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Abstract

A series of 19.1 metre wind turbine blades manufactured by LM Glasfiber A/S of Lunderskov, Denmark were subjected to a series of flapwise fatigue tests. The object of these fatigue tests is to evaluate the impact of an increased load on the blade in a fatigue test and to give information if it is possible to increase the load in fatigue test to shorten test time.

The tests were carried out as a part of a project financed by the Danish Energy Agency.

During the fatigue tests the blades have been surveyed with thermal imaging equipment to determine how an increase in fatigue load affects the blade material. In addition to the thermal imaging surveillance the blades were instrumented with strain gauges.

This report presents the temperature during test, calibration test results, moment range measurements, strain statistics, thermal imaging registrations and a determination of the size and cause of the damages. The report is also giving information on the blade-to-blade variation.

The total number of pages for this report is 72.

Measurements described in this report refer only to the specific blades, identified in this report.

The Danish Energy Agency and Risø National Laboratory financed testing, measurements and data analysis and LM Glasfiber A/S has delivered the blades used in test.

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Contents

1 Introduction

Traditionally a wind turbine blade is tested as part of a type approval. In these approval tests is determination of weight and centre of gravity. Determination of the natural frequencies, 1st and 2nd flapwise, 1st edgewise and 1st torsional are also a part of the blade-test. Static proof-test is carried out and the blade is also tested in a fatigue test. The fatigue test is normally separated in two, one for the edgewise direction and one for the flapwise direction. With an increase in blade length the time consumption in fatigue test is increasing. For the time being the normal fatigue test is carried out with a number of load-cycles of 5 million in each of the two directions. If an increase in load can be done without introducing higher temperatures in the material of the blade, which never appears in blades “on sites”, it might be possible to reduce the number of cycles needed for a fatigue test by increasing the load. It is a criterion that the failure mode on the three blades must be similar regardless of the load levels. The theory used for the reduction of load cycles by increasing the load is the Palmgren-Miner method of calculating fatigue damages and log-log S-N curve. Throughout this report a slope (m) of the S-N curve equal to 9 has been assumed.

These test series are carried out as traditional flapwise fatigue tests, but where the fatigue tests normally are carried out with one nominal load level for the entire fatigue test these tests have been carried out with increasing load levels to make damages to occur on the blades. For the first blade the fatigue test was devided in five parts to determine the impact of a load increase, on the temperature in the blade material. For the second and third blade the load was increased to damage the blade.
For the fatigue test the tips of the blades were cut of, the space available did not leave room for the tip of the blade. The determination of the natural frequencies were carried out on the complete blade i.e. including tip.
The test was conducted in accordance with the procedure in Ref. 2 chapter 5. Furthermore the test was conducted in accordance with the procedure in Ref. 3 QP8.103 “Fatigue test of wind turbine blades” and QP8.104 “Calibration test”; internal documents at Sparkær Testcentre.

The fatigue-tests were performed on the test rig “E”, at the Risø National Laboratory Blade Test Facility at the Sparkær Centre. The period of the fatigue tests was 7th of June 2001 to ultimo January 2002. The Sparkær Centre has carried out all instrumentation, tests and measurements described within this report. The thermal imaging surveillance was carried out in co-operation with HB Termografi, Aarhus.

This report presents the temperature history during test, calibration test results, moment range measurements and strain statistics. There is also presentation of the thermal images and an evaluation of the damages occurring on the blades.

The initial fatigue load level and test configuration is based on a prior test of a similar blade, i.e. design load at $5*10^6$ load cycles.

Within this report the abbreviation µS represent the unit for strain, i.e. 10^{-6} [m/m].

Distances and forces used in this report are related to a rectilinear co-ordinate system with origin at the blade root interface. The z-axis is parallel to the direction for the 0-degree twist chord (usually the tip chord) see Figure 1.

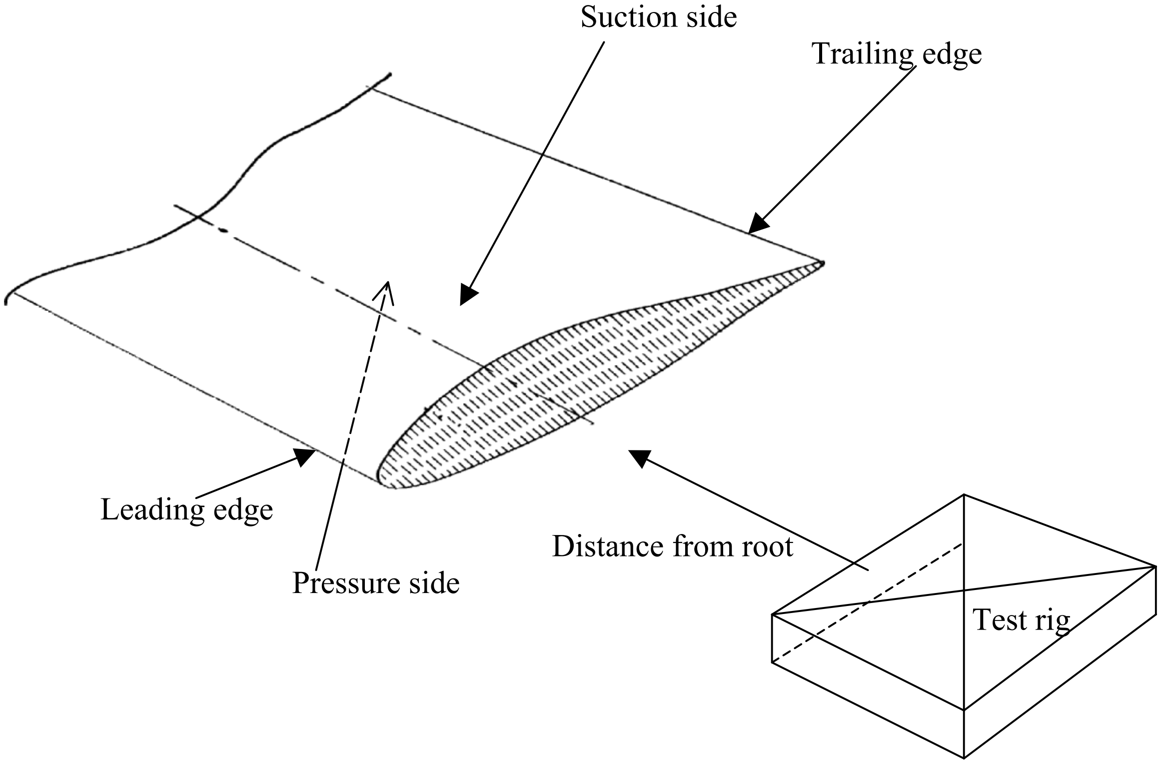


Figure 1. Sketch with the definitions that are used in this report

2 The tested blades

To determine the comparability of the three blades, a determination of the blades stiffness and the natural frequencies were made.

2.1 Blade stiffness

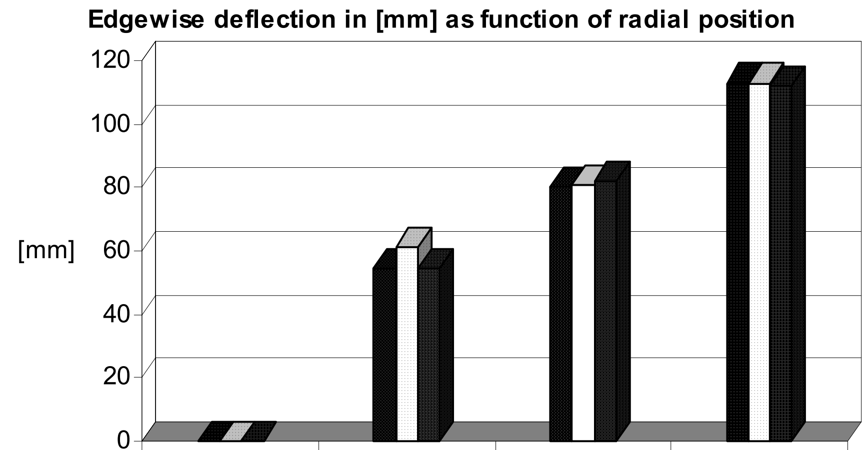
The tested blades were produced by LM Glasfiber A/S of Lunderskov, Denmark and had a grey gel-coat finish.

Type:	LM 19.1			LM 19.1			LM 19.1		
Serial no.	4703			4706			4700		
Date of measurement	01-03-2001			03-08-2001			03-08-2001		
Weight	19.23 [kN]			19.57 [kN]			19.67 [kN]		
Center of gravity	6.3 [m]			6.1 [m]			6.1 [m]		
Blade length	19.08 [m]			19.09 [m]			19.08 [m]		
Points of deflection measurement [m]	19.1	16.0	13.3	19.1	16.0	13.3	19.1	16.0	13.3
Initial stiffness, edgewise [mm]/[kNm]	0.870	0.610	0.413	0.855	0.621	0.463	0.859	0.622	0.415
Points of deflection measurement [m]	13.0	10.0	8.0	13.0	10.0	8.0	13.0	10.0	8.0
Initial stiffness, flapwise [mm]/[kNm]	0.746	0.333	0.162	0.725	0.323	0.161	0.749	0.333	0.167

Table 1. Blade data, for further details see appendix.

To determine the initial stiffness of the blades, two tests were conducted on each blade, one in edgewise direction and one in flapwise direction. For both tests the load was applied in steps, the values in Table 1 are based on the average deflection as function of applied root bending moment for the 4 load steps.
For all three blades the maximum applied load for the edgewise test was 8 [kNm] applied in Z = 16.3 [m]. In the flapwise direction the maximum load applied was 16 [kNm], this load was applied in Z = 13.15 [m].

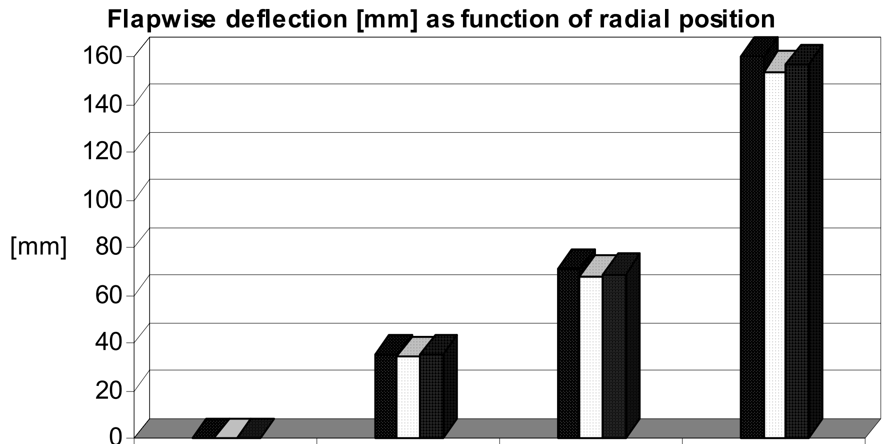
The blade with serial no. # 4706 is the blade with the highest stiffness i.e. the blade that shows the smallest deflection in a static test.
The data sheets with measured data for the static tests of the blades are available in the appendix.



	0	13.3	16	19.1
#4703	0	54.4	80	113
#4706	0	61	81	113
#4700	0	54.4	82	112

Distance from root intersection [m]

Figure 2. Graphical presentation of edgewise deflection for each of the three tested blades, shown for the highest load step.



	0	8	10	13
#4703	0	35	71	160
#4706	0	34.3	68	154
#4700	0	35	69	157

Distance from root intersection [m]

Figure 3. Graphical presentation of flapwise deflection for each of the three tested blades, shown for the highest load step.

As the flapwise stiffness determination was carried out just prior to the fatigue test there was also made strain measurements during these tests. The strains measured on the blade are evaluated in correspondence with the applied load, i.e. microstrain vs. local bending moment. Figure 4, Figure 5 and Figure 6 show that blade no. # 4706 and # 4700 are very similar to each other in the sense of lengthwise strain distribution and blade no # 4703 differs a little from the two others.

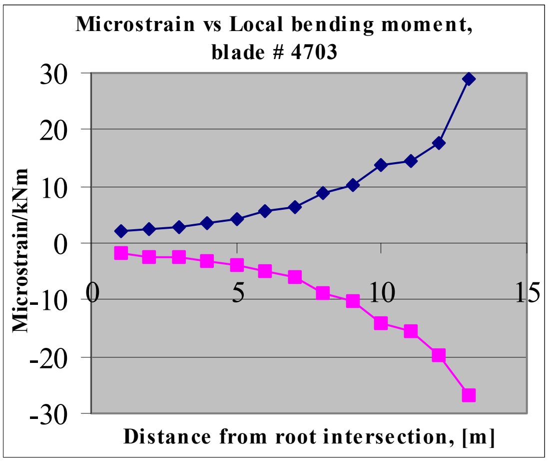


Figure 4. Normative strain distribution for blade # 4703

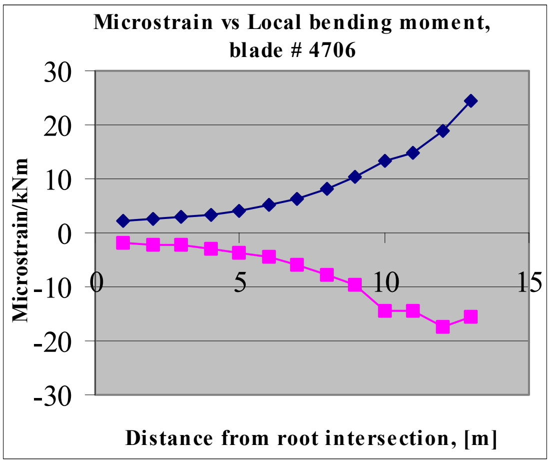


Figure 5. Normative strain distribution for blade # 4706

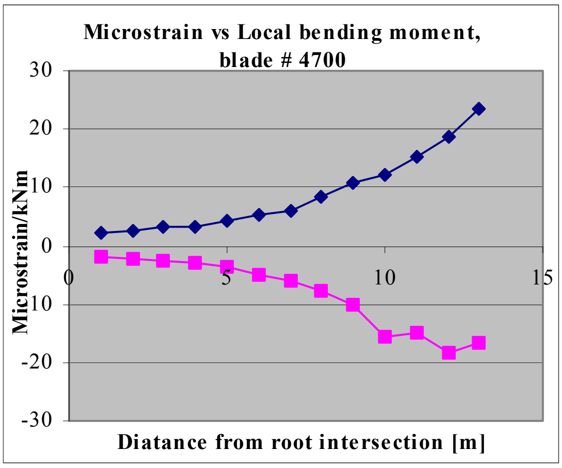


Figure 6. Normative strain distribution for blade # 4700

2.2 Determination of natural frequencies

The Natural frequencies have been determined for all three blades. The determined frequencies are 1st and 2nd flapwise, 1st edgewise and 1st torsional natural frequencies.
To determine the frequencies of the blades, tests were conducted in accordance with Ref. 3 (QP 8.101). The tests were performed on the following dates: 23rd of February 2001, 17th of May 2001 and 3rd of October 2001 on the blades with serial number 4703, 4706 and 4700 respectively. The frequency determinations were carried out on test-rig H at the test-facillity at the Sparkær Centre.
The tip-chords were in vertical position during the determination of the frequencies.

Measurement procedure

For the flap- and edgewise eigenfrequencies determination an accelerometer was mounted on the centreline of the blade, at the tip, and connected to an amplifier. A Labtech Notebook program has sampled the output data from the amplifier. To create a signal from the accelerometer, the blade was excited into its natural frequency by hand, the blade was allowed to oscillate free and the natural frequency was measured.
The torsional frequency was determined using two accelerometers on the blade, one on the leading edge, and one on the trailing edge. The two accelerometers were placed in equal distance, 14.48 [m], from the root-interface. The signals from the two accelerometers were amplified, and the difference between the two amplified signals was stored in an oscilloscope. A PC equipped with a Labtech Notebook program recorded the stored signal. The sampled file was analysed using a MathCad program.

Measurement results

The natural frequencies and damping values are determined by performing a curve-fit to the following equation:

$X(t)=Ae^{(\zeta\ \omega n\ t)}\cos(\omega_d t-\phi)$ for $0 < \zeta < 1$

Where: A is an amplitude scale factor.
ζ is the viscous damping factor.
ω_n is the natural frequency.
ω_d is the frequency of the damped free vibration.
ϕ is the phase angle.

Due to the excitation principle ω_n and ω_d are essentially equal.
The following natural frequencies and damping coefficients were measured for the blades.

Direction No.	# 4703	# 4706	# 4700
1. Flapwise	1.66	1.66	1.66
2. Flapwise	5.06	5.12	5.09
1. Edgewise	2.87	2.86	2.86
1. Torsion	23.9	23.4	23.3

Table 2. Measured natural frequencies.

Direction No.	# 4703	# 4706	# 4700
1. Flapwise	$3.49*10^{-3}$	$2.92*10^{-3}$	$2.99*10^{-3}$
2. Flapwise	$3.34*10^{-3}$	$3.36*10^{-3}$	$3.36*10^{-3}$
1. Edgewise	$4.00*10^{-3}$	$3.77*10^{-3}$	$3.97*10^{-3}$
1. Torsion	Not determined	Not determined	Not determined

Table 3. Measured damping coefficients.

2.3 Conclusion on similarity

The three tested blades are, in overall, similar. There is a minor difference in flapwise stiffness distribution for blade # 4703 compared to the two other blades. For the natural frequencies blade # 4703 differs from the two others in the flapwise damping. Blade # 4703 has a damping in the 1st flapwise mode that is 17 % higher than the two other blades; this might be due to higher amplitude during the measurement of the frequency and therefore a damping contribution from aerodynamic damping.

3 Experimental test set-up

3.1 Description of test set-up

The blade was mounted in the test-rig “E”. In a distance of 12 [m] an exciter was mounted. This exciter consists of two pair of yokes and two pair of clamps. On this exciter-frame was mounted a motor which drives an eccentric mass. This eccentric mass excites the blade when the motor revolves.

3.2 Description of measurement system

The measurement system consist of:
1) A PC with the software program ”HP Vee” for data acquisition.
2) HP82350 PCI card (communication between the PC and the data acquisition computer).
3) DAC02 card (communication between the PC and the frequency converter).
4) A HP3852 data acquisition computer.
5) Strain gauges.
6) Accelerometer (B&K).
7) Amplifier for the accelerometer.
8) A termocouple (PT100).

The accelerometer is mounted on the blade near the exciter frame. The temperature measurement is made using the voltmeter in the data acquisition computer. The temperature sensor is positioned on the blade, in the area of the root. Strains are measured by a voltmeter in the data acquisition computer. The strain gauges are connected in a quarter bridge configuration, using a tree wire connection.

For every 2500 oscillations strain gauge scan is performed (at the end of the test of blade # 4703 the interval of oscillations between every strain gauges scan was reduced to 1000 cycles). In the strain file the strain range is stored. Furthermore the moment range before and after the scan, the temperature and the bridge voltage are stored. At level 4 in the test of blade # 4703 the data acquisition system was set to store the accelerometer signal as well.

In the moment file, the moment range cycles are summed and stored. For the flapwise test the moment range cycles are stored in bins from 78-121% of the nominal root bending moment, each bin has a width of 1 %

Calibration-tests are performed on a regular basis. At the calibration test a static load is introduced at the exciter position. Corresponding values of load at the exciter and deflection at the accelerometer are measured. Additionally the strains are measured. Six load steps are imposed on the blade ranging from 0 to 15% of the root bending moment. In the calibration test file the loads deflections and strain are stored.

3.3 Calibration and configuration of measurement system

Prior to the fatigue test the accelerometer measurement chain is calibrated, such that the response from the amplifier is 1 [V] RMS. The calibration is performed using an accelerometer calibrator and a Fluke. The eigenfrequency of the system, including exciter etc, is determined using accelerometer, amplifier and a Fluke.

3.4 Description of control system

The relation between root bending moment and acceleration width is found using the relation:

$$\ddot{X} = \omega^2 \cdot a$$

where
$\ddot{X}$ = acceleration width
ω = eigenfrequency of the system
a = deflection width

At the static calibration test the relation between deflection and force is found. The relation between deflection width and prescribed root bending moment is determined. Using the equation above it is now possible to find the acceleration width. Based on the measured accelerations it is possible to control the root bending moment width, using software and a frequency converter. The absolute value of the root bending moment might induce a small error because of this procedure (not including inertia loads), but it does not affect the results of this project, because it is the same control system for all three blades.
Additionally a system using two photo diodes is used to prevent the blade from being overloaded. Furthermore the diodes count mechanically the number of oscillations.

3.5 Strain gauge locations

The strain gauges were of type CEA-06-500UW-350 from Measurements Group, Inc., see appendix C.

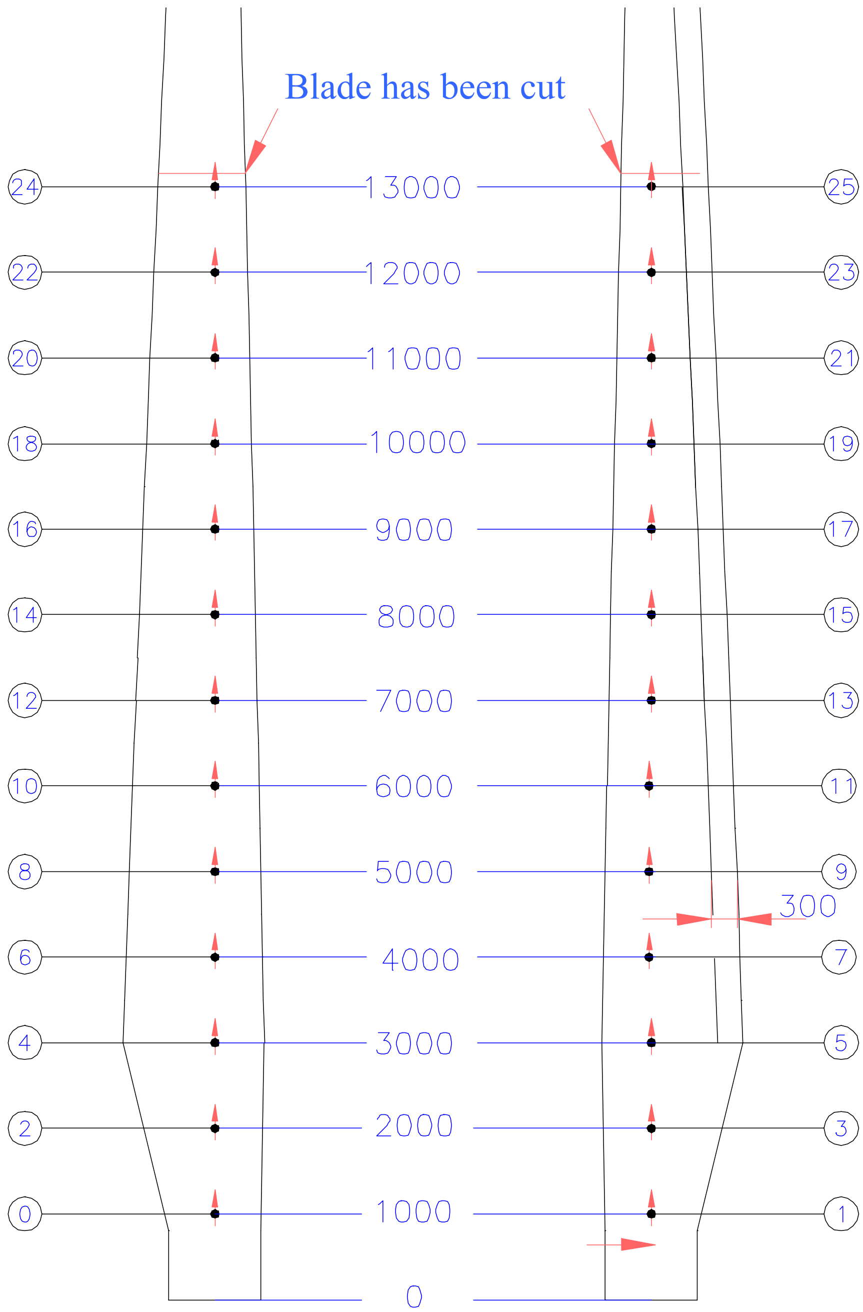


Figure 7. *Strain gauge position and numbering, LM 19.1 # 4703, initially.*

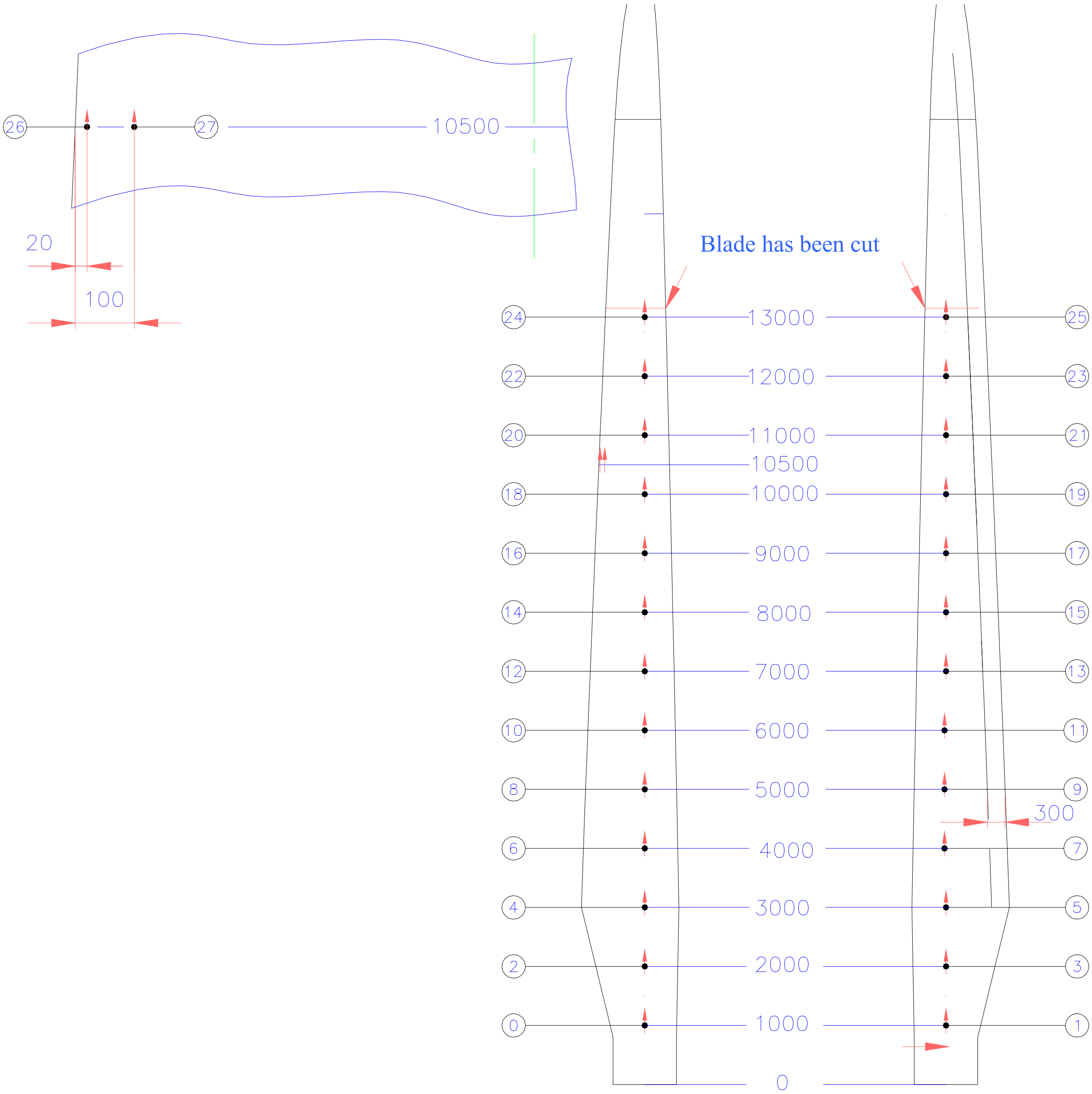


Figure 8. Strain gauge position and numbering, LM119.1 # 4706.

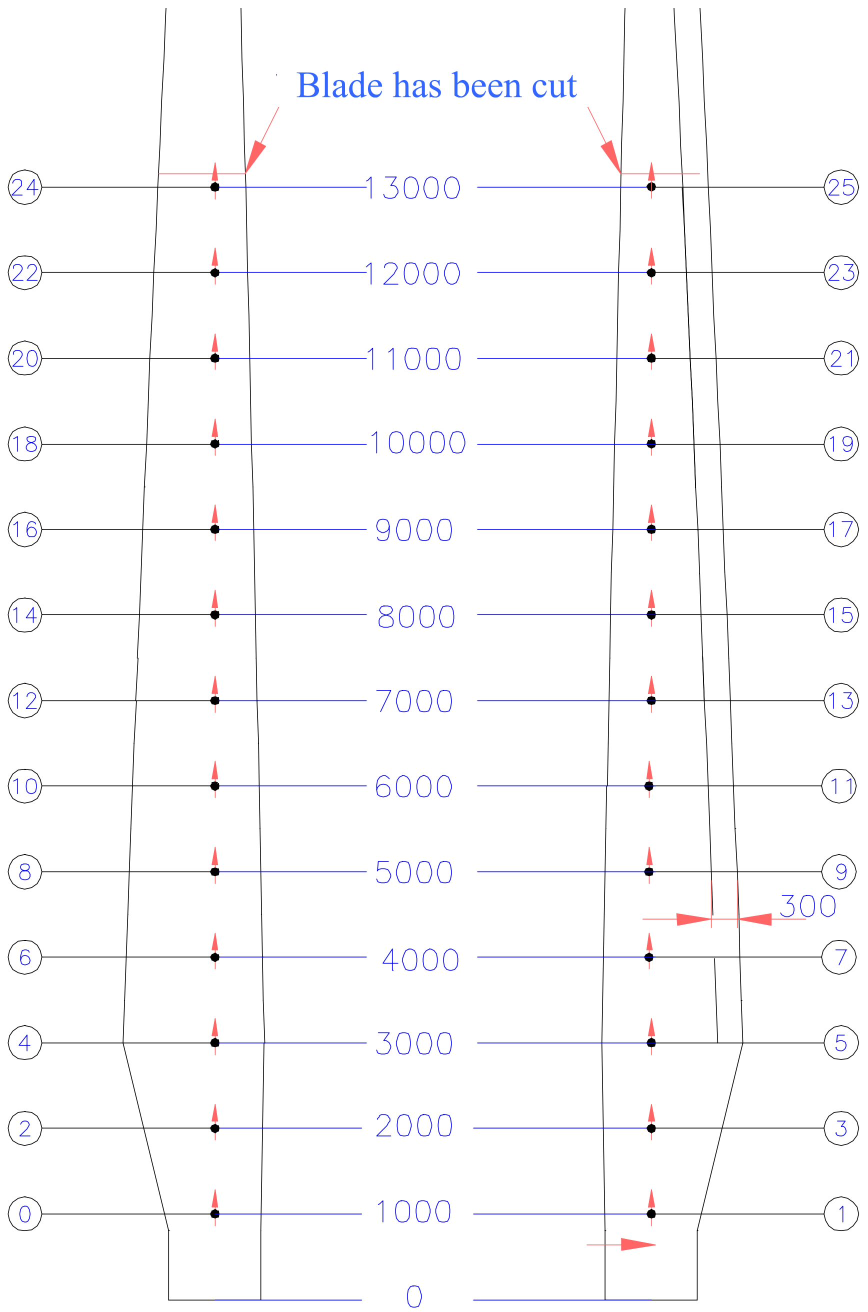


Figure 9. Strain gauge position and numbering, LM 19.1 # 4700.

Test set-up

3.6 Blade mounting

The blades were mounted on test rig ”E” at Risø National Laboratory, Sparkær Centre. As the maximum length of blade to be tested in test rig “E” is 14 [m] these three 19.1 metre blades were cut off in a length of 13.4 [m].

The suction side of the blade was downwards and the tip-chord in horizontal direction.

3.7 Equipment mounting

The exciter was mounted at 12 [m] from the root interface. The total mass mounted at this point was 2554.6 [kg]. The exciter system consists of a motor and an interface between the motor and the blade. The interface consists of four u-profiles and wood clamps. On the output shaft of the motor a triangular steel plate is mounted to form an eccentric load on the motor. This eccentric mass excites the blade as the motor revolves. In order to keep the prescribed root bending moment the motor revolution speed is controlled via a PC and a frequency converter. In addition to the load at the position of the exciter there was mounted a pre-load in Z = 13.0 [m]. This load had a mass of 145 [kg].

3.8 Photo of the test set-up

Figure 10. Test configuration at the flapwise fatigue test.

4 Flapwise fatigue test of blade no. # 4703

4.1 Blade one, test sequences

To determine if the temperature changes because of an increased bending moment in the blade, the first blade was tested in five different levels with increasing root bending moment. The root bending moment level used as basis is based on the type approval root bending moment applied to a similar blade, i.e the bending moment causing failure at $5*10^6$ cycles. To compensate for the rest lifetime of the blade (partial safety factor) the basic root bending moment is increased with 30 %. The 30 % is an estimated rest lifetime.
Each of the five root bending moment levels is applied to the blade for a period of what is equivalent to 16 % of a lifetime. By the end of the initial five levels the blade has used what is equivalent to 80 % of the total lifetime. The test will be continued at the last level, level 5, until the blade is damaged.

4.2 Phase definition

The test phases are defined in Table 4. The load at level 1 is equivalent to 130 % of a normal $5*10^6$-cycles fatigue test.

Phase and level	Date		Root bending moment [kNm]	Number of nominal cycles for a lifetime	Number of nominal cycles applied in current phase	Number of lifetimes applied to the blade in phase
	Start	Stop				
1	07/06-2001	19/06-2001	862	5000000	809733	0.16
2	19/06-2001	25/06-2001	931	2500000	446406	0.18
3	25/06-2001	28/06-2001	1005	1250000	192936	0.15
4	28/06-2001	02/07-2001	1086	625000	86567	0.14
5	03/07-2001	20/07-2001	1173	312500	103042	0.33
					Sum	0.96

Table 4. Phase definition

4.3 Events during test

The first blade was surveyed by thermal imaging equipment in 6 sessions. There were two sessions for the first level and one session for each of the following levels. There were no observations of hot spots under the first thermal surveillance.
On the 15th of June two additional strain gauges were mounted in the root section. The gauges were mounted on the centre line of the pressure side at distance Z = 0.79 [m] and Z = 1.49 [m]. The positions of these two gauges were determined after the second thermal surveillance of the blade; see

Figure 11 and Figure 13. During this second thermal surveillance, at this load level, there was also discovered a hot spot in the root section on the centre line on downwind side of the blade; see Figure 12 and Figure 14.

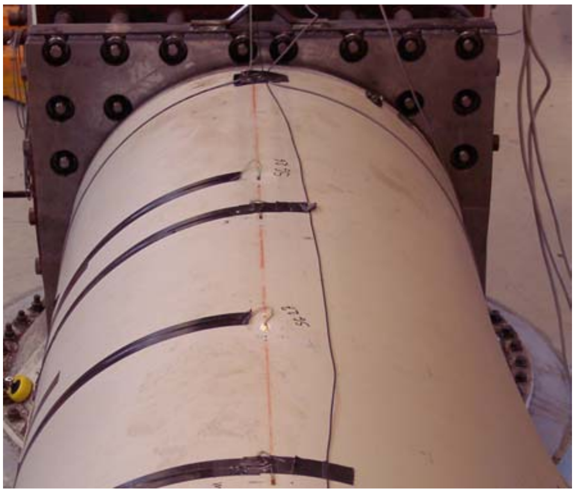


Figure 11. Two additional strain gauges on upwind centre line

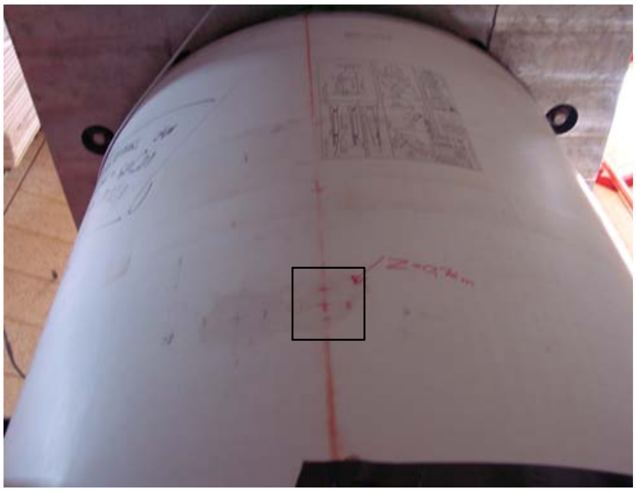


Figure 12. Downwind centre line, hot spot marked with red marker, in the black-lined square, diameter app. 3 [cm].

Figure 13. Thermal image of upwind side of root section

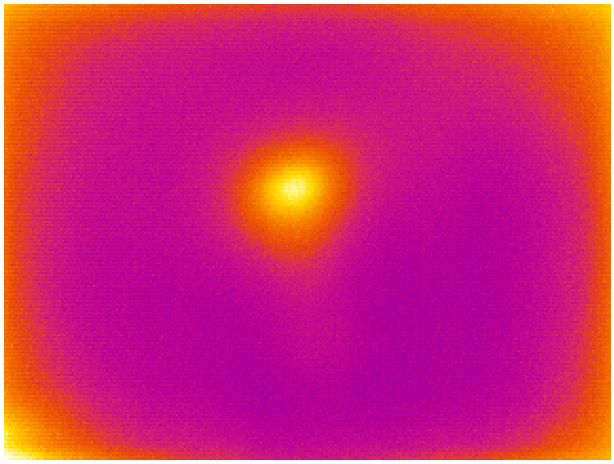


Figure 14. Thermal image of hot spot on centre line of downwind side at the root section

During the thermal session at the second load level there was no propagation in the thermal emission, no increase in the temperature, on the blade, except for the area on the downwind side of the root section were the single hotspot had developed into to two spots. The position of these spots is corresponding to the positions of the bushings in the root section. The bushings are for mounting the blade on the hub.

As the test was proceeding, by thermo graphic surveillance at level 3, there was observed a band of higher temperature on the up-wind surface. This band is shown in Figure 15 in the black lined square. The observations showed that the band was narrowed in at Z = 10[m].

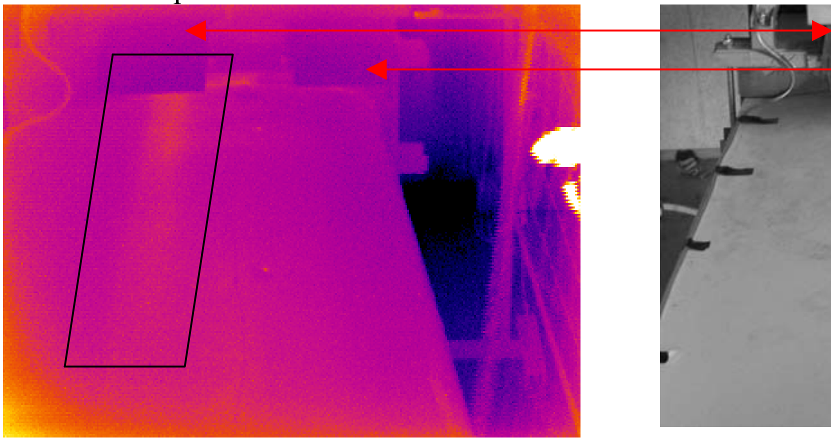


Figure 15. Thermo graphic image of up-wind surface, Z 9 [m] to Z 11.5 [m]. The red arrows are pointing out the two steel-bar pre-loads.

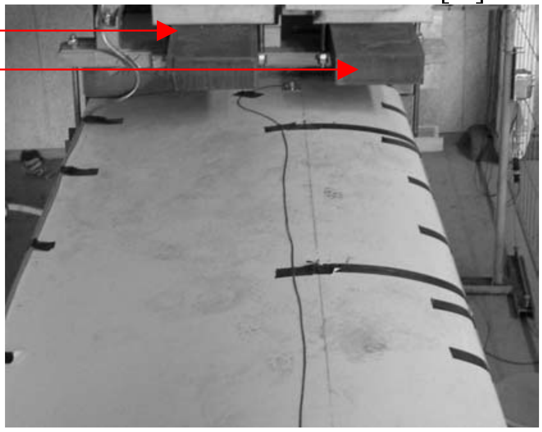


Figure 16. Picture of up-wind surface 9.3 [m] – 11.5 [m]. SG mounted on centre line in Z = 10 [m] og Z = 11 [m] (where the black gaffa-tape crosses the centre line).

At load level 4 there was no propagation in the area with increased temperature and no change in temperature level. Figure 17 shows the area as the blade was surveyed during level 4.

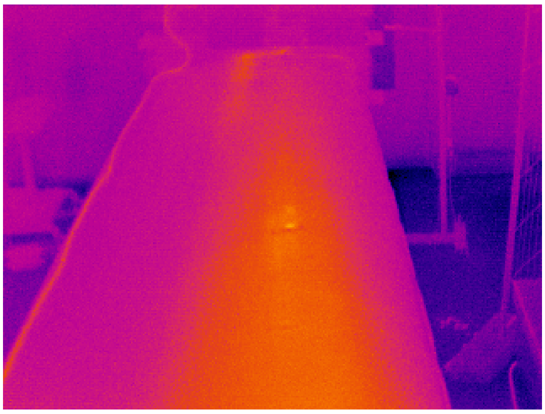


Figure 17. Up-wind surface at level 4

At level 5 the thermo graphic surveillance showed that the area with higher temperature had changed. What has been a continuous stripe from the exciter frame and one metre towards root section changed to a number of separated areas and additionally the temperature in the trailing edge was increased.

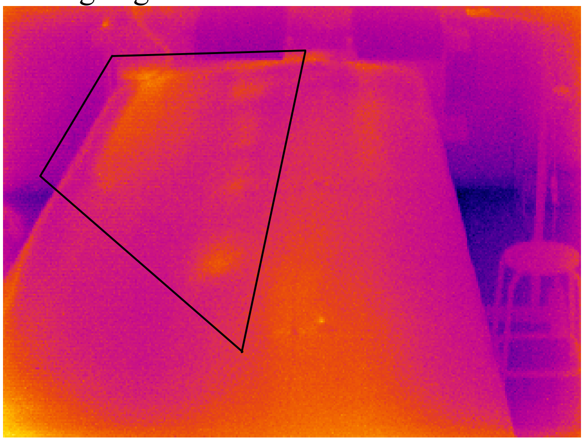


Figure 18. Up-wind surface at level 5. To the right in the black lined area, what used to be a continuous stripe has changed into a number of separated areas. To the left, the area near the trailing edge has increased in temperature.

Shortly after the thermal surveillance at level 5 the blade had a visible damage in that area of the trailing edge where an increase in temperature was observed.

4.4 Environment during test

Through the flapwise fatigue test temperature measurements were made. Figure 19 shows the temperature in the environment as a function of the cycles. The data-acquisition-computer measured the temperature and number of cycles. The temperature sensor is positioned on the blade near the root. The sensor is measuring the air temperature in the laboratory.

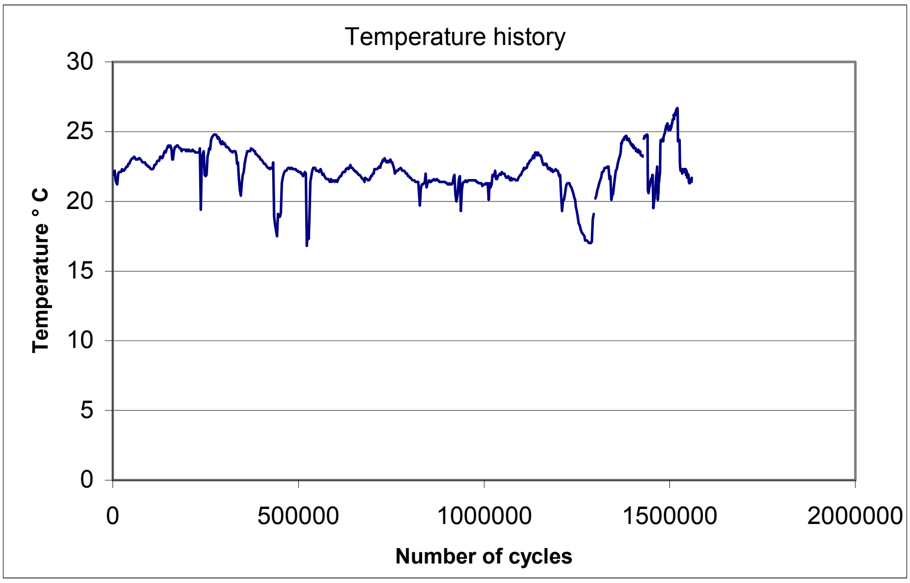


Figure 19. Temperature measurements during flapwise fatigue test blade #4703.

4.5 Calibration test results

During the fatigue test several calibration tests were performed. The calibration tests were performed as static tests with load applied to make bending towards suction (down wind) side of blade. Figure 20 shows the normative stiffness of the blade for discrete sections of the blade. The measurements show the µS/kNm local stiffness at maximum load for the calibration tests. The graphs are supposed to be linear i.e no change in stiffness of the blade. The graphs show a change in stiffness for the sections from 9 [m] to 11 [m] as the test is carried out. The change is starting when the test has run for 1.3 million cycles, i.e. app. 500 000 cycles before visual damage was seen on the blade.

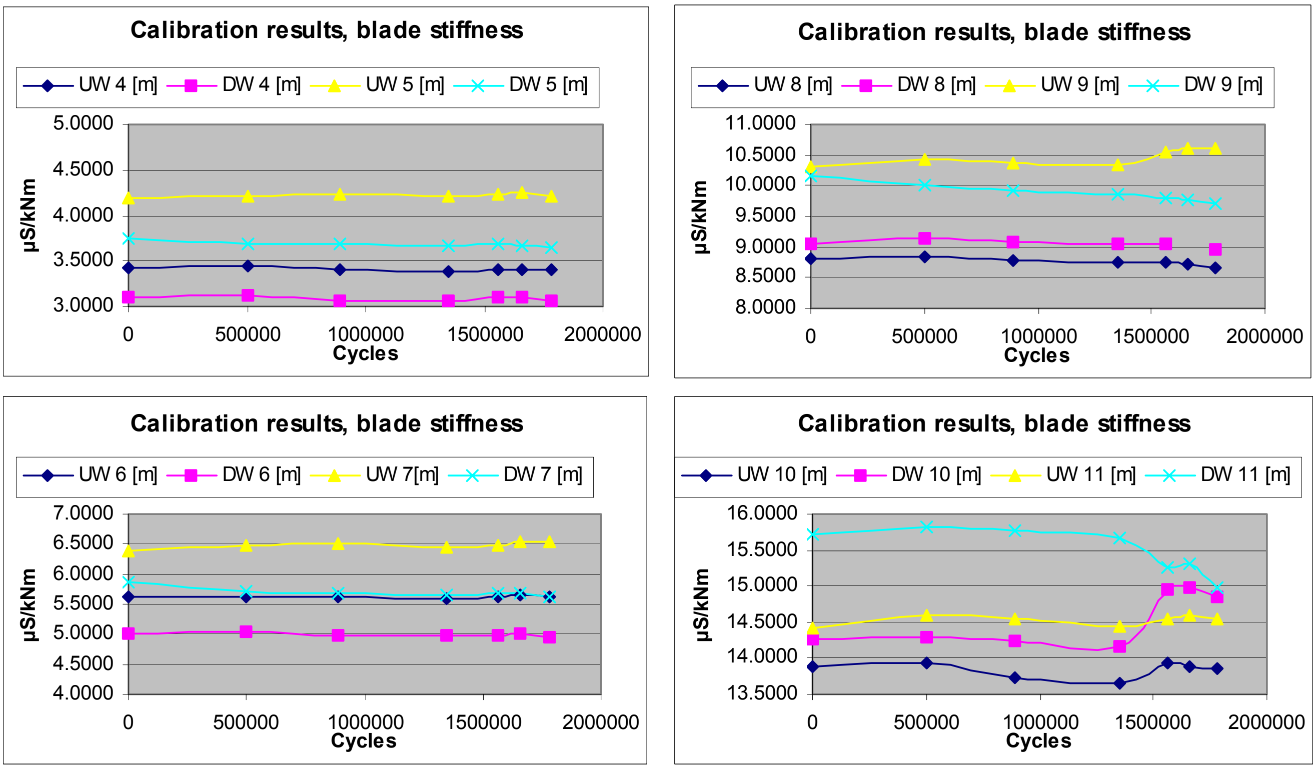


Figure 20. Discrete stiffness distribution for calibration tests of LM 19.1 # 4703, the x-axis is number of cycles applied to the blade

4.6 Moment range measurements

The number of cycles in Figure 21 - Figure 25 is determined from the data acquisition software.

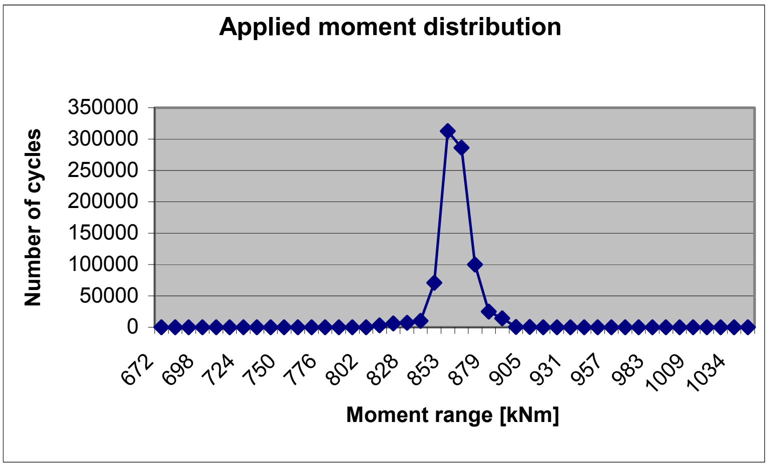


Figure 21. Moment distribution for blade # 4703 at load level 1

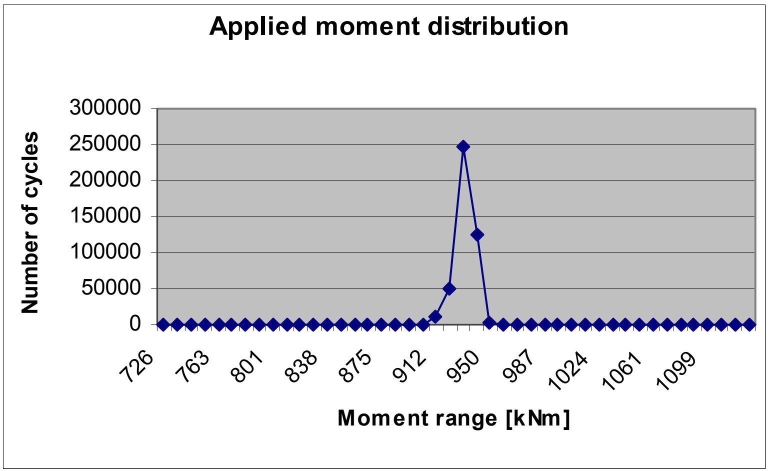


Figure 22. Moment distribution for blade # 4703 at load level 2

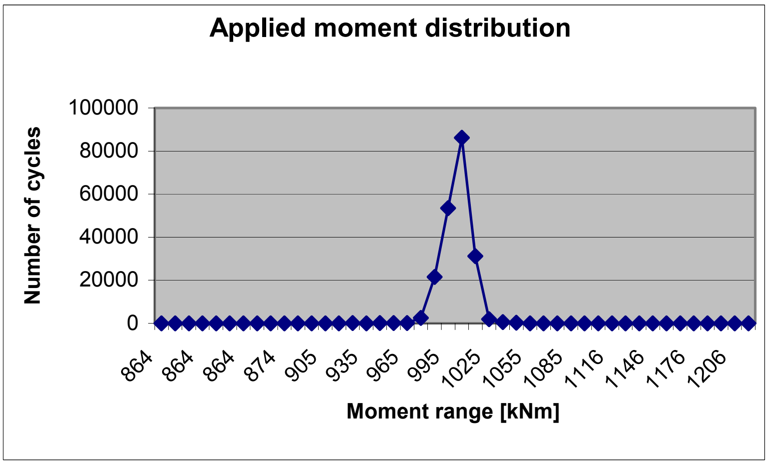


Figure 23. Moment distribution for blade # 4703 at load level 3

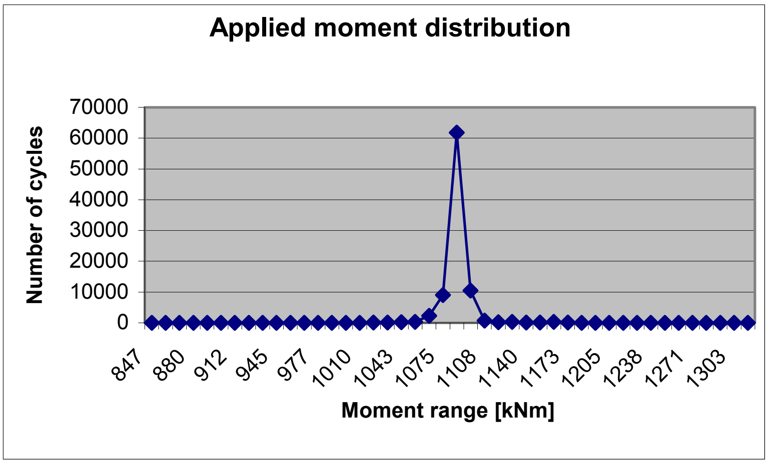


Figure 24. Moment distribution for blade # 4703 at load level 4

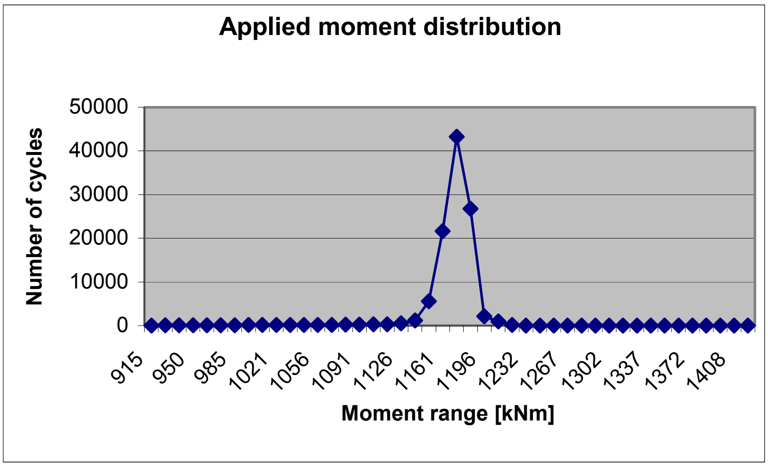


Figure 25. Moment distribution for blade # 4703 at load level 5

These moment distributions are used to calculate the equivalent moment applied to the blade. For a more detailed view of the moment distribution see app D.

Table 5 shows the equivalence between the counted number, and sizes, of applied cycles and the equivalent moment.
"∑n, Nominal" is the number of cycles pre-selected for each load level. These levels are for evaluation of the change in thermal emission from the blade when the load level is increased.
The column "∑n, Data acquisition software" and the moment distribution in Figure 21 - Figure 25 gives the resulting "Equivalent moment".
The "Lifetime" column shows the percentage of a lifetime used at each level of the test. The blade did brake at 107 % of a lifetime.

	Target		Measured		Calculated	
Series #	∑n, Nominal	Nominal moment [kNm]	∑n, Mechanical	∑n, Data acquisition software	Equivalent moment [kNm]	Calculated ∑n at nominal moment
Series 1	800000	862	890498	838164	858.7	809733
Series 2	400000	931	457923	440948	932.3	446406
Series 3	200000	1005	212227	198732	1001.7	192936
Series 4	100000	1086	100050	86430	1086.2	86567
Series 5	50000	1173	119692	104416	1171.3	103042

Table 5. Root Bending Moment statistic for flapwise fatigue test of blade # 4703.

4.7 Strain measurements

A strain measurement is considered incorrect when the recorded strain values are more than 4 times the standard deviation beyond or below the average. These values are removed from the files and are disregarded in the further data analysis. The strain statistics in the tables are based on all strain gauge scans in the respective load levels. The increase in load level is based on the average of the prior load level.

					%-increase compared to level 1	%-increase compared to level 2	%-increase compared to level 3	%-increase compared to level 1
	LEVEL 1				LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
SG-no. #	Min	Max	Average	Stdev				
0	1876	2001	1938,4	17,6	8,6	7,1	10.1	7,7
1	1606	1713	1655,1	17,4	6,8	7,1	9.5	7,4
2	1961	2090	2025,8	19,1	8,2	7,1	9.4	7,3
3	1940	2065	2000,0	19,0	8,1	7,0	9.5	7,2
4	2007	2144	2071,0	19,2	8,0	6,9	9.5	7,4
5	1771	1885	1824,0	17,5	8,1	7,0	9.4	7,1
6	2098	2238	2157,9	20,6	8,0	6,9	9.4	7,4
7	1919	2044	1975,6	19,2	8,1	7,0	9.4	7,1
8	2234	2390	2305,0	21,4	8,4	7,2	9.6	7,4
9	1988	2122	2048,0	18,8	8,2	6,9	9.3	7,0
10	2554	2723	2633,1	24,7	8,4	7,2	9.6	7,5
11	2283	2438	2350,0	22,0	8,2	7,0	9.5	7,1
12	2453	2620	2524,5	22,7	8,6	7,2	9.5	7,6
13	2195	2349	2265,5	22,1	8,0	6,9	9.3	6,9
14	2675	2859	2759,0	27,6	8,4	6,7	9.4	6,7
15	2778	2977	2866,9	27,4	8,2	7,0	9.2	6,1
16	2390	2563	2465,4	23,3	8,2	6,9	9.7	10,6
17	2327	2490	2397,6	22,5	8,0	6,9	9.2	6,7
18	2156	2318	2243,5	26,8	7,7	7,1	10.5	9,7
19	2239	2401	2308,6	21,8	8,3	7,1	11.1	12,5
20	1267	1361	1307,7	12,0	8,3	5,8	9.4	4,8
21	1362	1457	1403,2	13,2	8,3	7,4	8.7	0,3
22	465	500	481,2	5,0	7,7	1,1	3.3	-0,6
23	526	564	543,1	5,4	8,0	4,4	3.3	0,8
24	20	23	20,9	0,6	6,6	6,3	-0.1	-72,7
25	13	16	14,5	0,6	6,0	8,3	-8.5	1,6
26	675	711	688,1	6,8	7,5	6,6	6.7	6,5
27	2105	2220	2170,5	16,9	8,6	7,2	9.5	7,6
28								-0,8
29								6,0
Moment start	832,81	895,27	865,6	9,7	8,3	7,2	8.6	8,1
Moment end	835,26	901,4	866,9	9,8	8,3	7,4	8.4	8,2

Table 6. Strain statistics for load level 1 compared to increase in load in level 2-5, for blade # 4703. For the gauges # 24 and # 25 the basis measurement is at a low level, this explains the high percentage deviation for these gauges in the last load level

4.8 Results of inspections

During the flapwise fatigue test the blade was visually inspected at regular intervals. Before the appearance of the crack there was no visual impacts on the blade. The only observations of changes made on the blade were made with the thermal imaging equipment as discussed in paragraph 4.3.

4.9 Conclusion, Blade # 4703

Blade # 4703 was fatigue tested at five different load levels. During test the blade was monitored by use of strain gauges, thermal inspection equipment and visual inspection. The blade did not show significant increase in temperature as the load was increased, i.e. changes in temperature were less than 5 ° C. The damage on the blade started on the joint between the trailing edge web and the pressure side shell. The damage propagated along the web, and the test was stopped when the trailing edge was damaged. For further info on the damage see Ref 5. As the test was carried out a minor change in the strain distribution was seen. This change was seen in the gauges positioned where the damage was appearing.

5 Flapwise fatigue test of blade no. # 4706

5.1 Blade two, test sequence

The second blade was planned to be tested at only one load level, equal to the fourth level of the first blade (1086 [kNm]). This load is equal to a lifetime test carried out in 625.000 cycles.

When the blade has experienced 2.33 lifetime cycles the load was increased. The increase in load was 8 % and the new load was 1173 [kNm]. At this load the blade was tested for an additional 4.18 lifetime cycles. More load increases were made as described in paragraph 5.2. The intention was to excite the blade until visual damage occurred.

5.2 Phase definition

The test phases are defined in Table 7.

Phase and level	Date		Root bending moment [kNm]	Number of nominal cycles for a lifetime	Number of nominal cycles applied in current phase	Number of lifetimes applied to the blade in phase
	Start	Stop				
1	04/10-2001	26/10-2001	1086	625000	1454218	2.33
2	26/10-2001	12/11-2001	1173	312500	1306956	4.18
3	12/11-2001	16/11-2001	1267	156250	355116	2.27
4	16/11-2001	19/11-2001	1280	142851	255256	1.79
5	19/11-2001	23/11-2001	1368	78125	138818	1.78
					Sum	12.4

Table 7. Phase definition

5.3 Events during test

The second blade was surveyed by thermal imaging equipment in 6 sessions. There were two sessions for the first level and one session for each of the following levels. There were no observations of hot spots under the first thermal surveillance.

On the 11th of October two additional strain gauges were mounted. The gauges were mounted on the centre line of the pressure side at distance Z = 4.89 [m] and Z = 6.81 [m]. The positions of these two gauges were determined after the second thermal surveillance of the blade.

The thermal observations on this blade have been very similar to the observations made on the first blade. The difference is observed on the suction side of the blade. Where the first blade showed no thermal emission in the area of the webs on suction side, the second blade has had areas on the suction

side very similar to the picture from the pressure side, i.e. a hot area between the two webs, especially in the area of the web towards trailing edge, see Figure 26 and Figure 28.
Hot spots observed in the root section on this blade, were similar to the spots on the first blade. Figure 27 and Figure 29 shows the root section, when the the thermal images were made the root bending moment was 1267 [kNm].

Figure 26. Suction side of blade with part of preload and exciter

Figure 27. Downwind centre line, hot spot marked with red marker, diameter app. 3 [cm].

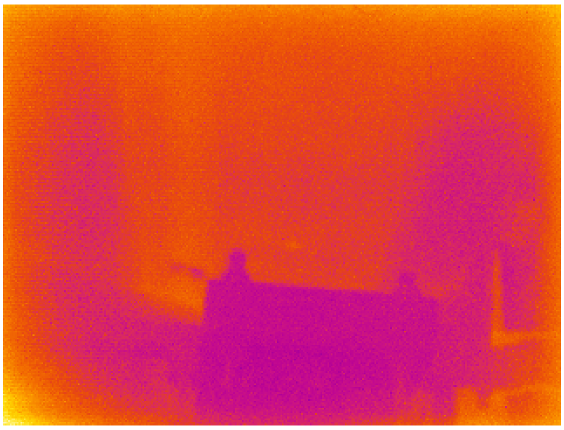


Figure 28. Thermal image of downwind side of exciter area at load level1086 [kNm]

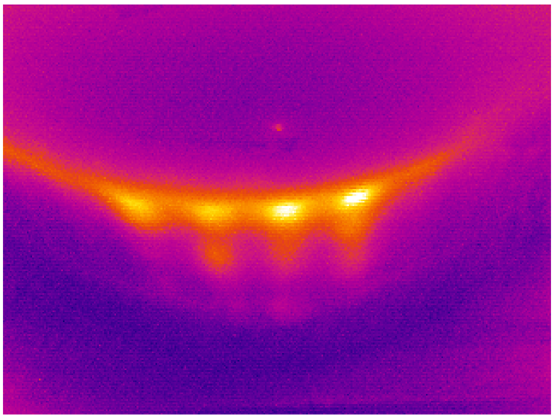


Figure 29. Thermal image of hot spot on centre line of downwind side at the root section at load level 1267[kNm]

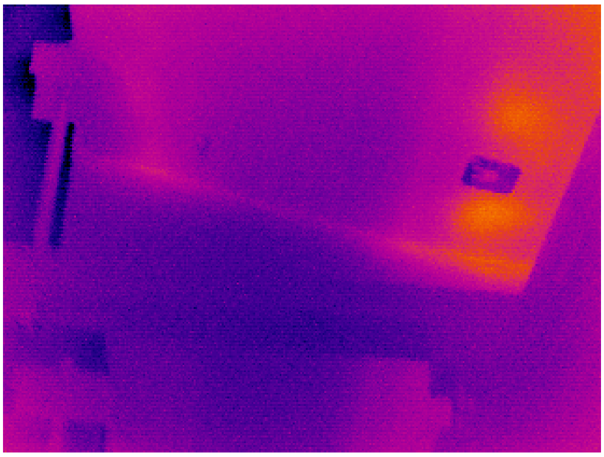


Figure 30. Thermal image of downwind side of exciter area at load level 1368 [kNm]

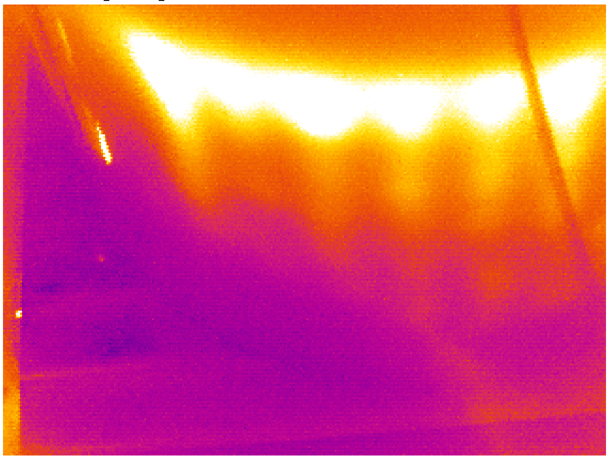


Figure 31. Thermal image of hot spot on centre line of downwind side at the root section at load level 1368[kNm]

The propagation in the thermal emission on the blade during test was limited to an increase in the heated area in the root section and, at the very end of the test, a change in heat distribution in the area of the exciter.

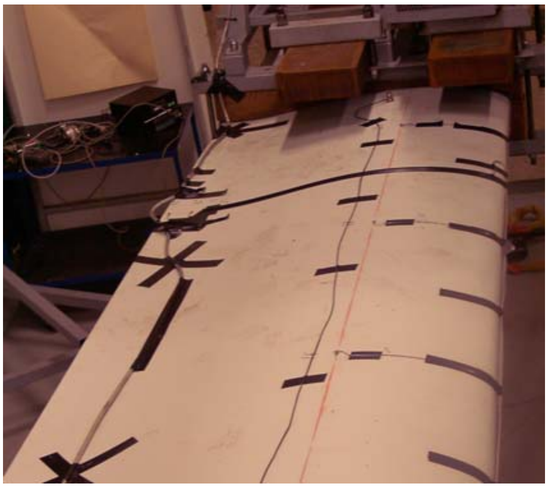


Figure 32. Pressure side of blade, area between 8.5 [m] and exciter

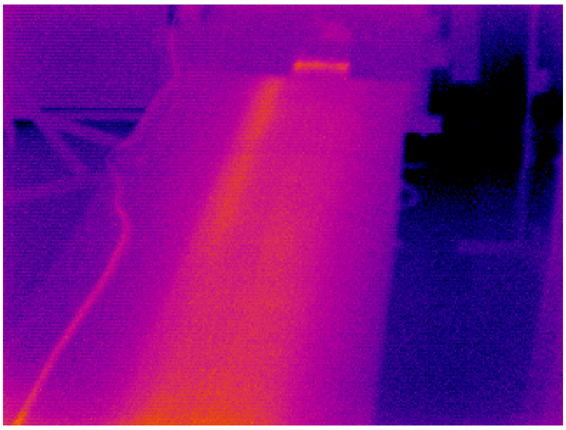


Figure 33. Thermal image of upwind side of exciter area at load level 1267 [kNm]

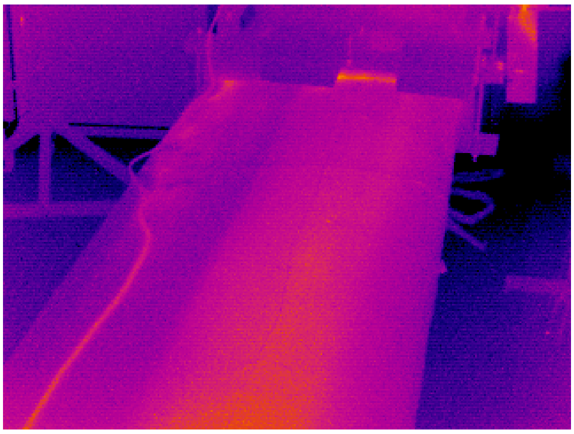


Figure 34. Thermal image of upwind side of exciter area at load level 1368 [kNm]

Figure 32 Figure 33 and Figure 34 shows the upwind side of the blade, and the change in thermal emission when the load is increased. A similar picture was seen on the first blade just prior to the damage in the trailing edge. On this blade are observed no damage by visual inspection when the blade was still mounted on the test-rig. Subsequent to the dismounting of the blade a small crack appeared in the trailing edge. The position of the crack was from 10.67 [m] to 10.85[m].

5.4 Environment during test

Through the flapwise fatigue test temperature measurements were made. Figure 35 shows the temperature in the environment as a function of the cycles. The data-acquisition-computer measured the temperature and number of cycles.

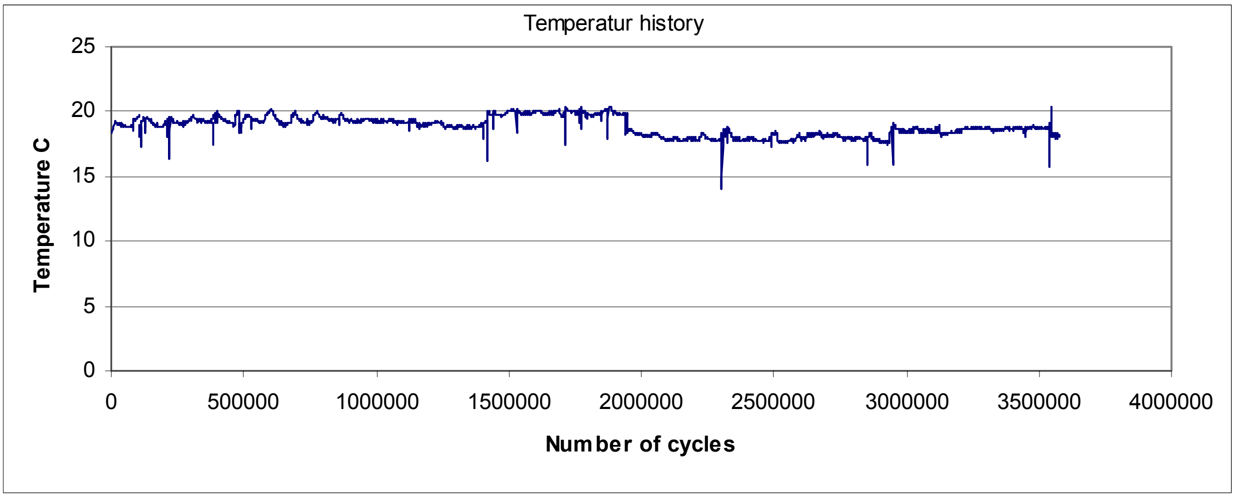


Figure 35. Temperature measurements during flapwise fatigue test.

5.5 Calibration test results

During the fatigue test several calibration tests were performed. The calibration tests were performed as static tests with load applied to make bending towards suction (down wind) side of blade. Figure 36 shows the normative stiffness of the blade for discrete sections of the blade. The measurements show the µS/kNm local stiffness at maximum load for the calibration tests. The graphs are supposed to be linear i.e no change in stiffness of the blade. The graphs show a change in stiffness for the sections from 9 [m] to 11 [m] as the test is carried out. The change is starting when the test has run for less than 500 000 cycles, i.e.
app. 1 500 000 cycles before visual damage was seen on the blade.

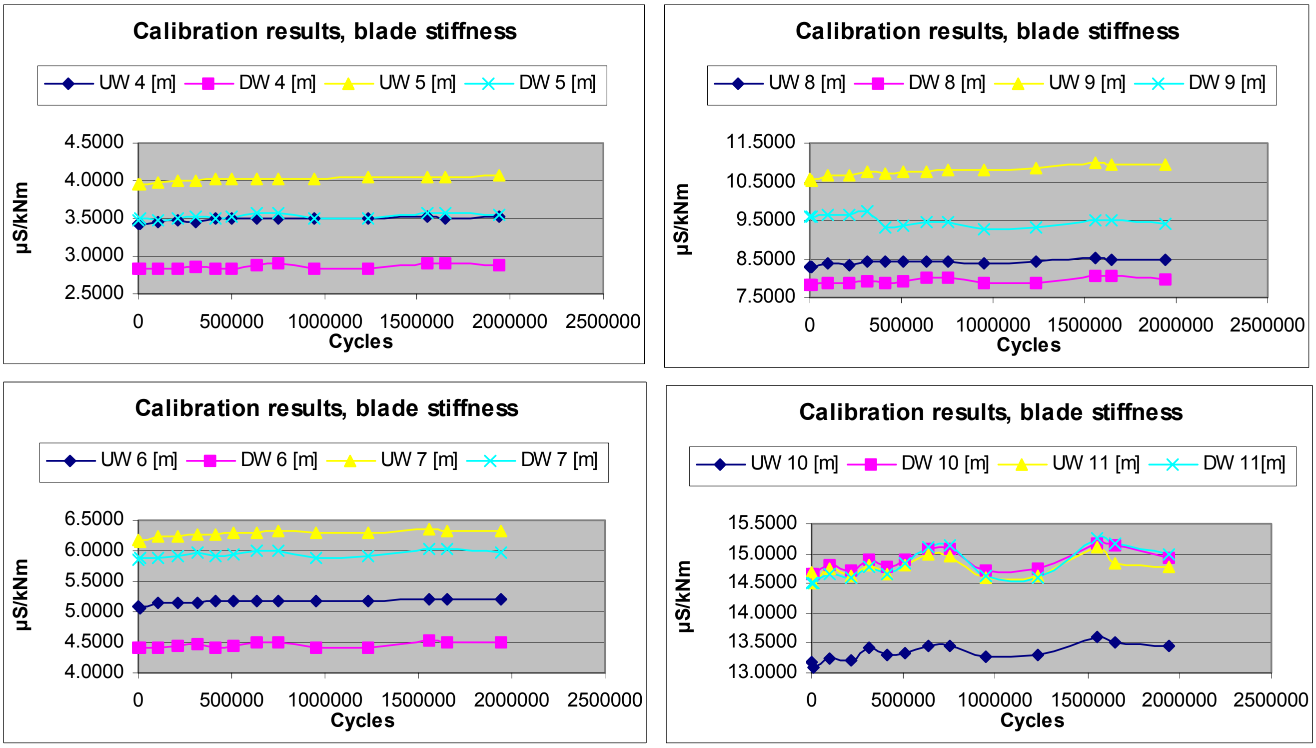


Figure 36. Discrete stiffness distribution for calibration tests of LM 19.1 # 4706, the x-axis is number of cycles applied to the blade

5.6 Moment range measurements

The number of cycles in - is determined from the data acquisition software.

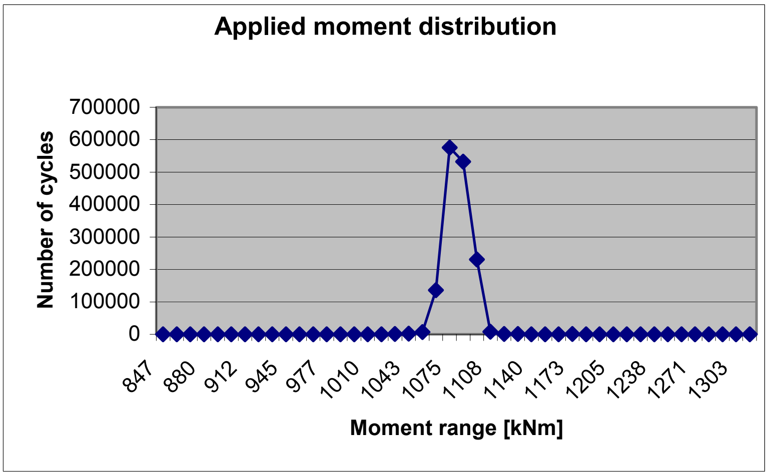


Figure 37. Moment distribution for blade # 4706 at load level 1

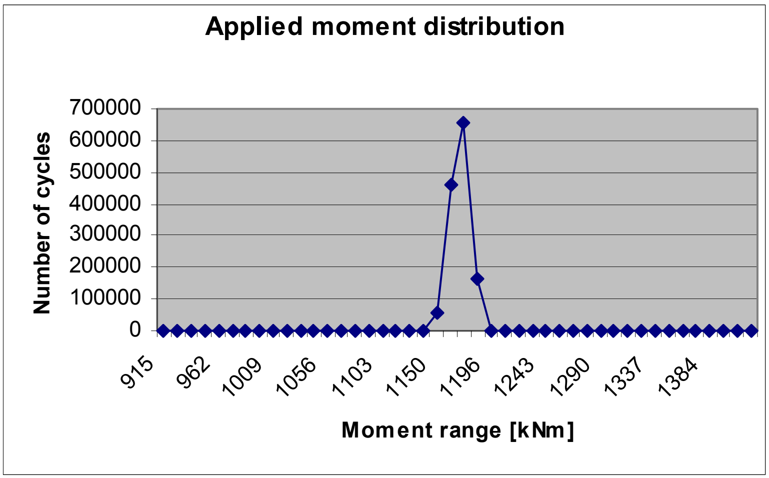


Figure 38. Moment distribution for blade # 4706 at load level 2

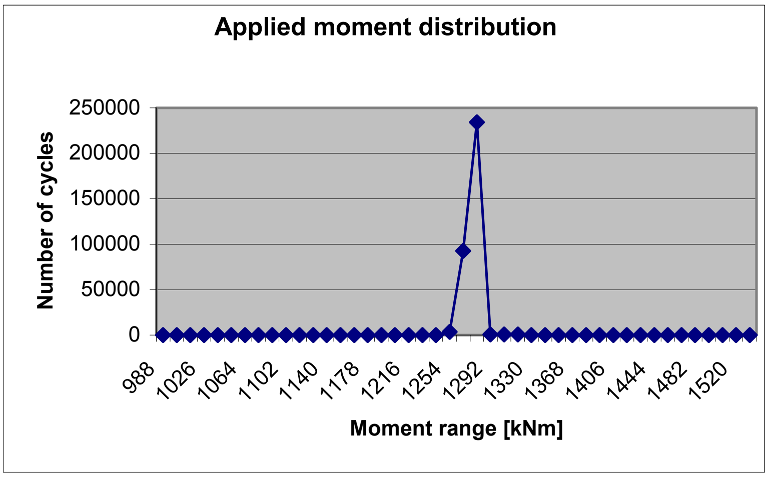


Figure 39. Moment distribution for blade # 4706 at load level 3

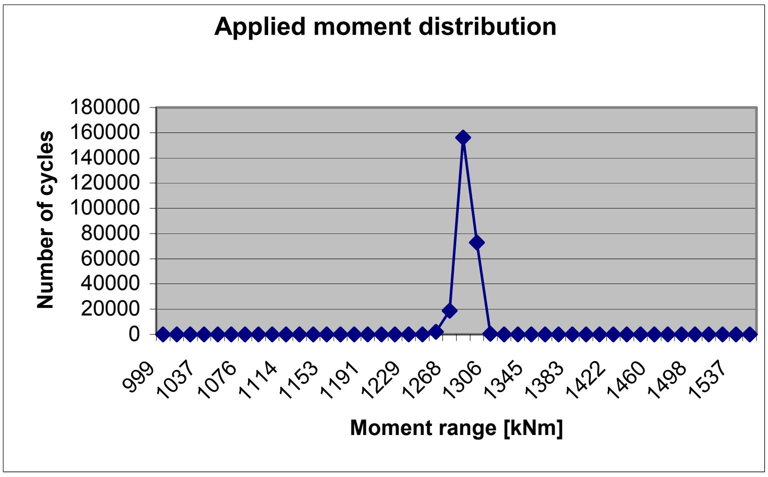


Figure 40. Moment distribution for blade # 4706 at load level 4

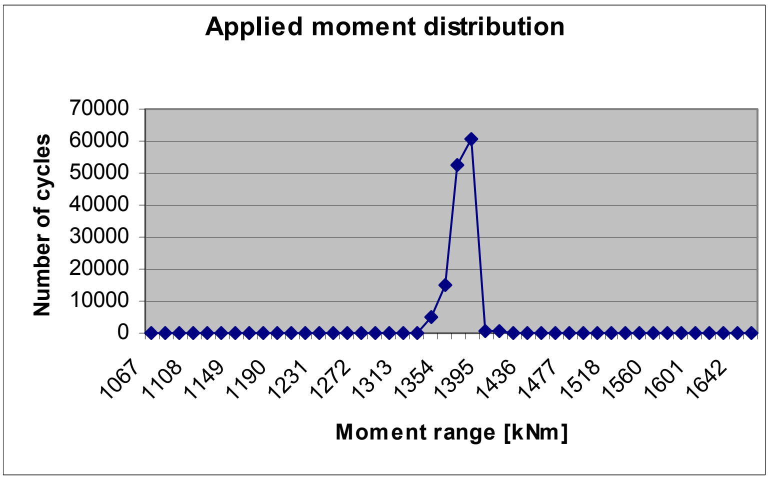


Figure 41. Moment distribution for blade # 4706 at load level 5

The number of cycles in Table 8 is determined from the data acquisition software

	Target		Measured		Calculated	
Series #	∑n, Nominal	Nominal moment [kNm]	∑n, Mechanical	∑n, Data acquisition software	Equivalent moment [kNm]	Calculated ∑n at nominal moment
Series 1	625000	1086.0	1649647	1501394	1082	1454218
Series 2	312500	1173.0	1487758	1339458	1170	1306956
Series 3	156250	1267.0	372731	332996	1276	355115
Series 4	150000	1280.7	275889	250338	1283	255256
Series 5	78125	1368.0	149476	135476	1371	138818

Table 8. Root Bending Moment statistic for flapwise fatigue test of blade # 4706.

5.7 Strain measurements

A strain measurement is considered incorrect when the recorded strain values are more than 4 times the standard deviation beyond or below the average. These values are removed from the files and are disregarded in the further data analysis. The strain statistics in the tables are based on all strain gauge scans in the respective load levels. The increase in load level is based on the average of the prior load level. For the strain statistic the load level at 1267 kNm and the load level at 1280 kNm is treated as one load level

					%-increase compared to level 1	%-increase compared to level 2	%-increase compared to level 3
	LEVEL 1				LEVEL 2	LEVEL 3	LEVEL 4
SG-no. #	Min	Max	Average	Stdev			
0	2137	2384	2259.5	46.7	9.6	8.5	8.3
1	1807	2023	1928.3	40.6	9.5	7.3	9.7
2	2365	2592	2481.3	46.6	9.5	8.4	8.1
3	2186	2405	2304.1	44.7	9.4	7.8	8.0
4	2461	2727	2601.8	52.0	8.2	7.0	8.1
5	1926	2109	2018.6	37.7	9.8	8.7	8.1
6	2541	2805	2681.9	51.0	9.7	8.4	8.1
7	2121	2319	2220.0	41.0	9.3	8.2	7.9
8	2548	2824	2695.0	53.2	9.9	8.2	8.1
9	2273	2504	2397.5	44.6	9.5	8.2	8.0
10	2796	3100	2964.6	56.8	9.8	9.0	7.6
11	2467	2713	2596.5	48.1	9.4	8.3	8.1
12	2833	3156	3015.3	59.6	9.6	7.8	7.9
13	2727	3004	2875.3	53.4	9.4	8.2	7.9
14	3052	3388	3240.0	60.9	11.1	8.3	8.9
15	2914	3218	3079.4	57.0	9.5	8.4	8.1
16	2946	3304	3142.6	62.1	10.5	7.9	9.1
17	2650	2913	2795.2	52.1	8.5	3.4	1.0
18	2512	2787	2665.3	50.1	9.7	8.0	12.8
19	2780	3070	2942.4	54.5	9.1	8.2	9.0
20	1524	1684	1610.2	30.0	9.1	8.8	5.3
21	1522	1686	1614.8	29.7	9.4	9.1	2.9
22	593	655	625.5	11.7	9.9	8.6	2.7
23	549	607	581.3	10.6	9.8	8.6	3.0
24	26	37	29.0	1.6	2.0	5.9	-12.1
25	15	26	17.4	1.7		33.4	7.6
26	585	655	623.6	12.3	9.1	8.4	4.3
27	543	620	588.4	12.9	11.1	10.0	-4.7
28	2805	3139	2971.6	79.0	6.4	7.4	7.9
29	3159	3505	3362.2	64.6	7.7	5.4	7.9
Moment start	1035.28	1129.98	1085.9	10.8	8.2	12.6	4.3
Moment end	996.66	1132.59	1088.7	10.9	8.2	12.6	4.1

Table 9. Strain statistics for load level 1- 4 for blade # 4706

5.8 Results of inspections

During the flapwise fatigue test the blade was visually inspected at regular intervals. There were no visual observations of damages on the blade; the only observations of changes were made with the thermal imaging equipment.

5.9 Conclusion, Blade # 4706

Blade # 4706 was fatigue tested at five different load levels. During test the blade was monitored by use of strain gauges, thermal inspection equipment and visual inspection. The blade did not show significant increase in temperature as the load was increased, i.e. changes in temperature were less than 5 ° C. As the test was carried out a minor change in the strain distribution was seen. This change was seen in the gauges positioned where the damage appeared. The test was stopped when the stiffness had changed with a magnitude and a rate that made it impossible for the regulation of the test to keep up with the changes. There was no visible damage on the blade when the test was aborted, but after dismantling the set-up a minor damage appeared on the trailing edge. The damage on the blade appears to have started on the joint between the trailing edge web and the pressure side shell. For further info on the damage see Ref 5.

6 Flapwise fatigue test of blade no. # 4700

6.1 Blade three, test sequence

The third blade was planned to be tested at only one load level, equal to the third level of the first blade (1005 [kNm]). This load is equal to a lifetime test carried out in 1250000 cycles.

When the blade has experienced 0.63 lifetime cycles the load was increased. The increase in load was 2 times 8 % and the new load was 1173 [kNm]. At this load the blade experiences one lifetime in 312500 cycles. At this level the test was carried out for 1453350 more cycles. This load-level and number of cycles is equivalent to 4.65 lifetime. The load increases were made as described in paragraph 6.2.
The intention was to excite the blade until visual damage occurred.

6.2 Phase definition

The test phases are defined in Table 10.

Phase and level	Date		Root bending moment [kNm]	Number of nominal cycles for a lifetime	Number of nominal cycles applied in current phase	Number of lifetimes applied to the blade in phase
	Start	Stop				
1	29/11-2001	07/12-2001	1005	1250000	592344	0.47
2	07/12-2001	21/12-2001	1173	312500	1090638	3.49
3	17/01-2002	19/01-2002	1267	156250	189691	1.21
					Sum	5.17

Table 10. Phase definition

6.3 Events during test

The third blade was surveyed by thermal imaging equipment in 3 sessions. There was one session for the first level and two sessions for the following level.

The thermal observations on this blade have been very similar to the observations made on the first and second blade.

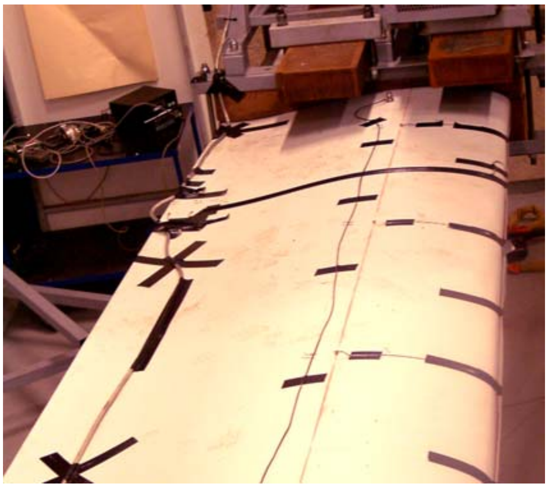


Figure 42. Pressure side of blade, area between 8.5 [m] and exciter. This picture is from blade 4706, this explains the difference in cabling

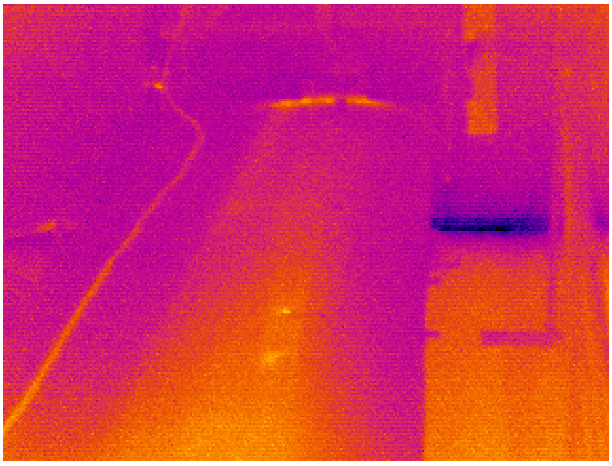


Figure 43. Thermal image of upwind side of exciter area at load level 1173 [kNm]

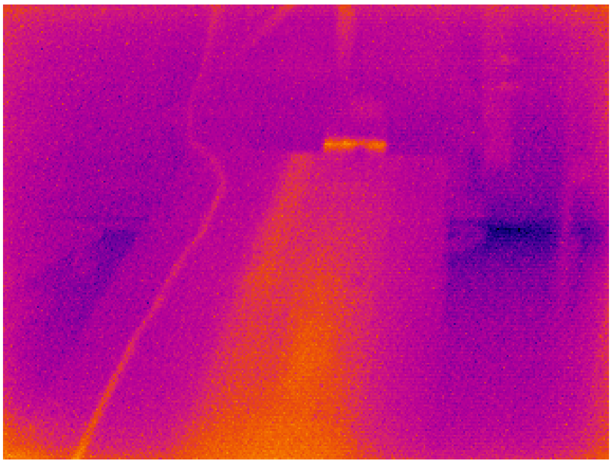


Figure 44. Thermal image of upwind side of exciter area at load level 1173 [kNm]

Figure 42, Figure 43 and Figure 44 show the upwind side of the blade, and the thermal emission from the blade. A similar picture was seen on the first two blades. On this blade are observed no damage by visual inspection but as the test of this blade was terminated a minor change in strain level were observed for some of the SG.

6.4 Environment during test

Through the flapwise fatigue test temperature measurements were made. Figure 45 shows the temperature in the environment as a function of the cycles. The data-acquisition-computer measured the temperature and number of cycles.

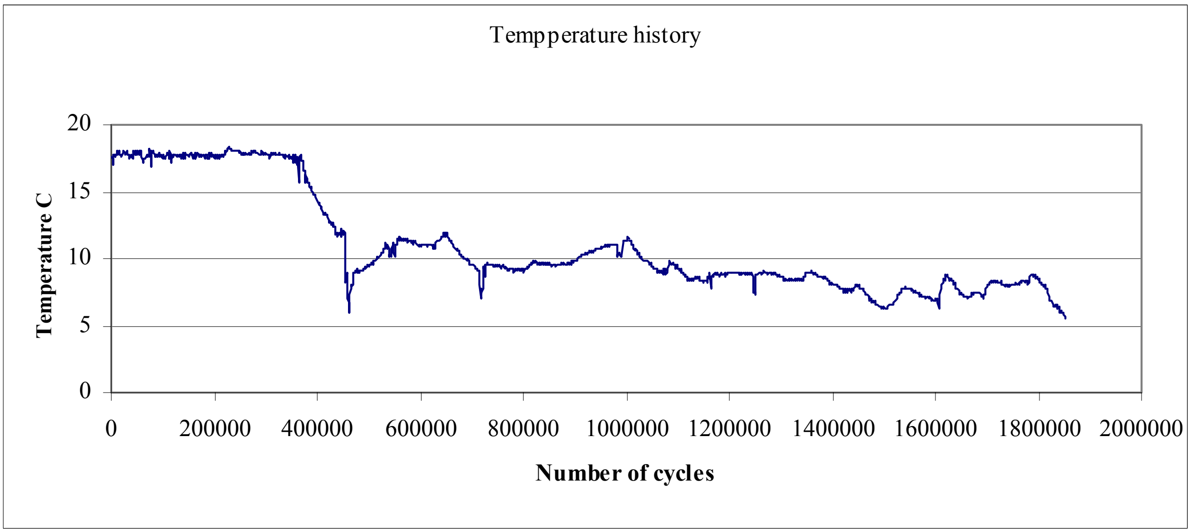


Figure 45. Temperature measurements during flapwise fatigue test.

6.5 Calibration test results

During the fatigue test several calibration tests were performed. The calibration tests were performed as static tests with load applied to make bending towards suction (down wind) side of blade. Figure 46 shows the normative stiffness of the blade for discrete sections of the blade. The measurements show the µS/kNm local stiffness at maximum load for the calibration tests. The graphs are supposed to be linear i.e no change in stiffness of the blade. The graphs show no change in stiffness for the different sections of the blade. The change seen on the UW 10 [m] in the early stage of the test is caused by a defect strain gauges.

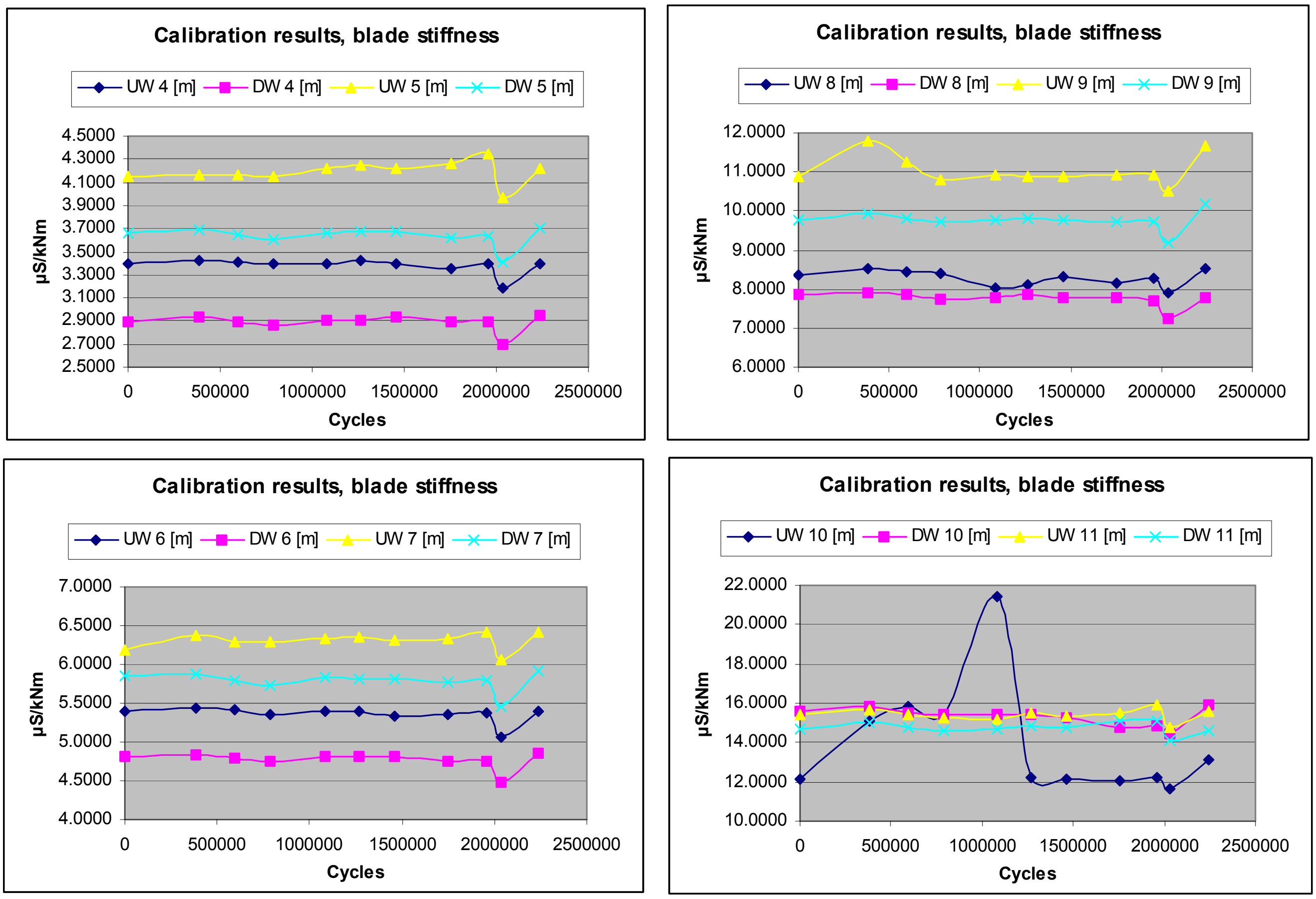


Figure 46. Discrete stiffness distribution for calibration tests of LM 19.1 # 4700, the x-axis is number of cycles applied to the blade

6.6 Moment range measurements

The number of cycles in - is determined from the data acquisition software.

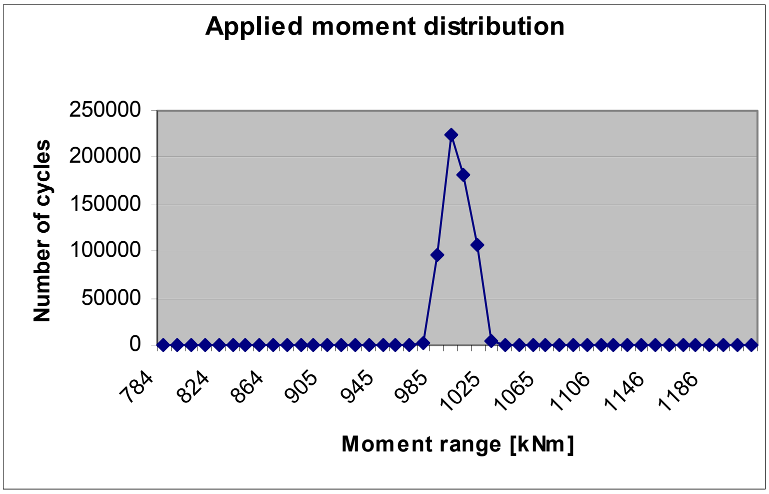


Figure 47. Moment distribution for blade # 4700 at load level 1

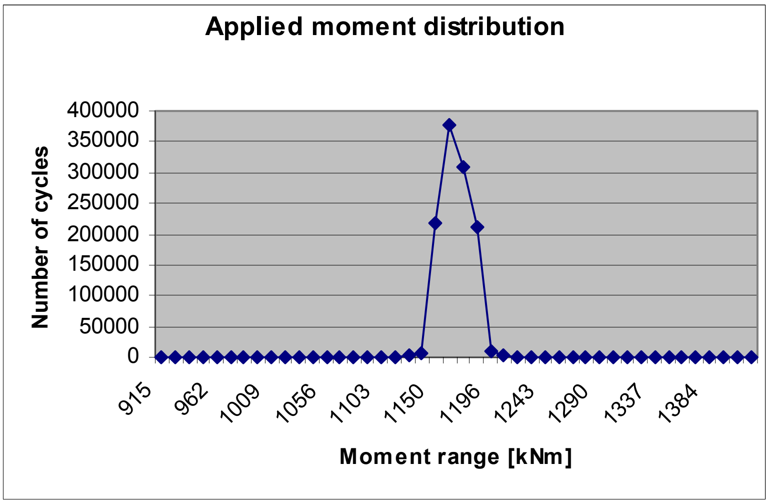


Figure 48. Moment distribution for blade # 4700 at load level 2

The number of cycles in Table 11 is determined from the data acquisition software

	Target		Measured		Calculated	
Series #	∑n, Nominal	Nominal moment [kNm]	∑n, Mechanical	∑n, Data acquisition software	Equivalent moment [kNm]	Calculated ∑n at nominal moment
Series 1	1250000	1005.0	786836	618538	1000.2	592344
Series 2	312500	1173.0	1247404	1139386	1167.3	1090638
Series 3	156250	1267.0	205946	188212	1268.1	189691

Table 11. Root Bending Moment statistic for flapwise fatigue test of blade # 4700.

6.7 Strain measurements

A strain measurement is considered incorrect when the recorded strain values are more than 4 times the standard deviation beyond or below the average. These values are removed from the files and are disregarded in the further data analysis. The strain statistics in the tables are based on all strain gauge scans in the respective load levels.

	LEVEL 1				%-increase compared to level 1
SG-no. #	Min	Max	Average	Stdev	
0	2083	2225	2163.7	24.2	17.4
1	1790	1913	1857.0	19.5	18.7
2	2330	2478	2411.5	25.6	17.5
3	2090	2231	2167.7	24.4	17.0
4	2543	2723	2638.4	31.2	16.0
5	2095	2247	2179.9	26.6	15.6
6	2387	2537	2467.7	25.3	16.6
7	2083	2218	2156.9	23.4	17.2
8	2528	2693	2618.4	25.6	18.4
9	2283	2433	2366.6	26.0	17.0
10	2747	3009	2887.0	55.9	13.9
11	2544	2720	2642.9	29.6	16.8
12	2683	2902	2817.5	30.0	17.8
13	2570	2746	2669.5	29.5	16.9
14	2943	3151	3061.0	34.2	13.7
15	2755	2949	2865.5	32.0	16.5
16	2879	3382	3031.7	74.1	15.0
17	2625	2814	2733.6	29.8	16.6
18	2217	2399	2302.1	28.2	17.3
19	2780	3002	2910.8	35.0	14.2
20	1502	1618	1569.4	16.9	18.0
21	1474	1586	1537.8	16.5	18.8
22	554	608	584.0	9.3	16.0
23	549	597	576.6	7.6	16.1
24	31	34	33.0	0.2	11.2
25	14	21	17.3	1.3	7.3
Moment start	973.39	1036.51	1004.1	9.1	16.9
Moment end	960.34	1044.09	1005.8	9.8	17.0

Table 12. Strain statistics for load level 1 and 2 for blade # 4700

6.8 Results of inspections

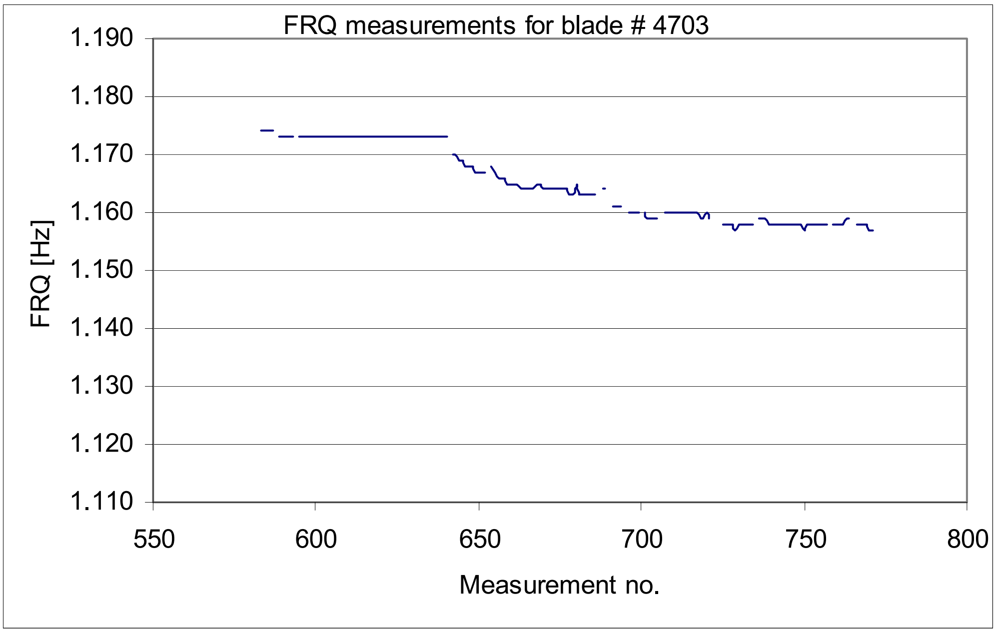
During the flapwise fatigue test the blade was visually inspected at regular intervals. There were no visual observations of damages on the blade.

6.9 Conclusion, Blade # 4700

Blade # 4700 was fatigue tested at three different load levels. During test the blade was monitored by use of strain gauges, thermal inspection equipment and visual inspection. The blade did not show significant increase in temperature as the load was increased, i.e. changes in temperature were less than 5 ° C. The damage on the blade started on the joint between the trailing edge web and the pressure side shell. The damage propagated along the web, and the test was stopped when the trailing edge was damaged. For further info on the damage see Ref 5. In the very end of the test, just before the blade broke a minor change in the strain distribution was seen. This change was seen in the gauges positioned where the damage was appearing.

7 Frequency measurements during test

The natural frequency (1st flapwise bending mode) was measured on the three blades during the fatigue tests. Changes in the stiffness of the blade will influence on the natural frequencies, and this is seen as changes in the structure.



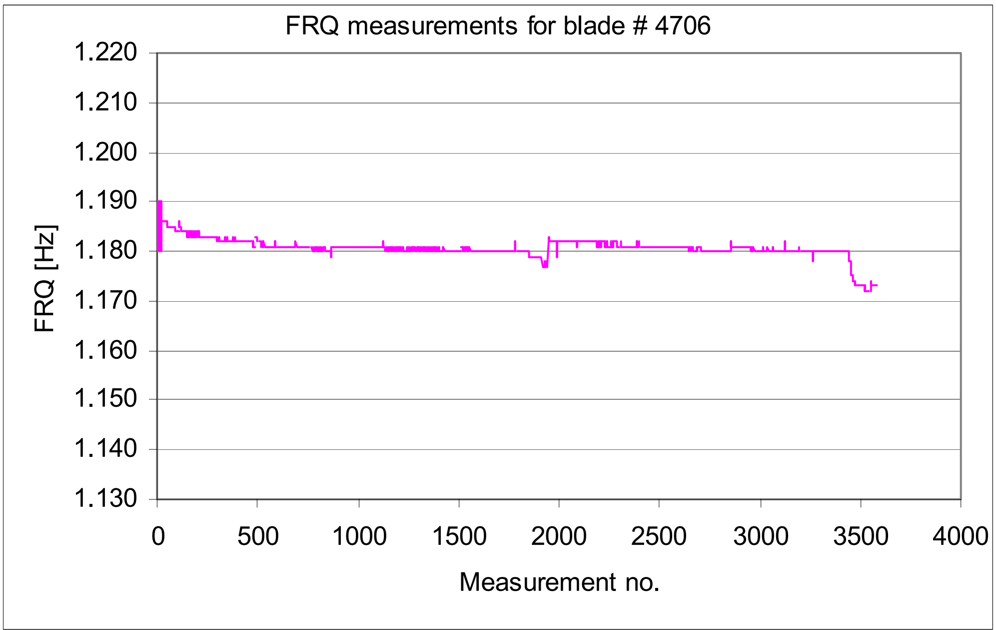


Figure 49. Changes in natural frequency (1st flapwise bending mode) as the tests proceeded.

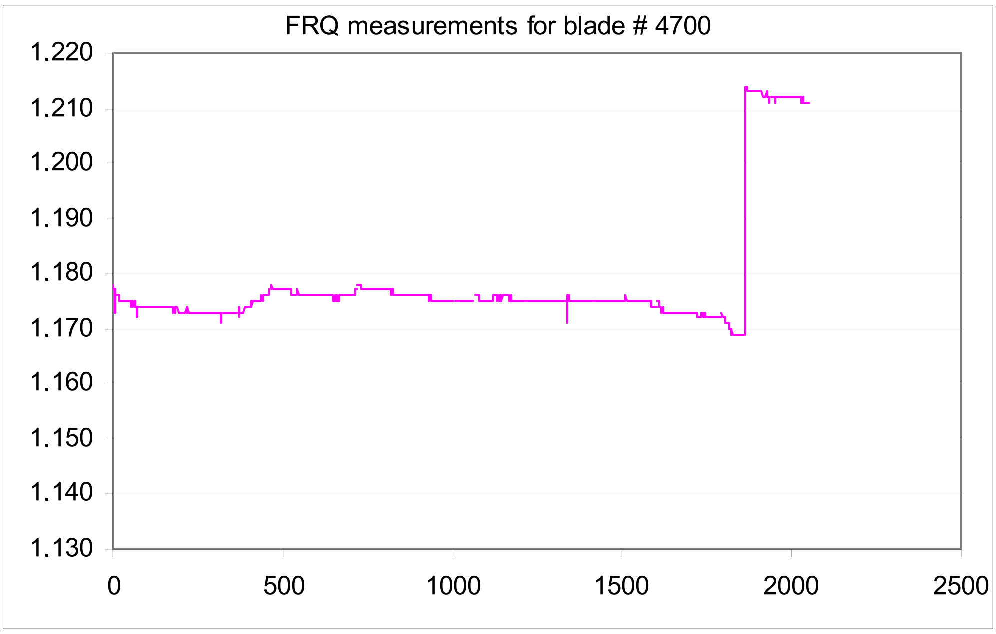


Figure 50. Changes in natural frequency (1st flapwise bending mode) as the test proceeded.

As the graphs showed a general decrease in the frequency of the blades as the fatigue tests proceeded were observed.
On the last of the three blades there was made an improvement of the test-rig during the test. The test rig became stiffer, and this is seen as a higher frequency of the blade, this explain the "jump" in the graph.

8 Conclusion

A series of fatigue tests have been applied to three LM 19.1 blades with the aim of investigating the influence of increasing the load range to shorten the duration of the fatigue test. During these tests at different load levels, the blades were surveyed with thermal imaging system to see if the areas getting the most energy are changed to other locations, i.e. creating new failure modes with new, higher, loads. During these sessions no observations were made regarding changing of the overall pattern of the thermal emission from the blades, but the heated areas were enlarged and the temperature was increased up to 5°. For one blade the increase in load range corresponds to full 5 million cycles fatigue test carried out in only 78125 cycles, i.e. corresponding to an increase in load range of more than 50%. Even at this load level there seems to be no change of the overall pattern of the damaged areas using the thermal emission as guidance.

In addition to the thermal surveillance of the blades, static calibration measurements with strain gauges were also carried out. These strain gauges measurements showed changes in strain level very long time in advance of the observations of damages in the blades.
The natural frequency (1^{st} flapwise bending mode) was measured on the three blades during the fatigue tests. This showed a general decrease in the frequency of the blade as the fatigue tests proceeded.

Based on the tests in this project, the shortening of a fatigue blade test duration by means of increasing the load level range does not lead to new heated areas of the blade and only a small increase of the maximum temperature in the materiel was seen.

9 References

1. “Rekommandation til opfyldelse af krav i Teknisk Grundlag for Typegodkendelse og Certificering af Vindmøller i Danmark”. (kapitel 5). 1. juli 1992.
2. “Teknisk Grundlag for Typegodkendelse og Certificering af Vindmøller i Danmark”. 15. april 2000. Issued by Danish Energy Agency.
3. “Kvalitetshåndbog Vindmøllevinger for Sparkær Centret”. Forskningscenter Risø.
4. “Dynamic test, windturbine blade LM”. Dated 2000.
5. Depel, C.P. (2003) “Identification of Damage Types in Wind Turbine Blades Tested to Failure”. Risø-R-1392(EN). Forskningscenter Risø, Roskilde.

APPENDIX

A. DATA SHEETS FOR STATIC TESTS

Edgewise deflection measurements

#1

Kalibreringstest for vinge udmattelse QS 8.104.1

Vinge id / serie nr. :	LM19.1	4703
Dato :	26 - 2 - 2001	
Antal lastcykler :	Bestemmelse af kantvis stivhed	
Nominel rodmoment [kNm] :	–	
Exciter og ~~accelerometer~~ ASM position [m] :	16,8	Tip - 16,0 - 13,3
Temperatur [°C] :	~~20~~ 19,2	
Parameterfil :	–	
Kalibreringsfilnavn :	–	
Skrevet af :	Peter Lind	

Last trin	Last [kN]	Udbøjning [mm] (måles ved accelerometer) 1	2	3	Δ [mm] 1	2	3
1	0	857	1186	1155	0	0	0
2	2,01	844,3	1166	1126	13,4	20,0	29,0
3	4,06	830,4	1146	1098	27,3	40,0	57,0
4	6,01	817,1	1126	1070	40,6	60,0	85,0
5	8,00	803,3	1106	1042	54,4	80,0	113,0
6	0	856,4	1185	1153	1,3	1,0	2,0
PFV no.	1533	1574	1516	1515		-	

1 : 1 m ASM @ 13.3 m
2 : 2 m -"- @ 16.0 m
3 : 3 m -"- @ tip

NB. Kalibrerings last skal minimum være 15 % af rodmomentvidden

Beregnet stivhed K [mm/kNm] Fra regressionsanalyse	
Beregnet skæringspunkt S [mm] Fra regressionsanalyse	Hvis S> 1 mm skal der laves en ny test
Beregnet udsvingsvidde [mm]	Kontrolleres med tidligere beregnet værdi
Opdatering af parameterfil (ja/nej):	

Bemærkninger

C:\Kvalitet\maskehandbog\Sparkær Kalibreringstest for vinge udmattelse.doc

Kopi

#2

Kalibreringstest for vinge udmattelse QS 8.104.1

Vinge id / serie nr. :	LM19.1	4706
Dato :	18/5-2001	
Antal lastcykler :	Bestemmelse af kantvis stivhed	
Nominel rodmoment [kNm] :	→	
Exciter og ~~accelerometer~~ ASM position [m] :	16,3	Tip 16m - 13,3m
Temperatur [°C] :	22,5°	
Parameterfil :		
Kalibreringsfilnavn :	–	
Skrevet af :	ARV	

Last trin	Last [kN]	Udbøjning [mm] (måles ved accelerometer) 1	2	3	Δ [mm] 1	2	3
1	0	438,6	645	1133	0	0	0
2	2,05	423,2	624	1105	15,4	21	28
3	4,07	407,8	604	1076	30,8	41	57
4	6,04	392,9	584	1048	45,7	61	85
5	8,06	377,6	564	1020	61,0	81	113
6	0	437,7	644	1131	0,9	1	2
PFV no.	1533	1518	1517	1516		-	

1. asm 13.3m
2. -"- 16.0m
3. -"- Tip

NB. Kalibrerings last skal minimum være 15 % af rodmomentvidden

Beregnet stivhed K [mm/kNm] Fra regressionsanalyse	
Beregnet skæringspunkt S [mm] Fra regressionsanalyse	Hvis S> 1 mm skal der laves en ny test
Beregnet udsvingsvidde [mm]	**Kontrolleres med tidligere beregnet værdi**
Opdatering af parameterfil (ja/nej)	

Bemærkninger

C:\Kvalitet\målehåndbog\Sparkær\Kalibreringstest_for_vinge_udmattelse.doc

#3

Kalibreringstest for vinge udmattelse QS 8.104.1

Vinge id / serie nr.:	LM 19,1	4700
Dato :	2/10 2001	
Antal lastcykler :	Bestemmelse af kontvis stivhed	
Nominel rodmoment [kNm] :	—	
Exciter og ~~accelerometer~~ ASm position [m] :	16,3	Tip-16,0-13,3
Temperatur [°C] :	22°	PFV 0586
Parameterfil :	—	
Kalibreringsfilnavn :	—	
Skrevet af :	AraU	

Last trin	Last [kN]	Udbøjning [mm] (måles ved accelerometer)			Δ [mm]		
		1	2	3	1	2	3
1	0	489,6	656	1104	0	0	0
2	2,00	476,3	636	1076	13,3	20,0	28,0
3	4,12	461,6	614	1046	28,0	42,0	58,0
4	6,02	448,7	595	1020	40,9	61,0	84,0
5	8,01	435,2	574	992	54,4	82,0	112,0
6	0	488,5	654	1102	1,1	2	2,0
PFV no.		1518	1517	1516		-	

1: 0,5m Asm 213,3m
2: 1m -"- 216,0m
3: 2m -"- Tip

NB. Kalibrerings last skal minimum være 15 % af rodmomentvidden

Beregnet stivhed K [mm/kNm] Fra regressionsanalyse	
Beregnet skæringspunkt S [mm] Fra regressionsanalyse	Hvis S> 1 mm skal der laves en ny test
Beregnet udsvingsvidde [mm]	**Kontrolleres med tidligere beregnet værdi**
Opdatering af parameterfil (ja/nej)	

Bemærkninger

Flapwise deflection measurements

FOTOKOPI

~~Serie 1~~

Kalibreringstest for vinge udmattelse QS 8.104.1

Vinge id / serie nr. :	LM 19.1	4703
Dato :	22/5 2001	
Antal lastcykler :	0 Flapvis stivhed	
Nominel rodmoment [kNm] :	—	
Exciter og accelerometer position [m] :	13.15	
Temperatur [°C] :	22.9	
Parameterfil :	LM 191 #PA	
Kalibreringsfilnavn :	LM 191 #CA1.DY	
Skrevet af :	ARV	

Last trin	Last [kN]	Udbøjning [mm] (måles ved accelerometer) 1	2	3	Δ [mm]
1	0	417	962	1209	0
2	4.09	408.5	944	1169	40
3	8.06	400.0	927	1130	79
4	12.06	391.1	909	1091	118
5	16.20	382.0	891	1049	160
6	0	417.0	961	1207	2
PFV no.	0575	1518	1517	1516	-

1 acc: 8m
2 -"- 10m
3 -"- 13m

9,88 mm/kN

NB. Kalibrerings last skal minimum være 15 % af rodmomentvidden

Beregnet stivhed K [mm/kNm] Fra regressionsanalyse	— 0.75
Beregnet skæringspunkt S [mm] Fra regressionsanalyse	— Hvis S> 1 mm skal der laves en ny test
Beregnet udsvingsvidde [mm]	— Kontrolleres med tidligere beregnet værdi
Opdatering af parameterfil (ja/nej)	—

Bemærkninger

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FOTO PI

Kalibreringstest for vinge udmattelse QS 8.104.1

Vinge id / serie nr. :	LM 19.1	4706
~~Dato~~ :	3/10 2001	
Antal lastcykler :	FLAPVIS STIVHED	
~~Nominel rodmoment [kNm]~~ :		
Exciter og accelerometer position ~~[m]~~ :	13.15	
Temperatur [°C] :	18.5	
Parameterfil :	LM 19.1 # PA	
Kalibreringsfilnavn :	LM 19.1 # CA1. DXF	
Skrevet af :	JB	

Last trin	Last [kN]	Udbøjning [mm] (måles ved accelerometer) 1.	2.	3.	Δ [mm]
1	0	395.5	670	1189	0
2	4.0	387.2	653	1151	38
3	8.0	378.5	636	1113	76
4	12.0	370	619	1075	114
5	16.0	361.2	602	1035	154
6	0	395.1	669	1188	1
PFV no.	0575	1518	1517	1516	-

1 ASM : 8m
2 ASM : 10m
3 ASM : 13m

9.63 mm/kN

NB. Kalibrerings last skal minimum være 15 % af rodmomentvidden

Beregnet stivhed K [mm/kNm] Fra regressionsanalyse	0.73 dhc 14/11-01
Beregnet skæringspunkt S [mm] Fra regressionsanalyse	Hvis S> 1 mm skal der laves en ny test
Beregnet udsvingsvidde [mm]	**Kontrolleres med tidligere beregnet værdi**
Opdatering af parameterfil (ja/nej)	

Bemærkninger

Kalibreringstest for vinge udmattelse QS 8.104.1

Vinge id / serie nr. :	LM 191	4700
Dato :	26/11-01	
Antal lastcykler :	[illegible] 0	Flapvis Stivhed
Nominel rodmoment [kNm] :		
Exciter og accelerometer position [m] :	13.15	
Temperatur [°C] :	18.1	
Parameterfil :	LM191#PA.DYF	
Kalibreringsfilnavn :	LM191#CA1.DYF	
Skrevet af :	MHOF	

Last trin	Last [kN]	Udbøjning [mm] (måles ved accelerometer) 1	2	3	Δ [mm]
1	0	292.7	780	1178	0
2	4	283.7	762	1138	40
3	8	275.2	745	1100	78
4	12	266.5	728	1060	118
5	16	257.7	711	1021	157
6	0	292.3	779	1177	1
PFV no.	0575	1518	1517	1516	-

1: 8m
2: 10m
3: 13m

NB. Kalibrerings last skal minimum være 15 % af rodmomentvidden

Beregnet stivhed K [mm/kNm] Fra regressionsanalyse	0,7433
Beregnet skæringspunkt S [mm] Fra regressionsanalyse	Hvis S> 1 mm skal der laves en ny test
Beregnet udsvingsvidde [mm]	**Kontrolleres med tidligere beregnet værdi**
Opdatering af parameterfil (ja/nej)	

Bemærkninger

B. GRAPHS FROM FREQUENCY DETERMINATION

LM 19.1 # 4703 frequency graphs

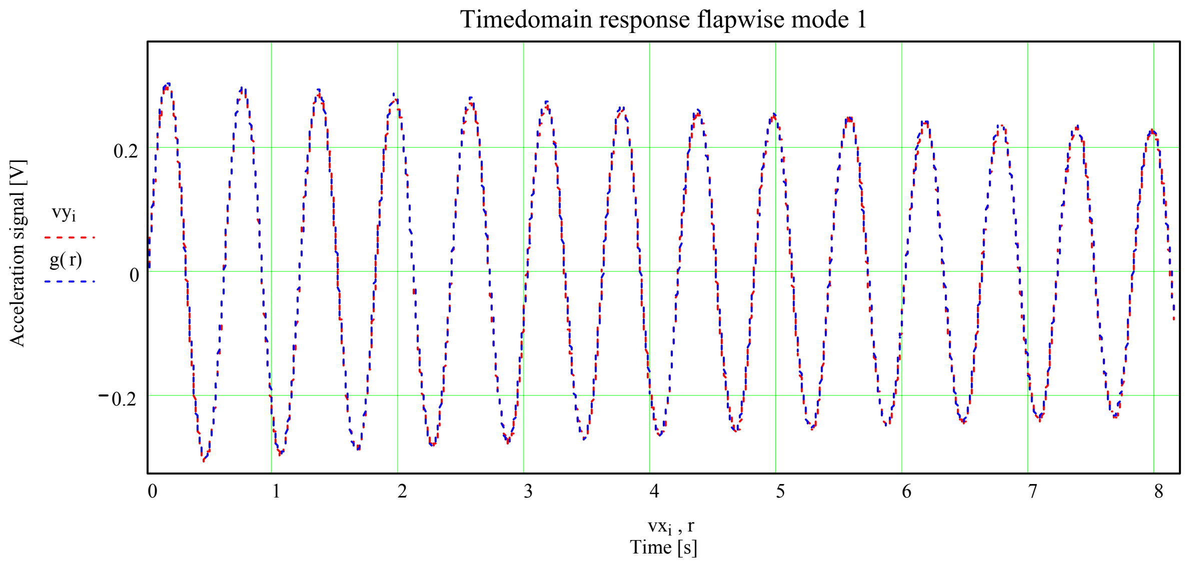


Figure 51. Time domain response, flapwise 1. mode.

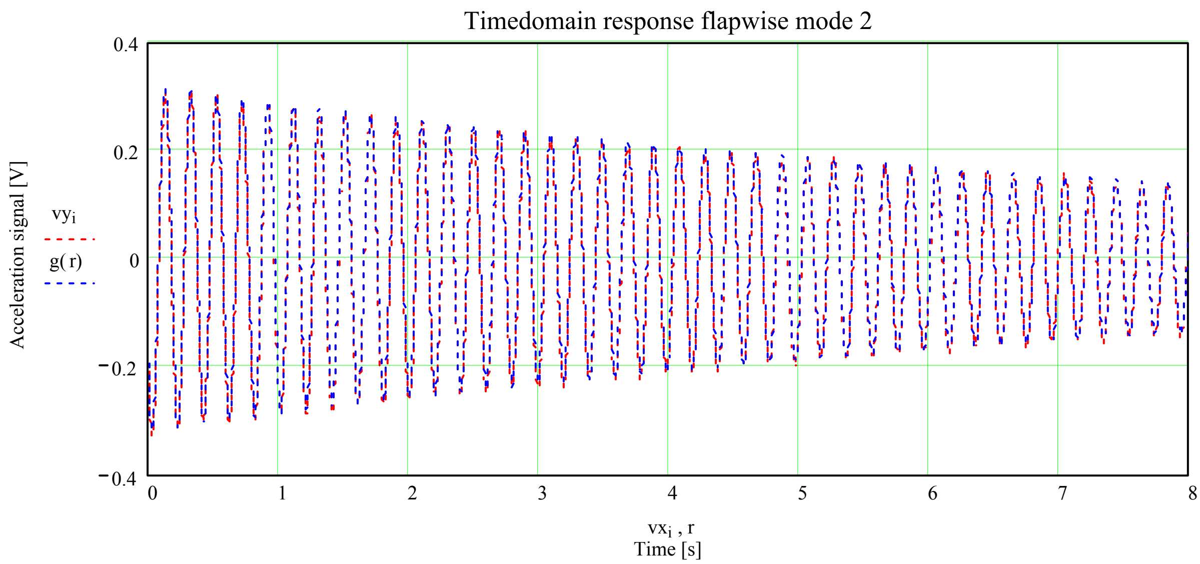


Figure 52. Time domain response, flapwise 2. mode.

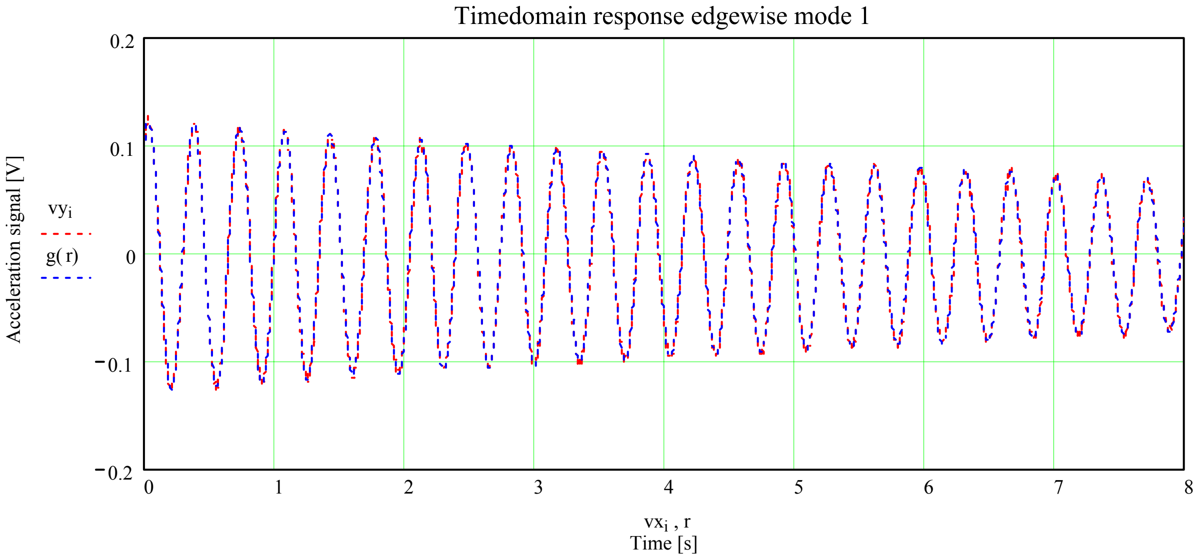


Figure 53. *Time domain response, edgewise 1. mode*

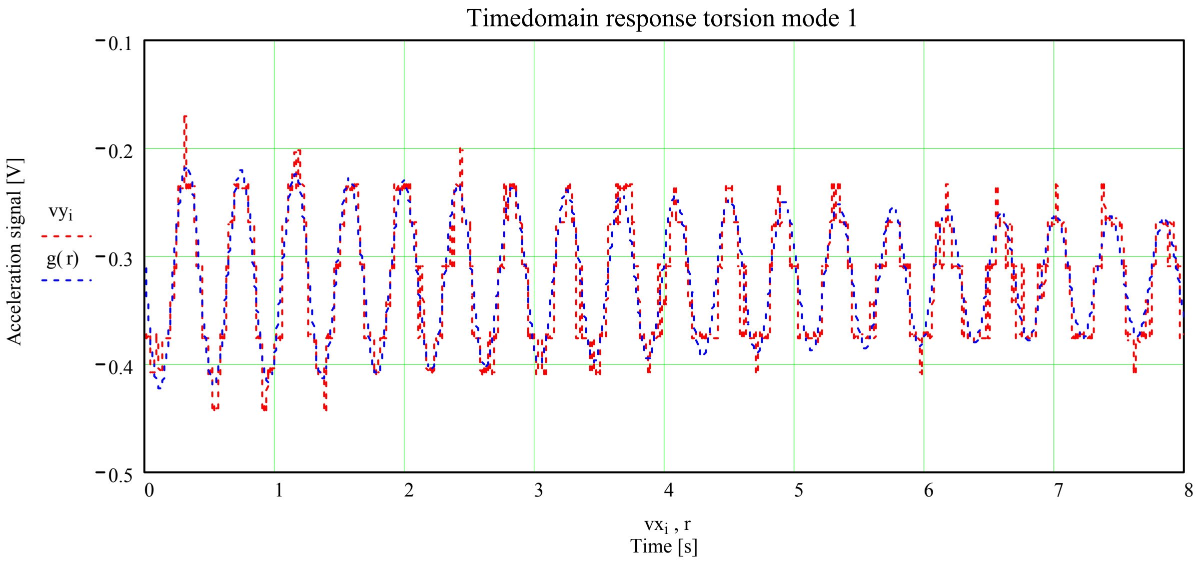


Figure 54. *Time domain response, torsional 1. Mode. The figure shows the torsional frequency replayed in a speed of 1/10 of the normal speed.*

LM 19.1 # 4706 frequency graphs

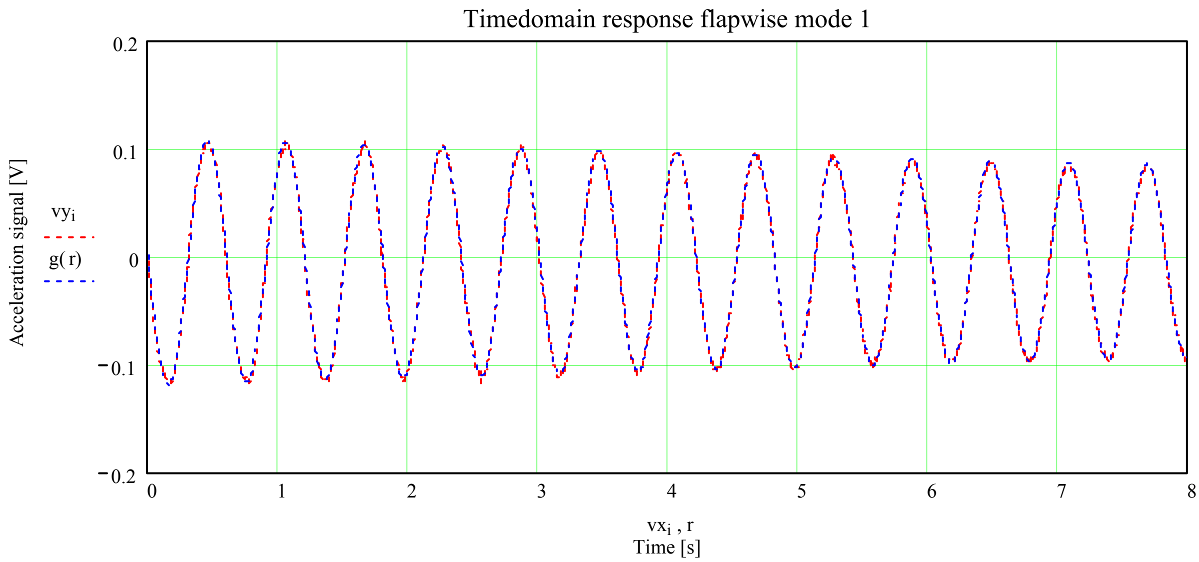


Figure 55. Time domain response, flapwise 1. mode.

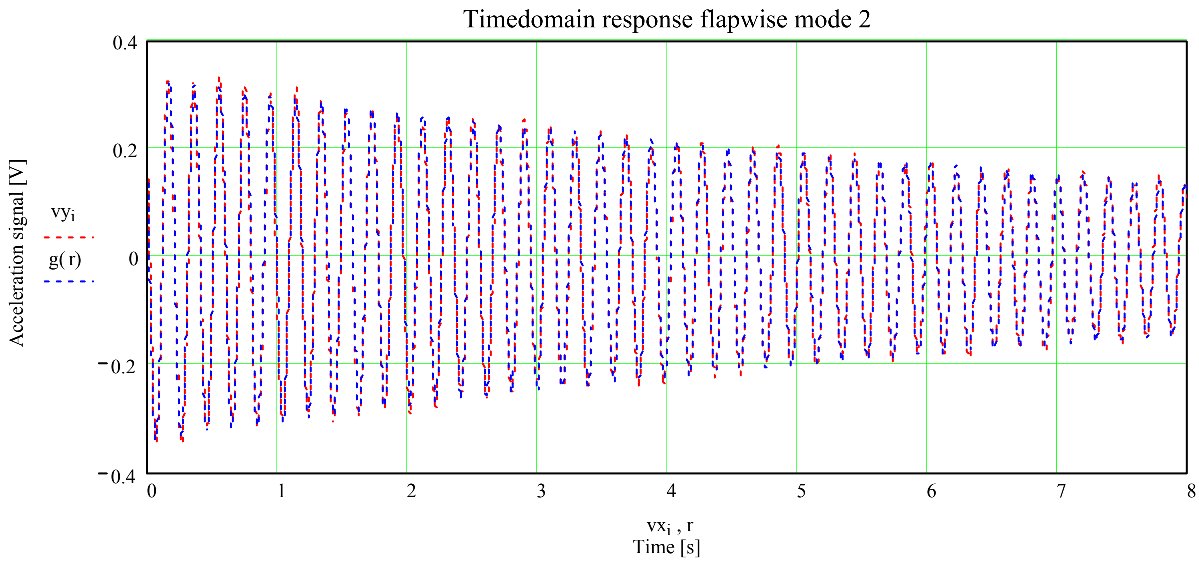


Figure 56. Time domain response, flapwise 2. mode.

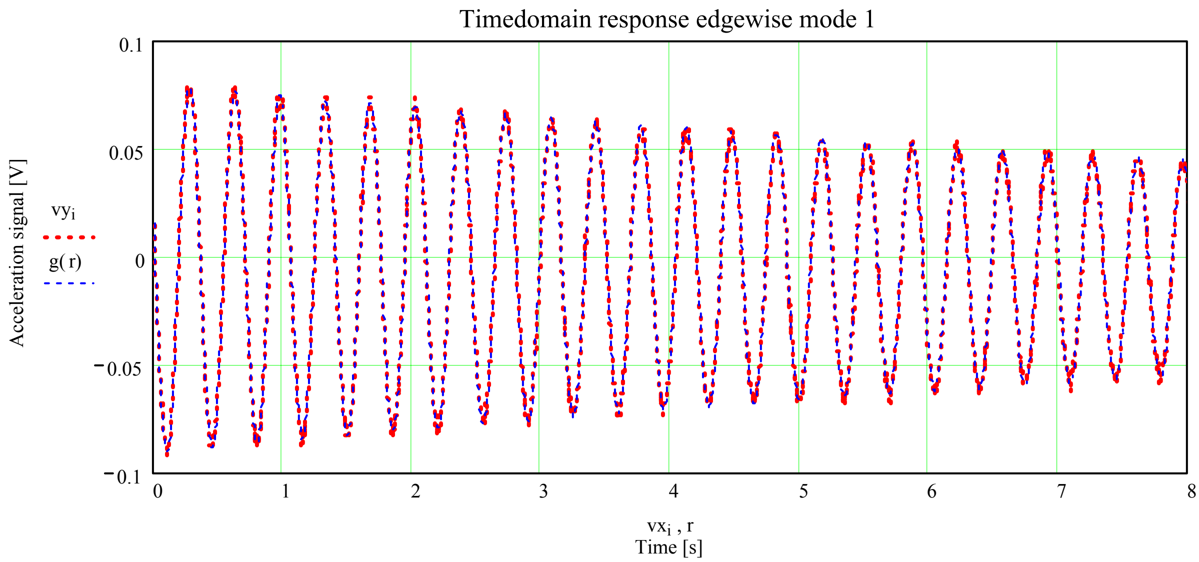


Figure 57. Time domain response, edgewise 1. mode

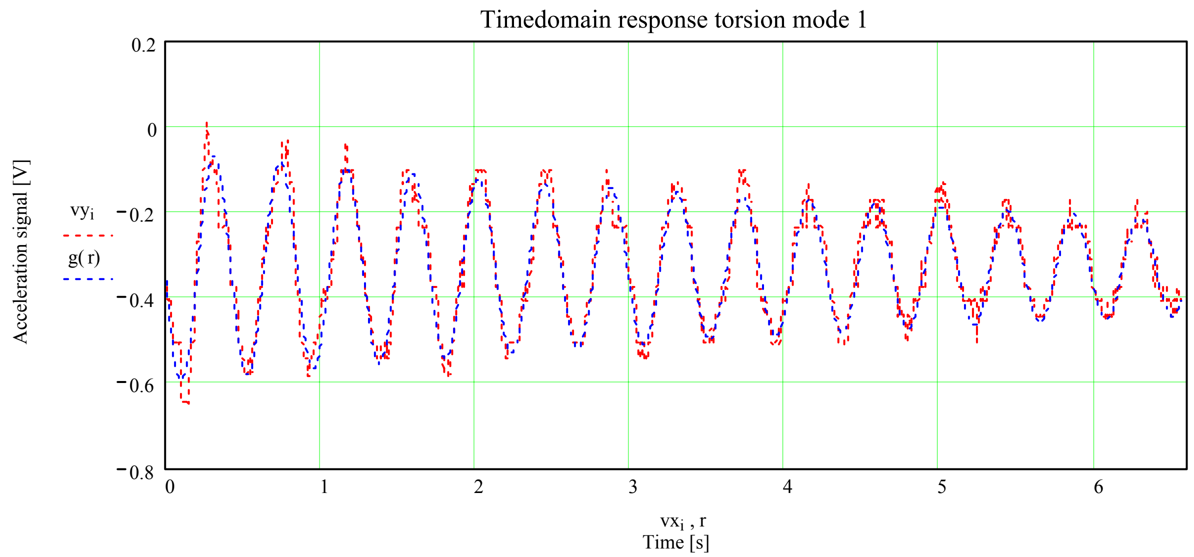


Figure 58. Time domain response, torsional 1. Mode. The figure shows the torsional frequency replayed in a speed of 1/10 of the normal speed.

LM 19.1 # 4700 frequency graphs

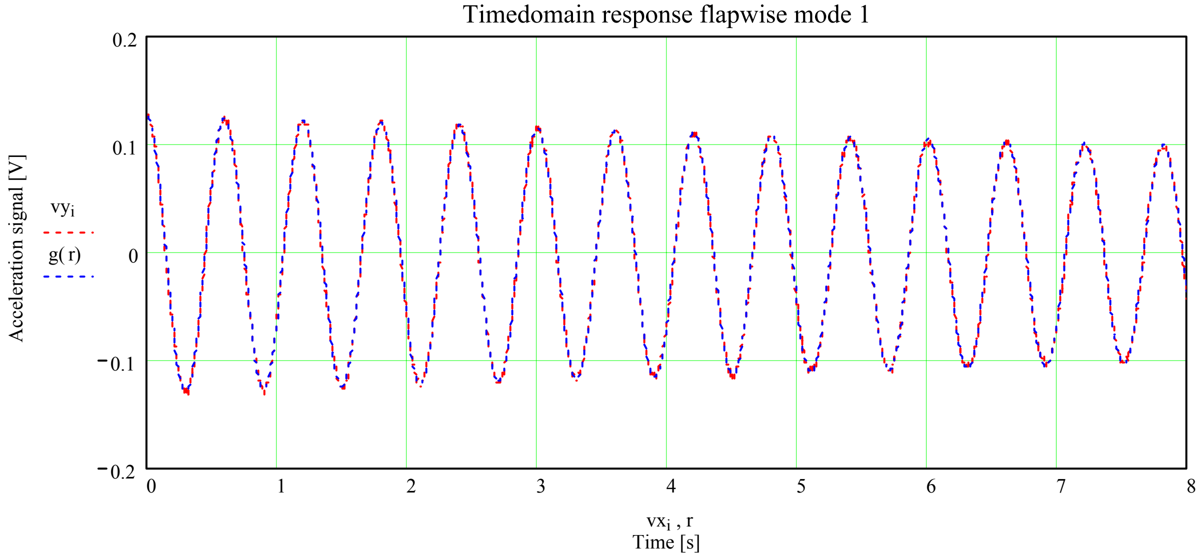


Figure 59. Time domain response, flapwise 1. mode.

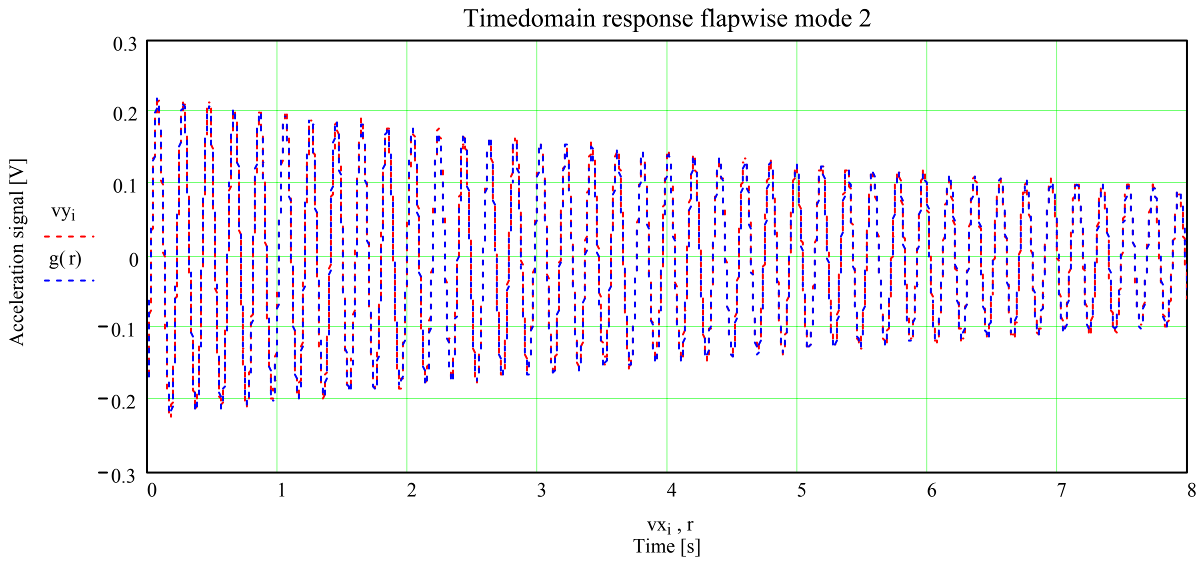


Figure 60. Time domain response, flapwise 2. mode.

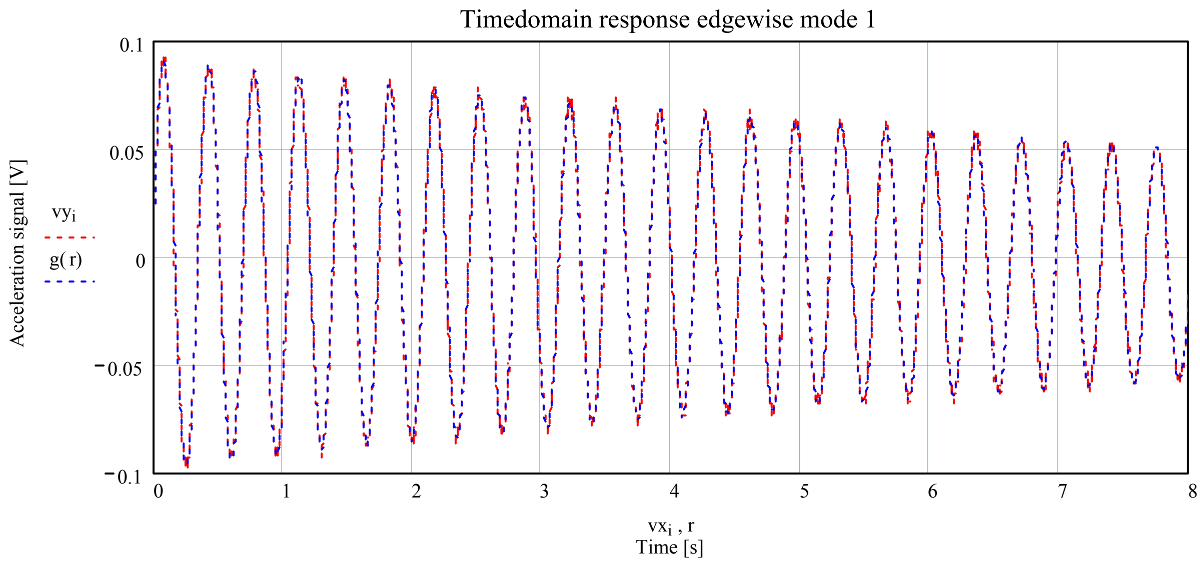


Figure 61. Time domain response, edgewise 1. mode

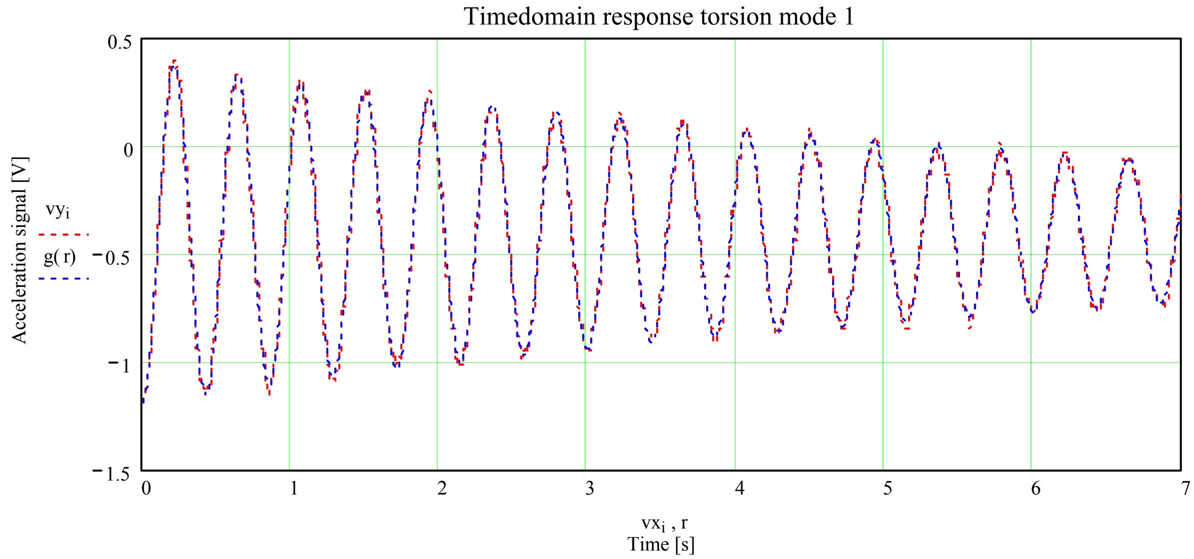


Figure 62. Time domain response, torsional 1. Mode. The figure shows the torsional frequency replayed in a speed of 1/10 of the normal speed.

C. EQUIPMENT USED DURING TEST

Equipment used during determination of natural frequencies

Equipment	Type	Pfv.-no.
Thermocouple	Ideline	1551
Accelerometer	Brüel og Kjær 4381	0579
Accelerometer amp.	Brüel og Kjær 2635	1554
Accelerometer	Brüel og Kjær 4381	0566
Accelerometer amp.	Brüel og Kjær 2635	1570
Accelerometer	Brüel og Kjær 4381	0580
Accelerometer amp.	Brüel og Kjær2635	1569
Oscilloscope	Kikusui DSS 6521	0585
PC	Toshiba T2130CS	1522
Data acquisition card	DAS 16/330	1523
Accelerometer calibrator	Brüel og Kjær 4294	0582
Software	Labtech Notebook	
Software	MathCad 2000	

Table 1. Equipment used for determination of natural frequencies.

Equipment used during the fatigue test

Equipment	Type	PFV. No.
Thermocouple with Amplifier	PT100	
Accelerometer	Brüel & Kjær 4381	1532
Accelerometer amplifier	Brüel & Kjær 2635	0532
Multimeter	Fluke	1581
Strain gauge scanner	HP 3852	1580
PC	JAI	1537
Software	NT 4.0 Rev. 04 09	
Software	NT 4.0 Rev. 04 10	
Load cell	20 [kN]	0575
Load cell		
Displacement-transducer	ASM 500 [mm]	1518
Displacement-transducer	ASM 1000 [mm]	1517
Displacement-transducer	ASM 2000 [mm]	1516

Table 13. Equipment used during fatigue- and calibration test.

D. DATA FROM FATIGUE TESTS

Strain statistics for blade no. # 4703

FASE 2										%-stigning i forhold til fase 2
						FASE 3				
SG-no. #	Min	Max	Average	Stdev	SG-no.	Min	Max	Average	Stdev	
0	2052	2158	2105,1	20,1	0	2199	2303	2254,5	23,6	7,1
1	1727	1810	1767,7	16,0	1	1851	1934	1893,7	18,7	7,1
2	2141	2247	2192,7	20,3	2	2289	2395	2347,8	24,0	7,1
3	2111	2216	2162,5	19,6	3	2257	2359	2312,6	23,5	7,0
4	2178	2290	2236,2	17,3	4	2330	2439	2390,2	25,0	6,9
5	1925	2022	1972,4	17,9	5	2059	2147	2109,6	21,2	7,0
6	2264	2923	2330,2	54,3	6	2429	2538	2489,4	24,7	6,9
7	2087	2188	2136,5	19,2	7	2228	2328	2285,5	23,0	7,0
8	2441	2553	2499,0	23,5	8	2612	2730	2677,8	28,1	7,2
9	2166	2269	2216,9	19,7	9	2307	2413	2370,2	23,6	6,9
10	2783	2918	2853,0	26,9	10	2982	3113	3058,3	31,9	7,2
11	2483	2599	2543,7	23,2	11	2653	2773	2720,6	28,3	7,0
12	2678	2800	2742,0	25,5	12	2864	2993	2937,7	30,7	7,2
13	2392	2498	2447,3	21,5	13	2548	2664	2615,0	26,7	6,9
14	2919	3056	2990,3	26,6	14	3099	3248	3189,5	32,2	6,7
15	3026	3162	3101,1	27,9	15	3229	3375	3317,6	34,0	7,0
16	2607	2720	2668,0	23,2	16	2774	2903	2852,0	28,5	6,9
17	2527	2767	2588,8	26,4	17	2693	2816	2766,0	28,2	6,9
18	2359	2465	2416,5	21,9	18	2521	2635	2587,9	26,7	7,1
19	2442	2545	2499,7	21,9	19	2606	2725	2676,2	27,1	7,1
20	1381	1445	1416,2	12,3	20	1460	1527	1498,1	15,3	5,8
21	1484	1547	1519,2	13,5	21	1590	1660	1630,6	16,6	7,4
22	507	528	518,2	4,2	22	509	532	523,7	5,0	1,1
23	573	598	586,3	5,0	23	595	623	611,9	6,0	4,4
24	21	24	22,3	0,6	24	23	25	23,7	0,6	6,3
25	15	17	15,4	0,5	25	15	18	16,6	0,6	8,3
26	725	760	739,8	5,4	26	766	801	788,2	6,9	6,6
27	2303	2403	2358,0	20,7	27	2460	2579	2526,8	27,1	7,2
28					28					
29					29					
Moment start	917,23	975,33	937,6	7,4	Moment start	977,38	1023,11	1005,5	9,7	7,2
Moment end	918,46	966,67	938,4	6,6	Moment end	978,6	1026,31	1007,9	9,6	7,4

Table 14. Strain statistics for load level 2 and 3 for blade # 4703

					%-stigning i forhold til fase 3					
	FASE 4						FASE 5			
SG-no.	Min	Max	Average	Stdev		SG-no.	Min	Max	Average	Stdev
0	2415	2534	2482.9	20.5	10.1	0	2565	2736	2674,3	33,6
1	2027	2118	2073.0	14.7	9.5	1	2134	2274	2225,0	28,1
2	2515	2629	2569.4	18.4	9.4	2	2647	2826	2756,2	33,1
3	2477	2590	2531.3	17.9	9.5	3	2596	2778	2713,5	33,7
4	2559	2675	2618.0	19.1	9.5	4	2712	2874	2810,7	34,1
5	2258	2356	2307.0	15.6	9.4	5	2371	2527	2469,0	29,3
6	2659	2784	2723.0	20.4	9.4	6	2814	2991	2921,9	34,5
7	2447	2549	2500.1	16.8	9.4	7	2571	2741	2677,1	32,8
8	2869	2994	2934.4	20.9	9.6	8	3025	3224	3151,4	38,2
9	2537	2642	2590.0	16.8	9.3	9	2656	2834	2769,4	34,6
10	3274	3417	3352.5	24.9	9.6	10	3461	3684	3601,5	45,0
11	2912	3037	2979.6	20.0	9.5	11	3064	3259	3190,5	40,1
12	3144	3279	3217.6	24.2	9.5	12	3307	3531	3460,7	43,9
13	2794	2915	2858.6	19.6	9.3	13	2925	3120	3054,7	37,3
14	3411	3554	3488.7	25.0	9.4	14	3567	3803	3721,8	42,0
15	3547	3695	3623.7	24.7	9.2	15	3691	3928	3842,5	41,2
16	3048	3224	3127.9	38.1	9.7	16	3341	3533	3456,7	47,9
17	2956	3081	3020.0	19.8	9.2	17	3100	3296	3221,8	39,9
18	2762	3037	2858.4	58.2	10.5	18	3033	3218	3136,3	41,2
19	2857	3255	2972.6	97.8	11.1	19	3231	3420	3345,3	40,9
20	1586	1795	1639.0	31.0	9.4	20	1638	1763	1717,2	20,6
21	1653	2042	1772.0	64.0	8.7	21	1685	1821	1775,1	22,5
22	421	580	541.1	47.0	3.3	22	483	556	536,8	21,0
23	468	679	632.0	56.5	3.3	23	578	660	635,4	22,5
24	15	27	23.7	3.3	-0.1	24	3	16	6,4	4,0
25	5	19	15.2	3.5	-8.5	25	2	22	15,4	6,8
26	825	872	840.7	8.7	6.7	26	870	918	894,7	9,6
27	2707	2827	2768.0	21.7	9.5	27	2873	3040	2975,9	37,4
28	1325	1803	1439.5	65.8		28	1381	1460	1426,7	11,4
29	1559	1679	1597.8	19.0		29	1613	1740	1692,4	22,7
Moment start	1074.67	1122.52	1092.0	7.3	8.6	Moment start	1149,55	1212,56	1179,9	10,0
Moment end	1075.9	1113.93	1092.6	6.5	8.4	Moment end	1146,02	1211,17	1181,3	10,9

Table 15. Strain statistics for load level 4 and 5 for blade # 4703

Moment distribution for blade no. # 4703

Bin [%]	Mi [kNm]	Cycles	Mi [kNm]	Cycles	Mi [kNm]	Cycles	Mi [kNm]	Cycles	Mi [kNm]	Cycles
78	672.4	0	726.2	0	783.9	0	847.1	0	914.9	0
79	681.0	30	735.5	40	794.0	34	857.9	16	926.7	46
80	689.6	34	744.8	36	804.0	24	868.8	12	938.4	40
81	698.2	28	754.1	28	814.1	36	879.7	14	950.1	38
82	706.8	36	763.4	50	824.1	40	890.5	18	961.9	48
83	715.5	42	772.7	48	834.2	40	901.4	24	973.6	68
84	724.1	38	782.0	40	844.2	34	912.2	12	985.3	64
85	732.7	44	791.4	38	854.3	34	923.1	20	997.1	120
86	741.3	40	800.7	52	864.3	44	934.0	20	1008.8	148
87	749.9	50	810.0	54	874.4	48	944.8	20	1020.5	154
88	758.6	62	819.3	58	884.4	46	955.7	18	1032.2	168
89	767.2	134	828.6	86	894.5	48	966.5	24	1044.0	152
90	775.8	118	837.9	96	904.5	52	977.4	36	1055.7	162
91	784.4	102	847.2	104	914.6	64	988.3	28	1067.4	150
92	793.0	74	856.5	68	924.6	88	999.1	28	1079.2	204
93	801.7	178	865.8	82	934.7	72	1010.0	40	1090.9	248
94	810.3	2894	875.1	110	944.7	86	1020.8	64	1102.6	272
95	818.9	6192	884.5	114	954.8	78	1031.7	102	1114.4	288
96	827.5	6970	893.8	214	964.8	140	1042.6	166	1126.1	482
97	836.1	10364	903.1	1272	974.9	2572	1053.4	352	1137.8	1198
98	844.8	70900	912.4	11718	984.9	21534	1064.3	2316	1149.5	5556
99	853.4	312992	921.7	51078	995.0	53422	1075.1	9056	1161.3	21628
100	862.0	286456	931.0	246236	1005.0	86152	1086.0	61822	1173.0	43234
101	870.6	100088	940.3	125676	1015.1	31272	1096.9	10488	1184.7	26762
102	879.2	24950	949.6	1580	1025.1	1896	1107.7	726	1196.5	2128
103	887.9	14226	958.9	1260	1035.2	592	1118.6	228	1208.2	932
104	896.5	518	968.2	414	1045.2	284	1129.4	264	1219.9	114
105	905.1	268	977.6	300	1055.3	0	1140.3	60	1231.7	12
106	913.7	158	986.9	96	1065.3	0	1151.2	80	1243.4	0
107	922.3	44	996.2	0	1075.4	0	1162.0	294	1255.1	0
108	931.0	132	1005.5	0	1085.4	0	1172.9	82	1266.8	0
109	939.6	2	1014.8	0	1095.5	0	1183.7	0	1278.6	0
110	948.2	0	1024.1	0	1105.5	0	1194.6	0	1290.3	0
111	956.8	0	1033.4	0	1115.6	0	1205.5	0	1302.0	0
112	965.4	0	1042.7	0	1125.6	0	1216.3	0	1313.8	0
113	974.1	0	1052.0	0	1135.7	0	1227.2	0	1325.5	0
114	982.7	0	1061.3	0	1145.7	0	1238.0	0	1337.2	0
115	991.3	0	1070.7	0	1155.8	0	1248.9	0	1349.0	0
116	999.9	0	1080.0	0	1165.8	0	1259.8	0	1360.7	0
117	1008.5	0	1089.3	0	1175.9	0	1270.6	0	1372.4	0
118	1017.2	0	1098.6	0	1185.9	0	1281.5	0	1384.1	0
119	1025.8	0	1107.9	0	1196.0	0	1292.3	0	1395.9	0
120	1034.4	0	1117.2	0	1206.0	0	1303.2	0	1407.6	0
121	1043.0	0	1126.5	0	1216.1	0	1314.1	0	1419.3	0
	∑ cycles	838164	∑ cycles	440948	∑ cycles	198732	∑ cycles	86430	∑ cycles	104416

Table 16. Moment distribution for flapwise fatigue test of blade # 4703, phase/level 1 – 5, level 5 in last columns.

Strain statistics for blade no. # 4706

	FASE 2			
SG-no. #	Min	Max	Average	Stdev
0	2383	2616	2477.4	30.1
1	2043	2220	2111.9	24.5
2	2641	2824	2718.1	25.4
3	2452	2611	2520.9	24.6
4	2712	2952	2816.1	47.6
5	2163	2298	2216.2	19.0
6	2865	3048	2941.2	26.9
7	2357	2515	2426.4	23.2
8	2885	3068	2962.2	26.7
9	2558	2720	2624.2	24.4
10	3171	3367	3254.4	29.0
11	2767	2939	2841.4	26.4
12	3213	3415	3304.0	31.4
13	3063	3251	3144.5	28.5
14	3509	4172	3601.0	55.4
15	3288	3485	3371.8	30.3
16	3389	3580	3471.5	29.4
17	2955	3123	3031.4	27.7
18	2849	3012	2922.6	25.2
19	3125	3318	3209.9	31.3
20	1714	1808	1757.3	15.3
21	1724	1820	1766.0	15.3
22	669	709	687.6	6.1
23	624	655	638.4	5.1
24	27	32	29.6	0.8
25	16	2777	2143.8	1063.0
26	662	715	680.5	7.5
27	636	685	653.8	5.8
28	3062	3265	3162.7	35.9
29	3451	3761	3622.3	67.3
Moment start	1123.97	1223.02	1174.5	9.3
Moment end	1152.91	1217.96	1177.5	8.5

Table 17. Strain statistics for load level 2 for blade # 4706

	FASE 3					FASE 4			
SG-no.	Min	Max	Average	Stdev	SG-no.	Min	Max	Average	Stdev
0	2618	2716	2689.0	12.9	0	2824	2964	2911.8	20.9
1	2210	2283	2265.4	10.8	1	2397	2537	2485.9	22.2
2	2856	2984	2947.3	16.1	2	3089	3249	3185.8	23.9
3	2633	2755	2717.4	16.4	3	2840	2994	2934.6	22.4
4	2921	3056	3013.9	16.9	4	3158	3325	3258.3	24.4
5	2343	2436	2409.4	12.3	5	2523	2656	2603.4	19.4
6	3095	3225	3187.5	17.0	6	3336	3515	3445.3	26.5
7	2551	2659	2625.5	14.4	7	2744	2888	2833.9	20.5
8	3111	3249	3205.7	18.1	8	3355	3537	3465.5	26.6
9	2752	2874	2840.0	15.6	9	2970	3128	3066.7	22.9
10	3477	3571	3546.4	16.9	10	3703	3863	3815.2	30.4
11	2985	3114	3076.0	17.0	11	3215	3389	3324.7	25.3
12	3444	3614	3560.7	24.1	12	3717	3920	3842.4	29.8
13	3298	3443	3403.7	18.9	13	3554	3748	3673.9	27.6
14	3830	3985	3901.3	20.8	14	4227	4264	4250.0	16.6
15	3546	3699	3654.9	19.7	15	3820	4031	3950.3	29.5
16	3615	3806	3744.5	27.9	16	3898	4191	4084.9	43.7
17	2845	3319	3134.3	176.9	17	3070	3222	3164.4	22.3
18	3098	3228	3157.3	20.8	18	3462	3604	3561.3	32.0
19	3376	3514	3473.0	17.9	19	3711	3919	3784.4	32.2
20	1876	1932	1911.3	11.0	20	1957	2087	2012.6	18.0
21	1847	1994	1927.1	19.8	21	1904	2032	1982.4	23.7
22	709	758	746.5	6.9	22	741	782	766.5	6.6
23	666	703	693.4	5.5	23	693	729	714.6	6.2
24	28	33	31.3	0.9	24	25	30	27.6	0.8
25	2763	2907	2859.5	20.5	25	2974	3134	3075.5	22.4
26	725	774	738.0	5.1	26	725	886	769.9	47.3
27	701	791	719.0	10.2	27	170	915	684.9	254.4
28	3271	3448	3397.1	23.9	28	3534	3736	3663.8	27.8
29	3690	3880	3819.1	26.8	29	3975	4204	4122.2	31.9
Moment start	1263.93	1397.91	1322.5	48.3	Moment start	1329.66	1395.08	1378.8	11.3
Moment end	1263.93	1397.91	1326.4	48.4	Moment end	1330.9	1403.99	1380.3	11.6

Table 18. Strain statistics for load level 3 and 4 for blade # 4706

Moment distribution for blade no. # 4706

Bin [%]	Mi [kNm]	Cycles	Mi [kNm]	Cycles	Mi [kNm]	Cycles	Mi [kNm]	Cycles	Mi [kNm]	Cycles
78	847.1	0	914.9	0	988.3	0	998.9	0	1067.0	0
79	857.9	136	926.7	22	1000.9	12	1011.7	2	1080.7	10
80	868.8	110	938.4	28	1013.6	18	1024.5	6	1094.4	6
81	879.7	94	950.1	30	1026.3	12	1037.3	4	1108.1	10
82	890.5	90	961.9	26	1038.9	14	1050.1	4	1121.8	8
83	901.4	106	973.6	28	1051.6	14	1062.9	4	1135.4	14
84	912.2	116	985.3	28	1064.3	16	1075.8	4	1149.1	6
85	923.1	104	997.1	24	1077.0	14	1088.6	4	1162.8	10
86	934.0	114	1008.8	32	1089.6	16	1101.4	6	1176.5	14
87	944.8	114	1020.5	40	1102.3	22	1114.2	8	1190.2	72
88	955.7	100	1032.2	36	1115.0	22	1127.0	4	1203.8	78
89	966.5	100	1044.0	38	1127.6	20	1139.8	8	1217.5	96
90	977.4	94	1055.7	42	1140.3	20	1152.6	4	1231.2	106
91	988.3	168	1067.4	52	1153.0	24	1165.4	8	1244.9	106
92	999.1	248	1079.2	180	1165.6	26	1178.2	10	1258.6	102
93	1010.0	312	1090.9	86	1178.3	30	1191.0	10	1272.2	108
94	1020.8	374	1102.6	92	1191.0	34	1203.8	8	1285.9	96
95	1031.7	696	1114.4	88	1203.7	32	1216.6	18	1299.6	94
96	1042.6	2232	1126.1	108	1216.3	48	1229.4	10	1313.3	120
97	1053.4	7054	1137.8	404	1229.0	54	1242.2	22	1327.0	250
98	1064.3	136530	1149.5	55682	1241.7	64	1255.0	1996	1340.6	5114
99	1075.1	575846	1161.3	461944	1254.3	3350	1267.9	18772	1354.3	15038
100	1086.0	532312	1173.0	652800	1267.0	92748	1280.7	156062	1368.0	52236
101	1096.9	230436	1184.7	164160	1279.7	234032	1293.5	72738	1381.7	60560
102	1107.7	7874	1196.5	1100	1292.3	732	1306.3	504	1395.4	524
103	1118.6	1328	1208.2	478	1305.0	742	1319.1	122	1409.0	332
104	1129.4	766	1219.9	356	1317.7	880	1331.9	0	1422.7	54
105	1140.3	454	1231.7	246	1330.4	0	1344.7	0	1436.4	78
106	1151.2	454	1243.4	158	1343.0	0	1357.5	0	1450.1	82
107	1162.0	324	1255.1	228	1355.7	0	1370.3	0	1463.8	148
108	1172.9	704	1266.8	330	1368.4	0	1383.1	0	1477.4	4
109	1183.7	384	1278.6	566	1381.0	0	1395.9	0	1491.1	0
110	1194.6	412	1290.3	26	1393.7	0	1408.7	0	1504.8	0
111	1205.5	188	1302.0	0	1406.4	0	1421.5	0	1518.5	0
112	1216.3	160	1313.8	0	1419.0	0	1434.3	0	1532.2	0
113	1227.2	222	1325.5	0	1431.7	0	1447.1	0	1545.8	0
114	1238.0	156	1337.2	0	1444.4	0	1460.0	0	1559.5	0
115	1248.9	70	1349.0	0	1457.1	0	1472.8	0	1573.2	0
116	1259.8	50	1360.7	0	1469.7	0	1485.6	0	1586.9	0
117	1270.6	50	1372.4	0	1482.4	0	1498.4	0	1600.6	0
118	1281.5	50	1384.1	0	1495.1	0	1511.2	0	1614.2	0
119	1292.3	86	1395.9	0	1507.7	0	1524.0	0	1627.9	0
120	1303.2	168	1407.6	0	1520.4	0	1536.8	0	1641.6	0
121	1314.1	8	1419.3	0	1533.1	0	1549.6	0	1655.3	0
	∑ cycles	1501394	∑ cycles	1339458	∑ cycles	332996	∑ cycles	250338	∑ cycles	135476

Table 19. Moment distribution for flapwise fatigue test of blade # 4703, phase/level 1 – 5, level 5 in last columns.

Strain statistics for blade no. # 4700

	LEVEL 2			
SG-no.	Min	Max	Average	Stdev
0	2392	2653	2541.2	46.9
1	2067	2314	2203.4	45.1
2	2664	2949	2833.2	50.9
3	2369	2632	2536.5	42.6
4	2868	3179	3061.1	51.2
5	2339	2611	2520.2	38.2
6	2663	2996	2877.6	42.4
7	2355	2622	2527.2	42.6
8	2887	3215	3099.0	52.4
9	2576	2871	2768.2	45.5
10	3133	3502	3289.6	78.7
11	2865	3208	3086.4	48.9
12	3125	3490	3318.6	59.1
13	2904	3251	3120.8	51.5
14	3272	3708	3480.9	76.8
15	3066	3489	3339.7	55.1
16	3246	3648	3485.2	48.8
17	2957	3323	3187.2	49.6
18	2446	3328	2700.4	68.5
19	3008	3486	3324.8	63.0
20	1754	2001	1852.6	40.9
21	1719	2015	1826.3	59.4
22	615	710	677.5	12.4
23	615	703	669.6	11.4
24	33	42	36.7	2.3
25	15	22	18.6	1.0
Moment start	1089.86	1225.75	1174.1	12.3
Moment end	1067.5	1219.4	1176.3	12.5

Table 20. Strain statistics for load level 2 for blade # 4700

E. UNCERTAINTY OF MEASUREMENTS

The accuracy for the load measurements is determined based on the rules in EAL-R2. The accuracy is determined by inserting the specific load level P in the expression given in the tabel below.

Equipment	Type	PFV no.	Calibration date	Calibration date	Accuracy
Thermocouple with Amplifier	PT100	NA	-		
Accelerometer	Brüel & Kjær 4381	0529			
Accelerometer	Brüel & Kjær 4381	1529			
Accelerometer amplifier	Brüel & Kjær 2635	0533			
Accelerometer amplifier	Brüel & Kjær 2635	1570			
Accelerometer amplifier	Brüel & Kjær 2635	1554	-		
Accelerometer amplifier	Brüel & Kjær 2634	1558	-		
Accelerometer calibrator	Brüel & Kjær 4294	0582	19-04-00	17-08-00	±0.03 [Hz]
Multimeter	Fluke 87	1560	02-02-00	28-03-01	0.01 [Hz]
Strain gauge scanner	HP3852A	1550			<1.5%
PC	NT 4.0	1555			
Software	SPAR revision B.04.03	NA		-	
Software	SPAR revision B.04.04	NA		-	
Load cell	50 [kN]	0596	25-06-00	31-08-00	$\pm(5.12\cdot10^{-3}\cdot P+5.03\cdot10^{-3})$
Load cell	20 [kN]	0575	26-01-00	16-01-01	$\pm(4.74\cdot10^{-3}\cdot P+9.95\cdot10^{-3})$
Load cell	20 [kN]	1511	14-02-00	16-01-01	$\pm(4.74\cdot10^{-3}\cdot P+9.86\cdot10^{-3})$
Displacement-transducer	1.0 [m]	1574	09-10-00	03-05-01	±2.40 [mm]
Displacement-transducer	1.0 [m]	1517	03-02-00	10-01-01	±2.39 [mm]
Displacement-transducer	0.5 [m]	1518	03-02-00	10-01-01	±1.23 [mm]

Table 21. Calibration status and accuracy for the equipment used in the tests.

F. DATA SHEET FOR STRAIN GAUGES

MM — **ENGINEERING DATA SHEET**

THE INFORMATION APPEARING ON THIS SHEET HAS BEEN COMPILED SPECIFCALLY 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

Final QA	Check	Batch
DD	SCY	S236596

MM — Micro-Measurements Division, *Made in USA*

MEASUREMENTS GROUP, INC.
RALEIGH, NORTH CAROLINA

PRECISION STRAIN GAGES

F007

TYPE	CEA-06-375UW-350
OPTION	
QUANTITY	5
LOT NUMBER	R-A58AD85
RESISTANCE IN OHMS AT 24°C	350.0±0.3%
GAGE FACTOR AT 24°C	2.080 ±0.5%
TRANSVERSE SENSITIVITY AT 24°C	(-0.2 ±0.2)%
CODE	103719-3263

CEA-06-375UW-350

GENERAL INFORMATION: CEA-SERIES STRAIN GAGES

GENERAL DESCRIPTION: CEA gages are a general-purpose family of constantan strain gages widely used in experimental stress analysis. The gages are supplied with a fully encapsulated grid and exposed copper-coated integral solder tabs.

TEMPERATURE RANGE: -100° to +350° F (-75° to +175° C) for continuous use in static measurements.

SELF-TEMPERATURE COMPENSATION: See data curve below.

STRAIN LIMITS: Approximately 5% for gage lengths 1/8 in. (3.2 mm) and larger; approximately 3% for gage lengths under 1/8 in. (3.2 mm).

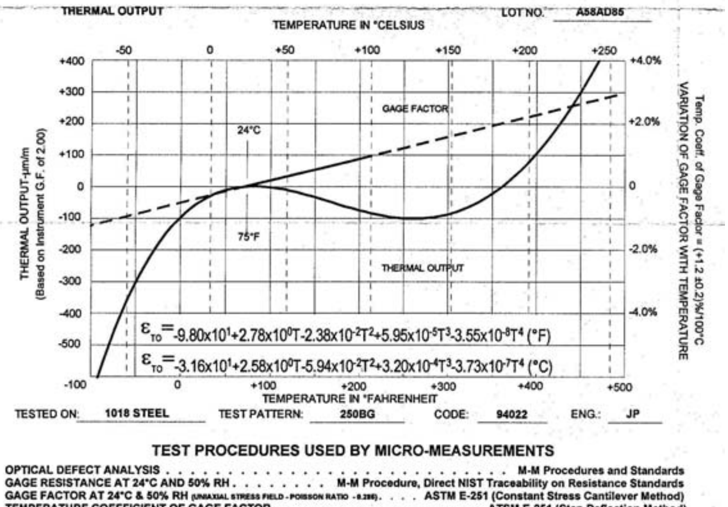
FATIGUE LIFE: Fatigue life is a marked function of solder joint formation. With 30-AWG leads directly attached to gage tabs, fatigue life will be 10^6 cycles at ±1500μin/in (μm/m) using M-Line 361A solder.

CEMENTS: Compatible with M-M Certified M-Bond 200, but it will normally not provide the greatest strain limit. Micro-Measurements M-Bond AE-10/15, M-Bond GA-2, M-Bond 600, and M-Bond 610 are excellent. M-Bond 610 is the best choice over the entire operating range. Refer to M-M Catalog A-110 for information on bonding agents, and Bulletins B-127, B-130, and B-137 for installation procedures.

SOLDER: If operating temperature will not exceed +300° F (+150° C), M-Line solder 361A (63-37) tin-lead solder may be used for lead attachment. M-Line solder (95-5) tin-antimony is satisfactory to +400° F (+205° C). Refer to M-M Catalog A-110 for further information on solders, and Tech Tip TT-609 for lead attachment techniques.

NOTE: The backing of CEA-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.

G045



TESTED ON: 1018 STEEL   TEST PATTERN: 250BG   CODE: 94022   ENG.: JP

TEST PROCEDURES USED BY MICRO-MEASUREMENTS

OPTICAL DEFECT ANALYSIS . . . . M-M Procedures and Standards
GAGE RESISTANCE AT 24°C AND 50% RH . . . . M-M Procedure, Direct NIST Traceability on Resistance Standards
GAGE FACTOR AT 24°C & 50% RH (UNIAXIAL STRESS FIELD - POISSON RATIO - 0.285) . . . . ASTM E-251 (Constant Stress Cantilever Method)
TEMPERATURE COEFFICIENT OF GAGE FACTOR . . . . ATSM E-251 (Step Deflection Method)
THERMAL OUTPUT . . . . ASTM E-251 (Slow Heating Rate, Continuously Recorded)
TRANSVERSE SENSITIVITY AT 24°C AND 50%H . . . . ASTM E-251
FATIGUE LIFE . . . . NAS-942 (Modified)
STRAIN LIMITS . . . . NAS-942 (Modified)
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. 62. "Performance characteristics of metallic resistance strain gages." Other tests are not included in I.R. NO. 62

T001

Figure 63. Datasheet for strain gauges used during fatigue test.

Bibliographic Data Sheet **Risø-R-1358(EN)**

Title and authors

Accelerated Fatigue Testing of LM 19.1 Blades

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Erik R. Jørgensen

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Abstract (max. 2000 characters)

A series of 19.1 metre wind turbine blades manufactured by LM Glasfiber A/S of Lunderskov, Denmark were subjected to a series of flapwise fatigue tests. The object of these fatigue tests is to evaluate the impact of an increased load on the blade in a fatigue test and to give information if it is possible to increase the load in fatigue test to shorten test time.
The tests were carried out as a part of a project financed by the Danish Energy Agency.
During the fatigue tests the blades have been surveyed with thermal imaging equipment to determine how an increase in fatigue load affects the blade material. In addition to the thermal imaging surveillance the blades were instrumented with strain gauges.
This report presents the temperature during test, calibration test results, moment range measurements, strain statistics, thermal imaging registrations and a determination of the size and cause of the damages. The report is also giving information on the blade-to-blade variation.

Descriptors INIS/EDB
DYNAMIC LOADS, FATIGUE; MATERIALS TESTING; THERMAL ANALYSIS, TURBINE BLADES; WIND LOADS, WIND TURBINES