FULL-SCALE STRUCTURAL FATIGUE TESTING OF A WIND TURBINE (WT) ROTOR BLADE

Gustavo D. Monjo[a], Nicolás Alday Hegovaburu[b]

[a]*Laboratorio de Investigación & Desarrollo, IMPSA, Carril Rodríguez Peña 2451, M5503AHY Mendoza, Argentina, gustavo.monjo@impsa.com, http://www.impsa.com*

[b]*Área de Materiales Compuestos, IMPSA, Carril Rodríguez Peña 2451, M5503AHY Mendoza, Argentina, nicolas.alday@impsa.com, http://www.impsa.com*

Keywords: Fatigue Test, Blade.

Abstract. This paper describes the structural fatigue testing of a IWPB-70, 32-m blade at IMPSA's Blade Test Laboratory.

1 SCOPE

The present document describes the procedure adopted by IMPSA for performing full-scale *single-axis constant amplitude* fatigue tests, part of our type certification according to IEC WT01. It follows mandatory aspects according to IEC/TS 61400-23 (Full-scale structural testing of rotor blades).

2 NOTATION

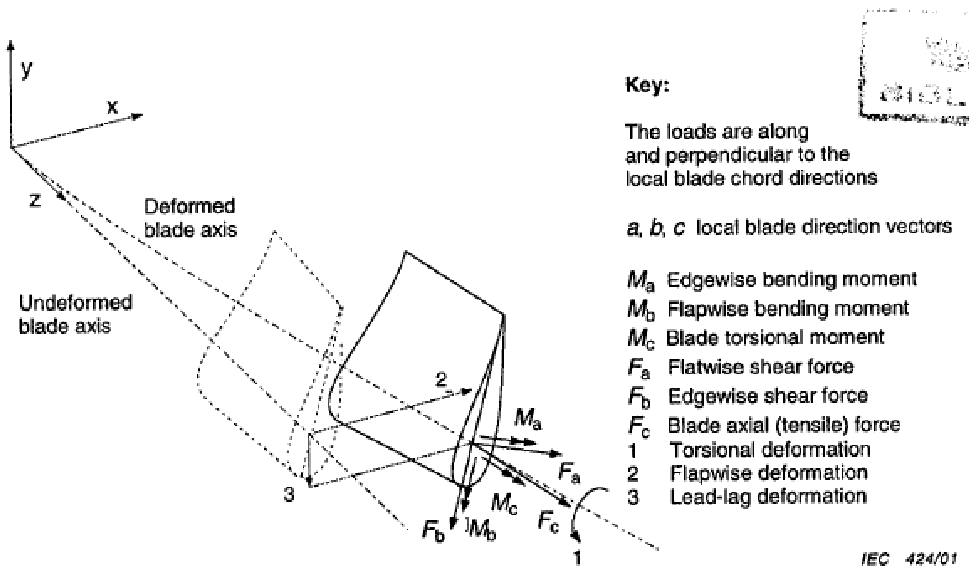

Figure 1: Chordwise (flatwise, edgewise) co-ordinate system

3 GENERAL PRINCIPLES

3.1 Purpose of the test

The fundamental purpose of a WT blade Fatigue Test is to demonstrate, to a reasonable level of certainty, that a blade type, when manufactured according to a certain set of specifications, possesses the service life provided for in the design. In other words, it must be demonstrated that the blade can withstand the fatigue loads to which it is expected to be subjected during its designed service life.

3.2 Limit state

The limit state is the maximum load that the blade can sustain and still meet the design requirement. According to this, a blade should pass the test if the limit state is not reached when the blade is exposed to the test load, representative of the design load. The representative test load can be higher than the design load to account for other influences, such as environmental effects, test uncertainties, and variations in production.

3.3 Results of test

If no damage to the blade has occurred during the test there is a strong indication that the blade design will fulfill its requirements.

3.4 What is tested

According to the design calculation, the blade must be able to survive the design loading. In these design calculations a number of assumptions are implicitly being made:

- The stresses or strains are calculated accurately or conservatively estimated;
- The classifications of strength and fatigue resistance of all relevant materials and details are estimated accurately or conservatively;
- The strength and fatigue formulations used to calculate the strength are accurate or conservative;
- The production is according to the design.

In a full-scale test used as a final design verification, the validity of the assumptions mentioned above are checked simultaneously. When a blade fails during testing, at least one of these assumptions has been violated, although without further analysis it might not be clear what caused this unexpected failure.

When the blade withstands the test without unexpected or severe damage, it gives some confidence that the design and production have no large errors leading to an unsafe situation. However, it is not an absolute proof.

3.5 What is not tested

During a full-scale test the following are not tested (and verified):

- The validity of the design loads;
- Effects due to environmental conditions that are different during testing;
- The scatter in the results;

4 BLADE DATA

4.1 Blade characteristics

Geometric properties can be found in Annex 1. Annex 2 shows a more detailed description of the blade’s components.

Actual values of the blade’s properties were previously determined following tests methods developed by IMPSA. These properties include mass properties such as weight and center of gravity, and structural properties such as natural frequencies and damping.

4.2 Areas to be tested

Representative loading was applied to critical areas (section 6.6 of IEC/TS 61400-23). The following are considered critical areas, where calculations showed the smallest reserve factors against buckling or fatigue life.

	Flapwise	**Edgewise**
Buckling	Span 1620	No critical point
Fatigue life	No critical point	Span 1420

Table 1: Critical points

5 DERIVATION OF TEST LOADS

Test loads where chosen to be load-based (section 8.2.1.3 of IEC/TS 61400-23).In this type of test, test loading has to be generated giving fatigue damage equivalent to the design loads.

5.1 Damage Equivalent Loads

The objective is to show the calculation procedure used by IMPSA to obtain the Damage Equivalent Load that reproduces the same damage as the design condition in the entire blade.

The following flow chart was used to determine the equivalent testing loads.

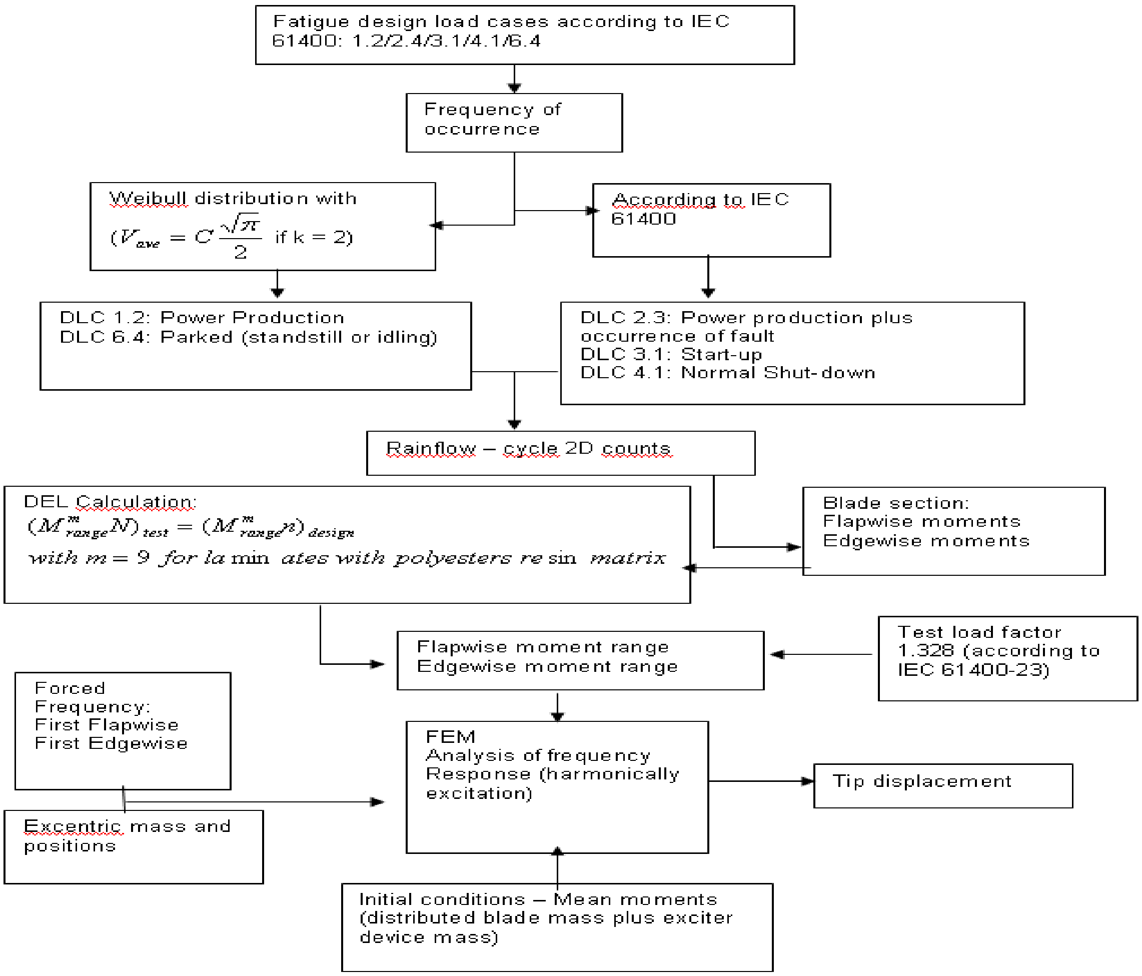

Figure 2: DEL calculation flow chart

In order to analyze the behavior to fatigue, the load conditions considered to build the DEL, were those established by the standard IEC 61400-1:

- Power production (DLC 1.2),
- Power production plus occurrence of fault (DLC 2.4),
- Start up (DLC 3.1),
- Normal shut down (DLC 4.1),
- Parked (standing still or idling) (DLC 6.4).

(DLC means Design Load Case)

The DLC were simulated with FAST[1] v5.1 for wind speeds between 3 mps and 25 mps (except for DLC 6.4 where only 36.4mps wind speed was considered). The resulting flapwise

[1] *"An Aeroelastic Design Code for Horizontal Axis Wind Turbines"* **by Jason Jonkman**
http://wind.nrel.gov/designcodes/simulators/fast/

and edgewise moments at the root blade (10 minutes simulations with steps of 0.1 seconds), generated for each blade, were analyzed with Crunch[2] v2.9.

Crunch is a software utility that generates binned a matrix with rainflow-cycle 2-D counts (cycle ranges as rows and cycle means as columns). Crunch also creates statistics data that provide information for binning the data in standard values. In our case, the dimension of the matrix generated was 100x100.

There are rainflow matrices for each wind speed. Each matrix was weighted with a Rayleigh curve[3] (mean wind speed of 12.2 mps was considered) for the annual distribution and multiplied by 20 years.

Vave mps	12.2
k	2
A	13.77
Vwind (mps)	Hours/Year
3	526.27
5	806.35
7	995.05
9	1081.21
11	1070.82
13	983.23
15	845.12
17	684.10
19	523.61
21	380.00
23	262.02
25	171.91

Table 2: Rayleigh distribution

Material characterization

If no S/N curve is available for the laminate, it shall be assumed to be as given in GL Wind Energy.

For laminate with polyesters resin matrix shall be used “m” equal 9. This value of “m” applies without further verifications for laminates with fiber content of at least 30% by weight and at most 55% by volume.

The values of blade’s material mechanical properties are presented in the internal document 99835-MC5001rev06 (Certification Report, Structural Analysis of Rotor Blade IWP70).

Rainflow – Cycles 2D counts

To estimate the DEL it is necessary before to make a rainflow counts over the FAST outputs (Aeroelastic Software). The loads were taken of the internal document 99835-MC8811rev10.

The rainflow counts was made over the flapwise bending moments and edgewise bending moments at the blade root section and 9- spanwise stations too.

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[2] “*A Batch-Style Postprocessor for Wind Turbine Data Analysis”* **by Marshall Buhl**
http://wind.nrel.gov/designcodes/postprocessors/crunch/

[3] IEC61400-1 3.65 wind shear law, 3.66 wind speed distribution.

DEL calculation

In order to calculate the Damage Equivalent Loads was used the follow expression:

$$R_{eq} = \left(\sum R_i^{\,m} n_i / n_{eq} \right)^{1/m} \qquad (1)$$

Where:

R_{eq} *:is the equivalent load*

R_i *:is the load of* i^{th} *class of the fatigue load spectrum*

n_i *: is the number of cycle in the* i^{th} *class of the fatigue load spectrum*

n_{eq} *:is the equivalent number of cycles*

m *: fatigue* exp*onent*

The rainflow count was made over design load case 1.1 (normal operation) at the root section and others stations. This load case generates more significant damage than the others fatigue load cases. The resultant fatigue damage might be consulted in the internal document 99835-MC5001rev06.

The range and mean spectra for cycle count matrix for the flapwise and edgewise bending moments are shown below:

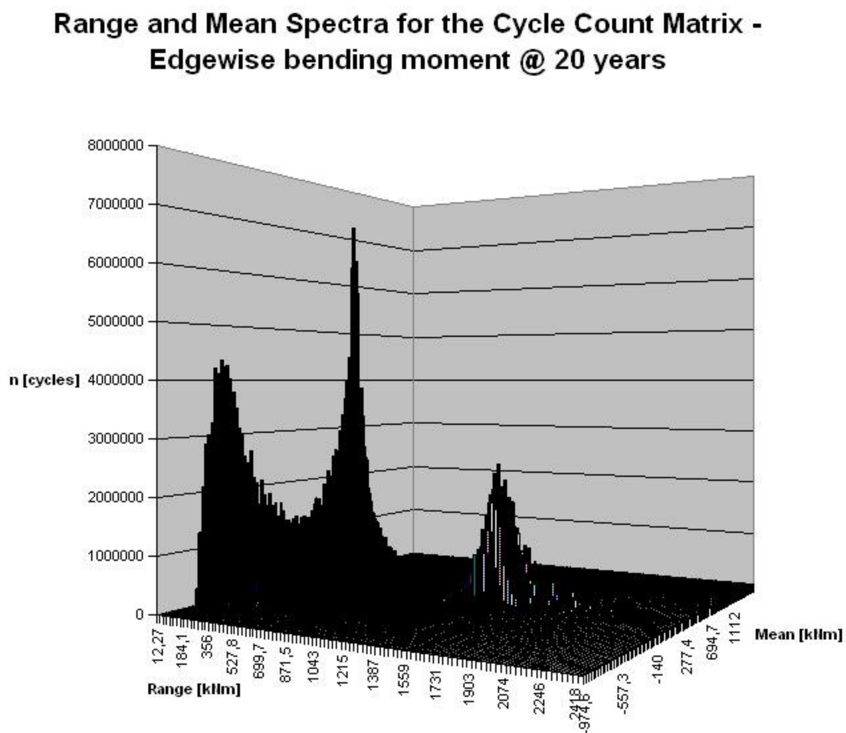


Figure 3: 2-D Cycle count matrix – Edgewise bending moment

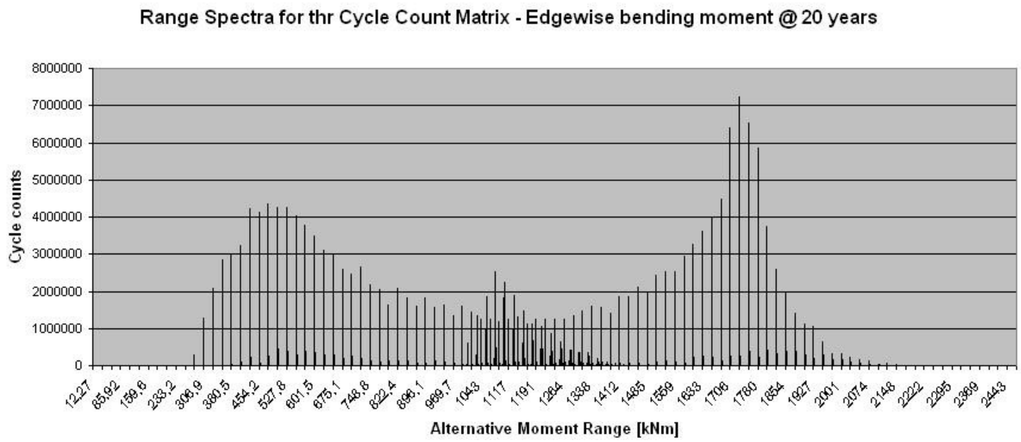


Figure 4: Range spectra – Edgewise bending moment

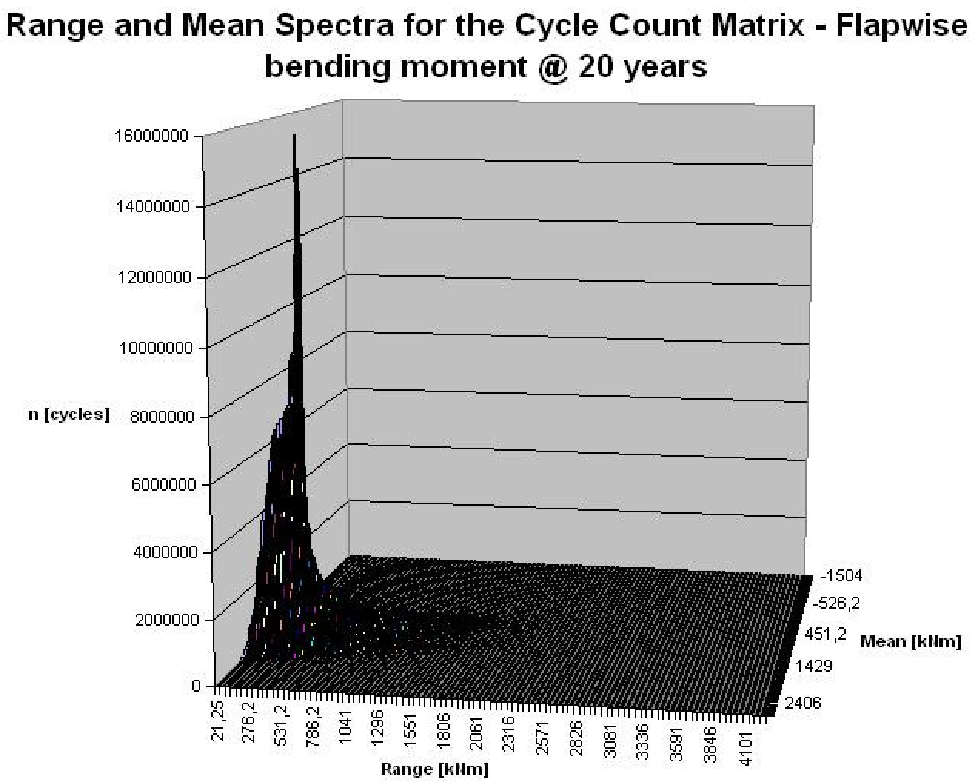


Figure 5: 2-D Cycle count matrix – Flapwise bending moment

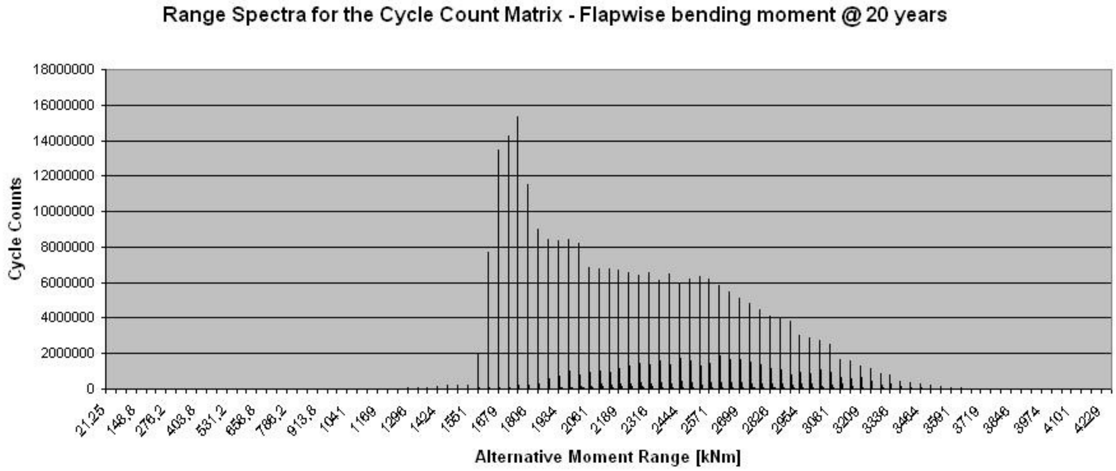


Figure 6: Range spectra - Flapwise bending moment

The Markov matrices were reduced in order to estimate the damage equivalent loads that reproduced the same fatigue damage decreasing the numbers of fatigue cycles.

The Damage Equivalent Loads were calculated following the expressions that consider constant mean moment:

$$DEL = \left[\frac{\left(M_{range}^{m} n \right)_{design}}{N_{test}} \right]^{\frac{1}{m}} \tag{2}$$

The results on the blade root were:

	root blade section	DEL @ 5M without load factor
range moment in system b	Mxb [kNm]	2303.3
	Myb [kNm]	2240.5

Table 3: Blade root loads without LF

Using the same analysis for the different blade sections, the DEL was calculated for the entire length of the blade, resulting in:

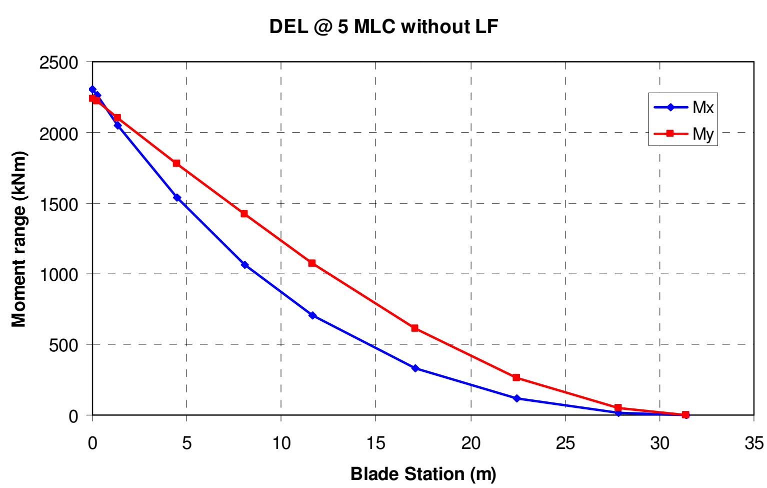


Figure 7: DEL @ 5 MLC without LF

In testing, various load factors have to be taken into account, so test loads are calculated using the following formula:

$$F_{Target} = F_d \times \gamma_n \times \gamma_s \times \gamma_e \tag{3}$$

Where:

F_{Target}	: target loading
F_d	: design loading (including partial factor for loads γ_f)
γ_n	: partial factor for consequence of failure
γ_s	: partial factor for blade to blade variation
γ_e	: partial factor for errors in fatigue formulation

We used the following values:
$\gamma_f = 1.0$
$\gamma_n = 1.15$
$\gamma_s = 1.1$
$\gamma_e = 1.05$

This gives:

$$F_{Target} \cong F_d \times 1.328 \tag{4}$$

Multiplying the DELs with the Load Enhancement factor we obtain the Target Load for the entire blade:

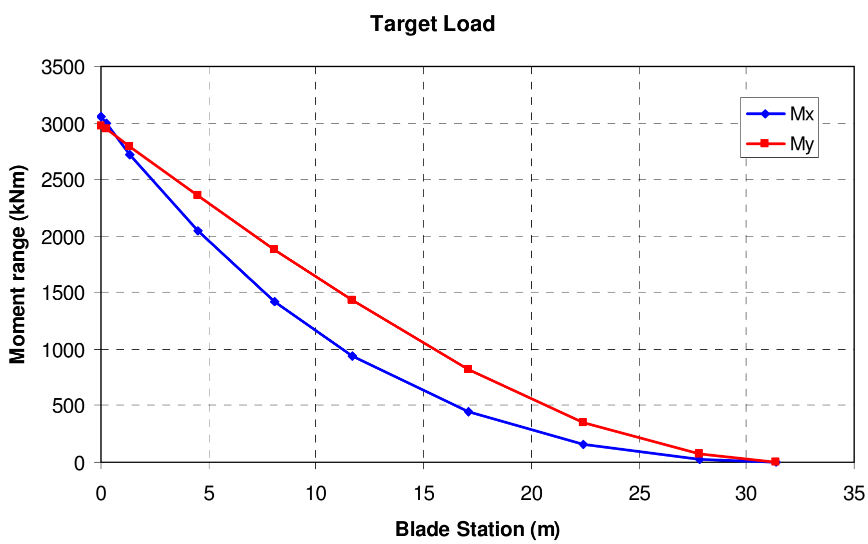


Figure 8: Target Load

This load distribution must be reproduced along approximately 70% of the blade length.

5.2 Test method

The calculation of the test loads depends on the chosen test method. IMPSA adopted:

- Type of loading: *Resonance loading* (section 12.5.1.8 of IEC/TS 61400-23)

It is achieved by exciting the blade at a frequency close to the natural frequency of the blade. As the spanwise load distribution follows the mode shape of the blade, the desired load can be obtained by adding mass in selected areas. This allows for a *single-axial*, *constant amplitude* loading.

- Test control method: *Resonance testing* (section 12.5.2.4 of IEC/TS 61400-23)

The principle is to excite the test blade in a narrow frequency range just below the natural frequency of the test blade. The amplitude of displacements is adjusted by varying the exciter frequency. Blade loads are controlled by directly maintaining deflections at the blade tip within a specific tolerance range.

- Loading devices: *Eccentric rotating mass* (section 12.5.3 of IEC/TS 61400-23)

Note: Since the first flapwise and edgewise natural frequencies are very near (1.57Hz flapwise and 1.79 edgewise) it is very difficult to effectively uncouple both modes using a resonant test method. As we fatigue the blade in a flapwise direction we are also creating movement in an edgewise direction, hence introducing edgewise load cycles and unwanted damage. For this reason we conducted two tests using two *different* test blades, avoiding accumulation of damage. The movement in the unwanted direction was recorded as a way to correlate any possible damage with this direction.

The dynamics of the Fatigue Test was simulated using MSC ADAMS (Automatic Dynamic Analysis of Mechanical Systems). This software let us build, simulate and test the behavior of the blade as we changed parameters such as:

- Distance from the root to the excitatory device
- Mass and eccentricity of the eccentric rotating mass
- Angular velocity of the rotating mass

The blade, a flexible body, was brought from NASTRAN as a modal neutral file (MNF) that considers the weight of the exciter and dead weights.

In order to identify the test rig coordinate system and the blade coordinate system see annex 1.

5.3 Flapwise Test Loads

The test parameters were determined after several iterations of trial and error. Since the blade exhibited a coupled edge and flapwise behavior we decided to rotate it 17° to obtain an almost vertical deflection. (For more details on the Flapwise Fatigue Test – General Assembly see 99835-943000r02).

In order to reach the DEL distribution for at least 70% of the blade length we had to add three saddles as dead weights. These are the results for the test parameters:

- Distance form the root to the excitatory device: 24 m
- Eccentric rotating mass, Mass: 77 kg
  Eccentricity: 272 mm
- Dead weights:

Saddle	Mass (kg)	Distance (m)
1	1139	9.537
2	793	14.400
3	387	29.811

Table 4: Fapwise test parameters

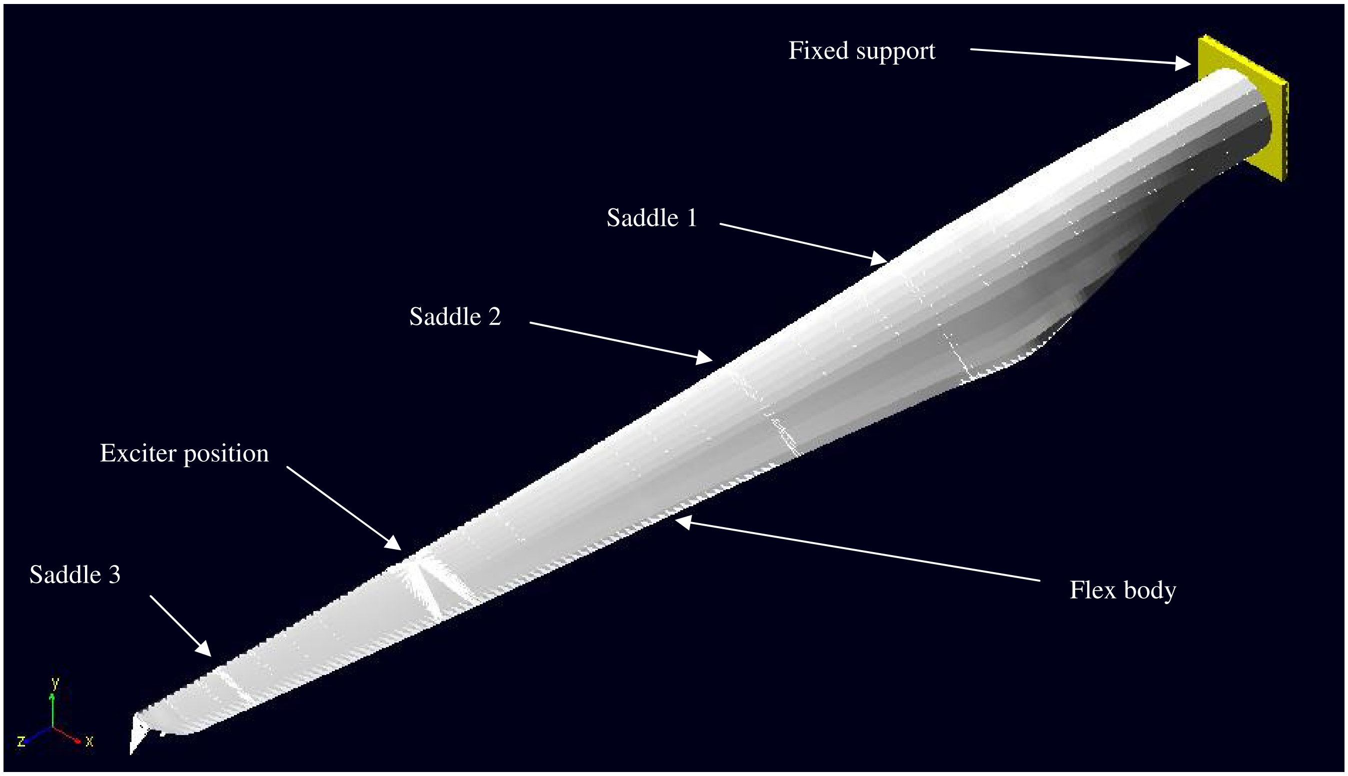


Figure 9: Flapwise test configuration

These are some its characteristics:

Blade properties with eccentric device and clamps	
Mass	10330 kg
Cg location	13.119 m
Mode 1: 1st flap	0.948 Hz
Mode 2: 1st edge	1.125 Hz
Mode 3: 2nd flap	2.972 Hz

Table 5: Blade with eccentric device and clamps properties

Static model

As the Fatigue Test takes place the blade oscillates around its static condition. Some values to have in mind are:

Static conditions			
Moment at root (kNm)	System b	x	-394
		y	1289
	System rig	x	1348
		y	0
Tip displacement (mm)	System b	x	540
		y	155
	System rig	x	-10
		y	-562

Table 6: Flapwise test static conditions

Dynamic model

Once the test parameters are chosen the blade dynamic response depends on the angular velocity of the eccentric mass. We did several simulations to determine the angular velocity that produced the desired moment range in the blade root (2975 kNm). The results were as follows:

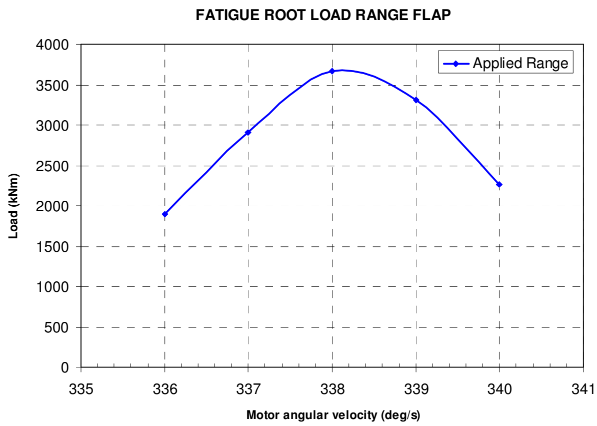


Figure 10: Flapwise test - root load range flap

We arrived to 2975 kNm using an angular velocity of 337.12 deg/s (0.936 Hz). The results were:

Moment range at root	
Edgewise	1037 kNm
Flapwise	2975 kNm

Table 7: Flapwise test - Moment range at root

The next figure shows the blade flapwise moment during the first 200 seconds of test.

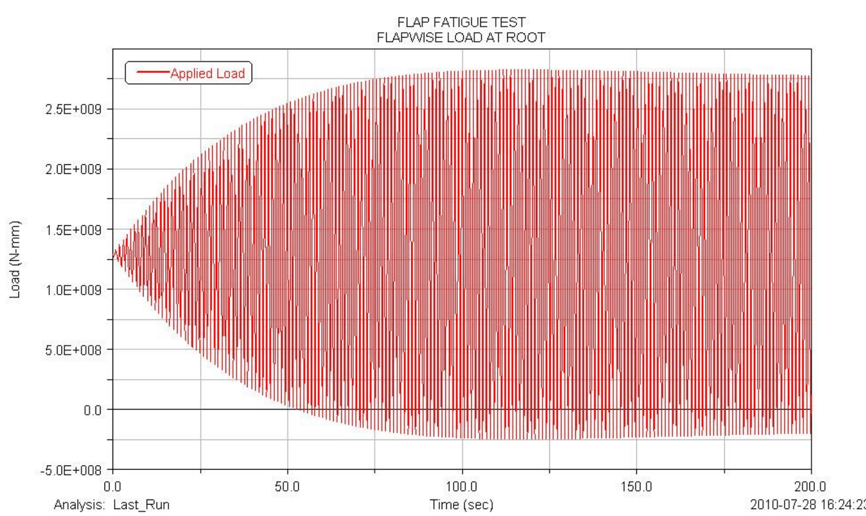


Figure 11: Flapwise test - Flap load at root

The blade tip moves in an almost vertical direction considering the rig coordinate system.

These are the values of tip displacement range, which was measured and controlled by the Control System.

Tip displacement range	
System b	x = 2690 mm
	y = 469 mm
System rig	x = 339 mm
	y = 2709 mm

Table 8: Flapwise test - tip displacement range

To calculate the moment at each blade section we used the simplified model of "beam". In strength of materials it is shown that:

$$\frac{M}{EI} = \frac{d^2 y}{dx^2} \tag{5}$$

Thus:

$$M = \frac{d^2 y}{dx^2} EI \tag{6}$$

We measured 3 displacement points near each blade section and analytically calculated its second derivative by means of a second degree polynomial.

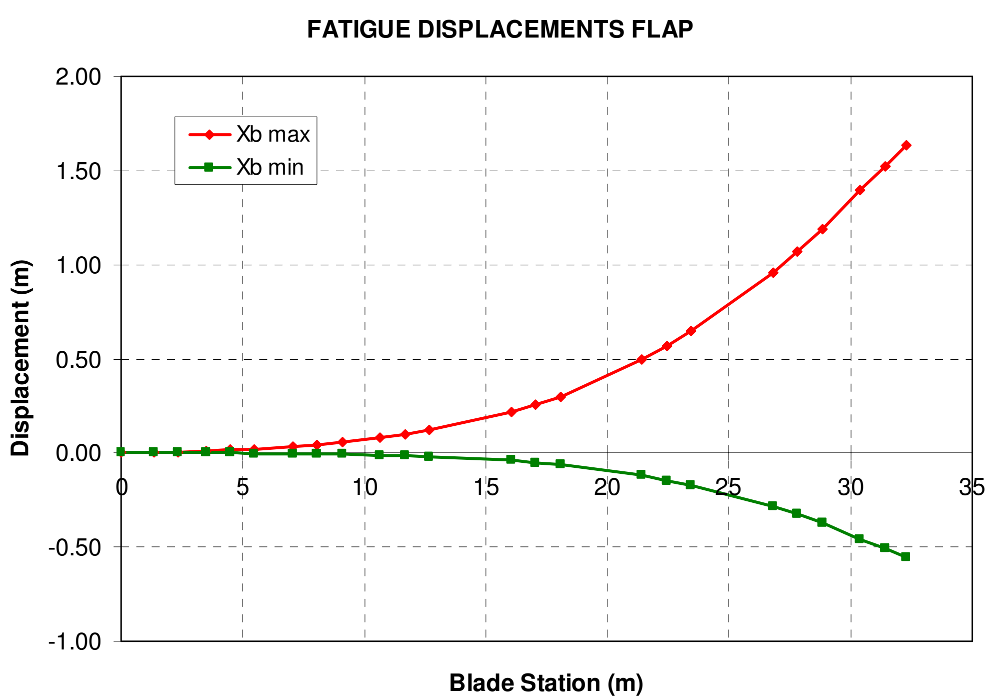


Figure 12: Flapwise test- displacement flap

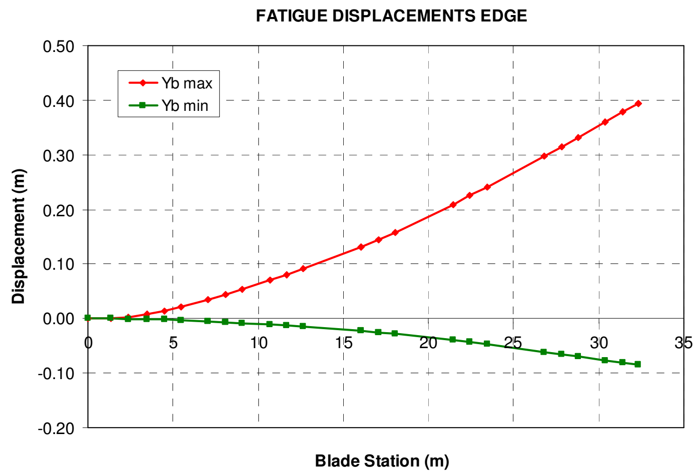


Figure 13: Flapwise test - displacements edge

We then multiplied these values by the In-plane and out-of-plane stiffness to obtain the bending moment at each blade section. It should be noted that the blade movement at sections 1, 2 and 3 were too small to obtain accurate results. They were left out from the calculation.

With the chosen parameters, the test load distribution on the flapwise direction approximated the DELs on 68% of the blade length, taking a 10% tolerance.

	Root	Spn 4	Spn 5	Spn 6	Spn 7	Spn 8	Spn 9
My range Test (kNm)	2974	1853	1402	782	309	57	2
My range DEL (kNm)	2975	1881	1426	817	348	71	3
Difference (%)	0.05	1.49	1.67	4.28	11.05	20.00	29.81

Table 9: Flapwise test - load comparison

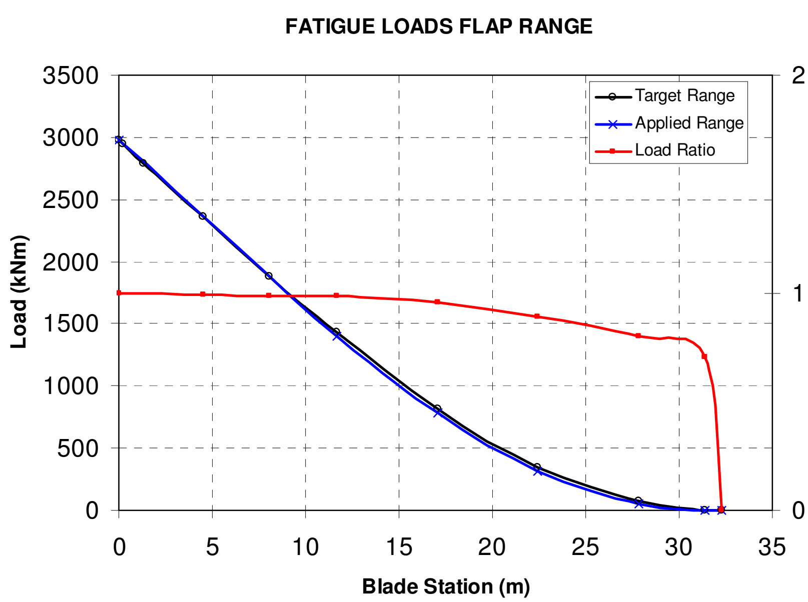


Figure 14: Fatigue test - loads flap range

As for the edgewise movement, which couples with the flapwise movement, this is the resulting moment range.

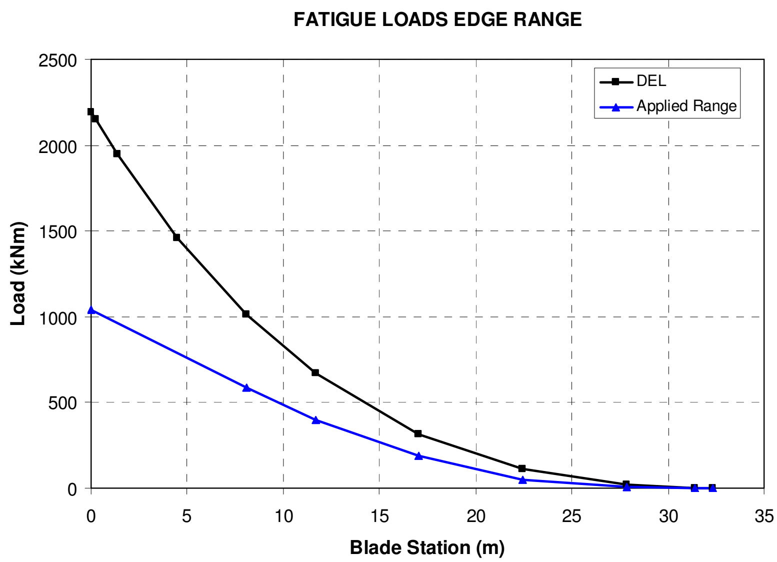


Figure 15: Flapwise test - loads edge range

5.4 Edgewise Test Loads

The Edgewise Fatigue test was simulated using the same procedure as the flapwise test.

- Distance form the root to the excitatory device: 15 m
- Eccentric rotating mass, Mass: 94 kg
  Eccentricity: 329 mm
- Dead weights:

Saddle	Mass (kg)	Distance (m)
1	554	22.553
2	442	25.807
3	399	28.311

Table 10: Edgewise test parameters

This is a diagram of the test setup.

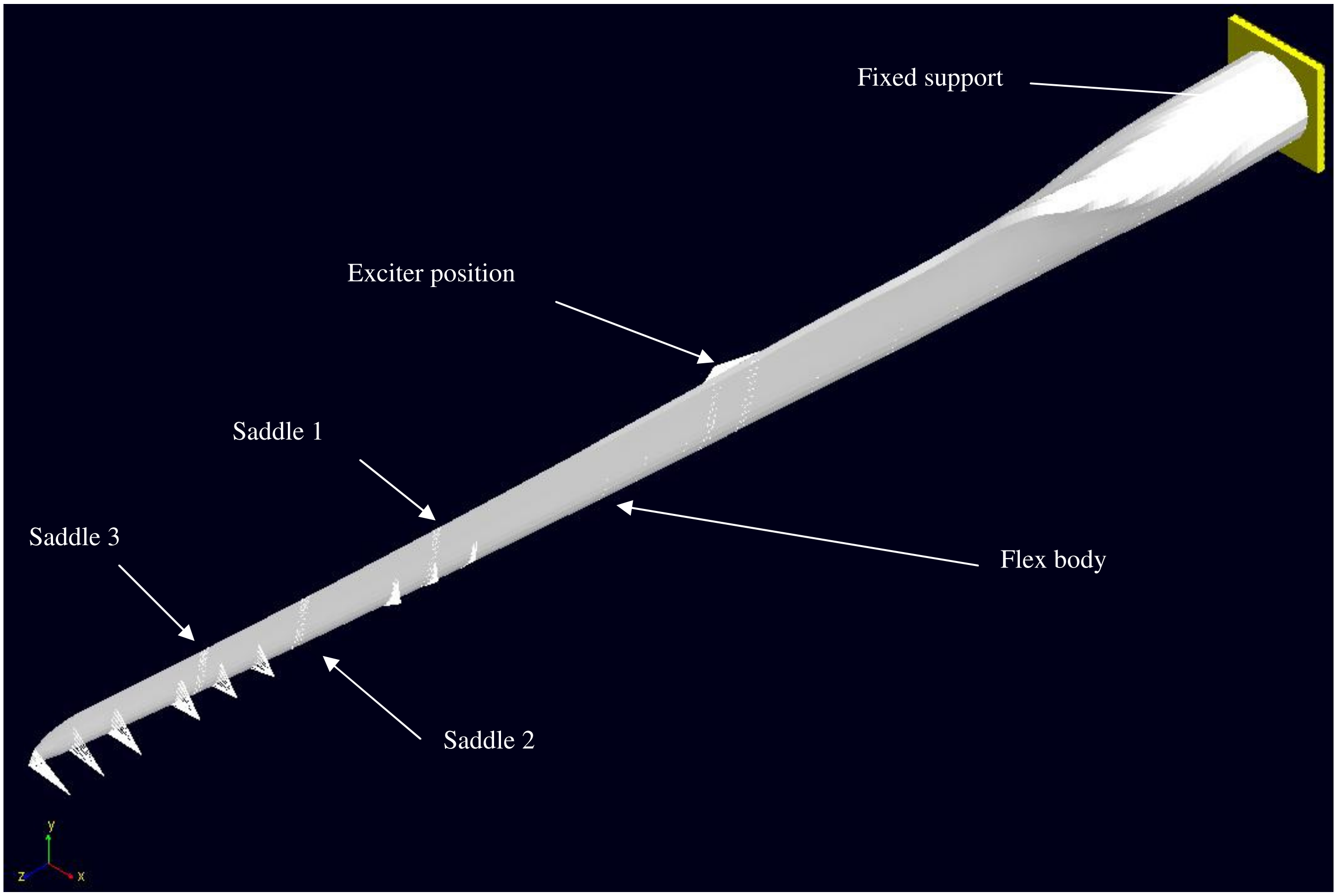


Figure 16: Edgewise test configuratoin

These are some its characteristics:

Blade properties with eccentric device and clamps	
Mass	9369 kg
Cg location	13.363 m
Mode 1: 1^{st} flap	1.016 Hz
Mode 2: 1^{st} edge	1.179 Hz
Mode 3: 2^{nd} flap	3.098 Hz

Table 11: Blade with eccentric device and clamps properties

Static model

The blade oscillates around this static condition. Some values to have in mind are:

Static conditions			
Moment at root	System b	x	1223 kNm
		y	374 kNm
	System rig	x	1279 kNm
		y	0 kNm
Tip displacement	System b	x	101 mm
		y	-333 mm
	System rig	x	-1 mm
		y	-348 mm

Table 12: Edgewise test static conditions

Dynamic model

As for the Flapwise simulation, we varied the eccentric mass angular velocity to reach the 3059 kNm for the Edgewise test.

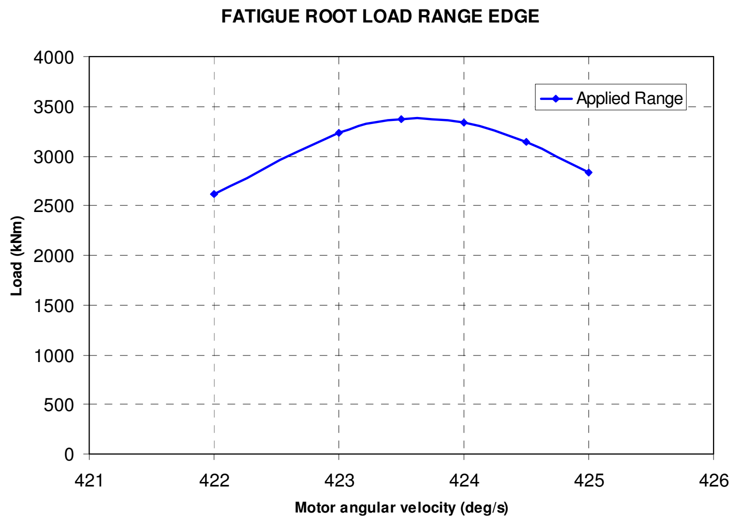


Figure 17: Edwise test - Rood load range edge

We reached this value with an angular velocity of 424.66 deg/s (1.18 Hz). The results were:

Moment range at root	
Edgewise	3059 kNm
Flapwise	1072 kNm

Table 13: Edgewise test - Moment range at root

The next figure shows the blade edgewise moment during the first 200 seconds of test.

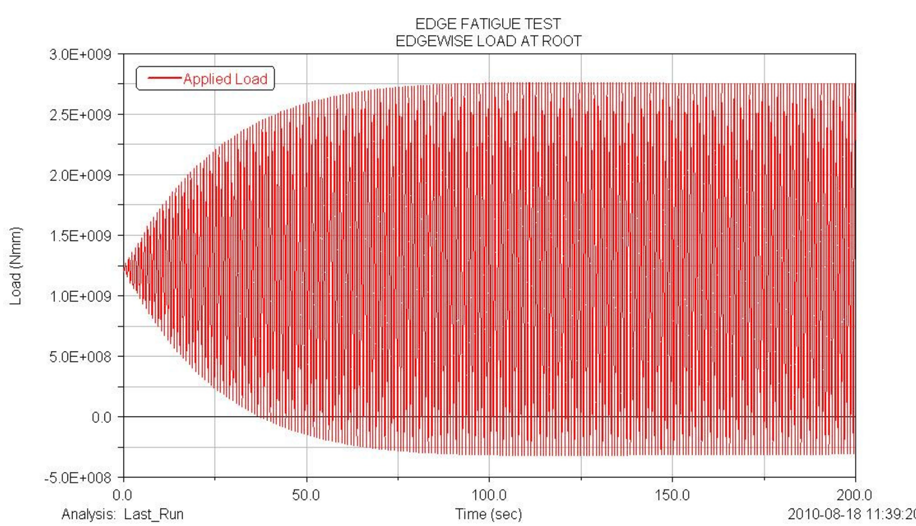


Figure 18: Edgewise test – Edge load at root

The blade tip moves in an almost vertical direction.

These are the values of tip displacement range.

Tip displacement range	
System b	x = 672 mm
	y = 1026 mm
System rig	x = 735 mm
	y = 1572 mm

Table 14: Edgewise test - tip displacement range

The displacements used to calculate the bending moments at each blade section were the following:

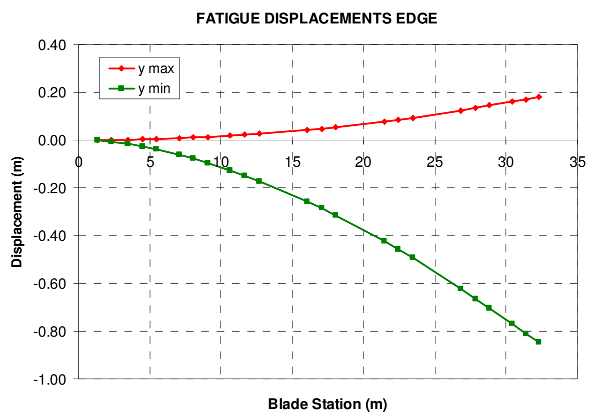


Figure 19: Edgewise test – displacements edge

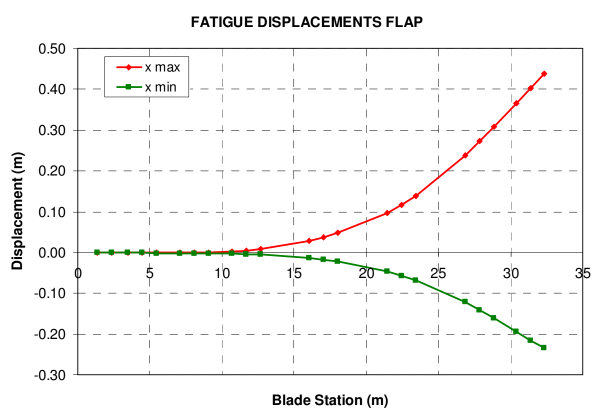


Figure 20: Edgewise test – displacements flap

With this simulation, the test load distribution on the edgewise direction was superior than the required DELs on 76% of the blade length, taking a 10% tolerance.

	Root	Spn 3	Spn 4	Spn 5	Spn 6	Spn 7	Spn 8	Spn 9
My range Test (kNm)	3057	2003	1922*	1178*	473	148	10	1
My range DEL (kNm)	3059	2039	1414	935	440	156	26	1
Difference (%)	0.06	1.78	35.9*	26.0*	7.4	4.8	62.9	1.7

Figure 21: Edgewise test - load comparison

* These values we believe are erroneous due to our calculation method

Graphically,

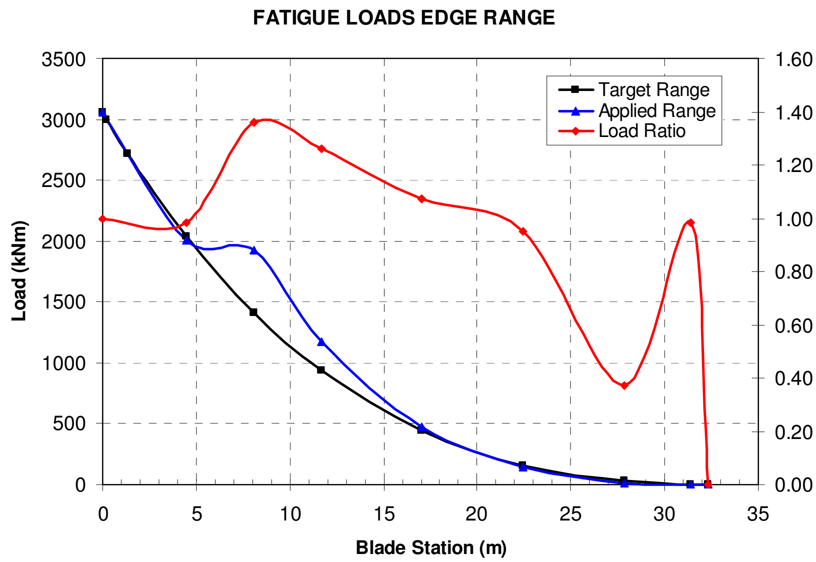


Figure 22: Edgewise test – loads edge range

The movement also causes a flapwise moment with the following moment range.

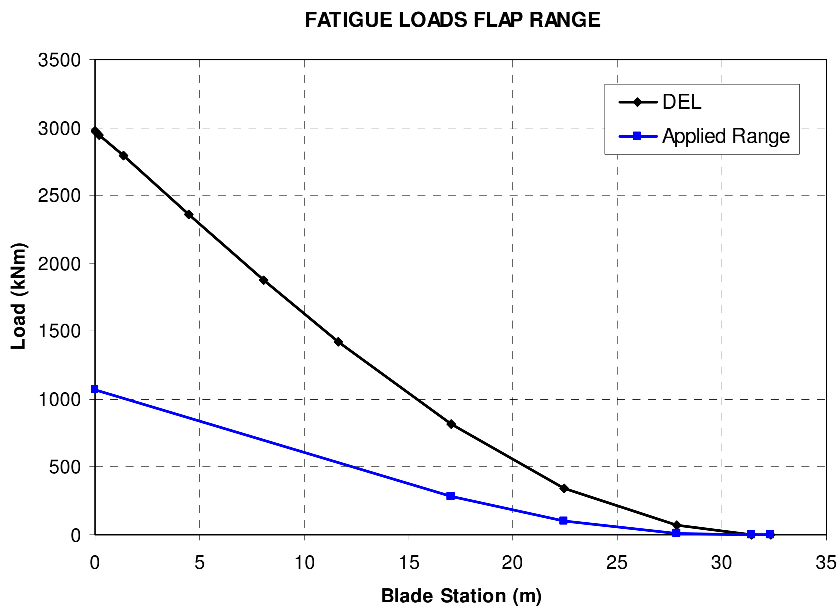


Figure 23: Edgewise test – loads flap range

6 FAILURE CRITERIA

The fatigue test would be stopped *unexpectedly* only on the occurrence of a critical failure. Following sections 11.2 to 11.4 of the IEC/TS 61400-23 standard, a critical failure is considered as a catastrophic or functional failure. Non-critical failures, or superficial failures on the IEC/TS 61400-23 standard, would not cause the stop of the test.

Non-Critical Items	**Critical Items**	
Superficial failure	*Functional failure*	*Catastrophic failure*
Small cracks	Decrease of 10% on flapwise stiffness	Breaking or collapse of the primary blade structure
Gel coat cracking		
Paint flaking		Complete failure of structural elements
Surface bubbles		
Minor elastic panel buckling		Major parts become separated from main structure
Delaminations near the surface		

Table 15: Types of failure

7 EXPERIMENTAL SET-UP AND PROCEDURES

The experimental set-up is sketched in the following diagram:

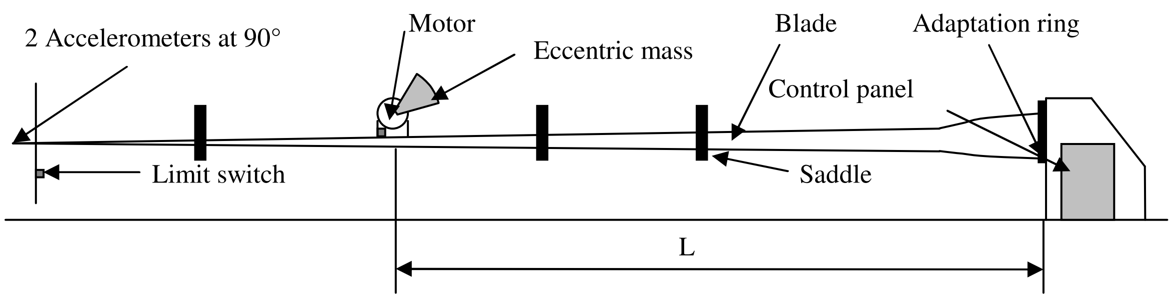


Figure 24: Fatigue test layout

7.1 Tasks

1. Strain-gages were bonded (see Annex 4).
2. The correct operation of the optical strain gages was verified before blade fixation on its support. An initial reference was defined by supporting the blade in its mould, i.e. in a nearly strain free condition. The corresponding readings was recorded to be further considered for local strain calculations (Section 12.7.1 IEC/TS 61422-23).
3. The adaptation ring to link the blade to the test rig was installed. The pre-tightening torque and tightening procedure was the same as the one used in the wind turbine (Section 12.2 IEC/TS 61400-23).
4. The blade was mounted on a special support designed by IMPSA to withstand testing loads.
5. The blade was attached to the test rig and the exciter device and saddles mounted to the blade. In both cases, the rotation plane of the eccentric mass should be coincident with the pitch axis. The saddles use appropriate fixation elements in order to avoid local damage along the test. Special care should also be taken during mounting operations to avoid local damage or scratches as they are potential sites for blade failure (Section 12.3, IEC/TS 61400-23)
6. Two accelerometers at a 90° angle were firmly attached at the blade tip so as to indirectly measure displacement. They should be mounted parallel to the ground coordinate system.

7. The control system was calibrated to maintain tip vertical acceleration within a specific tolerance range, which correlates to a specified displacement fixed for the test. The exciter, including its control, has been specifically developed by IMPSA for fatigue testing. A more detailed description is given in Annex 5.

8 TEST DATA ACQUISITION

A registry every 30 minutes was made with the following data:

- Number of cycles
- Test time
- Root strain
- Motor speed
- Acceleration 0°/90°
- Blade interior temperature
- Ambient temperature

Every 12hs a manual control was performed to guarantee that the Control System was working well. This value was recorded for further analysis.

We used the following stop intervals for inspection:

- Start of test
- 10 000
- 50 000
- 100 000
- 250 000
- 1 000 000
- 2 000 000
- 3 000 000
- 4 000 000
- 5 000 000

During each stop we executed the following tests:

- Stiffness
- Visual inspection
- Thermography

9 RESULTS

Upon date of submission the test was not yet finished. We hope to have some results before the beginning of conference.

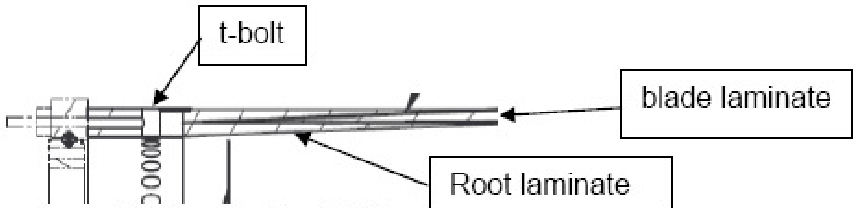
REFERENCES

International Electrotechnical Commission, International Standard IEC/TS 61400-23. *Wind turbine generation systems – Part 23: Full-scale structural testing of rotor blades*. First edition 2001-04

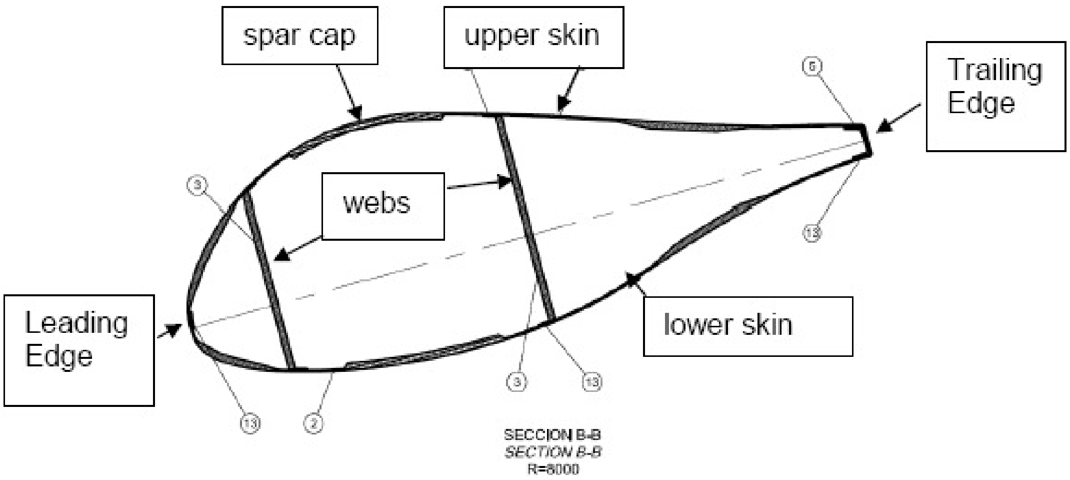
International Electrotechnical Commission, International Standard IES 61400-1: *Wind turbine generation systems – Part1: Safety requirements*. Second edition 1999-02.

ANNEX 1: Blade 1,5 MW Class S - General Assembly

ANNEX 2: Components of the blade



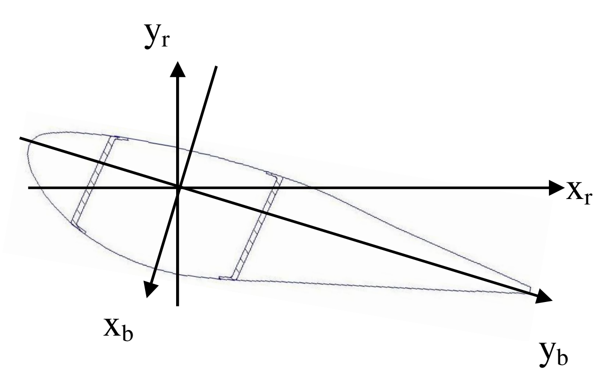
Root assembly detail



Typical section detail

ANNEX 3: COORDINATE SYSTEMS

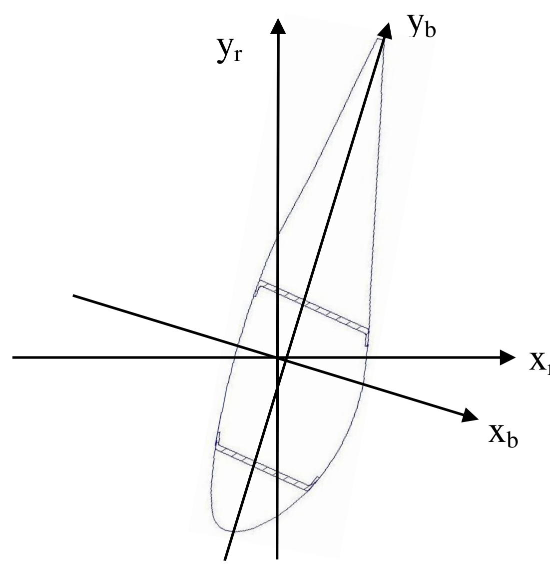
Flapwise coordinate system



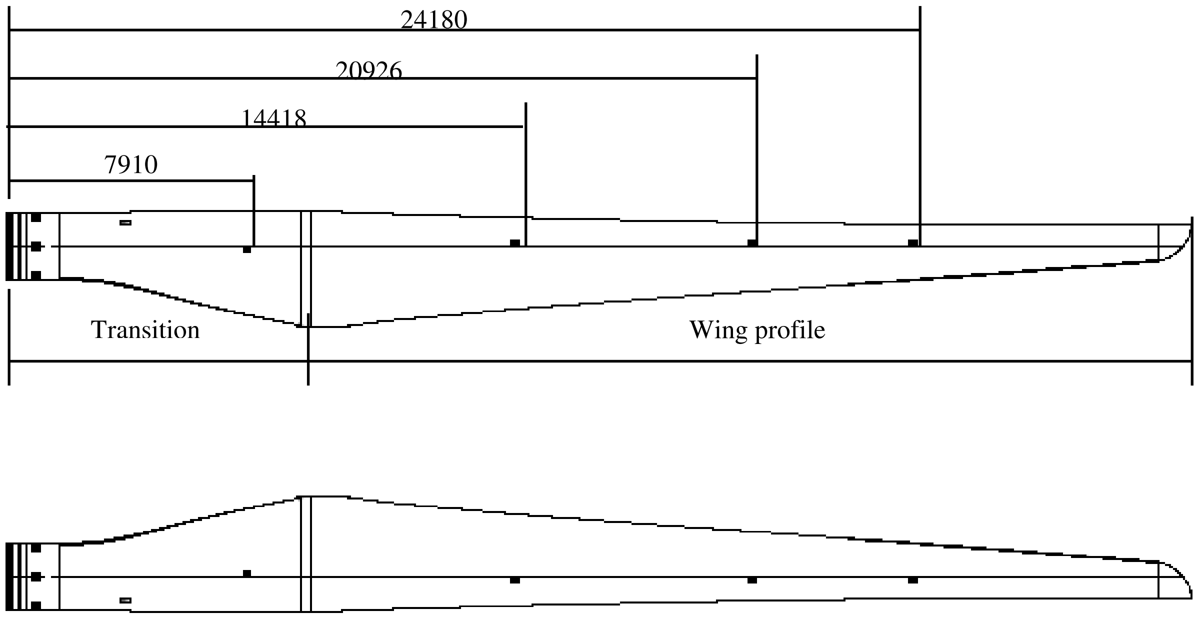
System rig: $\begin{cases} x_r \\ y_r \end{cases}$

System blade: $\begin{cases} x_b \\ y_b \end{cases}$

Edgewise coordinate system



ANNEX 4: Blade 1's Strain Gauges' Position



ANNEX 5: Control system