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BLADE FATIGUE TEST REPORT
REV-120927

LABORATORY FATIGUE TESTING OF THE 9-METER UML DEFECT WIND TURBINE BLADE

CONDUCTED BY

National Renewable Energy Laboratory
National Wind Technology Center
1617 Cole Blvd
Golden, CO 80401

CONDUCTED FOR

University of Massachusetts Lowell
One University Avenue
Lowell, MA 01854

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APPROVAL BY 27 Sep 12

Mike Jenks Date
Test Technician, National Renewable Energy Laboratory

APPROVAL BY 27 SEP 12

Michael Desmond Date
Test Engineer, National Renewable Energy Laboratory

APPROVAL BY 27 SEP 12

Scott Hughes Date
Test Manager, National Renewable Energy Laboratory

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1-DISCLAIMER

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2-EXECUTIVE SUMMARY

This work was performed as part of a collaborative effort with the University of Massachusetts Lowell (UML) and Sandia National Laboratories (SNL). This project was funded under an award through the Department of Energy (DOE) Funding Opportunity Announcement “20% Wind by 2030”, part of the American Recovery and Reinvestment Act (ARRA). (UML) was the prime recipient, with the National Renewable Energy Laboratory (NREL) acting as a sub-tier partner. The UML project title is “Effect of Manufacturing-Induced Defects on Reliability of Composite Wind Turbine Blades”, award DE-EE001374.DOE provided NREL direct funding; work by NREL staff was charged to subtask ARWE0500.

This report describes the laboratory fatigue testing of the UML Defect 9-m wind turbine blade conducted from November 2011 to March 2011 at the National Renewable Energy Laboratory

(NREL) National Wind Technology Center (NWTC) near Boulder, CO. The test was performed in the A60 test bay with the blade cantilevered to the 1,360-kN-m yellow test stand. Unique to this blade were manufactured wave defects that were fabricated in the spar cap laminates at the 3.5-m, 5-m, and 6-m stations, on both the high pressure (HP) and low pressure (LP) sides. An accelerated 1-million cycle design life fatigue load was applied to the blade before increasing loads in discrete steps up to 130% of the target fatigue loads, at which point a 2.5-cm long crack was observed at the 5-m station on the HP) surface spar cap, biased towards the leading edge (LE). The test ran for approximately 1.9-million cycles before the failure.

After the fatigue test was concluded, a single-point quasi-static load to failure was conducted to obtain additional information about the residual strength of the inboard wave defects located at the 3.5-m station. For this, the blade was cut at the 4.9-m station and the outboard tip section removed. The blade tip was then sandwiched with steel plates bolted through the spar caps to provide a fixed loading point. The blade was gradually loaded in steps in the negative flapwise direction until a buckling failure was observed at the 3.5-m station on the HP side (in compression for the negative flap loading), which occurred at approximately 115% of the target static loads.

Although this test was conducted for research and development purposes, it was performed with standard practices under NREL's Quality Assurance Program, which is accredited by A2LA for blade testing in accordance with the IEC 61400-23 standard (No. 1239-01), and in accordance with NREL Safe Operating Procedures [1].

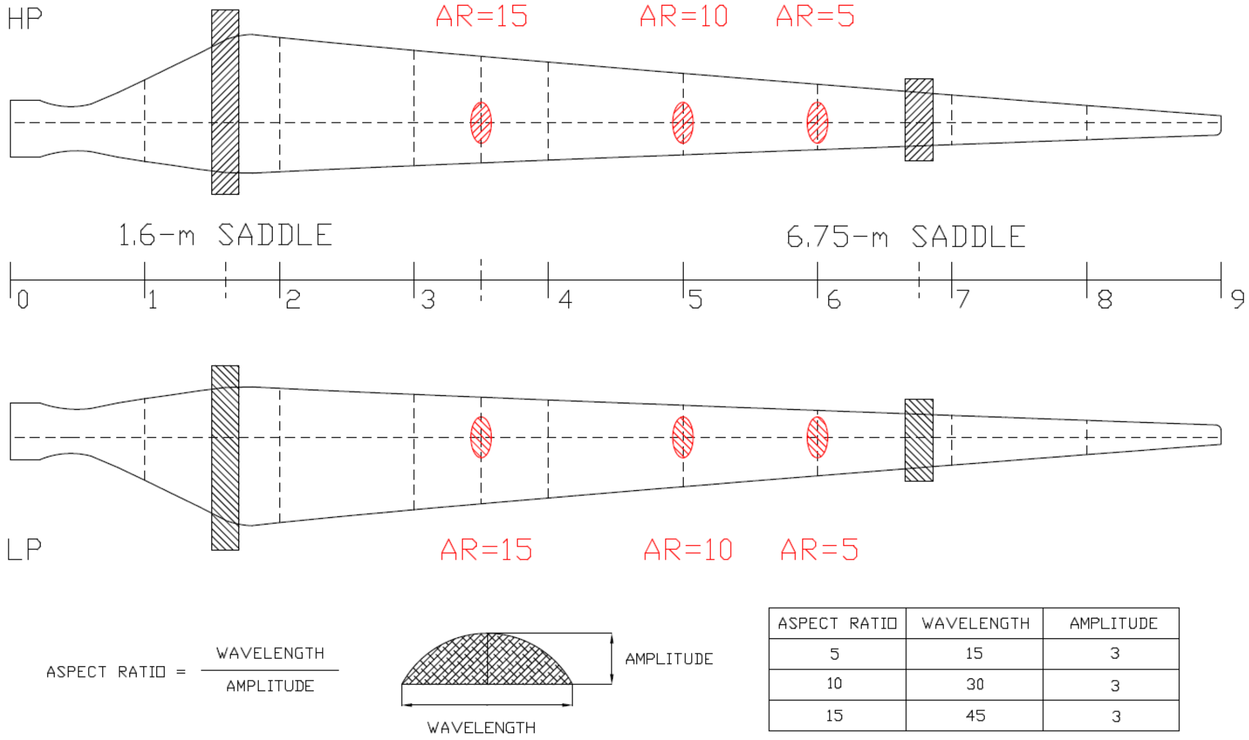
Testing was performed according to the signed test plan [2], and executed under the signed readiness verification, authorization to operate [3].

3-TEST OBJECTIVE

The primary objective of the laboratory fatigue test was to apply an accelerated lifetime fatigue load to quantify the degradation in blade performance due to the presence of wave defects in the laminates introduced during manufacturing. The results of this test may provide better information to the wind industry on the effect of defects.

4-TEST ARTICLE DESCRIPTION

The test article was a UML 9-m wind turbine blade, which was a structural equivalent of previous Sandia designed CX-100 blades but with intentional manufacturing defects. A total of six wave defects were introduced into the carbon fiber laminates of the spar caps with varying aspect ratios but constant defect amplitude of 3-mm, as shown in Figure 4.1. Aspect ratio is defined as the wavelength, or width, divided by the amplitude, or height, of the defect. Three different aspect ratios of 15, 10, and 5 were chosen, based on coupon testing and practical constraints, at spanwise locations of 3.5-m, 5-m, and 6-m respectively on both the HP and LP sides of the blade. The blade was fabricated by TPI Composites at their blade production facility located in Warren, Rhode Island. Primary blade construction materials include fiberglass and epoxy with carbon fiber spar caps. The blade was delivered with an opaque flat white gel coat.



ASPECT RATIO	WAVELENGTH	AMPLITUDE
5	15	3
10	30	3
15	45	3

Figure 4.1 – Test Article and Wave Defects

5-TEST SETUP

5.1-Location

The test was conducted at NREL's NWTC with the blade secured to the 1360-kN-m test stand in Bldg. 252 (A60).

5.2-Root Fixtures

The test stand was tilted to 0-deg.

A 4-in (10.16-cm) thick steel adapter plate was used to interface the test stand bolt circle and the blade root bolt circle. The adapter plate was secured to the test stand using quantity 24 UNC 1-8, 9-in (22.86-cm) length, Grade 8 steel fasteners on a 30-in (76.2-cm) bolt circle that were torqued to 550-ft-lbs (746-N-m) and lubricated with TS-70 moly paste.

The blade was secured to the adapter plate using quantity 12 UNF 3/4-16, 7-in (17.78-cm) length, Grade 8 steel fasteners on a 30-cm bolt circle that were torqued to 287-ft-lbs (389-N-m) and lubricated with TS-70 moly paste. To allow for internal sensor wiring, a 2-in (5.08-cm) thick steel shim plate with cable slots was positioned between the adapter plate and the blade root as shown in Figure 5.1.

Figure 5.1 – Root Fixtures

5.3-Blade Orientation

The blade was installed in the test fixture such that the HP surface was facing the laboratory ceiling. The blade was rotated such that the local chord at the 7-m station was at 0-deg relative to the laboratory floor, consistent with previous testing on CX-100 blades.

5.4-Load Introduction Method

Loads were introduced to the blade in the flapwise direction using a resonant loading method. The Universal Resonant Excitation (UREX) test system hardware was employed at the 1.6-m station, which provides inertial loading to the blade by oscillating masses with hydraulic actuators at the system resonant frequency, resulting in alternating moments about a mean bending moment. The mean bending moment is defined by the weight of the blade combined with the UREX and ballast saddle hardware. The actuators were displacement controlled using accelerometer feedback through MTS dual-mode control, which compensates for temperature effects and blade softening. While the mean test load is indeterminate (mass per unit length of blade is not precisely known a priori), the applied magnitude of the alternating load can be directly controlled by adjusting the displacement of the actuators. The UREX test system is shown in Figure 5.2.

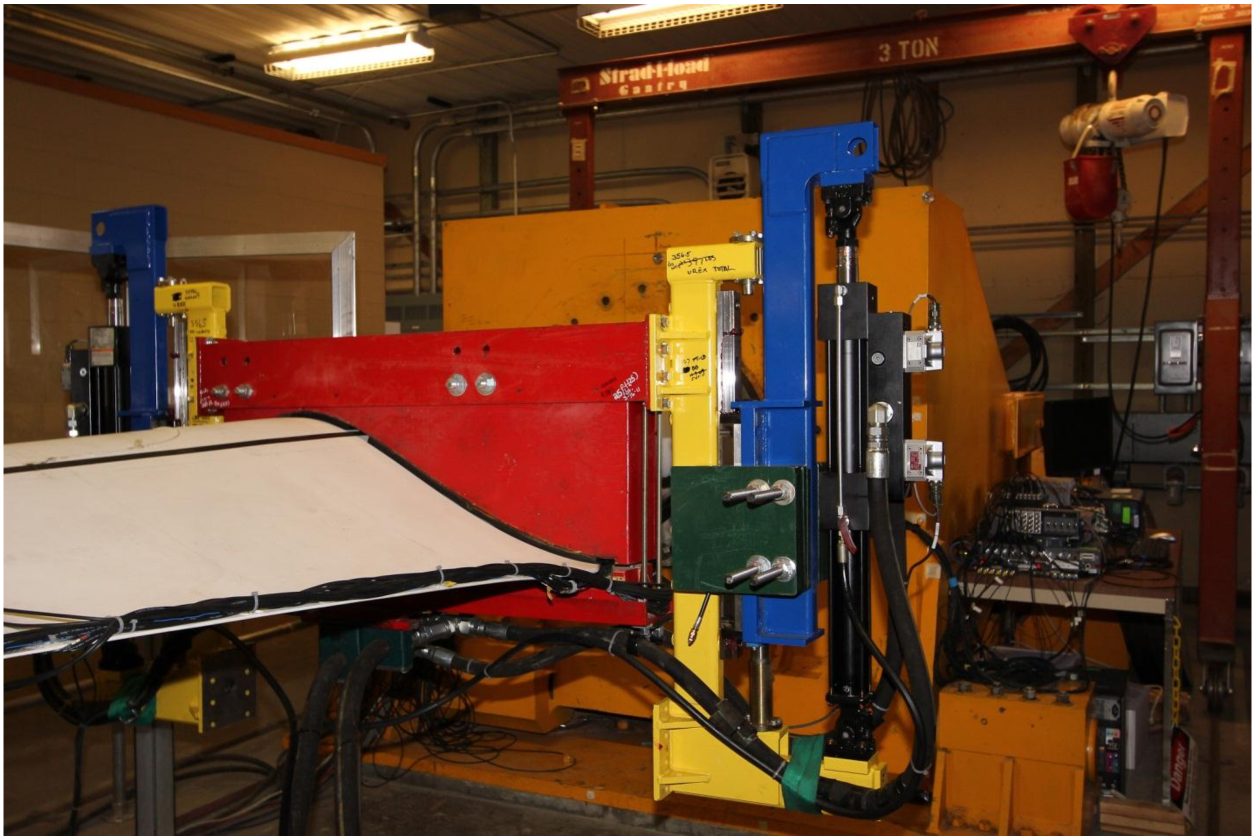


Figure 5.2 – UREX Test System

5.5-Load Saddles

Load saddles are utilized to transmit the inertial loads to the blade and to modify the moment distribution along the span of the blade. The saddles consist of wood forms surrounded by steel frames. The wood forms are constructed from 12.7-cm thick, in the spanwise direction, microlams which are custom fitted to the airfoil sections for that station. A thin strip of rubber is placed between the blade and wood form to protect the blade surface and ensure proper load distribution. The steel frames are constructed from I-beams and clamped together using quantity 4 Grade B7 threaded rods.

Two load saddles were used for this test, one centered at the 1.6-m station and one centered at the 6.75-m station. The UREX test system was mounted to the inboard 1.6-m saddle and the outboard 6.75-m was used as ballast to achieve the prescribed mean and oscillating loads.

Figure 5.3 – 6.75-m Ballast Saddle

5.6-Rigging Weights

The rigging weights of the UREX test system, load saddles, and adapter plates can be found Table 5.1. The weights were measured with a calibrated hanging scale.

Table 5.1 – Rigging Weights

Component	Weight (N)
2-in Steel Spacer Plate	356
4-in Steel Adapter Plate	4226
1.6-m Saddle	1148
UREX Test System	4564
Total at 1.6-m Station	**5712**
6.75-m Saddle	636
6.75-m Ballast Plates	783
Total at 6.75-m Station	**1419**

Note that the weights of the sensor systems and cabling have not been included in any analysis or measured, as the effect of these auxiliary packages is considered minor to the operation of the resonant system.

6-INSTRUMENTATION

Several condition monitoring and sensing systems were installed on the blade. However, the instrumentation described in the following sections refer to the NREL data acquisition systems only, as systems installed by test partners did not interface directly with the NREL data acquisition system. Additional instrumentation records including the BF06 document and calibration certificates can be found in Appendix C.

6.1-Load

A 1-kip load cell was used to measure the applied load during the static calibration pull and stiffness checks, and was employed in-line with the winch.

Table 6.1 – Load Cell Specifications

Type	Measurement Range	Manufacturer	Model	Serial
Load Cell	± 1-kip	Lebow	3132-1K	15899

6.2-Acceleration

Blade acceleration was measured using a biaxial Silicon Designs Model 2460-010 DC accelerometer, which was mounted in the center of the spar cap on the HP side of the blade at the 6.5-m station. The accelerometer X axis was oriented in the laboratory vertical direction to capture primary flapwise motion, and the Y axis was oriented in the laboratory horizontal to capture primary lead-lag motion. This accelerometer also served as feedback for our hydraulic controller.

Table 6.2 – Accelerometer Specifications

Type	Measurement Range	Manufacturer	Model	Serial
DC Accelerometer	± 10-g	Silicon Designs	2460-010	1337

6.3-Displacement

Blade tip displacements in the flapwise direction were measured during the calibration pull and stiffness checks using a Unimeasure HX-PA-30 string pot. The string pot was positioned directly beneath the blade tip, aligned with the laboratory vertical, and attached to the center of the tip on the LP side.

Table 6.3 – String Pot Specifications

Type	Measurement Range	Manufacturer	Model	Serial
String Pot	0 to 30-in	Unimeasure	HX-PA-30	32060221

Actuator displacements of the UREX test system hydraulics were measured using linear variable differential transformers (LVDTs).

Table 6.4 – LVDT Specifications

Type	Measurement Range	Manufacturer	Model	Serial	Direction
LVDT	± 10-in	MTS	244.12	10307278A	South
LVDT	± 10-in	MTS	244.12	10307278B	North

6.4-Temperature and Humidity

An Omega HX93DA sensor was used to measure the ambient temperature and relative humidity and was positioned near the blade root.

Table 6.5 – Omega Sensor Specifications

Type	Measurement Range	Manufacturer	Model	Serial
Temperature Humidity	-20° to 70°C 3 to 95 %RH	Omega	HX93A	1003018

6.5-Strain

A total of 27 strain gages were installed on the blade. These were single-axis foil gages of the type WK-05-250BG-350. They were oriented in the spanwise direction, 0-deg, and connected in a three-wire quarter-bridge 350-ohm configuration. Strain gages were used to both monitor local strain and indicate the applied loading during the fatigue test.

Table 6.6 – Foil Strain Gage Specifications

Type	Fatigue Life	Manufacturer	Model
Foil Strain Gage	± 2400-ue for 1e6 Cycles	Vishay	WK-05-250BG-350

6.6-Data Acquisition

The BSTRAIN data acquisition system was used for this test, which is based on National Instruments SCXI hardware technology and custom NREL developed LabVIEW software, BSTRAIN version 2.76. For the fatigue test, channels were sampled at 120-Hz and were recorded as peak-valley pairs. For the calibration pull and stiffness checks, time series data was recorded at 4-Hz. Channels are identified according to the channel map in Appendix B.

7-TEST LOADS

7.1-Design Loads

Test loading for the blade was based on the characteristic fatigue loading that was applied to previous CX-100 blades. Original target test loads were based on a 1-million cycle damage equivalent load and were provided by Sandia National Laboratories. Loads were represented as fully factored test loads for the flapwise direction. The design loads are shown in Table 7.1.

Table 7.1 – Fatigue Design Loads

Station (m)	Max (N*m)	Min (N*m)	Range (N*m)	Mean (N*m)
0.00	60770	6080	54690	33420
0.23	62420	6240	56180	34330
1.58	43360	4340	39020	23850
3.38	22950	2290	20660	12620
5.63	7100	710	6390	3910
7.43	1330	130	1200	730
9.00	0	0	0	0

7.2-Tare Loads

The tare load on the blade is due to the static weight of the blade and load saddles. This is a static bending moment that acts primarily in the flapwise direction and is present at all times during the test.

7.3-Partial Load Factors

The design loads presented were represented as fully factored test loads. No additional test load factors were applied to the design loads.

7.4-Test Loads

As the design loads were presented as fully factored loads, they were used as the target test loads.

Table 7.1 – Fatigue Target Test Loads

Station (m)	Range (N*m)
0.00	54690
0.23	56180
1.58	39020
3.38	20660
5.63	6390
7.43	1200
9.00	0

For resonance testing, the mean load is fixed and equal to the tare load. The alternating load was scaled by adjusting the excitation input (i.e. actuator stroke), but the characteristic shape about the mean load remains essentially unchanged.

8-TESTING AND RESULTS

8.1-Property Testing

The blade weight and center of gravity (CG) were measured prior to installation of blade on test fixture using a single point pick with a sling and are shown in Table 8.1.

Table 8.1 – Blade Weight and CG

Property	Measured Value
Weight	1778-N
CG	2.26-m

A basic modal test was conducted after the load introduction hardware was installed using strain gage response while applying a manual excitation force at the blade tip. The fundamental flap and edge frequencies were determined using a Fast Fourier Transform (FFT) synthesis of the recorded time series signals. The results are shown in Table 8.2.

Table 8.2 – Test System Frequencies

Mode	Frequency (Hz)
1st Flap	1.81
2nd Flap	4.20
1st Lead-Lag	2.64

A full modal survey was conducted by UML prior to saddles being installed. The results of their tests are not reported here.

8.2-Strain vs Load Calibrations

The applied test loads are measured based on strain gage signals, which are calibrated through the application of a single point static load. From the known applied bending moment and resulting strain measurements during the calibration and stiffness check test, the relationship between moment and strain was quantified. The static calibration loads were applied before the fatigue test and then repeated periodically throughout the test program, as strain sensitivities can change slightly during loading and for cases where gages fail and are replaced. All static load pulls were conducted at the 6.75-m station with an applied load of 2224-N to create a root moment of 15-kN-m, which is about 25% of the target range test loads.

The flapwise strain versus load calibration was performed by pulling up towards the ceiling with the overhead gantry crane in the negative flapwise direction (low pressure to high pressure). The load was applied in the horizontal center of the saddle, approximately 50% of blade chord.

The lead-lag strain versus load calibration was performed by using the overhead gantry crane pulling horizontal to the laboratory north in the negative lead-lag direction (leading edge to trailing edge). The load was applied in the vertical center of saddle, approximately in-line with the leading edge. A single sheave was used to apply a horizontal load to the saddle by redirecting the load from pulling vertical with the overhead gantry crane.

The calculated sensitivities from the static calibration pulls are shown in Table 8.3.

Table 8.3 – Calibration Pull Sensitivities

	Flapwise Calibration Pull			Lead-Lag Calibration Pull		
Strain Gage	**Range (ue)**	**Moment (kN-m)**	**Sensitivity (kN-m/ue)**	**Range (ue)**	**Moment (kN-m)**	**Sensitivity (kN-m/ue)**
SG-0000-HP	18.68	15.12	0.81	21.41	15.39	0.72
SG-0000-LP	20.04	15.12	0.75	20.96	15.39	0.73
SG-0444-HP	204.99	14.13	0.07	38.72	14.38	0.37
SG-0675-HP	314.32	13.61	0.04	50.11	13.85	0.28
SG-0675-LE	98.40	13.61	0.14	638.21	13.85	0.02
SG-0675-TE	56.49	13.61	0.24	708.36	13.85	0.02
SG-1200-HP	307.49	12.44	0.04	134.84	12.66	0.09
SG-1200-LP	262.39	12.44	0.05	38.27	12.66	0.33
SG-1350-HP	349.85	12.10	0.03	136.21	12.31	0.09
SG-1350-LE	191.78	12.10	0.06	674.19	12.31	0.02
SG-1350-TE	57.85	12.10	0.21	403.60	12.31	0.03
SG-2000-LE	80.18	10.64	0.13	388.12	10.83	0.03
SG-2550-HP	400.42	9.41	0.02	32.80	9.58	0.29
SG-2550-LE	101.58	9.41	0.09	397.68	9.58	0.02
SG-3000-HP	478.77	8.40	0.02	20.95	8.55	0.41
SG-3000-LP	452.35	8.40	0.02	63.78	8.55	0.13
SG-4500-HP	614.06	5.04	0.01	47.83	5.13	0.11
SG-4500-LP	577.16	5.04	0.01	34.62	5.13	0.15
SG-5500-HP	612.24	2.80	0.00	86.55	2.85	0.03
SG-5500-LP	615.43	2.80	0.00	23.69	2.85	0.12
SG-6950-HP	26.42	0.01	0.00	18.22	0.01	0.00
SG-6950-LP	22.32	0.01	0.00	23.23	0.01	0.00

8.3-Flapwise Fatigue Testing

The laboratory fatigue testing of the UML Defect 9-m wind turbine blade was conducted from November 2011 to March 2012 in the A60 test bay as shown in Figure 8.1. The blade was loaded primarily in the flapwise direction using a resonant excitation method. Applied loads were measured via calibrated strain gages. Matlab scripts were developed for all the post-processing and analysis performed on the data. The raw mean and range data versus cycle count collected for all active channels can be found in Appendix A.

Figure 8.1 – Flapwise Fatigue Test

A total of 14 load blocks were achieved during this test, which lasted for 1,968,186 cycles, before a structural failure occurred at the 5-m station on the HP side with the final applied load at 130% of the target load range. Load block information is shown in Table 8.4. Low-amplitude loading of the blade was conducted post-failure for a limited number of cycles in order to collect additional data sets for test partners and are not included in the testing matrix.

Table 8.4 – Fatigue Test Matrix

Load Block	% of Target Load Range	Applied Load Range (kN-m)	Start Cycle	End Cycle	# of Cycles in Block
1	7	4.69	0	5077	5077
2	15	8.83	5078	16960	11882
3	22	11.69	16961	25063	8102
4	30	17.09	25064	165003	139939
5	40	21.92	165004	227538	62534
6	50	27.65	227539	277745	50206
7	60	33.38	277746	392749	115003
8	70	38.25	392750	445440	52690
9	80	43.44	445441	498915	53474
10	90	49.18	498916	559379	60463
11	100	56.08	559380	1716088	1156708
12	110	60.71	1716089	1849101	133012
13	120	66.62	1849102	1915592	66490
14	130	72.33	1915593	1968186	52593

The applied test loads for each load block as compared to the target load are shown in Figure 8.2.

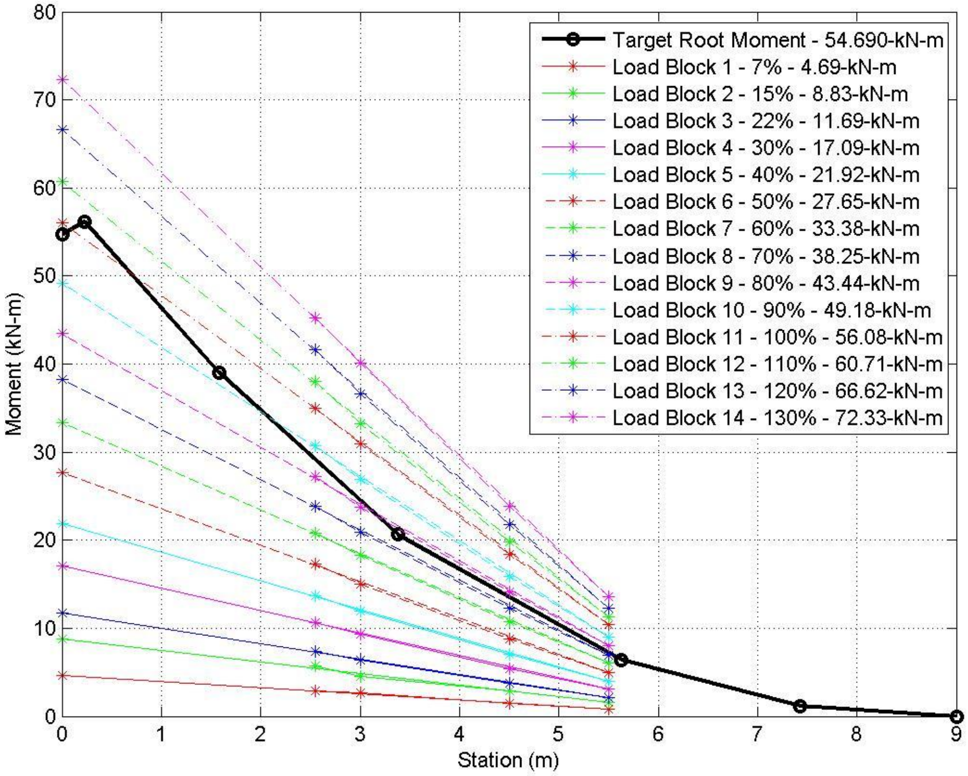


Figure 8.2 – Applied Test Loads

A representative timeline of the flapwise fatigue test is provided for the reference strain gage SG4500HP as shown in Figure 8.3. Prior to the primary crack failure, no significant structural changes were observed.

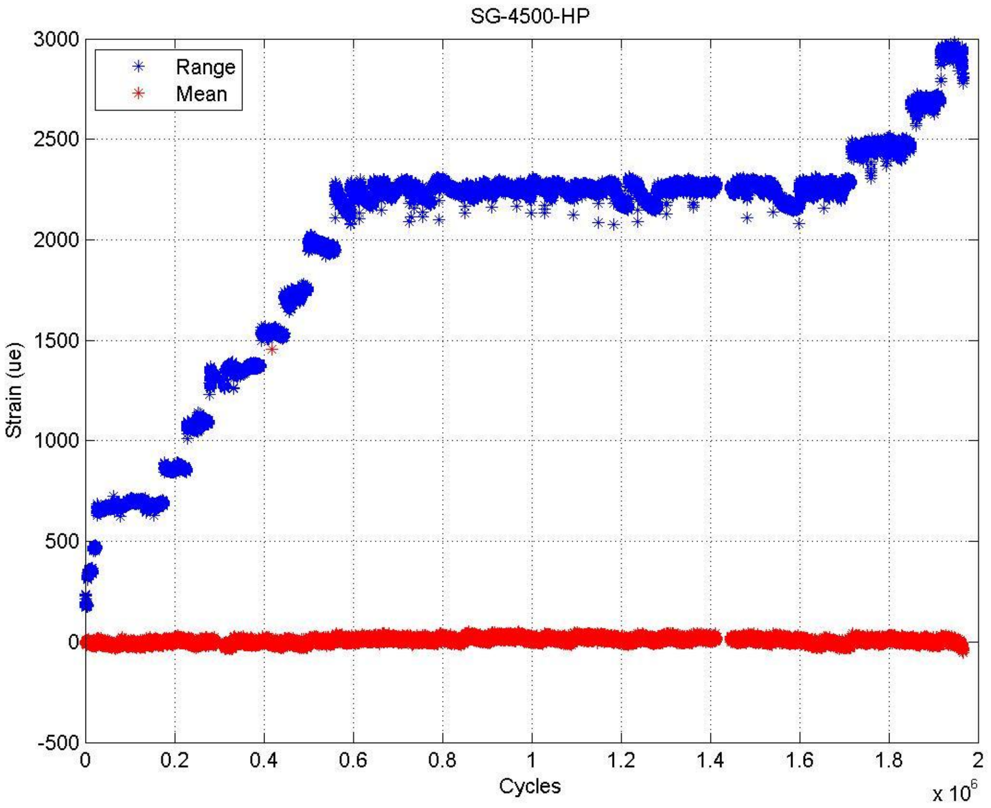


Figure 8.3 – Representative Timeline of Flapwise Fatigue Test

The structural failure was first observed as a 14-cm long crack at 1,956,280 cycles, which occurred on the high pressure surface at the 5-m station in the spar cap biased towards the leading edge as shown in Figure 8.4. This crack then propagated to 16.5-cm in length before resulting in the final failure mode which occurred during load block 14 at an applied load range of 130% of the target load range at 1,968,186 cycles. A post failure stiffness check was performed and the analysis results revealed approximately an 8% decrease in stiffness. Additional evidence confirming the failure was the inability to maintain a constant load amplitude and frequency.

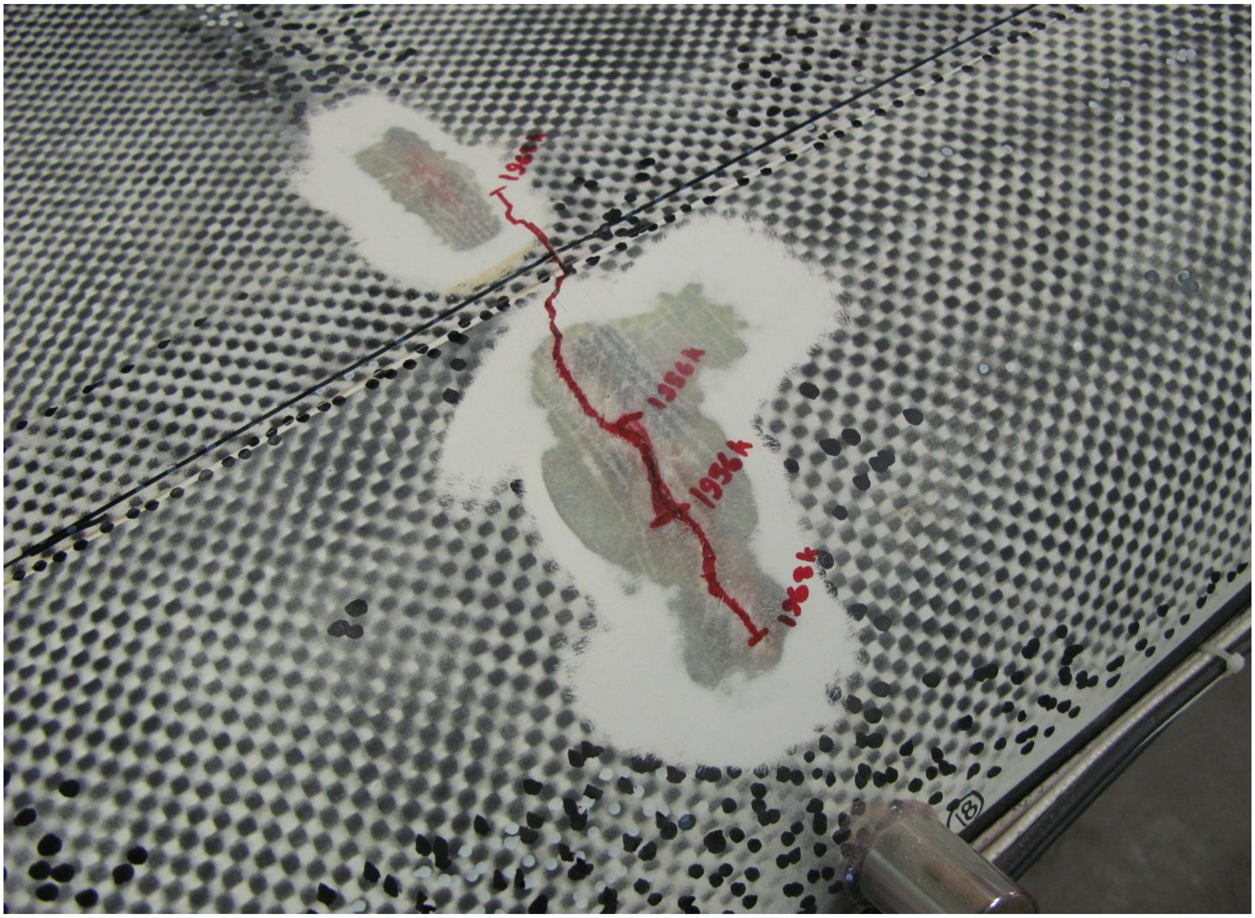


Figure 8.4 – Structural Failure (HP Side at the 5-m Station)

Luna Technologies system using fiber optics and UML digital image correlation measurements reported that there were stress risers on the order of 2-3 times in the defect areas (spikes at 2.5, 5 and 6-m) as compared to surrounding areas, as shown in Figure 8.5 [4]. Strain gages used in the primary data acquisition system were located approximately half a meter away from these defects.

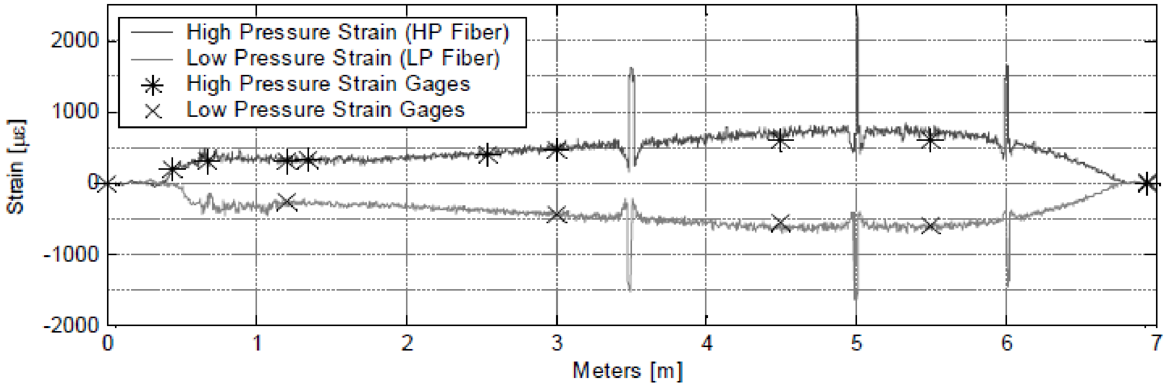


Figure 8.5 – Fiber Optic and Foil Strain Gage Measurement Comparison

(figure courtesy Luna Innovations Inc.)

In addition to visual inspections, thermal imaging of the blade revealed hot spots at the defect areas, as shown in Figures 8.6, 8.7, and 8.8.

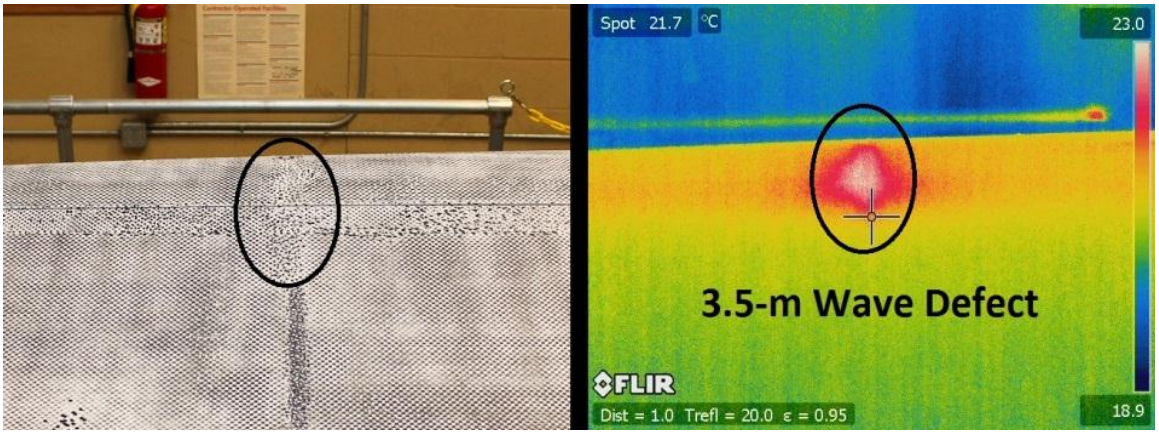


Figure 8.6 – Thermal Image of Wave Defect at 3.5-m

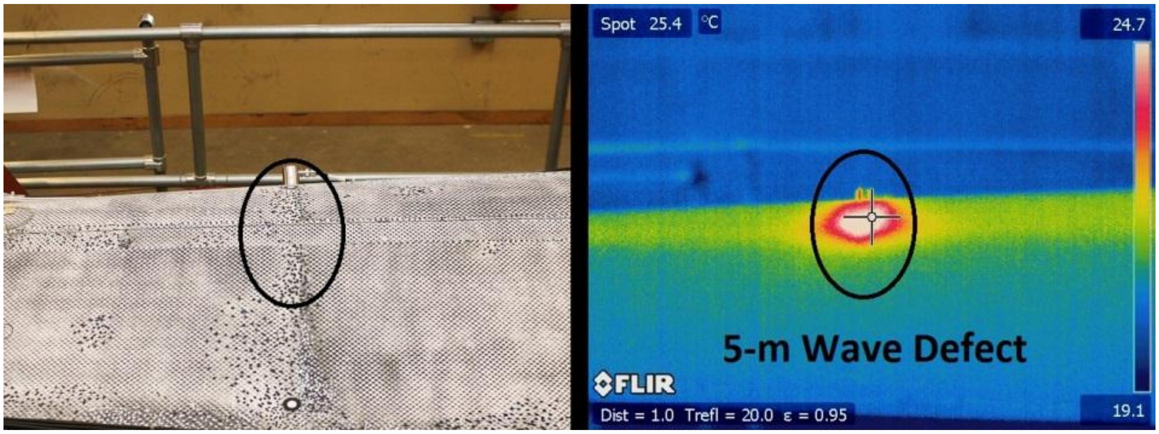


Figure 8.7 – Thermal Image of Wave Defect at 5-m

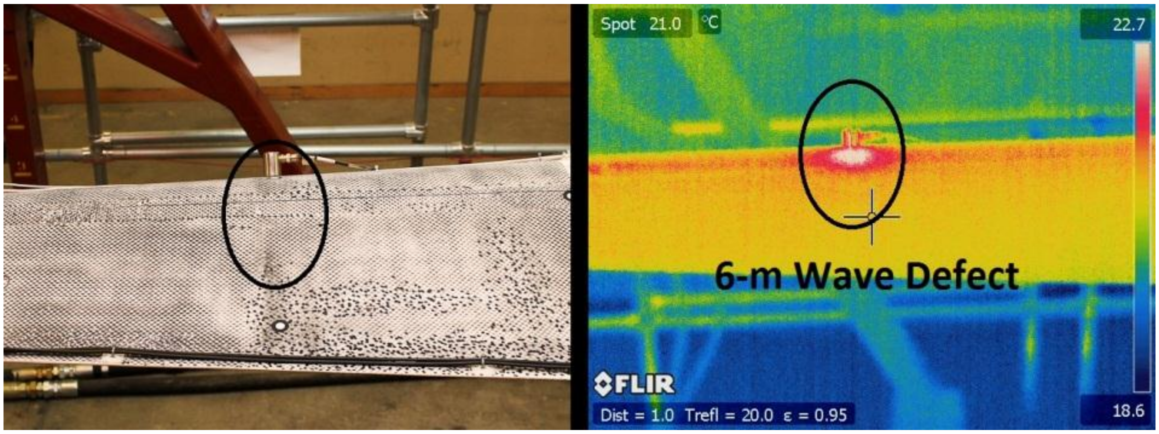


Figure 8.8 – Thermal Image of Wave Defect at 6-m

8.4-Stiffness Checks

Periodic stiffness checks were performed and the results are shown in Table 8.5. Stiffness values were calculated based on the load cell measuring applied load and the string pot measuring tip deflection. For the first 1-million cycles, there was observed to be about a 4% change in stiffness. At 1.9-million cycles there was an additional 2% change in stiffness with the final post failure stiffness check revealing another 2% change. The total change in stiffness from the calibration pull to the post failure stiffness check was about 8%.

Table 8.5 – Stiffness Check Results

Check	Stiffness (kN/m)	% Change
Calibration Pull	2.38	0.00
390k Cycles	2.34	1.72
613k Cycles	2.30	3.25
1.2M Cycles	2.29	3.92
1.7M Cycles	2.47	3.23
1.9M Cycles	2.24	5.89
End of Test	2.18	8.35

8.5-Damage Estimation

As an estimate of fatigue life performance, the damage equivalent load (DEL) was determined based on the relationship derived in the equations shown in Figure 8.5.

$$Eq.1 \quad d_i = \left(\frac{M_a}{M_u}\right)^m * \frac{N_a}{N_{eq}}$$

$$Eq.2 \quad D = \sum d_i$$

$$Eq.3 \quad DEL = M_u * D^{\frac{1}{m}}$$

Figure 8.5 – Damage Estimation Equations

Equation 1 is used to calculate the damage estimate for each bin, where *Ma* is the applied moment, *Mu* is the target moment, *m* is the fatigue inverse slope parameter (*m = 12*), *Na* is the applied number of cycles in the bin, and *Neq* is the equivalent target cycle count (*Neq = 1e6 cycles*). The bins are then summed to compute the total damage *D* in Equation 2. The DEL is then calculated by multiply the target moment *Mu* by the total damage *D* raised to a power of *1/m,* as shown in Equation 3. The inverse fatigue slope parameter of 12 was chosen as a compromise between the value of 10 typically used for glass composites and 14 used for carbon composites [5]. The results are shown in Figure 8.9.

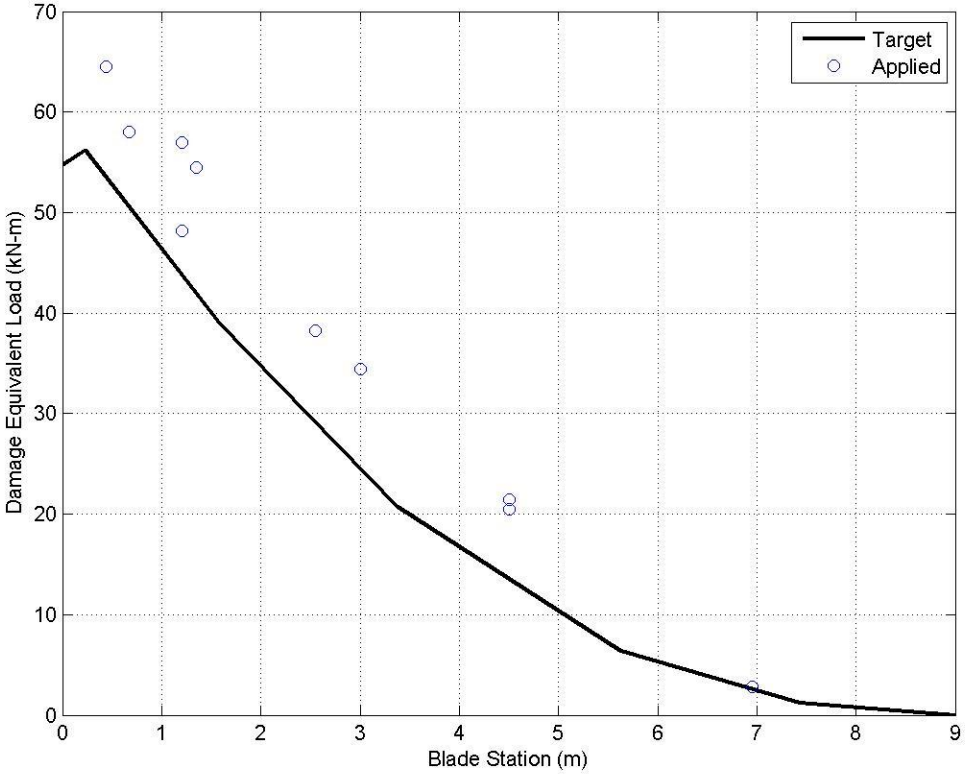


Figure 8.9 – Damage Equivalent Loads

8.6-Post Fatigue Failure Residual Strength Static Test

After the fatigue test was concluded, a single-point quasi-static load to failure was conducted to obtain additional information about the residual strength of the inboard wave defects located at the 3.5-m station. For this, the blade was cut at the 4.9-m station and the outboard tip section removed.

The test load was introduced to the blade via quasi-static single point load applied at the 4.8-m station with the overhead gantry crane pulling in the negative flapwise direction (LP to HP) as shown in Figure 8.7. The load introduction hardware consisted of a 44.5-kN hoist ring secured to 31.75-mm thick steel plates that was fastened together with 12.7-mm Grade B7 threaded rods. The inside of the airfoil was filled with wood laminates and epoxy for 100-mm on either side of the shear web and 200-mm deep, in order to prevent crushing and minimize airfoil deformation. The threaded rods penetrated through both high and low pressure skins, the wood epoxy filler, and the carbon fiber spar cap on the leading edge side, and were torqued to 40.7-N*m to prevent separation of the plates. The pull point was centered over the shear web.

Figure 8.10 – Post Fatigue Failure Residual Strength Flapwise Static Test

The characteristic, design, and target test loads are based on static bending moments applied to previous tests of CX-100 blades and are shown in Table 8.6. The design loads include a 1.35 factor over the characteristic loads. The target test loads include a 1.15 consequence of failure factor over the design loads, referenced from Annex A of the IEC 61400-23 standard [6].

Table 8.6 – Static Target Test Loads

Station (m)	Station (%R)	Characteristic Load (kN-m)	Design Load (kN-m)	Test Load (kN-m)
0.00	0.00	87.60	118.26	136.00
1.80	20.00	48.90	66.02	75.92
3.20	35.56	27.00	36.45	41.92
4.20	46.67	16.80	22.68	26.08
6.20	68.89	4.50	6.08	6.99
7.20	80.00	1.80	2.43	2.79
8.20	91.11	0.48	0.65	0.75
9.00	100.00	0.00	0.00	0.00

For the static test, the blade was loaded in steps of 25% of the target test load. The load was gradually applied, held for 30 seconds at load, and then returned to zero before moving to the next step. This was repeated until a buckling failure was observed at approximately 115% of the target test load at a maximum applied load 32.6-kN. The test matrix is shown in Table 8.7. The applied loads and tip deflection as a function of time are shown in Figures 8.11 and 8.12 respectively. Note the string pot was removed after 100% loading.

Table 8.7– Static Test Matrix

Step	% of Target Load	Applied Load (kN)	Applied Moment (kN-m)	Tip Deflection (m)
1	25	7.15	34.32	0.06
2	50	14.25	68.40	0.11
3	75	21.50	103.20	0.17
4	100	28.30	135.84	0.22
5	115	32.60	156.48	na

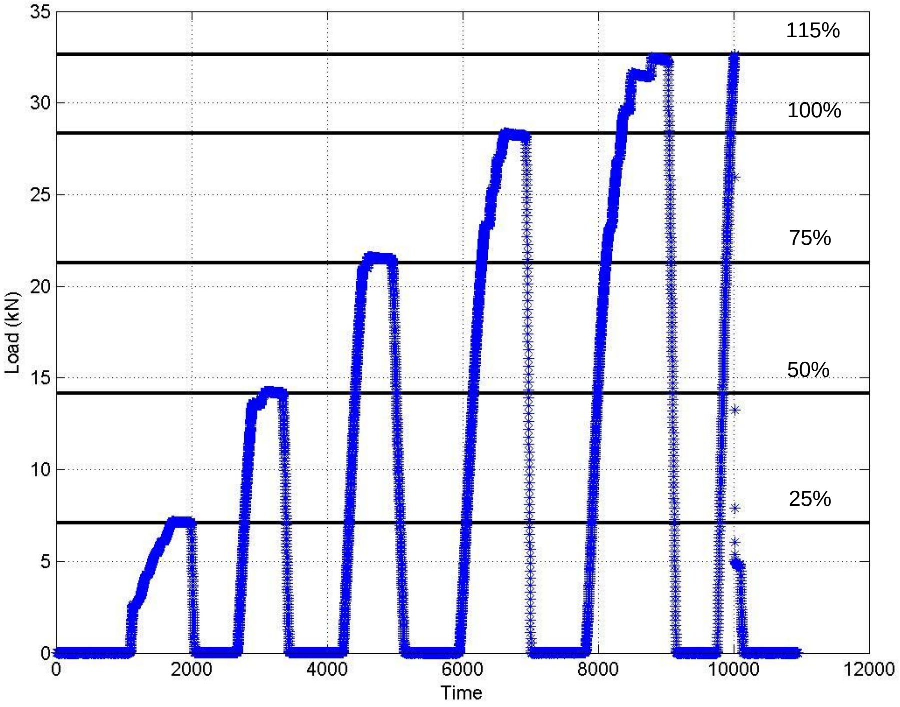


Figure 8.11 – Applied Loads for Residual Strength Static Test

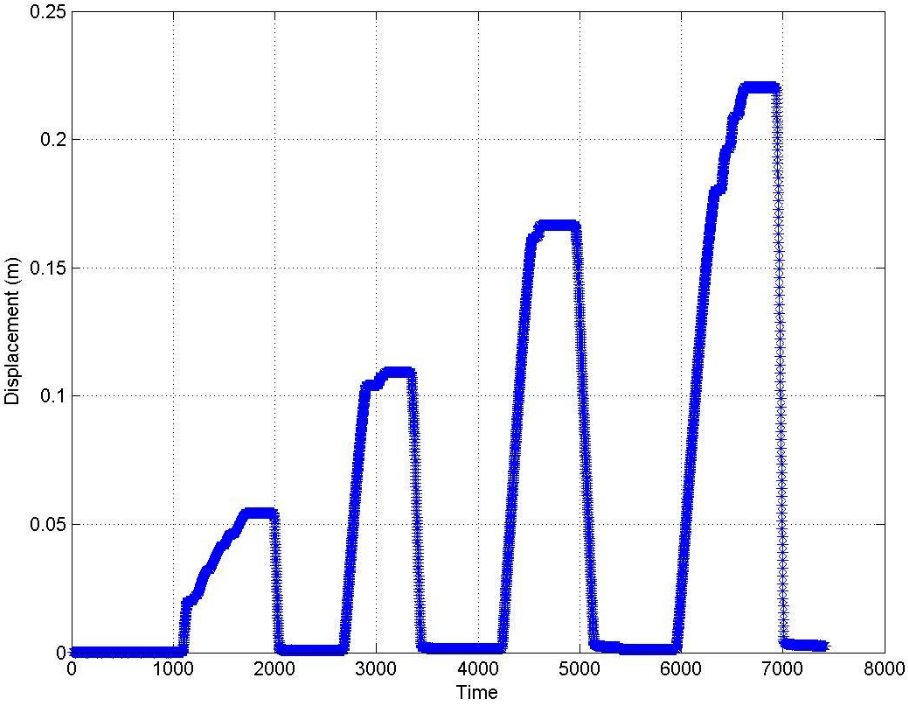


Figure 8.12 – Tip Deflection for Residual Strength Static Test

The failure mode appeared as localized buckling at the 3.5-m station on the high pressure surface as shown in Figure 8.13. The crack spanned the entire surface from the leading edge to the trailing edge.

Figure 8.13 – Static Test Buckling Failure (HP Side at 3.5-m Station)

9-POST MORTEM

No post mortem inspections or blade cutting was conducted.

10-MEASUREMENT UNCERTAINTITY

Table 10.1 provides uncertainty estimates for the recorded measurements with a 95% confidence level (coverage factor k = 2).

Table 10.1 – Uncertainty Estimates

Instrument	Serial Number	Uncertainty (% FS)	Uncertainty (FS)	Units
Load Cell	15899	0.26	11.53	N
Temperature	1003018	1.25	0.94	degC
String Pot	32060221	0.29	2.18	mm
Accelerometer	1337	2.02	0.10	g
Strain Gages	WK-05-250BG-350	1.78	42.68	ue

11-EXCEPTIONS FROM STANDARD PRACTICE

11.1-Deviations from the Test Plan

Post fatigue failure, a residual strength static test to failure was conducted.

11.2-Deviations from the Standard

Not applicable, research and development test, not for certification purposes.

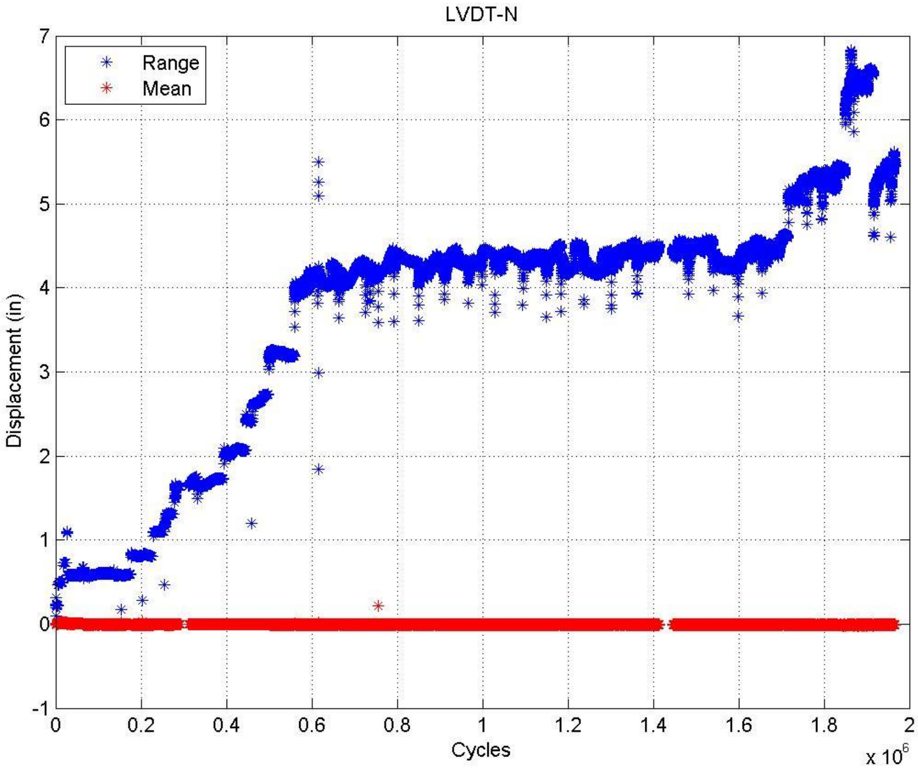
11.3-Deviations from Quality Assurance

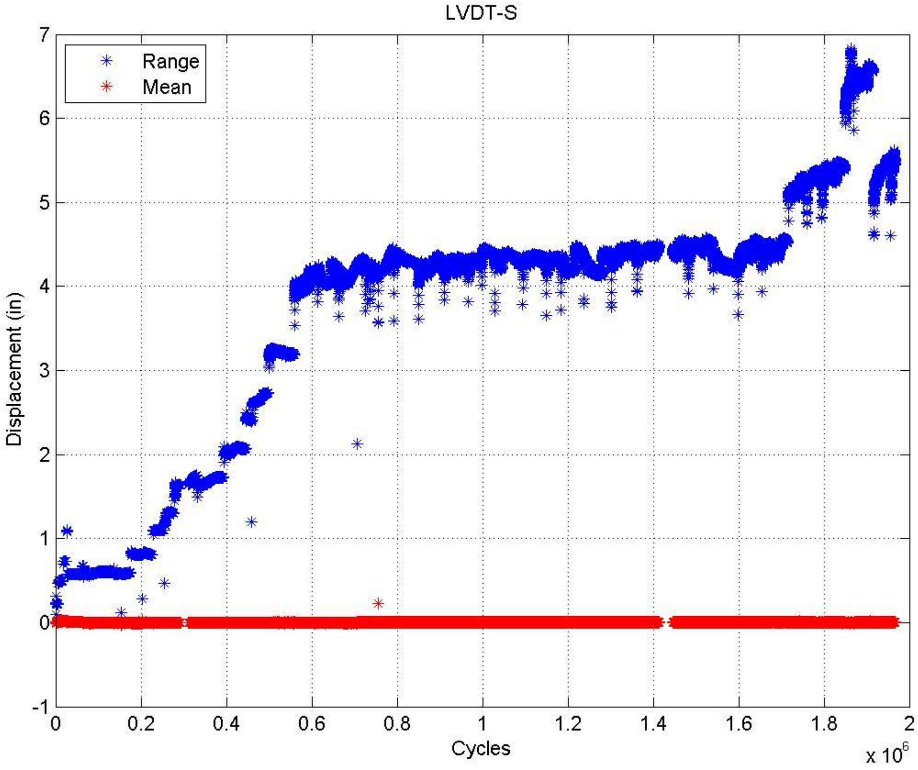
Fluke process calibrator and Omega temperature sensor were post calibrated.

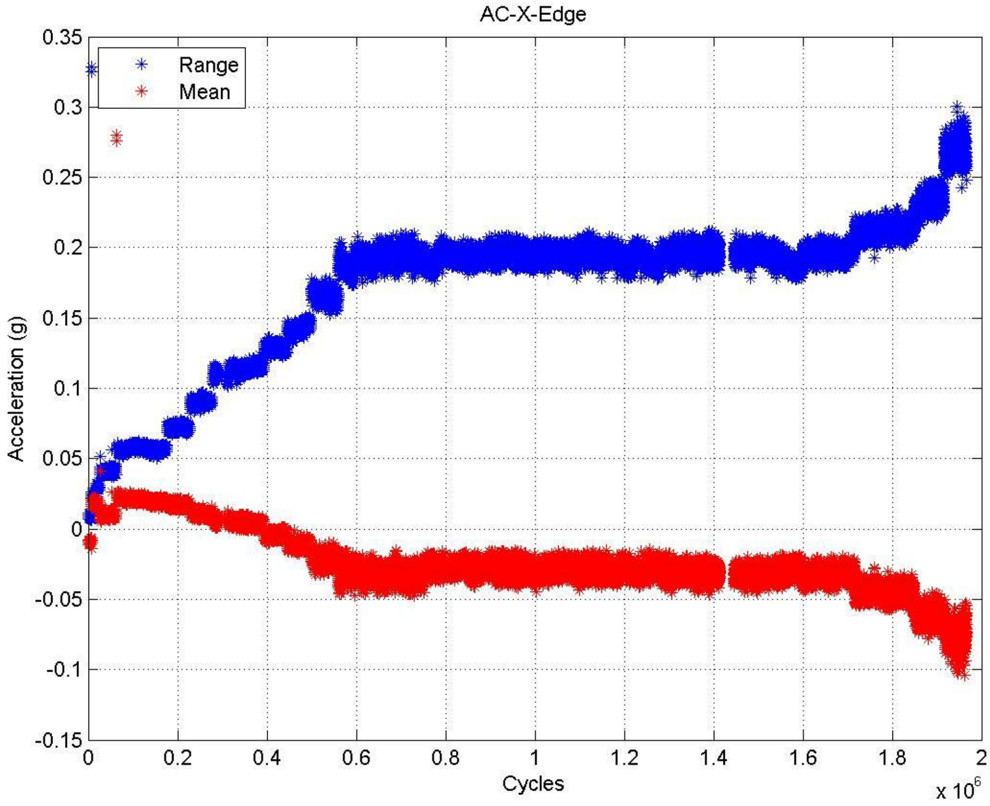
12-REFERENCES

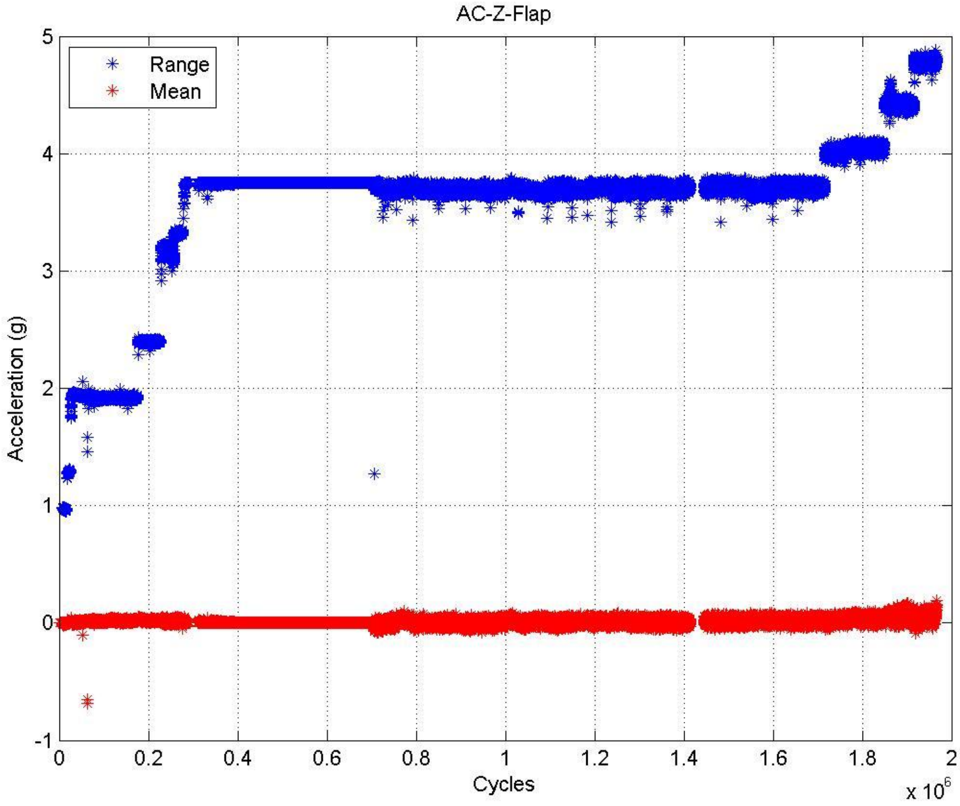
1. Safe Operating Procedures, No. 515009412, *Conducting Structural Tests at the NWTC,* M. Jenks, Center 5000.
2. Test Plan, LANL 9m Blade Fatigue Test Plan 110802.
3. Readiness Verification, Final RV MS-11-08-04 NWTC-252 Signed.
4. J. Renee Pedrazzani, Sandie M. Klute, Dawn K. Gifford, Alex K. Sang, Mark E. Froggatt, Embedded and Surface Mounted Fiber Optic Sensors Detect Manufacturing Defects and Accumulated Damage as a Wind Turbine Blade is Cycled to Failure, Luna Innovations Inc.
5. Josh Paquette, Jeroen van Dam, Scott Hughes, and Jay Johnson, Fatigue Testing of 9 m Carbon Fiber Wind Turbine Research Blades, AIAA paper.
6. IEC 61400-23 Technical Specification, Wind turbine generator systems – Part 23: Full-scale structural testing of rotor blades, First Edition, Published April 2001.

APPENDIX A-Peak-Valley Data during fatigue testing






AC-X-Edge
Range
Mean
Acceleration (g)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Cycles
x 10^6


AC-Z-Flap
Range
Mean
Acceleration (g)
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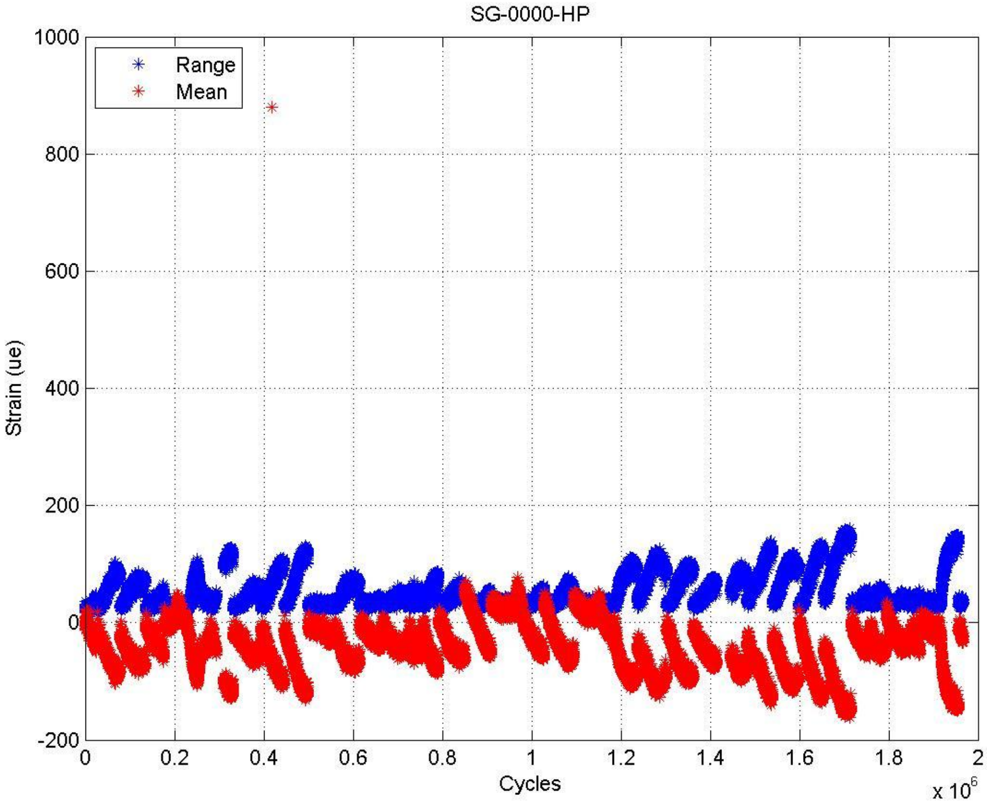
4
3
2
1
0
-1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Cycles
x 10^6


SG-0000-HP
Range
Mean
Strain (ue)
1000
800
600
400
200
0
-200
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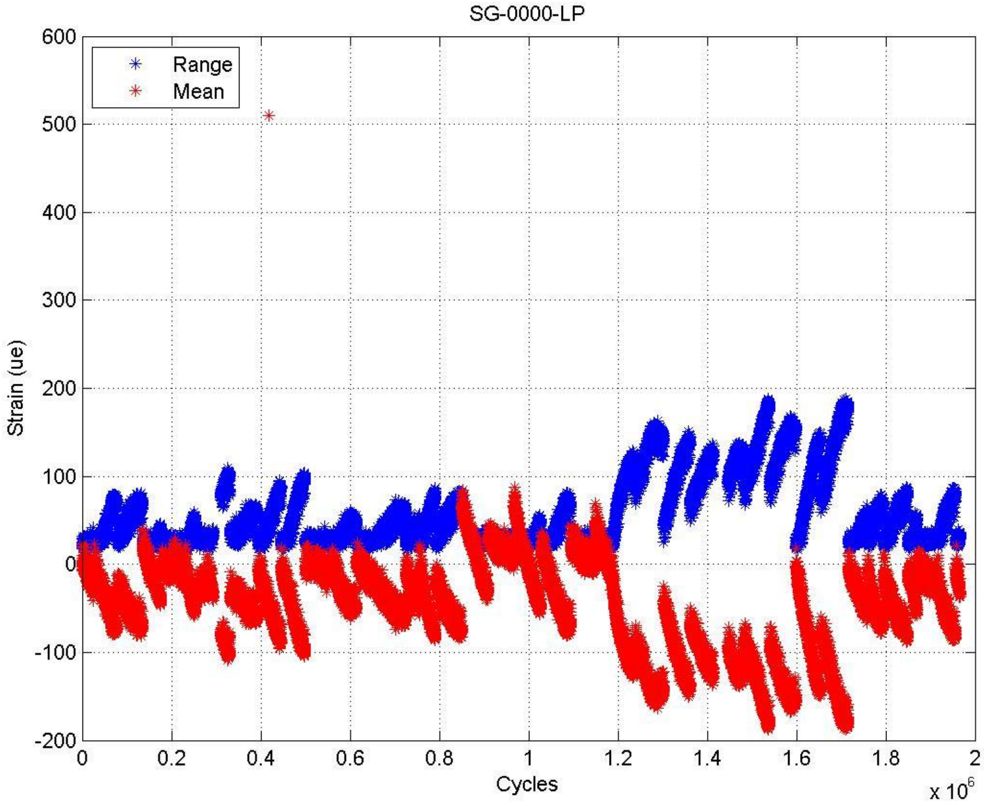
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Cycles
x 10^6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Range
Mean
Strain (ue)
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500
400
300
200
100
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-100
-200
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1
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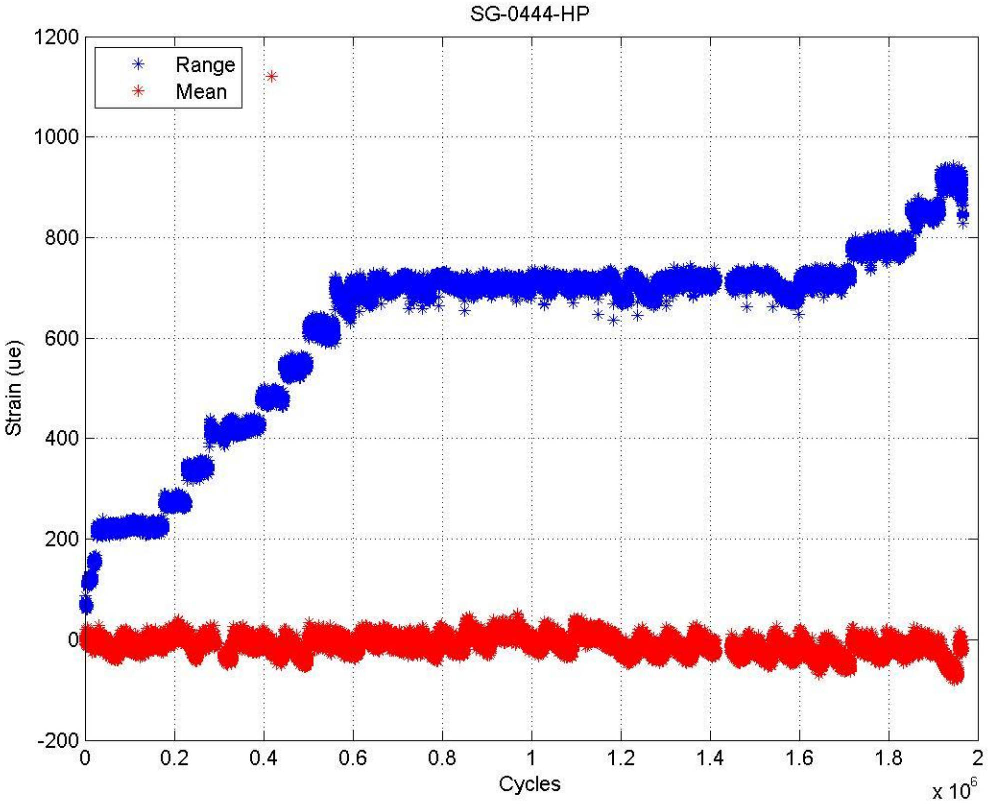
1.4
1.6
1.8
2
Cycles
x 10^6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Strain (ue)
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600
400
200
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1.2
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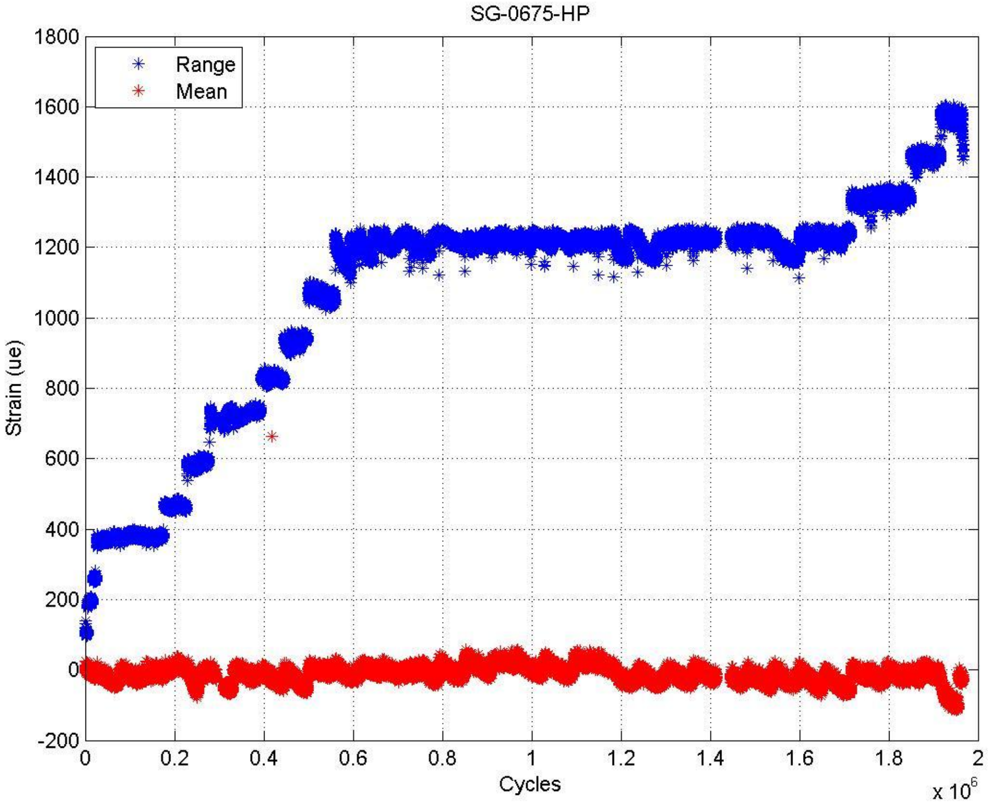
1.6
1.8
2
Cycles
x 10^6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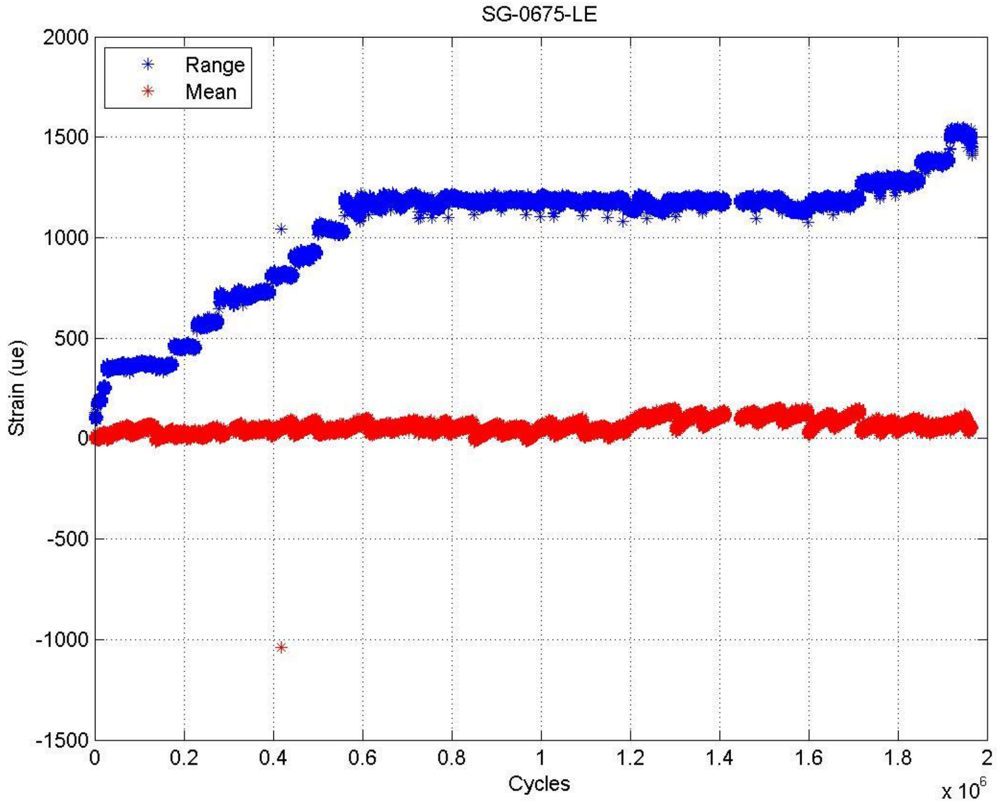
Mean
Strain (ue)
1800
1600
1400
1200
1000
800
600
400
200
0
-200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Cycles
x 10^6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Mean
Strain (ue)
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1500
1000
500
0
-500
-1000
-1500
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0.8
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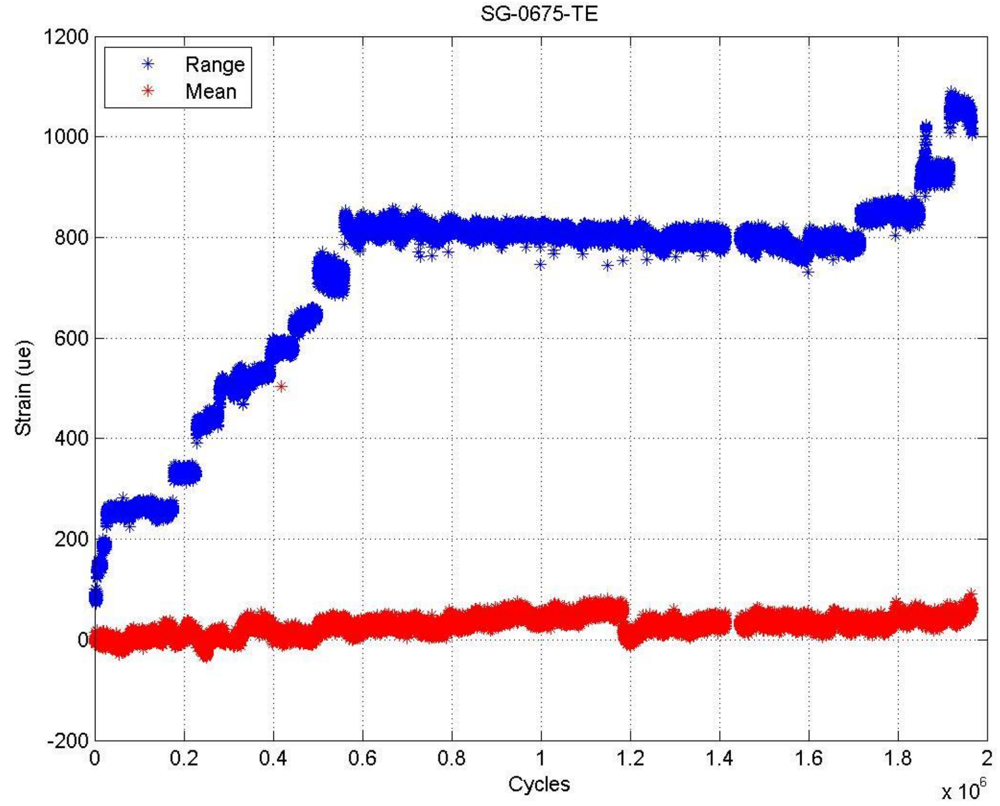
1.2
1.4
1.6
1.8
2
Cycles
x 10^6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Mean
Strain (ue)
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1000
800
600
400
200
0
-200
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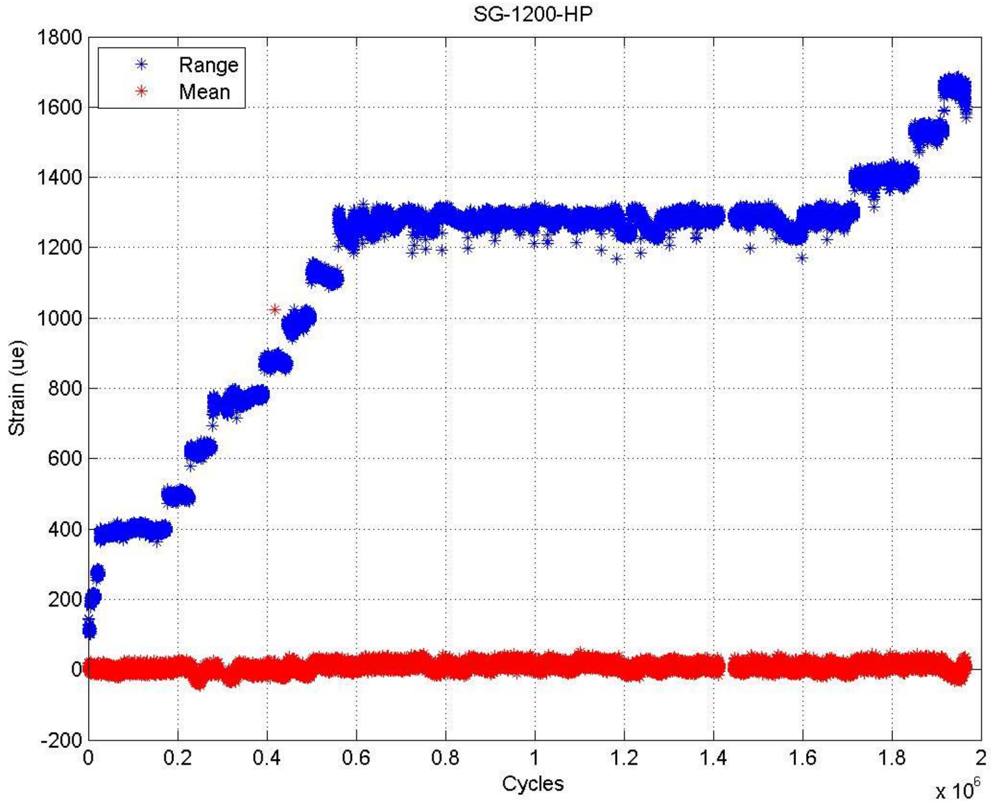
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Cycles
x 10^6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Mean
Strain (ue)
Cycles
x 10^6
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1600
1400
1200
1000
800
600
400
200
0
-200
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0.2
0.4
0.6
0.8
1
1.2
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1.6
1.8
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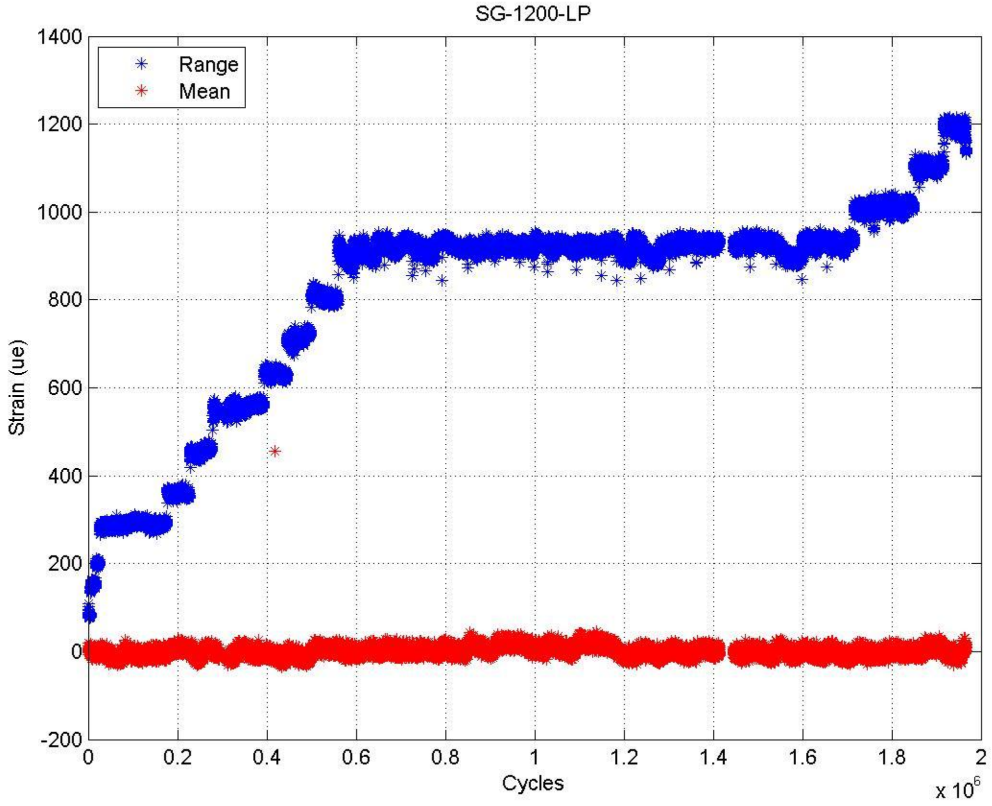
SG-1200-LP
Range
Mean
Strain (ue)
Cycles
x 10^6
1400
1200
1000
800
600
400
200
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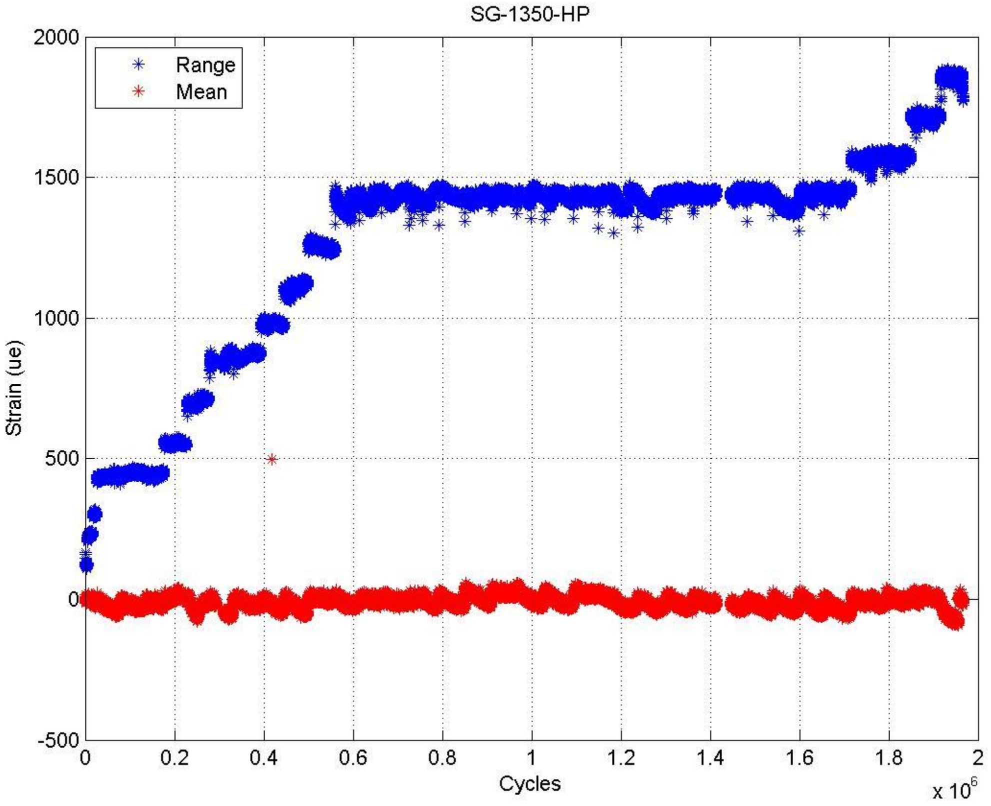
-200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2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Range
Mean
Strain (ue)
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1500
1000
500
0
-500
0
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0.6
0.8
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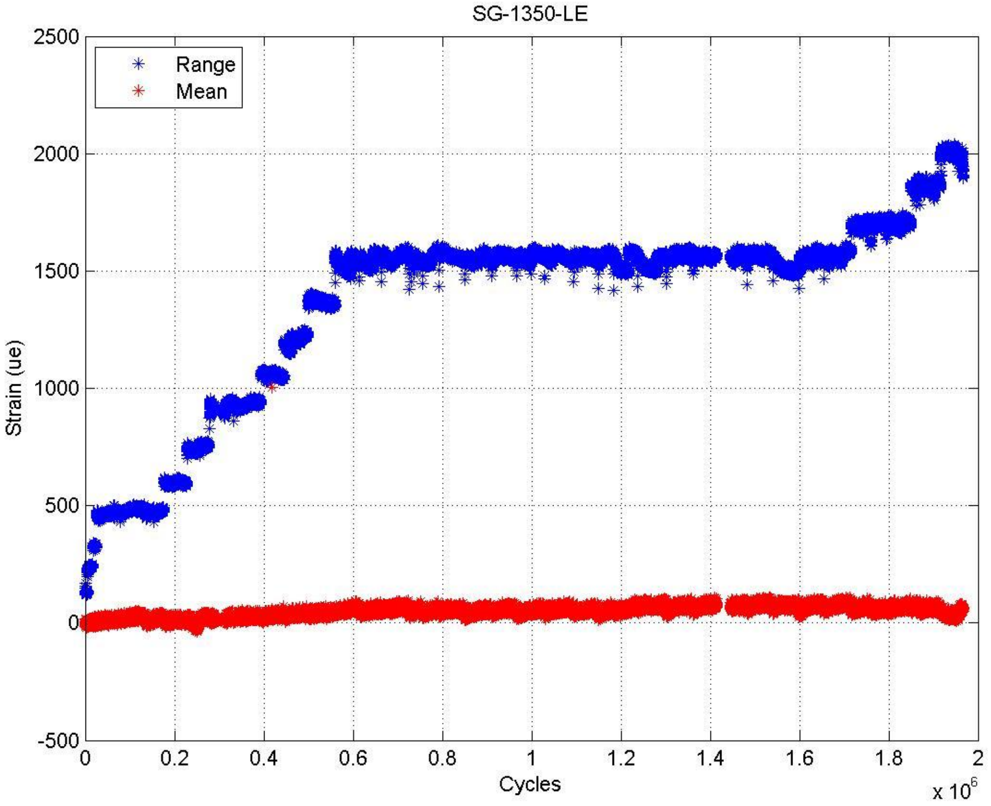
1.2
1.4
1.6
1.8
2
Cycles
x 10^6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Strain (ue)
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2000
1500
1000
500
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-500
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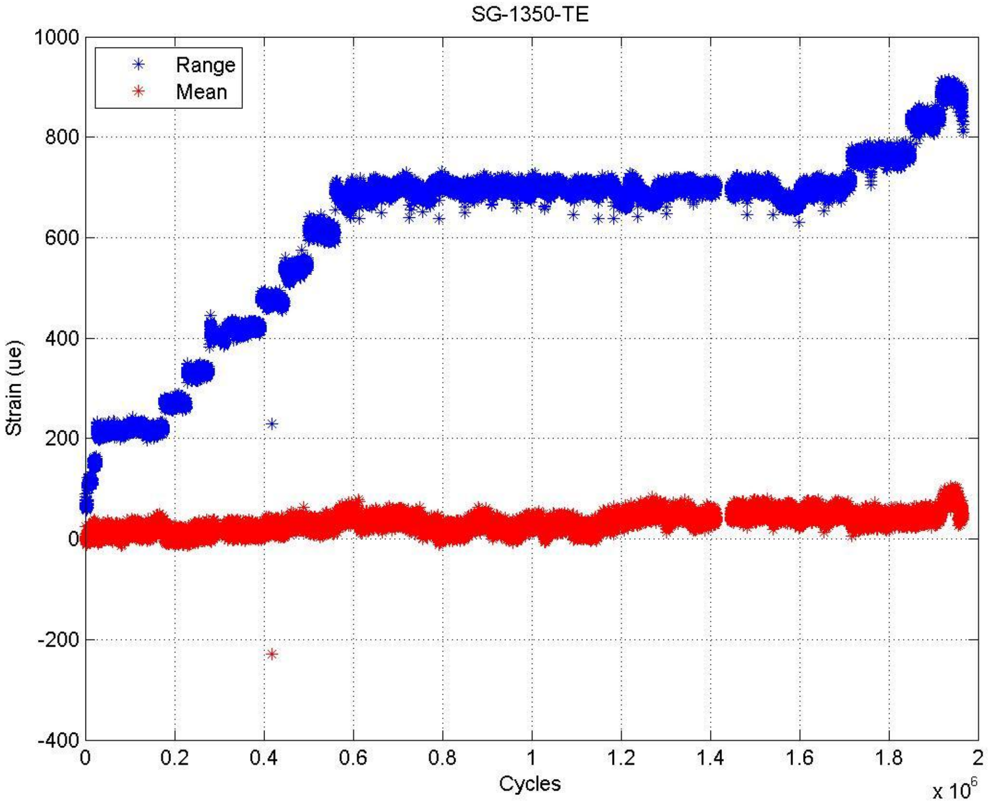
1.2
1.4
1.6
1.8
2
Cycles
x 10^6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Mean
Strain (ue)
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800
600
400
200
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-200
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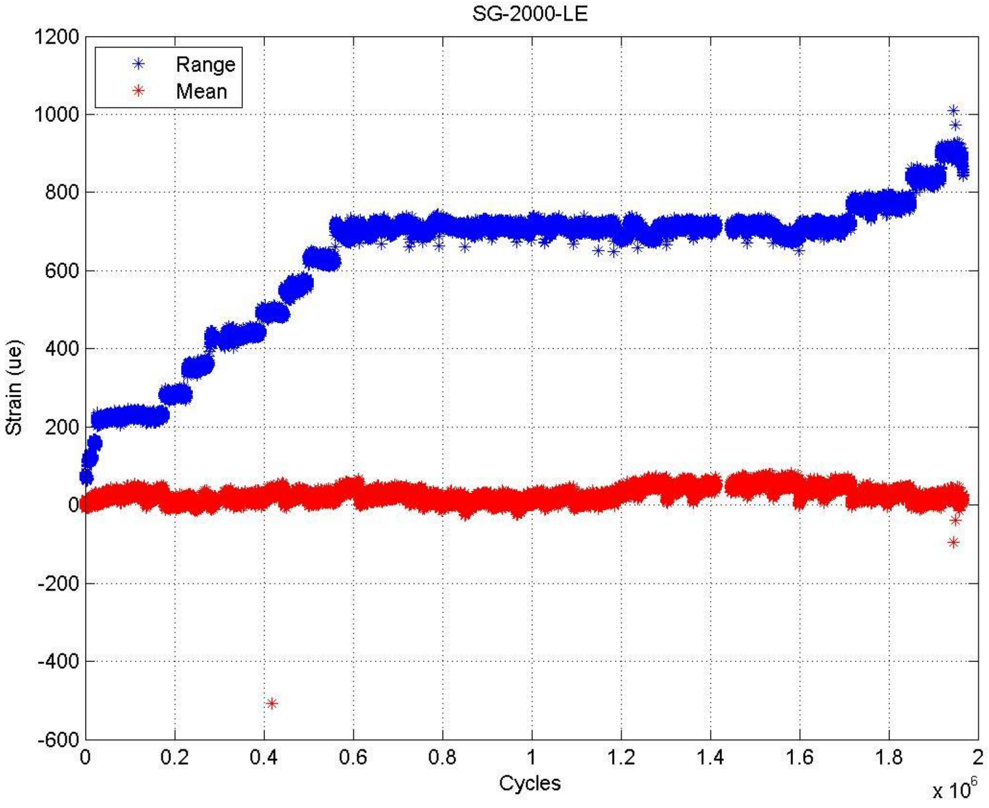
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Cycles
x 10^6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Mean
Strain (ue)
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1000
800
600
400
200
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-400
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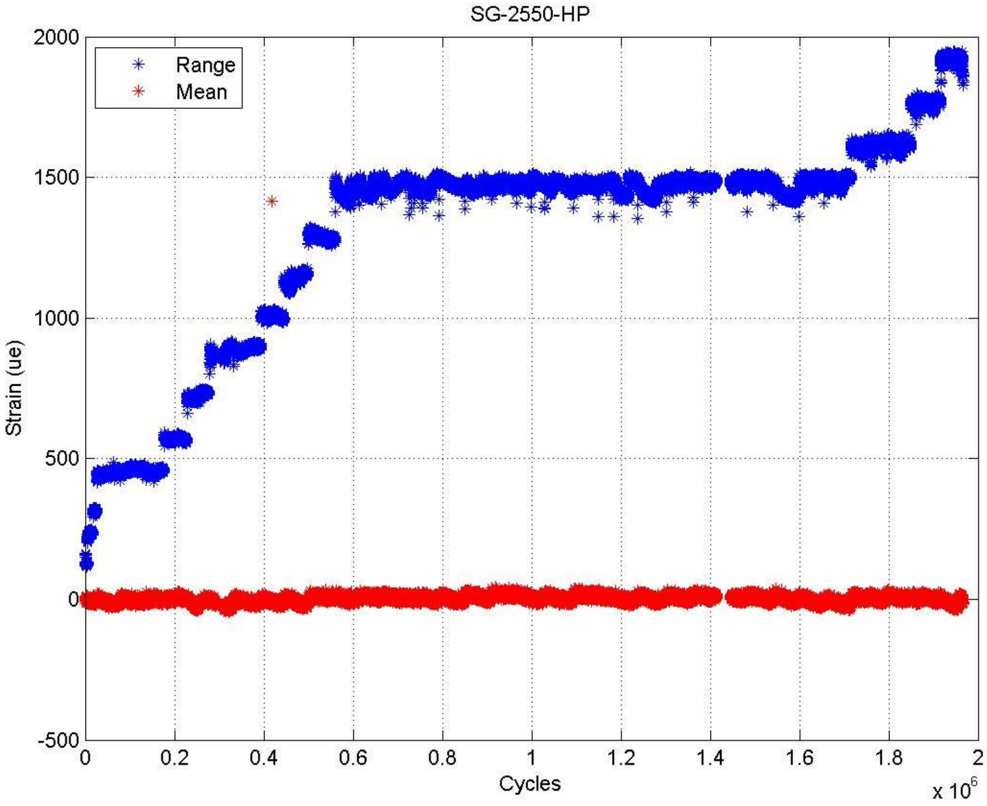
1.2
1.4
1.6
1.8
2
Cycles
x 10^6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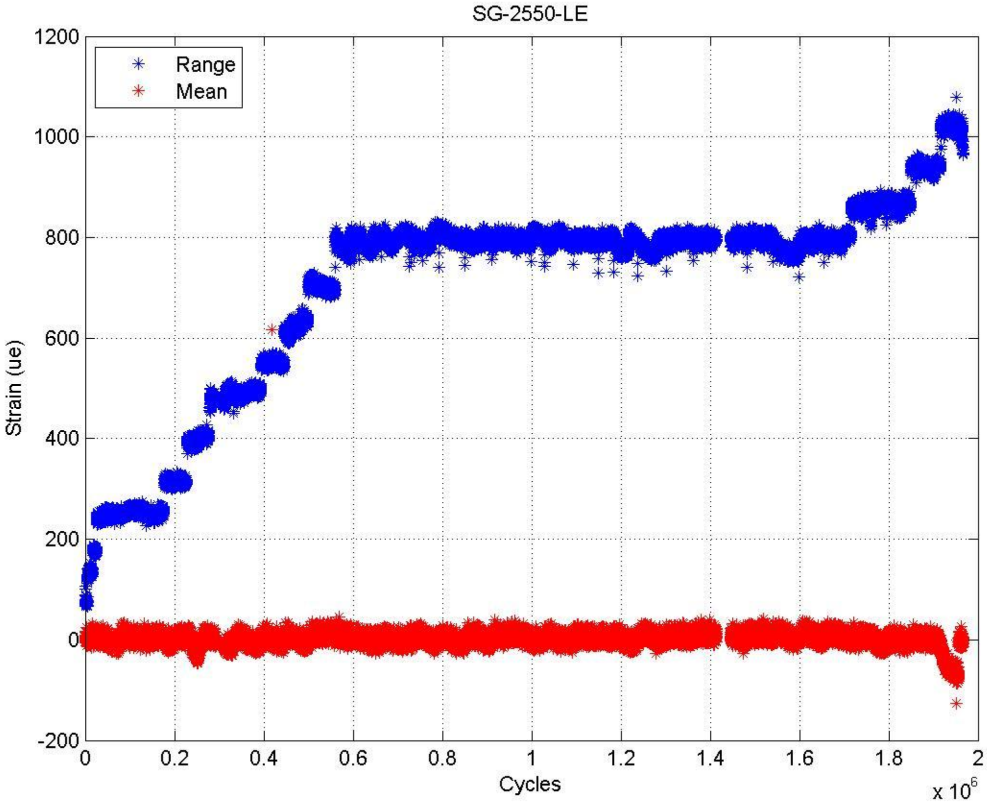
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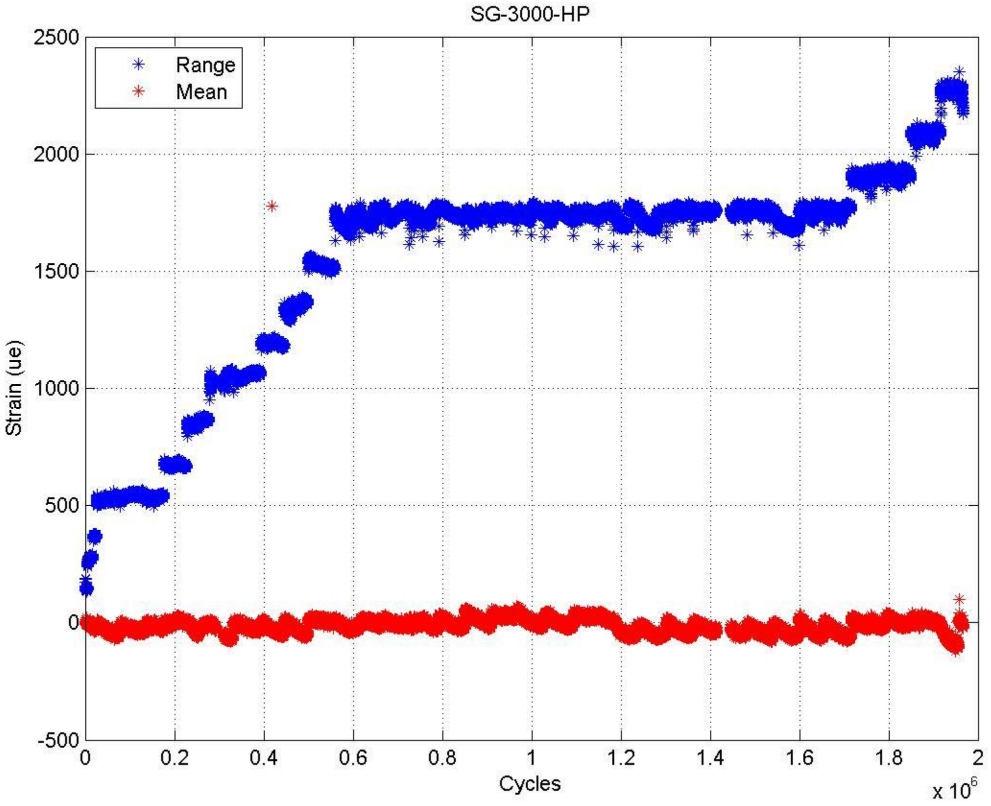
SG-3000-HP
Range
Mean
Strain (ue)
2500
2000
1500
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0.8
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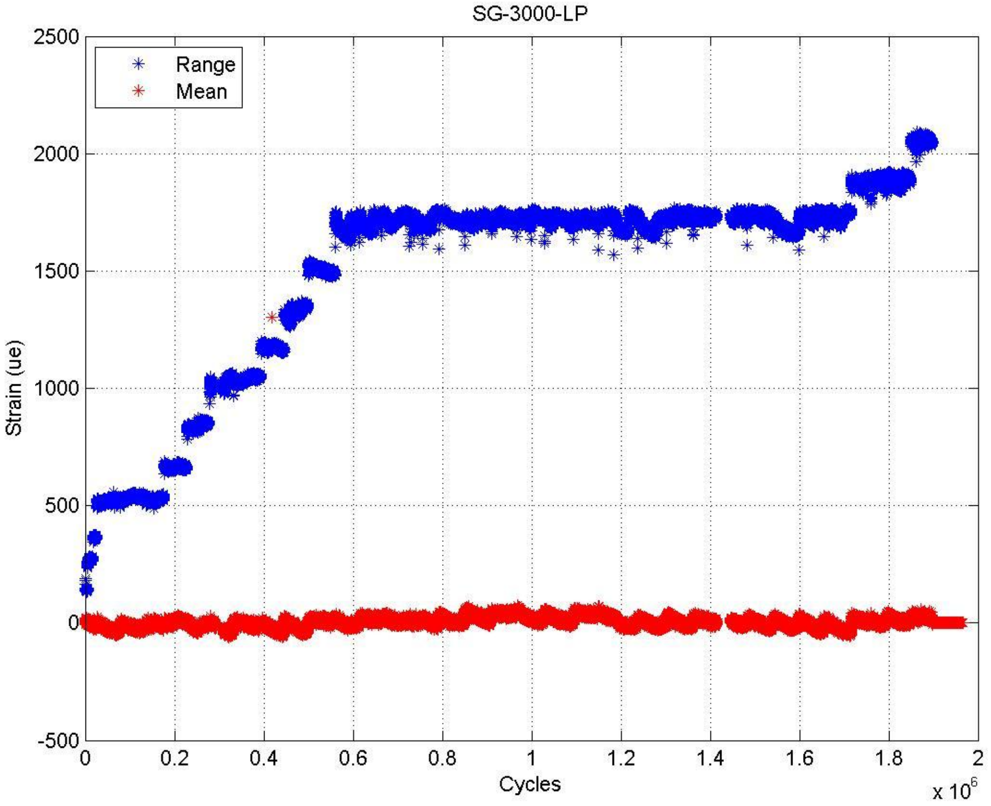
1.2
1.4
1.6
1.8
2
Cycles
x 10^6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Mean
Strain (ue)
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2000
1500
1000
500
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0.8
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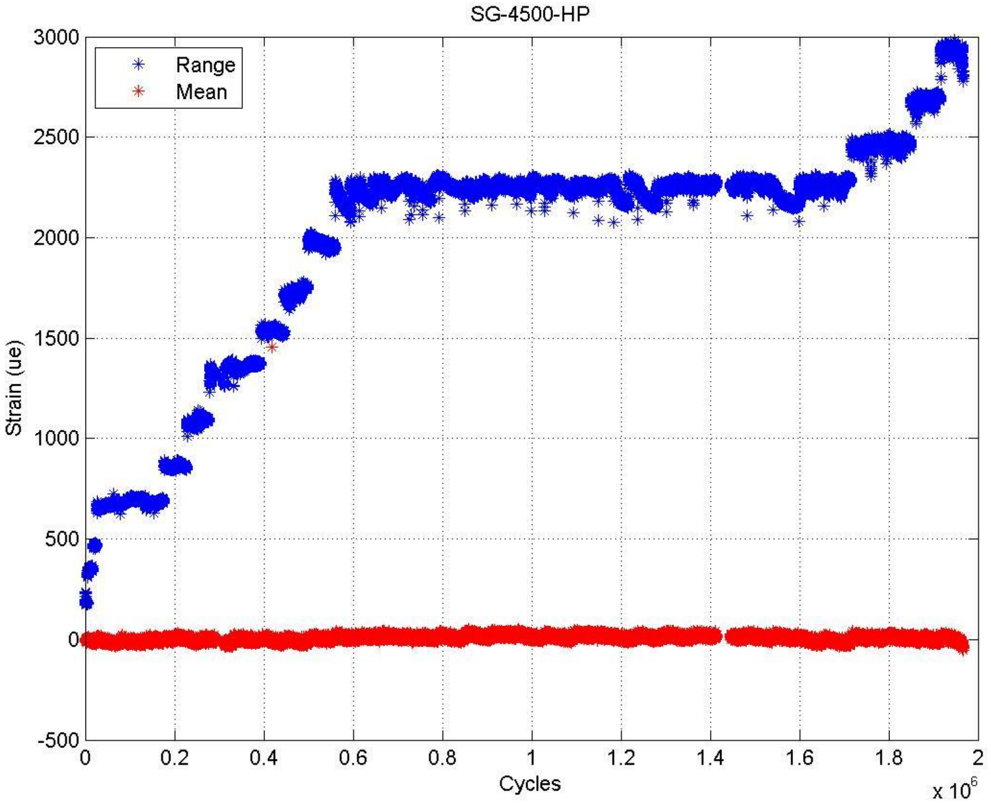
1.2
1.4
1.6
1.8
2
Cycles
x 10^6


SG-4500-HP
Range
Mean
Strain (ue)
3000
2500
2000
1500
1000
500
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-500
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0.6
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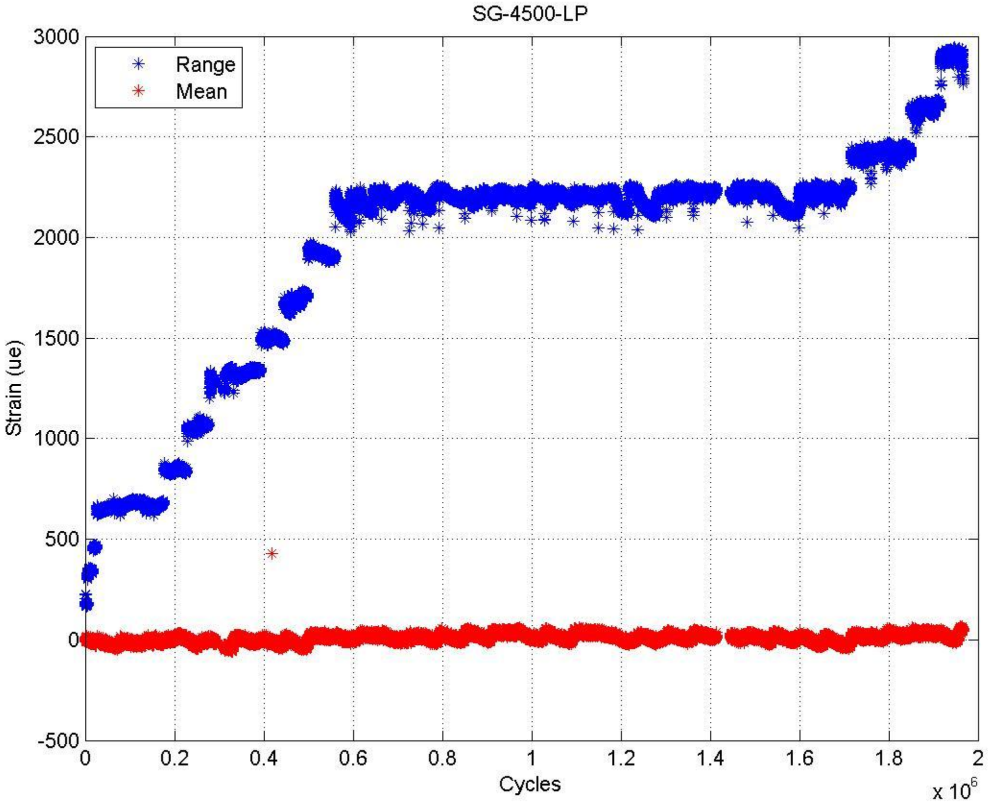
1.2
1.4
1.6
1.8
2
Cycles
x 10^6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Range
Mean
Strain (ue)
3000
2500
2000
1500
1000
500
0
-500
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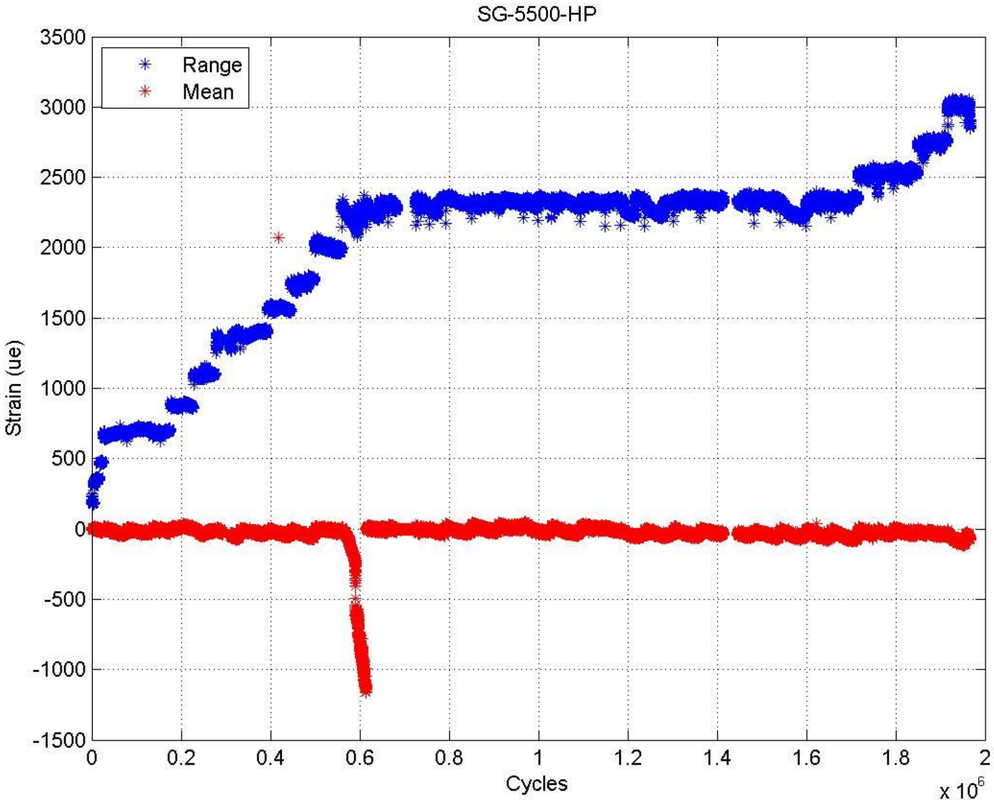
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Cycles
x 10^6


SG-5500-HP
Range
Mean
Strain (ue)
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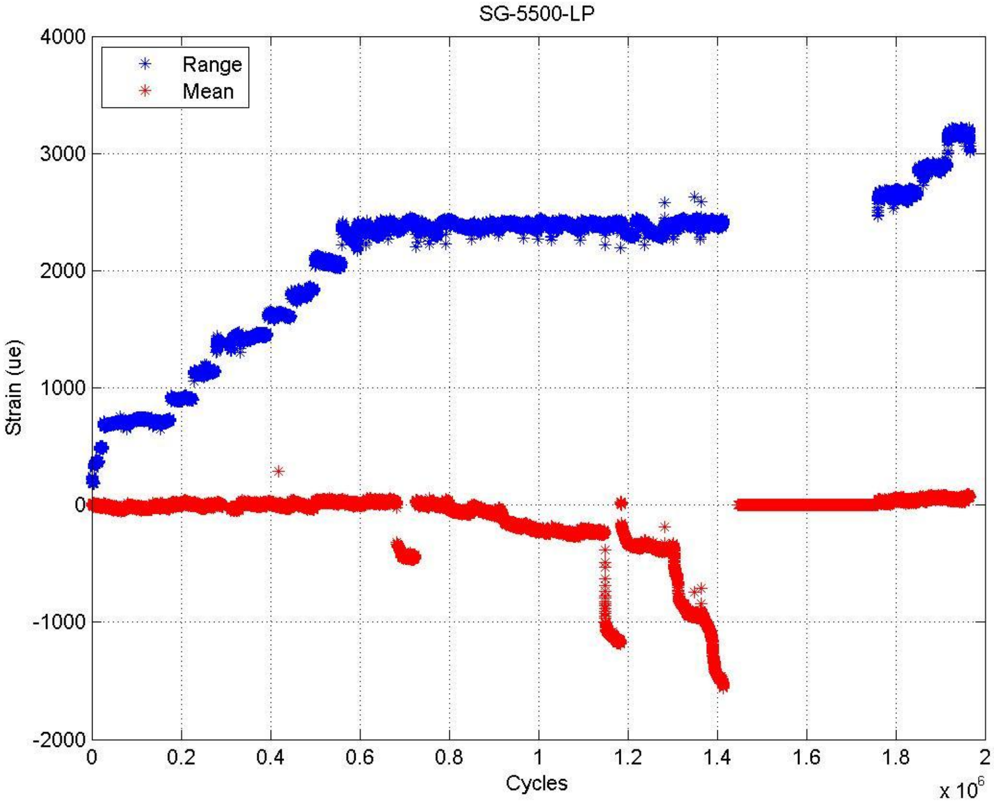
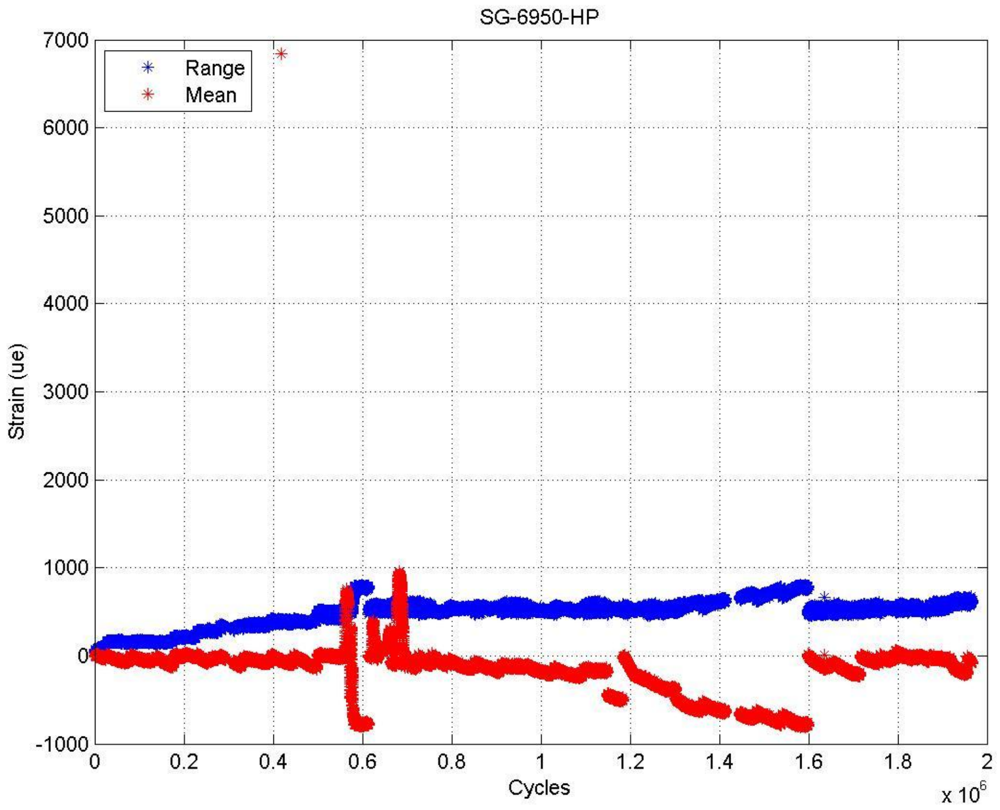
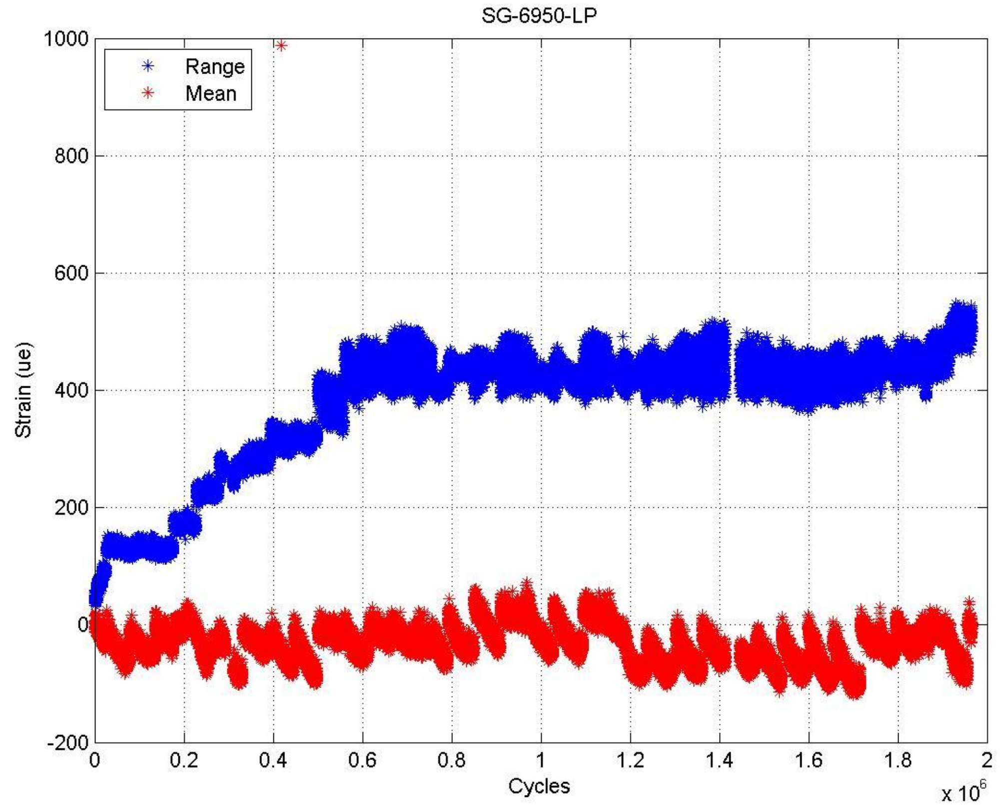
3000
2500
2000
1500
1000
500
0
-500
-1000
-1500
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Cycles
x 10^6


SG-5500-LP
Range
Mean
Strain (ue)
4000
3000
2000
1000
0
-1000
-2000
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Cycles
x 10^6

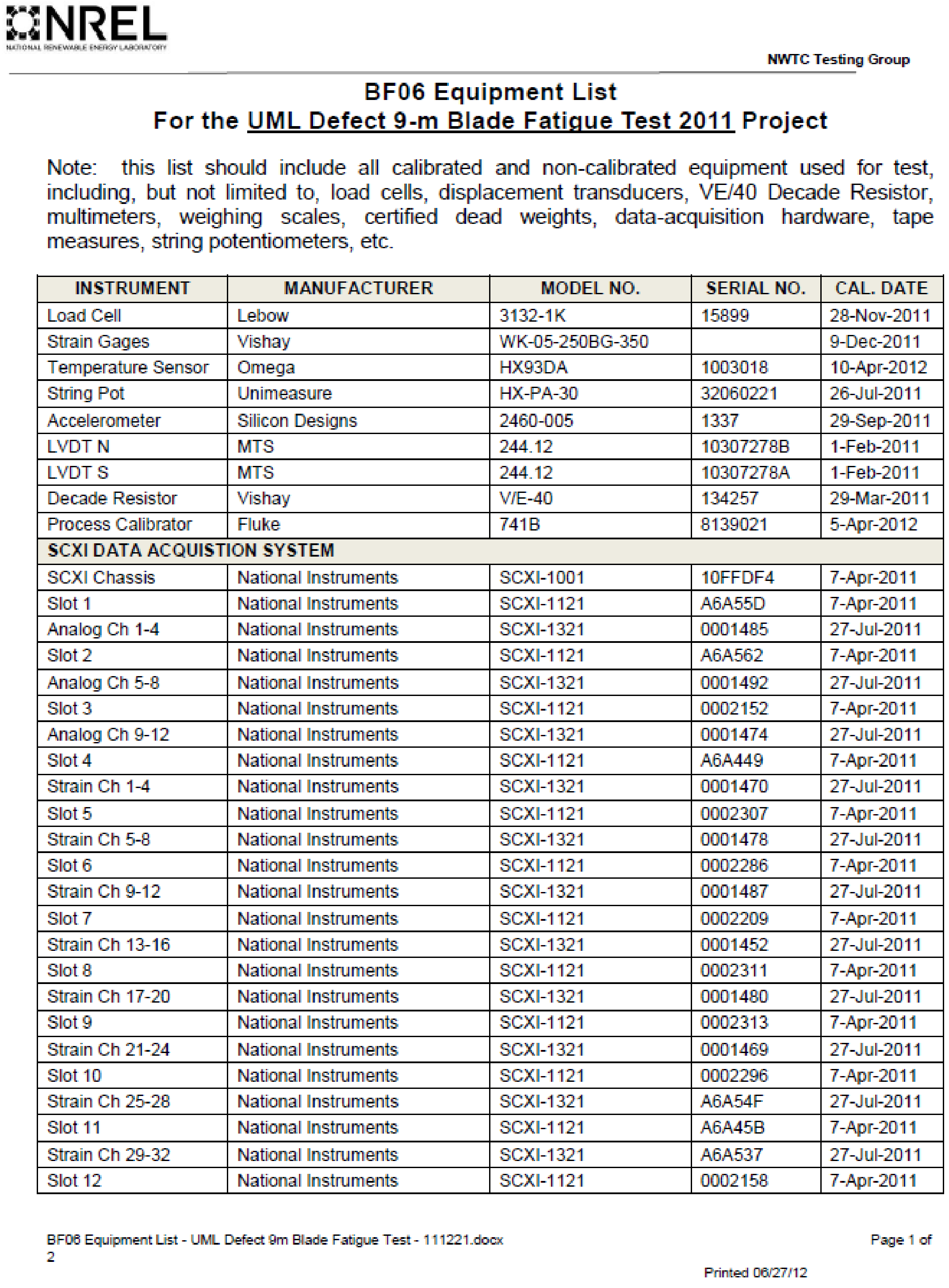

SG-6950-HP
Range
Mean
Strain (ue)
7000
6000
5000
4000
3000
2000
1000
0
-1000
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Cycles
x 10^6


SG-6950-LP
Range
Mean
Strain (ue)
1000
800
600
400
200
0
-200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Cycles
x 10^6

APPENDIX B-NREL Data Acquisition Channel Map

Channel	Name	Type	Location (mm)	Surface
0	LVDT-N	Displacement	UREX Actuator	North
1	LVDT-S	Displacement	UREX Actuator	South
2	AC-Y-Edge	Accelerometer	6750	HP
3	AC-Z-Flap	Accelerometer	6750	HP
4	LC-6750	Load	6750	
5	SP-Tip	Displacement	9000	LP
6	TEMP-Root	Temperature	0	Ambient
7	SG-0000-HP	Strain	0	HP
8	SG-0000-LP	Strain	0	LP
9	SG-0444-HP	Strain	444	HP
10	SG-0675-HP	Strain	675	HP
11	SG-0675-LE	Strain	675	LE
12	SG-0675-TE	Strain	675	TE
13	SG-1200-HP	Strain	1200	HP
14	SG-1200-LP	Strain	1200	LP
15	SG-1350-HP	Strain	1350	HP
16	SG-1350-LE	Strain	1350	LE
17	SG-1350-TE	Strain	1350	TE
18	SG-2000-LE	Strain	2000	LE
19	SG-2550-HP	Strain	2550	HP
20	SG-2550-LE	Strain	2550	LE
21	SG-3000-HP	Strain	3500	HP
22	SG-3000-LP	Strain	3500	LP
23	SG-4500-HP	Strain	4500	HP
24	SG-4500-LP	Strain	4650	LP
25	SG-5500-HP	Strain	5000	HP
26	SG-5500-LP	Strain	5000	LP
27	SG-6950-HP	Strain	6950	HP
28	SG-6950-LP	Strain	6950	LP

APPENDIX C-BF06 Instrumentation Records and Calibration Certificates



NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NWTC Testing Group

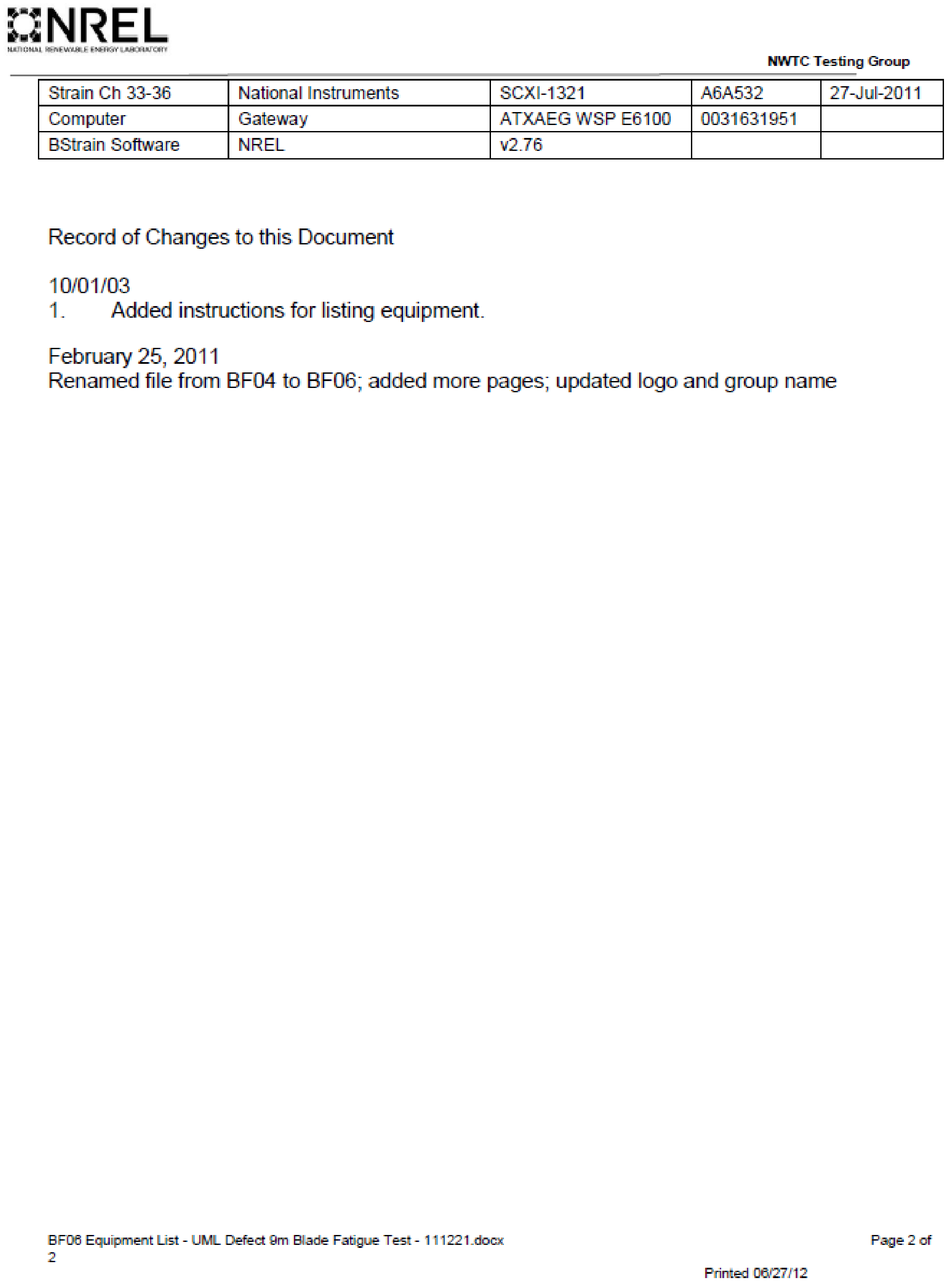
BF06 Equipment List
For the UML Defect 9-m Blade Fatigue Test 2011 Project

Note: this list should include all calibrated and non-calibrated equipment used for test, including, but not limited to, load cells, displacement transducers, VE/40 Decade Resistor, multimeters, weighing scales, certified dead weights, data-acquisition hardware, tape measures, string potentiometers, etc.

INSTRUMENT	MANUFACTURER	MODEL NO.	SERIAL NO.	CAL. DATE
Load Cell	Lebow	3132-1K	15899	28-Nov-2011
Strain Gages	Vishay	WK-05-250BG-350		9-Dec-2011
Temperature Sensor	Omega	HX93DA	1003018	10-Apr-2012
String Pot	Unimeasure	HX-PA-30	32060221	26-Jul-2011
Accelerometer	Silicon Designs	2460-005	1337	29-Sep-2011
LVDT N	MTS	244.12	10307278B	1-Feb-2011
LVDT S	MTS	244.12	10307278A	1-Feb-2011
Decade Resistor	Vishay	V/E-40	134257	29-Mar-2011
Process Calibrator	Fluke	741B	8139021	5-Apr-2012
SCXI DATA ACQUISTION SYSTEM				
SCXI Chassis	National Instruments	SCXI-1001	10FFDF4	7-Apr-2011
Slot 1	National Instruments	SCXI-1121	A6A55D	7-Apr-2011
Analog Ch 1-4	National Instruments	SCXI-1321	0001485	27-Jul-2011
Slot 2	National Instruments	SCXI-1121	A6A562	7-Apr-2011
Analog Ch 5-8	National Instruments	SCXI-1321	0001492	27-Jul-2011
Slot 3	National Instruments	SCXI-1121	0002152	7-Apr-2011
Analog Ch 9-12	National Instruments	SCXI-1321	0001474	27-Jul-2011
Slot 4	National Instruments	SCXI-1121	A6A449	7-Apr-2011
Strain Ch 1-4	National Instruments	SCXI-1321	0001470	27-Jul-2011
Slot 5	National Instruments	SCXI-1121	0002307	7-Apr-2011
Strain Ch 5-8	National Instruments	SCXI-1321	0001478	27-Jul-2011
Slot 6	National Instruments	SCXI-1121	0002286	7-Apr-2011
Strain Ch 9-12	National Instruments	SCXI-1321	0001487	27-Jul-2011
Slot 7	National Instruments	SCXI-1121	0002209	7-Apr-2011
Strain Ch 13-16	National Instruments	SCXI-1321	0001452	27-Jul-2011
Slot 8	National Instruments	SCXI-1121	0002311	7-Apr-2011
Strain Ch 17-20	National Instruments	SCXI-1321	0001480	27-Jul-2011
Slot 9	National Instruments	SCXI-1121	0002313	7-Apr-2011
Strain Ch 21-24	National Instruments	SCXI-1321	0001469	27-Jul-2011
Slot 10	National Instruments	SCXI-1121	0002296	7-Apr-2011
Strain Ch 25-28	National Instruments	SCXI-1321	A6A54F	27-Jul-2011
Slot 11	National Instruments	SCXI-1121	A6A45B	7-Apr-2011
Strain Ch 29-32	National Instruments	SCXI-1321	A6A537	27-Jul-2011
Slot 12	National Instruments	SCXI-1121	0002158	7-Apr-2011

BF06 Equipment List - UML Defect 9m Blade Fatigue Test - 111221.docx Page 1 of 2

Printed 06/27/12

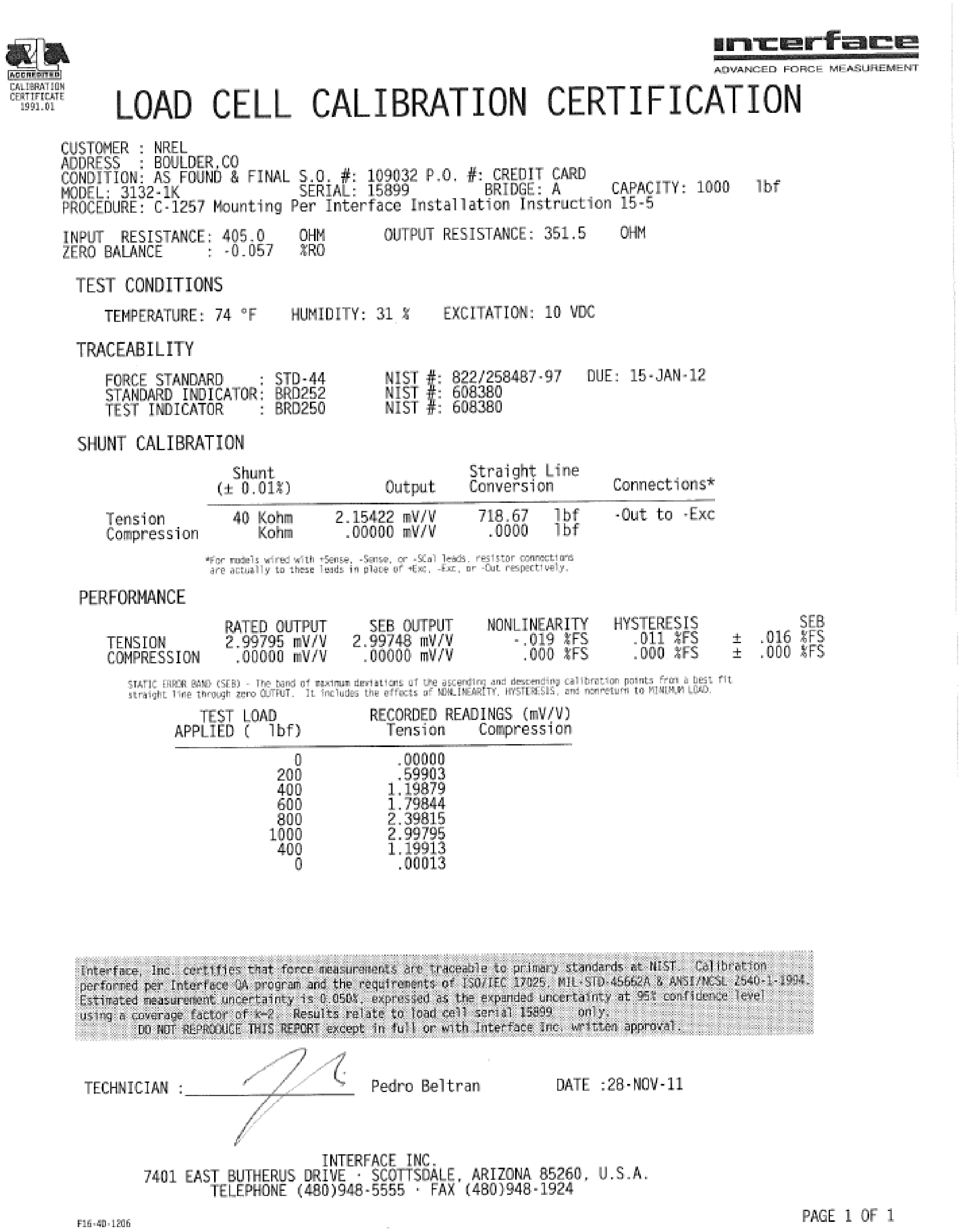


Strain Ch 33-36	National Instruments	SCXI-1321	A6A532	27-Jul-2011
Computer	Gateway	ATXAEG WSP E6100	0031631951	
BStrain Software	NREL	v2.76		

Record of Changes to this Document

10/01/03
1. Added instructions for listing equipment.

February 25, 2011
Renamed file from BF04 to BF06; added more pages; updated logo and group name



ACCREDITED
CALIBRATION
CERTIFICATE
1991.01

interface
ADVANCED FORCE MEASUREMENT

LOAD CELL CALIBRATION CERTIFICATION

CUSTOMER : NREL
ADDRESS : BOULDER,CO
CONDITION: AS FOUND & FINAL S.O. #: 109032 P.O. #: CREDIT CARD
MODEL: 3132-1K SERIAL: 15899 BRIDGE: A CAPACITY: 1000 lbf
PROCEDURE: C-1257 Mounting Per Interface Installation Instruction 15-5

INPUT RESISTANCE: 405.0 OHM OUTPUT RESISTANCE: 351.5 OHM
ZERO BALANCE : -0.057 %RO

TEST CONDITIONS

TEMPERATURE: 74 °F HUMIDITY: 31 % EXCITATION: 10 VDC

TRACEABILITY

FORCE STANDARD : STD-44 NIST #: 822/258487-97 DUE: 15-JAN-12
STANDARD INDICATOR: BRD252 NIST #: 608380
TEST INDICATOR : BRD250 NIST #: 608380

SHUNT CALIBRATION

	Shunt (± 0.01%)	Output	Straight Line Conversion	Connections*
Tension	40 Kohm	2.15422 mV/V	718.67 lbf	-Out to -Exc
Compression	Kohm	.00000 mV/V	.0000 lbf	

*For models wired with +Sense, -Sense, or -SCal leads, resistor connections are actually to these leads in place of +Exc, -Exc, or -Out respectively.

PERFORMANCE

	RATED OUTPUT	SEB OUTPUT	NONLINEARITY	HYSTERESIS	SEB
TENSION	2.99795 mV/V	2.99748 mV/V	-.019 %FS	.011 %FS	± .016 %FS
COMPRESSION	.00000 mV/V	.00000 mV/V	.000 %FS	.000 %FS	± .000 %FS

STATIC ERROR BAND (SEB) - The band of maximum deviations of the ascending and descending calibration points from a best fit straight line through zero OUTPUT. It includes the effects of NONLINEARITY, HYSTERESIS, and nonreturn to MINIMUM LOAD.

TEST LOAD APPLIED (lbf)	RECORDED READINGS (mV/V) Tension	Compression
0	.00000	
200	.59903	
400	1.19879	
600	1.79844	
800	2.39815	
1000	2.99795	
400	1.19913	
0	.00013	

Interface, Inc. certifies that force measurements are traceable to primary standards at NIST. Calibration performed per Interface QA program and the requirements of ISO/IEC 17025, MIL-STD-45662A & ANSI/NCSL Z540-1-1994. Estimated measurement uncertainty is 0.050%, expressed as the expanded uncertainty at 95% confidence level using a coverage factor of k=2. Results relate to load cell serial 15899 only.
DO NOT REPRODUCE THIS REPORT except in full or with Interface Inc. written approval.

TECHNICIAN :__________ Pedro Beltran DATE :28-NOV-11

INTERFACE INC.
7401 EAST BUTHERUS DRIVE · SCOTTSDALE, ARIZONA 85260, U.S.A.
TELEPHONE (480)948-5555 · FAX (480)948-1924

F16-40-1206

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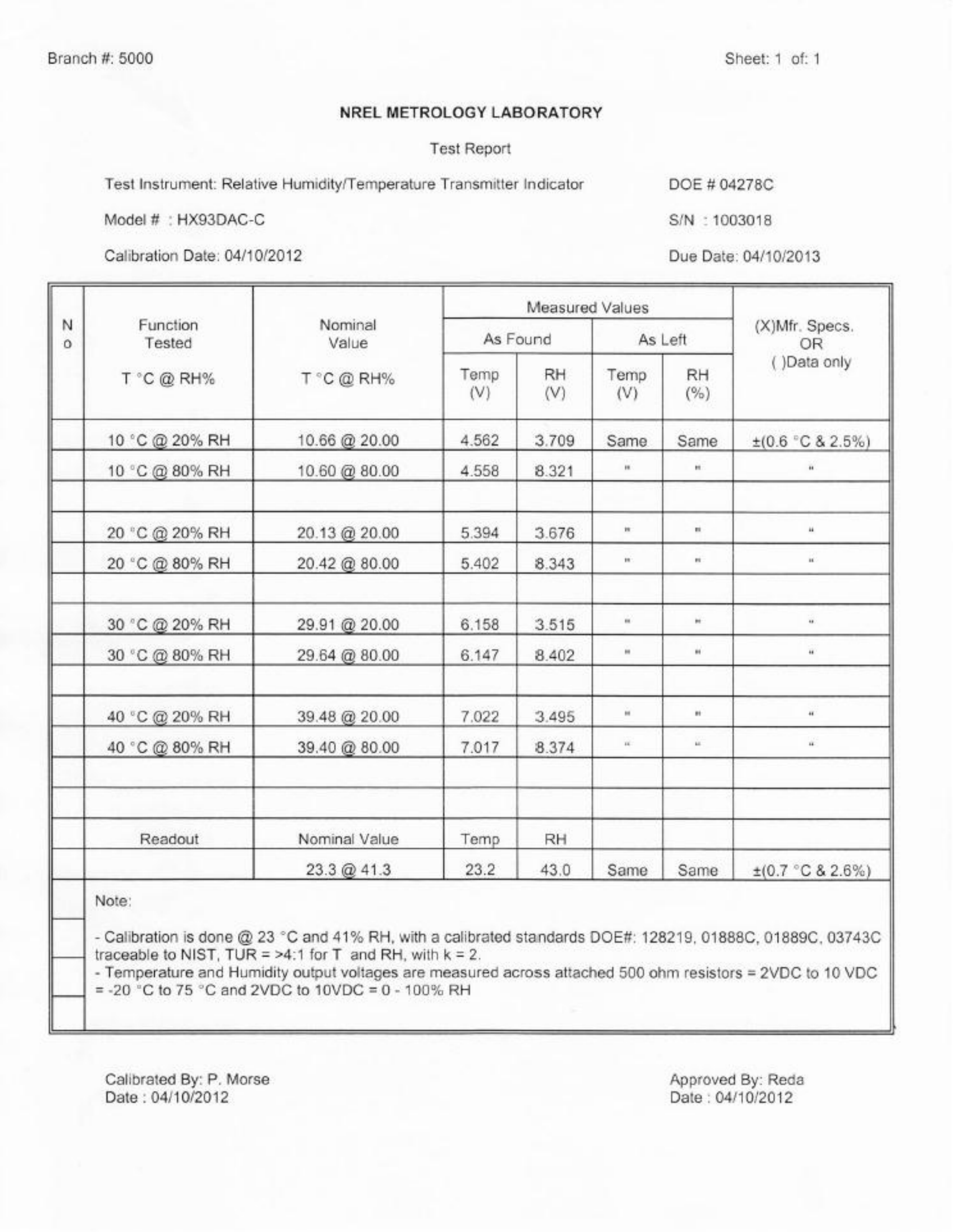


Branch #: 5000 Sheet: 1 of: 1

NREL METROLOGY LABORATORY

Test Report

Test Instrument: Relative Humidity/Temperature Transmitter Indicator DOE # 04278C

Model # : HX93DAC-C S/N : 1003018

Calibration Date: 04/10/2012 Due Date: 04/10/2013

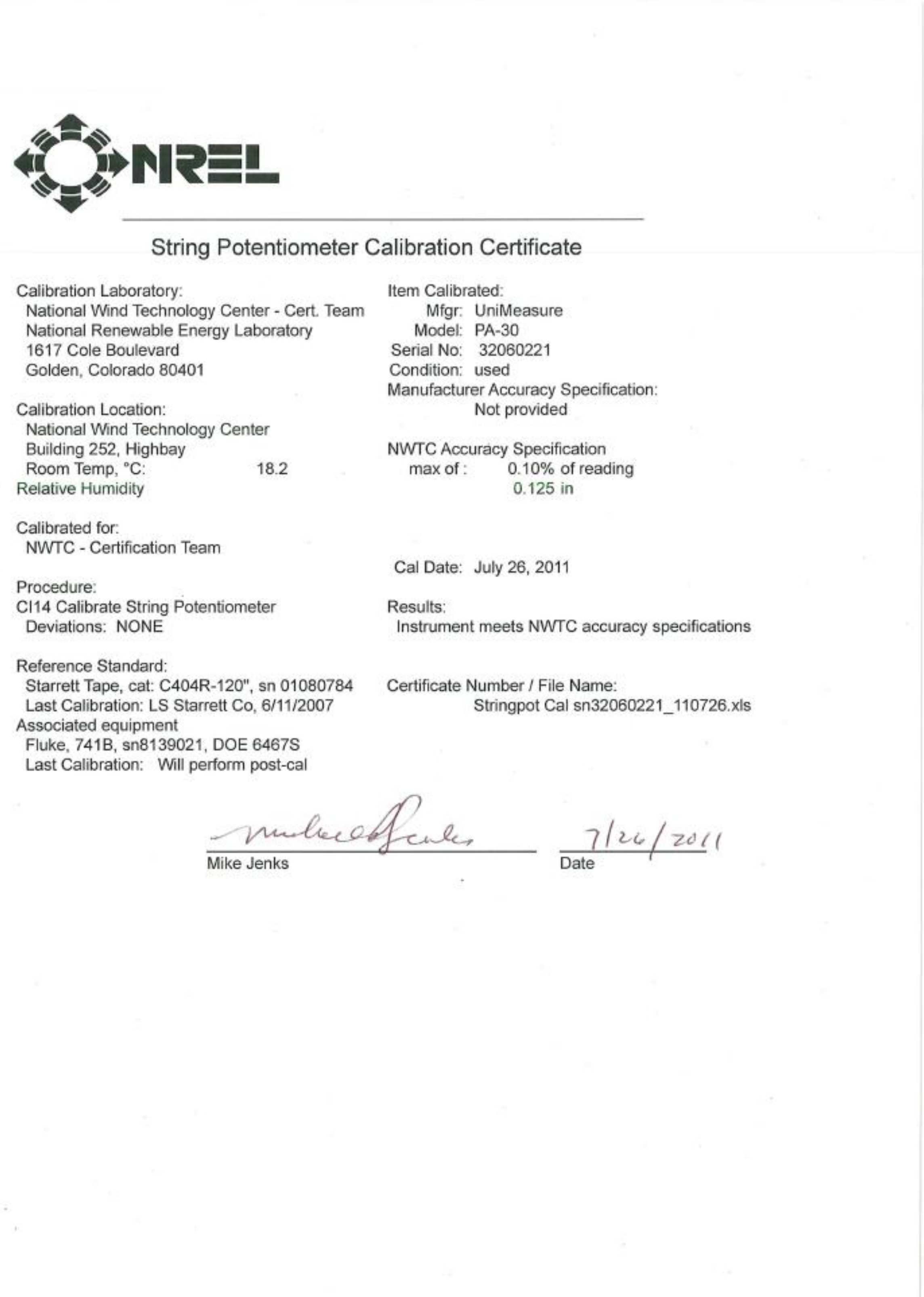
No	Function Tested T °C @ RH%	Nominal Value T °C @ RH%	Measured Values				(X)Mfr. Specs. OR ( )Data only
			As Found		As Left		
			Temp (V)	RH (V)	Temp (V)	RH (%)	
	10 °C @ 20% RH	10.66 @ 20.00	4.562	3.709	Same	Same	±(0.6 °C & 2.5%)
	10 °C @ 80% RH	10.60 @ 80.00	4.558	8.321	"	"	"
	20 °C @ 20% RH	20.13 @ 20.00	5.394	3.676	"	"	"
	20 °C @ 80% RH	20.42 @ 80.00	5.402	8.343	"	"	"
	30 °C @ 20% RH	29.91 @ 20.00	6.158	3.515	"	"	"
	30 °C @ 80% RH	29.64 @ 80.00	6.147	8.402	"	"	"
	40 °C @ 20% RH	39.48 @ 20.00	7.022	3.495	"	"	"
	40 °C @ 80% RH	39.40 @ 80.00	7.017	8.374	"	"	"
	Readout	Nominal Value	Temp	RH			
		23.3 @ 41.3	23.2	43.0	Same	Same	±(0.7 °C & 2.6%)

Note:

- Calibration is done @ 23 °C and 41% RH, with a calibrated standards DOE#: 128219, 01888C, 01889C, 03743C traceable to NIST, TUR = >4:1 for T and RH, with k = 2.
- Temperature and Humidity output voltages are measured across attached 500 ohm resistors = 2VDC to 10 VDC = -20 °C to 75 °C and 2VDC to 10VDC = 0 - 100% RH

Calibrated By: P. Morse
Date : 04/10/2012

Approved By: Reda
Date : 04/10/2012



String Potentiometer Calibration Certificate

Calibration Laboratory:
National Wind Technology Center - Cert. Team
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401

Calibration Location:
National Wind Technology Center
Building 252, Highbay
Room Temp, °C: 18.2
Relative Humidity

Calibrated for:
NWTC - Certification Team

Procedure:
CI14 Calibrate String Potentiometer
Deviations: NONE

Reference Standard:
Starrett Tape, cat: C404R-120", sn 01080784
Last Calibration: LS Starrett Co, 6/11/2007
Associated equipment
Fluke, 741B, sn8139021, DOE 6467S
Last Calibration: Will perform post-cal

Item Calibrated:
Mfgr: UniMeasure
Model: PA-30
Serial No: 32060221
Condition: used
Manufacturer Accuracy Specification:
Not provided

NWTC Accuracy Specification
max of : 0.10% of reading
0.125 in

Cal Date: July 26, 2011

Results:
Instrument meets NWTC accuracy specifications

Certificate Number / File Name:
Stringpot Cal sn32060221_110726.xls

Mike Jenks

7/26/2011
Date

SILICON DESIGNS INC. 1445 NW Mall St., Issaquah WA 98027-5344, (425) 391-8329, FAX (425) 391-0446

CALIBRATION CERTIFICATE

Model: **2460-005**

Part #: **153-00066-06**

Doc. Rev. -

Lot #: **11M262A**

Serial #: **1337**

Full Scale: **5 G**

Op. Number: **700**

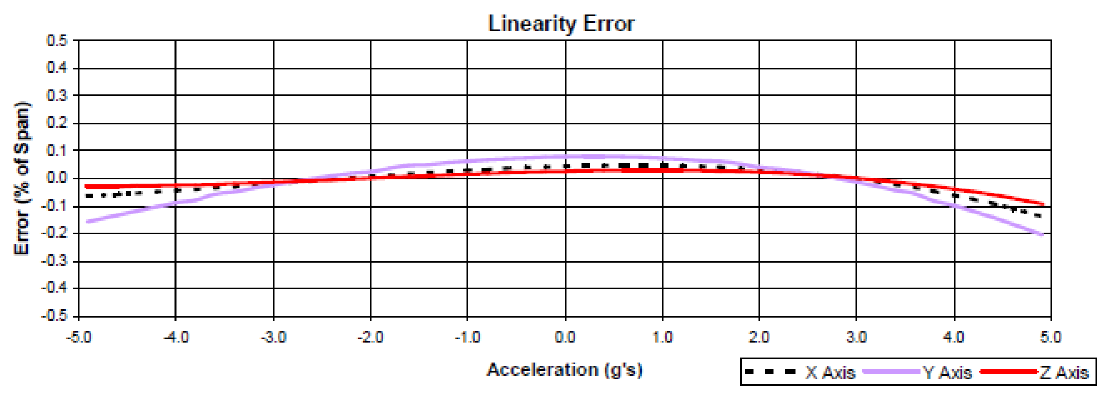
Operator: **MPC**

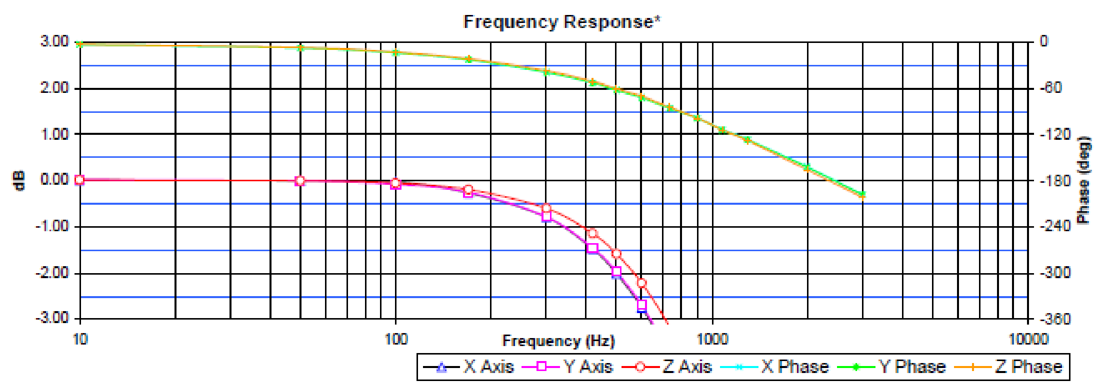
Calibration Date: **09/29/11**

Supply Current: **19.88 mA**

Calibration Freq. **50 Hz**

	X-Axis	Y-Axis	Z-Axis	
+1 G DC:	788.3	783.1	826.4	mV DC
-1 G DC:	-817.6	-826.5	-787.9	mV DC
0 G Bias	-14.7	-21.7	19.3	mV DC
Scale Factor	799.5	802.9	805.4	mV/G
Sensor ID	390236	390237	390238	





Freq. (Hz)**	10	50	100	170	300	420	500	600	735	900	1080	1300	2000	3000
dB Out - X	0.01	0.00	-0.02	-0.27	-0.79	-1.48	-2.01	-2.75	-3.80	-5.16	-6.64	-8.53	-13.88	-20.39
Phase (deg)	-2.8	-7.2	-13.3	-22.7	-39.0	-52.8	-62.3	-71.9	-85.5	-98.5	-113.4	-126.4	-162.0	-197.9
Freq. (Hz)**	10	50	100	170	300	420	500	600	735	900	1080	1300	2000	3000
dB Out - Y	0.02	0.00	-0.08	-0.25	-0.78	-1.45	-1.97	-2.69	-3.74	-5.10	-6.60	-8.48	-13.91	-20.56
Phase (deg)	-2.7	-7.2	-13.7	-22.7	-38.8	-52.8	-62.3	-71.9	-85.8	-98.9	-113.9	-127.1	-162.6	-198.5
Freq. (Hz)**	10	50	100	170	300	420	500	600	735	900	1080	1300	2000	3000
dB Out - Z	0.02	0.00	-0.05	-0.19	-0.60	-1.15	-1.58	-2.21	-3.17	-4.46	-5.94	-7.75	-13.35	-20.21
Phase (deg)	-2.7	-6.8	-12.9	-21.4	-36.9	-50.8	-60.3	-70.1	-84.4	-98.3	-114.0	-128.1	-165.6	-201.6

* Reference Frequency is 50 Hz

** 2 g Peak Acceleration Traceable to NIST through Vibration Calibration Standard M-90157

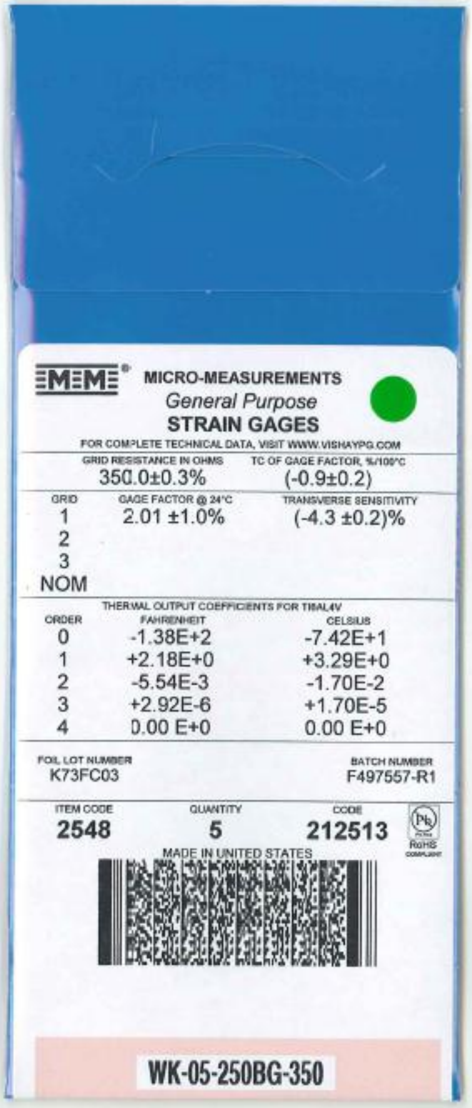
Final Status:

Pass:

website: **www.silicondesigns.com** e-mail: **sales@silicondesigns.com**

Form: 0-000-00501 Rev 20 November 2000

Report Generator Rev. 5.3.0 : September 02, 2011



MICRO-MEASUREMENTS

General Purpose

STRAIN GAGES

FOR COMPLETE TECHNICAL DATA, VISIT WWW.VISHAYPG.COM

GRID RESISTANCE IN OHMS	TC OF GAGE FACTOR, %/100°C
350.0±0.3%	(-0.9±0.2)

GRID	GAGE FACTOR @ 24°C	TRANSVERSE SENSITIVITY
1	2.01 ±1.0%	(-4.3 ±0.2)%
2		
3		
NOM		

THERMAL OUTPUT COEFFICIENTS FOR TI6AL4V

ORDER	FAHRENHEIT	CELSIUS
0	-1.38E+2	-7.42E+1
1	+2.18E+0	+3.29E+0
2	-5.54E-3	-1.70E-2
3	+2.92E-6	+1.70E-5
4	0.00 E+0	0.00 E+0

FOIL LOT NUMBER	BATCH NUMBER
K73FC03	F497557-R1

ITEM CODE	QUANTITY	CODE
2548	**5**	**212513**

RoHS COMPLIANT

MADE IN UNITED STATES

WK-05-250BG-350