E+05	0.12E+09	0.70E+08	0.18E+06
16min	0.76E+05	0.89E+08	-0.15E+08	0.10E+06
16max	0.98E+05	0.12E+09	0.70E+08	0.10E+06
17min	0.76E+05	0.12E+08	-0.41E+08	0.75E+06
17max	0.98E+05	0.72E+08	0.48E+08	0.75E+06
18min	0.76E+05	0.17E+08	-0.40E+08	0.83E+06
18max	0.98E+05	0.11E+09	0.57E+08	0.83E+06
19min	0.76E+05	0.36E+08	-0.37E+08	0.74E+06
19max	0.98E+05	0.11E+09	0.64E+08	0.74E+06
20min	0.76E+05	0.55E+08	-0.33E+08	0.55E+06
20max	0.98E+05	0.12E+09	0.68E+08	0.55E+06
21min	0.76E+05	0.64E+08	-0.28E+08	0.35E+06
21max	0.98E+05	0.12E+09	0.70E+08	0.35E+06
22min	0.76E+05	0.73E+08	-0.24E+08	0.19E+06
22max	0.98E+05	0.12E+09	0.70E+08	0.19E+06
23min	0.76E+05	0.79E+08	-0.21E+08	0.88E+05
23max	0.98E+05	0.12E+09	0.70E+08	0.88E+05

Tabel 1. Belastinggeval 1 t/m 23.

road cases 1 through 23

Belast. geval	Fc [N]	Mklap [Nmm]	Mzwaai [Nmm]	n [-]
24 min	0.76E+05	0.85E+08	- .18E+08	0.52E+05
24 max	0.98E+05	0.13E+09	0.70E+08	0.52E+05
25 min	0.76E+05	0.13E+08	- .41E+08	0.84E+06
25 max	0.98E+05	0.72E+08	0.47E+08	0.84E+06
26 min	0.76E+05	0.18E+08	- .39E+08	0.93E+06
26 max	0.98E+05	0.11E+09	0.57E+08	0.93E+06
27 min	0.76E+05	0.37E+08	- .37E+08	0.83E+06
27 max	0.98E+05	0.11E+09	0.64E+08	0.83E+06
28 min	0.76E+05	0.57E+08	- .32E+08	0.62E+06
28 max	0.98E+05	0.12E+09	0.68E+08	0.62E+06
29 min	0.76E+05	0.65E+08	- .28E+08	0.39E+06
29 max	0.98E+05	0.12E+09	0.70E+08	0.39E+06
30 min	0.76E+05	0.74E+08	- .24E+08	0.21E+06
30 max	0.98E+05	0.12E+09	0.70E+08	0.21E+06
31 min	0.76E+05	0.80E+08	- .20E+08	0.99E+05
31 max	0.98E+05	0.12E+09	0.70E+08	0.99E+05
32 min	0.76E+05	0.86E+08	- .17E+08	0.59E+05
32 max	0.98E+05	0.13E+09	0.70E+08	0.59E+05
33 min	0.76E+05	0.67E+07	- .42E+08	0.34E+06
33 max	0.98E+05	0.79E+08	0.49E+08	0.34E+06
34 min	0.76E+05	0.94E+07	- .41E+08	0.37E+06
34 max	0.98E+05	0.11E+09	0.60E+08	0.37E+06
35 min	0.76E+05	0.26E+08	- .39E+08	0.33E+06
35 max	0.98E+05	0.12E+09	0.66E+08	0.33E+06
36 min	0.76E+05	0.41E+08	- .37E+08	0.25E+06
36 max	0.98E+05	0.12E+09	0.69E+08	0.25E+06
37 min	0.76E+05	0.52E+08	- .33E+08	0.16E+06
37 max	0.98E+05	0.12E+09	0.70E+08	0.16E+06
38 min	0.76E+05	0.64E+08	- .29E+08	0.85E+05
38 max	0.98E+05	0.12E+09	0.71E+08	0.85E+05
39 min	0.76E+05	0.72E+08	- .25E+08	0.40E+05
39 max	0.98E+05	0.13E+09	0.71E+08	0.40E+05
40 min	0.76E+05	0.78E+08	- .22E+08	0.23E+05
40 max	0.98E+05	0.13E+09	0.70E+08	0.23E+05
41 min	0.76E+05	0.78E+06	- .43E+08	0.17E+06
41 max	0.98E+05	0.85E+08	0.51E+08	0.17E+06
42 min	0.76E+05	0.13E+07	- .42E+08	0.19E+06
42 max	0.98E+05	0.11E+07	0.61E+08	0.19E+06
43 min	0.76E+05	0.15E+08	- .41E+08	0.17E+06
43 max	0.98E+05	0.12E+09	0.67E+08	0.17E+06
44 min	0.76E+05	0.27E+08	- .39E+08	0.12E+06
44 max	0.98E+05	0.12E+09	0.70E+08	0.12E+06
45 min	0.76E+05	0.34E+08	- .38E+08	0.79E+05
45 max	0.98E+05	0.12E+09	0.71E+08	0.79E+05
46 min	0.76E+05	0.46E+08	- .35E+08	0.43E+05
46 max	0.98E+05	0.13E+09	0.71E+08	0.43E+05

Tabel 2. Belastinggeval 24 t/m 46.

Belast. geval	Fc [N]	Mklap [Nmm]	Mzwaai [Nmm]	n [-]
47 min	0.76E+05	0.58E+08	- .31E+08	0.20E+05
47 max	0.98E+05	0.13E+09	0.71E+08	0.20E+05
48 min	0.76E+05	0.67E+08	-.28E+08	0.12E+05
48 max	0.98E+05	0.14E+09	0.71E+08	0.12E+05
49 min	0.76E+05	0.36E+07	-.43E+08	0.94E+05
49 max	0.98E+05	0.82E+08	0.50E+08	0.94E+05
50 min	0.76E+05	0.52E+07	-.42E+08	0.10E+06
50 max	0.98E+05	0.11E+09	0.60E+08	0.10E+06
51 min	0.76E+05	0.20E+08	-.40E+08	0.92E+05
51 max	0.98E+05	0.12E+09	0.66E+08	0.92E+05
52 min	0.76E+05	0.34E+08	-.38E+08	0.69E+05
52 max	0.98E+05	0.12E+09	0.69E+08	0.69E+05
53 min	0.76E+05	0.42E+08	-.35E+08	0.44E+05
53 max	0.98E+05	0.12E+09	0.71E+08	0.44E+05
54 min	0.76E+05	0.56E+08	-.32E+08	0.24E+05
54 max	0.98E+05	0.12E+09	0.71E+08	0.24E+05
55 min	0.76E+05	0.66E+08	-.28E+08	0.11E+05
55 max	0.98E+05	0.13E+09	0.71E+08	0.11E+05
56 min	0.76E+05	0.73E+08	-.25E+08	0.65E+04
56 max	0.98E+05	0.14E+09	0.70E+08	0.65E+04
57 min	0.76E+05	-.59E+07	-.44E+08	0.37E+05
57 max	0.98E+05	0.91E+08	0.53E+08	0.37E+05
58 min	0.76E+05	-.79E+07	-.44E+08	0.41E+05
58 max	0.98E+05	0.12E+09	0.63E+08	0.41E+05
59 min	0.76E+05	0.34E+07	-.43E+08	0.37E+05
59 max	0.98E+05	0.12E+09	0.68E+08	0.37E+05
60 min	0.76E+05	0.13E+08	-.42E+08	0.28E+05
60 max	0.98E+05	0.12E+09	0.70E+08	0.28E+05
61 min	0.76E+05	0.16E+08	-.41E+08	0.17E+05
61 max	0.98E+05	0.13E+09	0.71E+08	0.17E+05
62 min	0.76E+05	0.24E+08	-.39E+08	0.95E+04
62 max	0.98E+05	0.13E+09	0.71E+08	0.95E+04
63 min	0.76E+05	0.32E+08	-.38E+08	0.44E+04
63 max	0.98E+05	0.14E+09	0.71E+08	0.44E+04
64 min	0.76E+05	0.39E+08	-.36E+08	0.26E+04
64 max	0.98E+05	0.15E+09	0.71E+08	0.26E+04
65 min	0.76E+05	-.15E+08	-.46E+08	0.19E+05
65 max	0.98E+05	0.96E+08	0.56E+08	0.19E+05
66 min	0.76E+05	-.20E+08	-.46E+08	0.21E+05
66 max	0.98E+05	0.12E+09	0.65E+08	0.21E+05
67 min	0.76E+05	-.13E+08	-.45E+08	0.19E+05
67 max	0.98E+05	0.12E+09	0.70E+08	0.19E+05
68 min	0.76E+05	-.71E+07	-.45E+08	0.14E+05
68 max	0.98E+05	0.12E+09	0.71E+08	0.14E+05
69 min	0.76E+05	-.73E+07	-.44E+08	0.87E+04
69 max	0.98E+05	0.13E+09	0.71E+08	0.87E+04

Tabel 3. Belastinggeval 47 t/m 69.

Belast. geval	Fc [N]	Mklap [Nmm]	Mzwaai [Nmm]	n [-]
70 min	0.76E+05	-0.32E+07	-0.44E+08	0.47E+04
70 max	0.98E+05	0.14E+09	0.72E+08	0.47E+04
71 min	0.76E+05	0.11E+06	-0.43E+08	0.22E+04
71 max	0.98E+05	0.15E+09	0.72E+08	0.22E+04
72 min	0.76E+05	0.33E+07	-0.42E+08	0.13E+04
72 max	0.98E+05	0.16E+09	0.71E+08	0.13E+04
73 min	-0.11E+05	-0.55E+07	-0.41E+08	0.77E+04
73 max	0.99E+05	0.73E+08	0.93E+08	0.77E+04
74 min	-0.11E+05	-0.13E+08	-0.42E+08	0.85E+04
74 max	0.99E+05	0.92E+08	0.93E+08	0.85E+04
75 min	-0.11E+05	-0.69E+07	-0.43E+08	0.76E+04
75 max	0.99E+05	0.11E+09	0.93E+08	0.76E+04
76 min	-0.11E+05	-0.11E+07	-0.44E+08	0.57E+04
76 max	0.99E+05	0.12E+09	0.92E+08	0.57E+04
77 min	-0.11E+05	-0.85E+05	-0.44E+08	0.36E+04
77 max	0.99E+05	0.12E+09	0.91E+08	0.36E+04
78 min	-0.11E+05	0.62E+07	-0.46E+08	0.19E+04
78 max	0.99E+05	0.12E+09	0.91E+08	0.19E+04
79 min	-0.11E+05	0.13E+08	-0.46E+08	0.90E+03
79 max	0.99E+05	0.12E+09	0.90E+08	0.90E+03
80 min	-0.11E+05	0.20E+08	-0.47E+08	0.54E+03
80 max	0.99E+05	0.12E+09	0.88E+08	0.54E+03
81 min	0.76E+05	0.26E+08	-0.39E+08	0.76E+08
81 max	0.98E+05	0.49E+08	0.43E+08	0.76E+08
82 min	0.76E+05	0.39E+08	-0.34E+08	0.84E+08
82 max	0.98E+05	0.82E+08	0.49E+08	0.84E+08
83 min	0.76E+05	0.60E+08	-0.27E+08	0.75E+08
83 max	0.98E+05	0.95E+08	0.57E+08	0.75E+08
84 min	0.76E+05	0.73E+08	-0.22E+08	0.56E+08
84 max	0.98E+05	0.10E+09	0.62E+08	0.56E+08
85 min	0.76E+05	0.77E+08	-0.18E+08	0.35E+08
85 max	0.98E+05	0.11E+09	0.66E+08	0.35E+08
86 min	0.76E+05	0.84E+08	-0.15E+08	0.19E+08
86 max	0.98E+05	0.12E+09	0.68E+08	0.19E+08
87 min	0.76E+05	0.88E+08	-0.13E+08	0.89E+07
87 max	0.98E+05	0.12E+09	0.69E+08	0.89E+07
88 min	0.76E+05	0.92E+08	-0.12E+08	0.53E+07
88 max	0.98E+05	0.12E+09	0.69E+08	0.53E+07
89 min	0.76E+05	0.18E+08	-0.41E+08	0.32E+08
89 max	0.98E+05	0.26E+08	0.41E+08	0.32E+08
90 min	0.76E+05	0.53E+08	-0.21E+08	0.23E+07
90 max	0.98E+05	0.16E+09	0.67E+08	0.23E+07
91 min	0.00E+00	0.00E+00	0.00E+00	0.38E+06
91 max	0.11E+05	0.15E+09	0.50E+08	0.38E+06
92 min	-0.59E+04	0.15E+08	-0.46E+08	0.12E+06
92 max	0.16E+05	0.51E+08	0.34E+08	0.12E+06

Tabel 4. Belastinggeval 70 t/m 92.

Belast. geval	Fc [N]	Mklap [Nmm]	Mzwaai [Nmm]	n [-]
93 min	-0.11E+05	0.90E+08	-0.25E+08	0.10E+01
93 max	0.11E+05	0.22E+09	0.56E+08	0.10E+01
94 min	0.76E+05	0.91E+08	-0.98E+07	0.10E+01
94 max	0.98E+05	0.19E+09	0.73E+08	0.10E+01
95 min	0.76E+05	0.59E+08	-0.16E+08	0.10E+01
95 max	0.98E+05	0.17E+09	0.74E+08	0.10E+01
96 min	-0.18E+05	0.19E+08	-0.75E+08	0.10E+01
96 max	0.18E+05	0.38E+08	0.79E+08	0.10E+01
97 min	0.76E+05	0.10E+09	0.49E+08	0.10E+01
97 max	0.98E+05	0.11E+09	0.13E+09	0.10E+01

Tabel 5. Belastinggeval 93 t/m 97.

loadcase Belasting- geval	max. compression stress Max. druk- spanning (MPa)	Allowable Toelaatbare drukspanning (MPa)
93max	82.1	326
94max	80.3	326
95max	71.6	326
96max	23.5	326
97max	68.1	326

Tabel 6. Max. drukspanningen in GVP onder de pasbouten.

max ~~pressure~~ stress in glass-fiber under the bolts of plastic/steel connection
compression

Belasting- geval	Max. druk- spanning		Toelaatbare drukspanning (MPa)
	buitenflens (MPa) outer FLANGE	binnenflens (MPa) inner FLANGE	
93max	90.8	77.8	166
94max	89.6	75.4	166
95max	80.4	67.3	166
96max	29.1	23.4	166
97max	77.4	64.0	166

Tabel 7. maximum compression stress in steel under the plastic/steel-bolt connection
Max. drukspanningen in GGG40.3 onder de pasbouten.

Belasting- geval	Max. trek- spanning		Toelaatbare drukspanning (MPa)
	buitenflens (MPa)	binnenflens (MPa)	
93max	111.6	125.8	166
94max	110.4	122.5	166
95max	100.6	111.5	166
96max	46.2	51.7	166
97max	97.1	107.0	166

Tabel 8. Max. trekspanningen in GGG40.3 tussen de pasbouten.

tensile stress

between bolts

Figur 3. Smith-diagram GGG40.3 trek/druk.

tensile / pressure

Die nicht dargestellten Vergütungsstähle können wie folgt eingesetzt werden:

34CrNiMo6 } wie 30CrNiMo8
30CrMoV4 }

42CrMo4 } wie 50CrMo4
36CrNiMo4 }
50CrV4 }

34CrMo4 wie 41Cr4

28Cr4 wie 46Cr2

C45 wie Ck45

C22 wie Ck22

C60 und C50 liegen etwa zwischen Ck45 und 46Cr2.

C40, 32Cr2, C35, C30, C25 liegen etwa zwischen Ck22 und Ck45.

Figur 4. Smith-diagram 42CrMo4 buiging.

bending

Sorte		gewährleistete Eigenschaften an getrennt gegossenen Probestücken ^{3) 4)}				
		Zugfestigkeit σ_B	0,2%-Dehngrenze ⁵⁾ $\sigma_{0,2}$	Bruchdehnung δ_5	Kerbschlagarbeit (DVM-Proben) — A_v in J min.	
Kurzzeichen	Werkstoffnummer	N/mm ² min.	N/mm ² min.	% min.	Mittelwert ⁶⁾ aus 3 Proben	Einzelwert ⁶⁾
GGG-35.3	0.7033	350	220	22	14 bei -40 °C	11 bei -40 °C
GGG-40.3	0.7043	400	250	18	14 bei -20 °C	11 bei -20 °C

Tabel 9. Mechanische eigenschappen GGG40.3.

Mechanical properties

Werkstoff	zulässige Flächenpressung p_{zul} in N/mm ² bei Belastung		
	ruhend	schwellend	stoßartig
Stahl, ungehärtet	100 ... 200	70 ... 150	40 ... 80
Stahl, gehärtet	150 ... 250	100 ... 170	50 ... 100
Stahlguß	100 ... 150	80 ... 100	40 ... 60
Gußeisen, Temperguß	80 ... 100	60 ... 80	30 ... 50
Kupferlegierungen (Bronze, Messing)	40 ... 50	30 ... 40	15 ... 20
AlCuMg ausgehärtet	100 ... 160	70 ... 100	40 ... 60
AlMg, AlMn, AlMgSi, ausgehärtet	80 ... 150	60 ... 90	30 ... 50
G-AlSi, G-AlSiMg	60 ... 70	40 ... 50	25 ... 30

Tabel 10. Toelaatbare vlaktedruk gietijzer.

allowable plain stress casting steel

Larwood, Scott

From: Bernard Bulder [bulder@ecn.nl]
Sent: Wednesday, December 09, 1998 8:42 AM
To: 'SMT Distribution'
Subject: [98] [Fwd: Strain gauge location & Project plan]

Strain gauge location &
Projec...

Dear all,

I received a strain gauge position measurement document from Cres. I noticed today that I have to redistribute this to all partners. Due to the fact that the email addresses from Cres members did change the distribution list did not work well.

Sorry for this delay.

Kind regards,

--

Bernard Bulder
Netherlands Energy Research Foundation ECN
Unit Renewable Energy, section Wind Energy
tel. +31 (0) 224 564102
fax. +31 (0) 224 563214
mail: bulder@ecn.nl

Larwood, Scott

From: Vassilis Kolovos [vkolov@cress.gr]
Sent: Monday, December 07, 1998 8:14 AM
To: bulder@ecn.nl
Subject: Strain gauge location & Project plan

smt-sg-pos-procedure.
doc

Dear Bernard,

Since I don't know if the e-mails I sent, regarding the strain gauge location measurement procedure & Project plan, have been distributed via the mailbox, I am sending to you just to make sure they will be distributed.

1. Attached is the procedure, in Word97 format, for measuring the (common) strain gauge positions. It is in response to **action 5.05**
2. Regarding the **project planning**, the best we can do at CRES is to start the second fatigue test on 1st April with an end date the 31st of May. According to the project planning you have produced, the finish data in this case appears to be the 5th of June. I'm afraid this is the only realistic dates, in which case we have to take advantage of the two months deadline after the end of the project for submitting the final reports.

Best Regards,

Vassilis Kolovos, Wind Energy Department
Center for Renewable Energy Sources
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STRAIN GAUGE POSITION MEASUREMENT

The purpose of this procedure is to establish a common reference system for the measurement of the strain gauge positions among the partners of the project.

Reference System Definition

The radial position of the strain gauges, i.e. along the longitudinal (pitch) axis of the blade, is referenced with respect to the flange (root) separation plane.

The circumferential position of the strain gauges is referenced with respect of the trailing edge of the blade assigned as the starting point with measuring direction along the pressure side of the blade.

Root hole notation

Having positioned the blade horizontally with the tip cord perpendicular to the ground and trailing edge upward, there are two hammer markings on the flange of the blade. The first root hole (bolt) toward the pressure side of the blade is denoted as hole #1P, and the following ones as 2P, 3P, etc. Following the same pattern, the first hole toward the suction side of the blade is denoted as #1S, and the ones thereafter as 2S, 3S, etc.

okay

Blade/flange bolt notation

Having the blade horizontal with the tip chord perpendicular to the ground and trailing edge upward, the middle bolt of the upper steel segment is aligned with the trailing edge of the blade. This bolt is denoted as the "**trailing edge bolt**". (Alternatively, it is the fourth bolt of the upper steel segment, irrespective of which side of the segment is chosen for starting the numbering).

okay

Trailing edge line marking

Since there is not a clear trailing edge from the cylindrical part of the blade up to the first aerodynamic section, one has to be defined and marked on the blade.

The following procedure is suggested:

1. Mark the section being 2.10m distance from the flange on the trailing edge. Starting point is the root separation plane at the two hammer marks spots on the flange.
2. At this location, the trailing edge is curved, hence the midpoint of this arc has to be defined. Measuring the thickness of the trailing edge with a vernier three (3) cm below the trailing edge, the midpoint is marked as the half of this distance, denoted as the "**2.10m trailing edge spot**".
3. Position one end of a chord at the center of the trailing edge bolt. Mark the second point at end of the strain gauge at 400mm from the root, on its longitudinal axis on the trailing edge of the cylindrical part of the blade. The other end of the chord has to be the "**2.10m trailing edge spot**". Now the **trailing edge line** can be marked on the blade as the projection of this chord on the blade surface. (The **trailing edge line** should pass through/from strain gauge on the trailing edge of the cylindrical part of the blade at 400mm from the root.) Practically, by pushing the chord on the blade surface starting from the "**2.10m trailing edge spot**" every ten (10) cm, up to the trailing edge strain gauge, should yield the **trailing edge line** with no more than 1 or 2 mm discrepancy between the four labs.

how does me get this accurately

okay

Radial strain gauge position measurement

1. Position the beginning of the measuring tape at the root separation plane, passing it through hole 3P for measuring the distance of (common) strain gauges having been glued above the beam (according to **JEROEN8**) on the pressure side of the blade.
2. Record the distance of the strain gauge midpoint from the root separation plane.

For the rest of the strain gauges the procedure is the same but the reference holes are as follows:

- Gauges below the beam (on the pressure side), hole 6P has to be the reference
- Strain gauges having been glued above the beam (according to **JEROEN8**) on the suction side of the blade, hole 4S has to be the reference
- Gauges below the beam (on the suction side), hole 7S has to be the reference

NOTE: The measuring tape has to be parallel to the pitch axis. Since the strain gauges are will not be on the line of the measuring tape, use of a right angle instrument will give the reading of the strain gauge midpoint distance from the root.

okay

Circumferential strain gauge position measurement

➤ For section 1500mm from flange:

Starting from the *trailing edge line* toward the pressure side of the beam, and measuring along the already marked section, record the distance of the strain gauge midpoint (*from the trailing edge line*). The measuring tape has to follow the shape of the airfoil section that the measurement is taken. *shun*

➤ For section 400mm from the flange:

Starting point is the trailing edge strain gauge axis. Measuring procedure as above.

➤ For section 2500mm from flange:

Starting point is the (trailing) edge on the pressure side (since the "actual trailing edge" has a few millimetres thickness). Measuring procedure as above. *shun*

Comments

Regarding the positioning of the (common) rosettes, the position of the midpoint of each individual strain gauge of the rosette has to be measured and not of the whole grid. As Scott noticed in mail[92], the make and type of the strain gauges used has to be mentioned.

I believe this is a quite simple way to be followed, and it should not introduce more than 2 or 3 mm uncertainty in the measured positions. If it looks vague, a set of photographs illustrating the marking procedure can be produced and distributed via the mailbox, in *.jpg format.

Larwood, Scott

From: J.J.D. van Dam [vandam@ecn.nl]
ent: Thursday, February 18, 1999 9:18 AM
To: smt
Subject: [100] Nomenclature for common gages

smt_gages_nomen.doc

c (Microsoft...

In the accompanying document I have made a proposal for the common gages.

E-Mail : vandam@ecn.nl - J.J.D. van Dam
ECN - Energy Research Foundation Department: ECN - Duurzame Energie, Zon & Wind
Telephone: (+31) 224 564903 Fax: (+31) 224 563214
P.O. box 1 1755 ZG Petten Country: The Netherlands

=====

SMT [100]

For the pressure side the same names can be used but then with a "P" instead of an "S"

For the section at R =400, four gages:

Larwood, Scott

From: Jeroen van Dam [vandam@ecn.nl]
ant: Tuesday, June 02, 1998 4:23 AM
To: smt-2-l@ecn.nl
Subject: [25] radial position, pull direction, etc.

Dear colleagues,

There was some uncertainty on the radial positions for the loads given in the timeseries. The time series files were based on the files NW25.CMB and NW25.CSB. The radial positions for the loads in these files were given in the file NW25.LKB. However in Bernard1 a different version of this file is printed as in Jeroen4. We checked with rotorline which version should be used and their answer was that the radial positions in the file on the floppy disk should be used. This version was also put on the FTP-site.

Pulling direction for edgewise. The loads are given as M_x and M_y these are loads in the rotorplane and perpendicular to that plane. We shall assume that the tip angle is zero. Thus the loads are parallel and perpendicular to the tip chord. Edgewise = parallel, flatwise = perpendicular.

Coordinate files/ points plotted in Bernard 1: Plotting these files and comparing these with the graphs in Bernard1 seems to lead to the conclusion that, if there is any difference it will be small. Thus I assumed that the points are comparable.

Deflection static test: The deflections given in email [11] were taken from a rotorline report. In that report the blade is roughly modelled in three ismastic pieces, each with an E-modulus of 25000 N/mm².

R (mm from flange)	I_flat	I_edge
0-2500	$1.15 \cdot 10^9$	$1.7 \cdot 10^9$
2500-4500	$4.7 \cdot 10^8$	$1.55 \cdot 10^9$
4500-7000	$1.6 \cdot 10^8$	$8 \cdot 10^8$

Roughly checking the input data does give large deviations between this model and the farob data.

Of course to get better results one could do the calculations with the farob data available and using more elements.

If required I could fax a copy of the simple-beam calculations.

Jeroen van Dam

Larwood, Scott

From: Jeroen van Dam [vandam@ecn.nl]
Sent: Wednesday, July 15, 1998 6:09 AM
To: smt-2-l@ecn.nl
Subject: [47] data sets

There are some differences between the data of Bernard 1 and Alex 9. After a discussion with rotorline, Alex and I have decided that we think the following data should be used:

- UTS, UCS, E-modulus, coordinates and table I with cross-sectional properties from ALEX - 9

Meaning for the strength laminate: UTS = 372, UCS = 260; for the nose\tail laminate UTS = 87 and UCS = 76. These values are without the material factors C1, C2 and C3.

E-modulus for the strength laminate = 24500 and for nose\tail E= 7000

- SCF's, load factor and material factor from Bernard 1.

- Loads from NW25time.***

The fatigue damage mentioned in the tables on pages A15 - A22 is later corrected by the use of a correction factor which is explained on page 13 of bernard1. This is an explanation of why fatigue damage found in our models could deviate from the one found in these tables.

With the data mentioned above I found a fatigue damage of 0.11 on the tail at the cross section at R =3151. Alex found a damage of 0.24 on the same point.

Jeroen van Dam

Appendix G

Acoustic Emissions Report

Acoustic Emission Monitoring of Static and Fatigue Tests On a Nedwind 25 Wind Turbine Blade

A.G. Beattie

Executive Summary

A Nedwind 25 wind turbine blade was subjected to both a static load test and a fatigue test at the National Wind Technology Center. Both tests were acoustically monitored with a 24 channel Physical Acoustics Corp. Spartan AT acoustic emission system.

In the static test, the blade was loaded from rest to four successively higher peak loads. These loads were 5800 lbs., 6240 lbs., 8150 lbs. and 8900 lbs. applied to a saddle fixture at station 8650 mm from the axis of rotation of the blade. The acoustic emission indicated at least minor damage to the bottom (tension side) of the root during the two higher loadings. On the blade upper surface (compression side), a small clustering of emission events was seen near the end of a fabric ply. All of this emission occurred at the peak load of 8900 lbs. The conclusions were that there was some damage to the root very close to the edge of the steel clamp and the possible start of a crack in the epoxy at the end of a ply on the upper surface.

The fatigue test was conducted primarily at a frequency of 1.5 Hz and a peak load of approximately 6550 lbs. applied to the same fixture used in the static test. In one of the preliminary setup runs, a peak load of 7400 lbs. was applied for about 400 cycles at 0.5 Hz. This produced emission on the bottom of the blade. Emission was also located over a wide band on the top of the blade. During this preliminary test, the acoustic emission data rate from the whole blade was about 160 sensors excited per second per second. After this test, the data rate dropped to about half and remained down for approximately 1,500,000 cycles. It then started increasing and was 250 to 350 hits per second for the last half of the fatigue test. This is expected acoustic emission behavior.

The root area generated large amounts of located emission in a band about 45 degrees from the tension maximum toward the trailing edge at around 700,000 to 900,000 cycles. This was the most intense emission seen during the test but did not appear to effect the performance of the blade. Lesser amounts of emission were seen on the bottom of the root for the rest of the test with the region of maximum density rotating towards the bottom of the blade.

The top of the blade started to develop areas of high located emission density around 700,000 cycles. Five different clusters showed up during the rest of the test with some of them showing periods of increased and then decreased emission rates.

In the end, the blade did not experience structural failure so the significance of the acoustic emission data is not known. Several regions of apparently intense damage were seen but they did not result in structural failure. One has to conclude that a well designed FRP structure is extremely damage tolerant.

Acoustic Emission Monitoring of Static and Fatigue Tests on a Nedwind 25 Wind Turbine Blade

Dr. Alan G. Beattie
Physical Acoustics Corporation*
PO Box 464
Corrales, NM 87048

Abstract:

A Nedwind 25 wind turbine blade was subjected to both a static and a fatigue test at the National Wind Technology Center near Boulder CO. This blade was acoustically monitored during both tests. The blade did not physically fail during these tests even though large amounts of apparent damage were detected by the acoustic monitoring and several physical cracks were seen in the blade. In this report, areas where there was damage detected will be listed along with the approximate test time when they occurred.

Experimental Set Up:

The acoustic instrumentation was a Physical Acoustics Corp. (PAC) Spartan AT acoustic emission system. There were twenty-four acoustic emission channels, twenty-three which were used in the test. The sensors used were PAC R6-I sensors having a resonant frequency around 60 KHz and containing integral 40 dB. preamplifiers. The bandwidth of the sensor-preamp package is 30 to 100 KHz. A PAC 9100A voltage-time gate was used restrict the acquired data to the upper 10 % of the load range during the fatigue test. The Nedwind blade had its root bolted to a large fixed steel fixture. The blade tip was cut off and a saddle fixture placed around the blade at spanwise station 8650 mm. The load was applied to this fixture by a hydraulic actuator.

Two different regions of the blade were monitored, the root region adjacent to the mounting ring and the top of the blade, about from spanwise station 2300 mm to station 4800 mm. Eight sensors were applied to the root region. Two rows of four sensors were glued onto the blade with G.E. Silicone II glue. The first row (sensors 1-4) were at station 150 mm, mounted on the outer metal clasp between the attachment bolts. The second row (sensors 5-8) were mounted at station 404 mm on the FRP surface of the blade. The sensors were 90 degrees apart in both rows with the rows rotated by 45 degrees from each other. Sensor 5 was on the top of the blade and sensor 7 on the bottom.

Fifteen sensors (sensors 9 to 23) were applied to the top of the blade. There were three rows of five sensors, each row running parallel to the long axis of the blade. The center row was mounted along the center line of the blade with sensors 610 mm apart starting a station 2335 mm. The other two rows were parallel to the center row, 305 mm toward the leading edge and 305 mm toward the trailing edge. The overall pattern consisted of two series of adjoining rectangles. The sensors were numbered with 9 at station 2335 near the leading edge, 11 at station 2335 toward the trailing edge, 21 at station 4775

near the leading edge and 23 at station 4775 toward the trailing edge. Sensors 18 and 21 were respectively +280 and +255 mm from the center line to accommodate the blade taper.

Slightly different programs were used for analysis of two regions on the blade. The location algorithm calculated the most probable source location from the signal arrival times. An event was defined as all the sensors hit either on the blade or in the root area within a time period of 800 microseconds. For the root region, The data set used in the calculation was the arrival times of the first four sensors hit. There were no restrictions on which four sensors were hit. The use of the extra sensor in the data set means that the calculated location is the most probable location for those four arrival times. An arrival sequence of sensors 5,6,7,8 is a legal hit sequence for a location some distance toward the tip from that row of sensors. For the root region, the surface was treated as the plane created by unrolling the cylinder. No attempt was made before the calculation to determine whether the data were consistent or not. The program contains a parameter which gives an estimate of the goodness of the fit for the solution. A solution was accepted only if this parameter indicated a relatively consistent set of arrival times and the calculated location fell within the circumferential boundaries of the root and within the blade station range of 0 to 1000 mm.

For the region on the top of the blade, the surface was treated as a plane. The data set used was any four of the first five sensors hit which lay on the corners of one of the small rectangles in the sensor pattern. Again, the fitting criteria had to be met and the calculated location had to lie within a rectangle with dimensions 20% larger than the sensor pattern.

The experimental intention had been to use the voltage time gate to restrict the collected data to emission occurring in the top 10% of the load cycle. Unfortunately, the signal out of the load cell showed some noise and some apparent effects of blade resonances. The voltage-time gate was quite difficult to use because of the jitter on the sine wave and it became moot when the Spartan AT stopped responding to the time gate output signal. As a result, for all but two of the preliminary tests, all of the acoustic emission data was collected. This resulted in 750 Mbyte data files. The Spartan AT would stop when the file reached this size and wait until the file was removed. Thus there was quite a bit of missed data. Because of data overload and a computer mishap where an entire file was lost, it is estimated that somewhere between one half and two thirds of the three million cycles were actually acoustically monitored. However, it is thought that few, if any, trends were missed since the monitored intervals were spread through out the test.

The fatigue test showed many located events which occurred in the load range between 5000 and 6000 lbs. The peak load seen in most of the fatigue test was 6600 lbs. Since the original intention had been to ignore data from the lower 90% of the load range, the computer was programmed to discard all hits which occurred at loads below 6000 lbs. A check showed that the absence of the events occurring at lower loads, had no appreciable effect on the apparent damage patterns.

Acoustic emission event locations on the root during the third static loading

Figure 1.

Acoustic emission event locations on the blade top during the fourth static loading

Figure 2

Static Test:

The static load was always positive. Four separate loadings were performed. They were from 0. to 5800. lbs., from 0. to 6240 lbs., from 0. to 8150 lbs. and from 0. to 8900. lbs. load. In the root region, some located acoustic events were seen on each loading. Events were seen on the bottom of the root in the triangle formed by sensors 3, 4 and 7 with the number of events increasing on the second and third loadings and decreasing somewhat on the fourth. On the first two loadings, a few events were seen on the top of the blade. Figure 1 shows the event map for the third loading. It is evident that some damage was occurring on the static test on the bottom of the blade. However, because of the large acoustic velocity differences between fiberglass and steel, it was impossible to determine whether the damage was occurring inside the steel mount or in the fiberglass beyond the mount.

In the instrumented region on the top surface of the blade, little emission was seen on the first two loadings. The third loading produced well scattered emission, generally between the center and rear sensor rows. A small cluster appeared in the rectangle formed by sensors 13, 14, 16 and 17. In the fourth loading, most of the emission was in this cluster. Examining the load values, it was found that almost all of the emission in this cluster occurred at the peak load of 8900 lb. Going back to the engineering drawings, a fiberglass ply dropout was found at approximately the location of the cluster. Figure 2 shows the located events during the fourth loading. The vertical lines are the locations of the ply ends from the blade drawings.

The static test results indicated that the blade survived with only minor damage. However the cluster of events on the top of the blade at a ply dropout suggests that the onset of substantial damage near the ply dropout was starting at the peak load of 8900 lbs. A conclusion, drawn from the acoustic data from the static test is that the bottom of the root was experiencing some damage throughout the static loadings. On the top of the blade, the cluster at station 3250 mm, 150 to 300 mm behind the center line indicated that around 8900 lbs. load, the fiberglass or epoxy in this region near the ply end was starting to crack.

Fatigue tests:

After the static test, the blade was rotated - degrees with the leading edge being raised. The load was applied to the same fixture, again at station 8650 mm. The fatigue test was started on 13 October and ran into 17 November. It was shut down several times for maintenance and repair during this period. The acoustic emission system was also down for part of this period and the down time of the two systems did not always coincide. It might be desirable to tie the occurrence of features in the acoustic data to the cycle count. However, the amount of work necessary to correlate the cycle count to the acoustic time data did not appear worth while at this time. Therefore only the test day(s) over which a feature was seen will be given. The test days when acoustic data was taken were 1-8,12-15,24,25,28-30,32,33,35. The missing file covered the period day 17-21. During some of the days not covered, the test was down for equipment repair and some of the days toward the end of the test were only partially covered when the system stopped due to a full data file.

The cyclic rate for the test began at 1.5 Hz and was raised to 1.75 Hz early in the test. This appeared to be too fast so the load rate was dropped back to 1.5 Hz. The peak

Acoustic emission event locations on the root during the first 500 cycles

Figure 3.

Acoustic emission locations on the blade top during the first 500 cycles

Figure 4

load was set between 6500 and 6600 lbs. load. The exact value was hard to determine because of jitter on the load cell signal, possibly caused by low frequency resonances in the blade. Several short preliminary runs were made in order to check the functioning of the test equipment and to set the test parameters. On the second preliminary run, the cycle rate was set at 0.5 Hz. However the peak load on this run was measured on the load cell at a maximum of 7440 lbs. This test was run for 571 cycles above 6000 lbs. load. It was not set to full load immediately. The last 400 cycles reached 7400 lbs. load during this run. For the rest of the fatigue test, the peak load did not exceed 6500 lbs.

During this preliminary run, 567 located events were seen in the root area and 1362 on the blade, an average of 1.0 events per cycle from the root area and 2.4 events per cycle from the blade. The number of hits detected averaged 160 per second. The data from the root region showed most of the emission to be located on the bottom of the blade, as shown in figure 3. Most of the apparent damage was on the bottom of the blade near end of the clamp between the steel mounting ring and the FRP. It is probable that the epoxy bond between the steel and the FRP was degrading during this run. The monitored region on the top of the blade also showed considerable located emission, shown in figure 4. A band of apparent damage is seen running the length of the monitored region between 100 and 200 mm behind the middle row of sensors.

After the second preliminary run, the cycle rate was raised and the peak load was reduced. Both the located emission and the hit rate (77 hits per second) was lower than the preliminary run for the first week of the test. Then on day 7, a large number of locatable events were seen on the bottom of the root. Figure 5 shows these located events seen during a fifteen hour period during day 7 and 8. These events are seen on the root about 45 degrees between the rear and the bottom of the blade. They appear to extend from about the edge of the steel clamp out to station 1000. This is the highest density of located events that was seen during the testing. The number of events located on the root decreased and then slowly increased toward the end of the test. Figure 6 shows the located events in the root region from a twenty-four hour file taken over days 32 and 33. There is again much located emission near the bottom of the root. The location of maximum emission density appears to have moved about 20 degrees towards the bottom of the root from the locations seen in figure 5.

Visual observation of the root showed that early in the test, there was a crack in the epoxy on the bottom quadrant of the root along the edge of the steel clamp. Later on this crack had spread along the edge of the clamp completely around the root. It appears that the epoxy-steel adhesive bond failed early in the test and that the FRP blade was held to the steel root mount only by the clamp and bolts for at least the last 80% of the fatigue test.

There were few located events on the blade top for the seven days following the preliminary run but those which were located spread out in the same general location pattern seen in figure 4. Then small regions of apparently dense damage start showing up. Figure 7 shows the approximate locations of these regions. Region A showed a few locations on day one at peak loads below 6600 psi. It appeared strongly during the 15 hour file over days 7-8 and then reappeared on days 25, 28-30 and 32-33. The location suggests that the damaged area curves around the leading edge onto the lower surface of the blade. Region B first showed up as a small indication on days 12-15 and 24-25. It then appeared much stronger on days 28-30, 32-33 and 35. Region C was seen only on

Acoustic emission event locations on the root during days 7 and 8

Figure 5

Acoustic emission event locations on the root during days 32 and 33

Figure 6

Locations of damage regions on the blade top during the fatigue test

Figure 7.

Acoustic emission event locations on the blade top during days 29 and 30

Figure 8.

day 25 while D was seen on days 25, 28-30, and 35. Finally, region E was seen quite strongly on days 29-30 and again on day 35. Figure 8 shows the located data from the 29 hour file starting on day 29. Locations in regions A, B D and E are seen. The unusual shapes in region B and E were not changed by varying the values of the fitting parameter values in the location program.

Discussion

After the initial data from the first 571 cycles, the data rate from the blade decreased by a factor of three to four. The data rate did not reach the level seen in the first 500 cycles until day 25. It then slowly increased to about a rate of 1.5 to 2.0 times that initial rate by the end of the test. It appears that the 571 cycles at 7400 lbs. load preempted much of the damage which would have occurred at the load of 6550 lbs. for the next 1,500,000 cycles.

The data rate in hits per second did not correlate with the rate of located events, either on the root or on the blade top. After day 25, the hit rate was high and relatively constant through out each run. However the rate of located events for most of the runs was relatively steady for the first 10,000 seconds and then slowly dropped to zero by twenty to thirty thousand seconds. Usually a few events then showed up toward the middle or end of the run. This drop off was not caused by the lack of AE hits but by the lack of hits in the short time period which defined an event. The same number of sensors were hit over a period of several minutes, but the sensors were excited individually at random, not the 4 to 15 sensors hit within the same one millisecond time span which defines a locatable event. At the end of a run, the test was usually stopped for a few minutes to an hour while the data was transferred out of the acoustic emission system computer for storage. It is difficult to understand how a short respite from cyclic loading could restart the generation of emissions from single flaws which hit multiple sensors. This observation is included for completeness. At the moment it is not understood.

Conclusions:

The most important conclusion about this blade is that after a static test and 3,000,000 cycles of a fatigue test, the blade was still apparently intact. The epoxy bond between the FRP blade and the root ring clamp had long since broken but the mechanical clamp was still holding the blade. A visible crack appeared on the trailing edge of the blade within the first few days of the fatigue test. At the end of the test it had shown no apparent growth.

The acoustic signature of the static test indicated that some damage occurred on the bottom of the root region and that there was damage at the maximum load near a ply end on the top of the blade. The fatigue test continued the damage at the bottom of the root region. At seven days, the acoustic data suggested that the FRP might be turning to powder on the bottom of the root. Despite this, the root region was apparently intact at the end of the test. The apparent damage during the static test at the ply end on the top of the blade was not seen in the fatigue test. Figure 9 shows a map of the first 6000 mm of the top of the blade, including sensor locations and areas of damage seen during the fatigue test. No gross visible indications of damage were seen in the five areas located by the acoustic monitor. The amount of acoustic emission generated and located on this

Top of Blade showing sensor locations and areas of acoustically determined fatigue damage

Figure 9.

blade was extremely high. But while the blade groaned and jiggled during the test, it survived. I can only draw two conclusions from this test. 1) If the loads were a realistic emulation of field conditions, the blade was over designed. 2) FRP is an extremely damage tolerant material when designed correctly.

Acknowledgement:

This was a joint project carried out by Sandia National Lab and the National Wind Technology Center. The Wind Energy staffs of both laboratories were very helpful. I would especially like to thank Mark Rumsey of Sandia and Scott Larwood, Scott Hughes, Mike Jenks and Cynthia Szydiek of NREL for their help.

*This work was performed under contract BD-7680 between Sandia National Laboratory and Physical Acoustics Corporation.

Appendix H

Drawings and Calibration Records

Adapter plate

Load saddle

Strain-gauge data sheets

NOTES;

1. MATERIAL IS A-36 (4-IN NOMINAL) STEEL PLATE
2. FINISH: SPRAY GALVANIZE
3. BREAK ALL SHARP EDGES
4. NC FLAME/WATER CUT ACCEPTABLE IF SURFACE IS GROUND SMOOTH
5. LOCATED AT NOMINAL CENTER OF PLATE THICKNESS (LIFTING EYE)

No.	Date	Description	By
Revisions			
SCOTT HUGHES	5-7-98		
Drawn By	Date		
SCOTT HUGHES			
Engineer			
Checked By			
Approved By
National Renewable Energy Laboratory 1617 Cole Boulevard Golden, Colorado 80401 Sponsored for the U.S. Department of Energy by National Research Institute			
WHD	Drawing Number	NED-AP-1	
	Sheet Number

12 x 2 x 3/4 Inch plate drilled for 21.5 Inches of 1/2 Inch b7 all thread

ENGINEERING DATA SHEET

THE INFORMATION APPEARING ON THIS SHEET HAS BEEN COMPILED SPECIFICALLY FOR THE GAGES CONTAINED IN THIS PACKAGE. THIS FORM IS PRODUCED WITH ADVANCED EQUIPMENT & PROCEDURES WHICH PERMIT COMPREHENSIVE QUALITY ASSURANCE VERIFICATION OF ALL DATA SUPPLIED HEREIN. SHOULD ANY QUESTIONS ARISE RELATIVE TO THESE GAGES, PLEASE MENTION GAGE TYPE, BATCH, AND LOT NUMBER.

H001

Q115598
BSR
DPA
Final QA
Check
Batch

Micro-Measurements
Division
Made in USA

MEASUREMENTS GROUP, INC.
RALEIGH, NORTH CAROLINA

PRECISION STRAIN GAGES

F007

WK-09-250BF-10C
WK-09-250BF-10C
TYPE
QUANTITY
5
LOT NUMBER
DU-K22FE02
RESISTANCE IN OHMS AT 24°C
1000.0 ± 0.3%
GAGE FACTOR AT 24°C
2.04 ± 1.0%
GAGE FACTOR AT 75°C
(-3.0 ± 0.2)%
CODE
054113-16481

GENERAL INFORMATION: WK-SERIES STRAIN GAGES

GENERAL DESCRIPTION: WK-Series gages are a family of fully encapsulated K-alloy strain gages used in both experimental stress analysis and transducer applications. These gages have integral high-endurance lead ribbons with a backing and encapsulation matrix consisting of a high-temperature epoxy-phenolic resin system reinforced with glass fiber.

TEMPERATURE RANGE: -452° to +550° F (-269° to +290° C) for continuous use in static measurements. Useful to +700° F (+370° C) for short term exposure.

SELF TEMPERATURE COMPENSATION: See data curve below.

STRAIN LIMITS: ±1.5% at room temperature; ±1.0% at -320° F (-195° C); ±3% at +400° F (+205° C).

FATIGUE LIFE: 10⁶ cycles at ±1500µin/in (µm/m); 10⁷ cycles at ±1800µin/in (µm/m). Longer gage lengths and lower resistances show greater endurance and less scatter in fatigue life.

BONDING AGENTS: High-temperature epoxy adhesives are recommended for best performance over the entire temperature range. Micro-Measurements M-Bond 810, 600 and M-Bond GA-60 are particularly compatible with WK-Series gages. Refer to M-M Catalog A-110 for information on bonding agents, and Bulletin B-130 for installation procedures.

LEADWIRE SYSTEM: Two flat, high-endurance leads attached to each tab permit 3-wire or 4-wire systems to be carried directly to the gage, minimizing leadwire errors over the wide useful temperature range of the WK-Series strain gages. Option SP-30 WK-Series gages are supplied with single 0.005 in. (0.13 mm) diameter nickel-clad copper wire leads. Option SP-30 reduces fatigue life of WK-Series gages and should not be selected where best cyclic endurance is required. Internal tab connections on these gages are made with +770° F (+410° C) solder. Leadwires may be soft soldered, spot-welded or silver soldered. Refer to M-M Bulletin B-132 for information on solders.

NOTE: The backing of WK-Series gages has been specially treated for optimum bond formation with all appropriate strain gage adhesives. No further cleaning is necessary if contamination of the prepared surface is avoided during handling.

G038

TEST PROCEDURES USED BY MICRO-MEASUREMENTS

OPTICAL DEFECT ANALYSIS M-M Procedure, Direct NIST Traceability on Resistance Standards

GAGE RESISTANCE AT 24°C AND 50% RH ASTM E-251 (Constant Stress Cantilever Method)

GAGE FACTOR AT 24°C & 50% RH (UNIAXIAL STRESS FIELD - POISSON RATIO - 0.285) ASTM E-251 (Step Deflection Method)

TEMPERATURE COEFFICIENT OF GAGE FACTOR ASTM E-251 (Slow Heating Rate, Continuously Recorded)

TRANSVERSE SENSITIVITY AT 24°C AND 50% RH NAS 942 (Modified)

FATIGUE LIFE NAS 942 (Modified)

STRAIN LIMITS M-M Procedure (Similar to NAS 942 Method)

GAGE THICKNESS

CREEP AND DRIFT

NOTE: Gage resistance, gage factor, temperature coefficient of gage factor, thermal output, and transverse sensitivity testing and information presentation are in compliance with OIML International Recommendation NO. 62, "Performance characteristics of metallic resistance strain gages". Other tests are not included in I.R. NO. 62.

ENGINEERING DATA SHEET

THE INFORMATION APPEARING ON THIS SHEET HAS BEEN COMPILED SPECIFICALLY FOR THE GAGES CONTAINED IN THIS PACKAGE. THIS FORM IS PRODUCED WITH ADVANCED EQUIPMENT & PROCEDURES WHICH PERMIT COMPREHENSIVE QUALITY ASSURANCE VERIFICATION OF ALL DATA SUPPLIED HEREIN SHOULD ANY QUESTIONS ARISE RELATIVE TO THESE GAGES, PLEASE MENTION GAGE TYPE, BATCH AND LOT NUMBER.

H001

Micro-Measurements
Division
Made in USA

MEASUREMENTS GROUP, INC.
RALEIGH, NORTH CAROLINA

PRECISION STRAIN GAGES

F015

Q135197	JBH	JDF
Final QA	Check	Batch

WK-09-250RD-10C	WK-09-250RD-10C	QUANTITY	5
LOT NUMBER	DU-K31FE16	RESISTANCE IN OHMS AT 24°C	1000.0±0.4%
SECTION 1	2.04±1.0%	SECTION 2	2.07±1.0%
SECTION 3	2.04±1.0%	SECTION 4	2.05±2.0%
NOMINAL (all sections)	063716-15614	CODE	

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TEMPERATURE RANGE: -452° to +550° F (-269° to +290° C) for continuous use in static measurements. Useful to +700° F (+370° C) for short term exposure.

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STRAIN LIMITS: ±1.5% at room temperature; ±1.0% at -320° F (-195° C); ±3% at +400° F (+205° C).

FATIGUE LIFE: 10⁸ cycles at ±1500µin/in (µm/m); 10⁷ cycles at ±1800µin/in (µm/m). Longer gage lengths and lower resistances show greater endurance and less scatter in fatigue life.

BONDING AGENTS: High-temperature epoxy adhesives are recommended for best performance over the entire temperature range. Micro-Measurements M-Bond 610, 600 and M-Bond GA-60 are particularly compatible with WK-Series gages. Refer to M-m Catalog A-110 for information on bonding agents, and Bulletin B-130 for installation procedures.

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G038

TEST PROCEDURES USED BY MICRO-MEASUREMENTS

OPTICAL DEFECT ANALYSIS	M-M Procedure, Direct NIST Traceability on Resistance Standards
GAGE RESISTANCE AT 24°C AND 50% RH	ASTM E-251 (Constant Stress Cantilever Method)
GAGE FACTOR AT 24°C & 50% RH (UNIAXIAL STRESS FIELD - POISSON RATIO - 0.248)	ASTM E-251 (Step Deflection Method)
TEMPERATURE COEFFICIENT OF GAGE FACTOR	ASTM E-251 (Slow Heating Rate, Continuously Recorded)
THERMAL OUTPUT	ASTM E-251 (Slow Heating Rate, Continuously Recorded)
TRANSVERSE SENSITIVITY AT 24°C AND 50% RH	NAS-942 (Modified)
FATIGUE LIFE	NAS-942 (Modified)
STRAIN LIMITS	M-M Procedure
GAGE THICKNESS	M-M Procedure
CREEP AND DRIFT	M-M Procedure (Similar to NAS 942 Method)

NOTE: Gage resistance, gage factor, temperature coefficient of gage factor, thermal output, and transverse sensitivity testing and information presentation are in compliance with OIML International Recommendation NO. 82. "Performance characteristics of metallic resistance strain gages." Other tests are not included in I.R. NO. 82

T001

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