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DYNAMIC MEASUREMENTS OF A STEEL WIND TOWER

Rui M. M. P. de Matos*[1], Carlos A. da S. Rebelo[1]

[1]ISISE – Institute for Sustainability and Innovation in Structural Engineering
{ruimatos, crebelo}@dec.uc.pt

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Abstract. *This paper describes the developments undertaken in the monitoring of an 80 meters high steel wind tower supporting a 2.1 MW wind turbine Wind Class III IEC2a erected in the central part of Portugal. The signals measured (strains, accelerations, inclinations and temperature) were obtained in 4 different levels along the tower height. There were also some environmental and operational data measured directly from the tower sensors in order to correlate them with the measurements. The calibration of the measuring system will also be presented. The results obtained during the tower monitoring period (15 months) will be presented in terms of stress distribution along the tower shell and in the bolts at different levels, stress fatigue spectra, section forces along height evaluated from the stress measurements and comparison with design forces, dynamic response in terms of accelerations, stresses, deflections and rotations.*

1 INTRODUCTION

The work reported in this paper was carried out in the scope of the European project HISTWIN (High Strength Steel Towers for Wind Turbines) [1] with the main goal of evaluating and improving the competitiveness of the new generation of the higher steel wind towers. A full description of the project can be found on [2] and [3].

This topic of the work, the monitoring of a full functional steel wind tower has the objective of estimate the real behaviour of the system in order to have a more realistic design and damage estimation during extreme events.

In this document will be presented both the architecture and functioning of the acquisition system as well as its calibration, structural modal identification of the structure and measurement results of the long-term monitoring (15 months). The dynamic behaviour of the tower during operation and the characterization of internal stresses and related internal forces acting on the shell and on the connection at different tower levels were acquired and processed. The fatigue spectra was also estimated. These type of measurements allow a better understanding of the structural performance in the tower shells and of the bolts behaviour in the flange connections and their vicinities.

The physical quantities under observation are the strains on the inner surface of the steel conical shell and inside some of the bolts used in the connections, the accelerations at various levels, the inclinations in the upper part of the tower, the surface temperature at a fixed level and several parameters related to the wind turbine operation.

The measurements recordings were triggered by the wind speed value. The records were divided into two phases. In the first phase it was recorded measurements over 4m/s of wind speed and in phase 2 it was recorded over 14 m/s. When the trigger is activated the recordings took a time of 1 hour independently of the wind speed. After that the trigger was ready for a new activation.

The numerical simulation of the measurements was calibrated considering the estimated modal identification. The tower simulation was carried out according to the production drawings provided by the manufacturer for the eighty meters high steel tower supporting a 2.1MW turbine Wind Class III IEC2a. This specific tower was erected in the central area of Portugal. The soil-foundation interaction was taken into account as well as the linear elastic behaviour. It was considered for this work the use of the software LUSAS® [4].

2 DESCRIPTION OF THE TOWER

The wind turbine is a 2.1MW turbine Wind Class III IEC2a and is mounted on an 80 meters high steel tower erected in the central part of Portugal. The structure of the tower (Figure 1) is a free standing tube with varying diameter and wall thickness along the height. To enable transportation and assembling on the construction site the tower is divided in three segments with lengths 21770, 26620 and 27760 mm. The diameter varies between 2955 mm at the tower top and 4300 mm at the tower bottom. The shell thickness varies between 12 and 30 mm at the same levels.

The tower segments were connected with pre-stressed flange connections with M36 and M42 class 10.9 bolts.

As those type of connections are very sensitive to imperfections (loss of contact between the flanges) leading to water infiltrations and to low performance of the bolts which remain subjected to higher stress ranges, tight fabrication tolerances are purposed by the manufacturer. The fabrication tolerance limit for the 10 cm thick flange is 1.5 mm for the amplitude of the waviness and for the external-internal inclination of the ring surface.

Figure 1 - Instrumented tower and levels position.

3 MEASUREMENT SYSTEM

Along the four measurement levels presented, four types of signals were measured, namely the accelerations, strains, temperature and inclination. The position and designation of the sensors is presented on Table 1.

For the estimation of the modal parameters and the dynamic behaviour of the tower were used nine piezoelectric accelerometers are used of the type PCB393B04 with a dynamic frequency range of 0.1 Hz to 1000 Hz and a nominal sensitivity of 0.1 $Volt/ms^{-2}$.

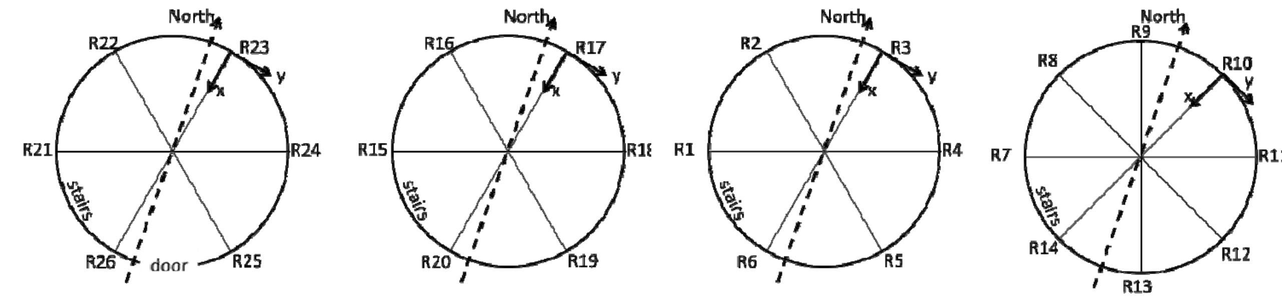
The strains were measured on the inner surface of the shells using gauge rosettes of type TML PFR-20-11 are used to measure shell strains in two orthogonal directions, vertical and horizontal, and in a 45º-direction. The bolts strains were measured using gauges of type TML BTM-6C. A total of 96 strain channels were monitored, whose position and identification are given in Table 2.

The four thermocouples used for the temperature measurement were type K placed at level 2 and the inclinometers were type TML – KB-5EB, placed at levels 2 and 3 to measure the inclination of the tower in two directions.

The data acquisition was made using data loggers manufactured by National Instruments (NI). The types used in those tests were NI cRio 9012 (able to digitalize dynamic data but more expensive) with a sample rate of 100Hz and NI cFP1808 ((quasi-)static signal recording) with a sample rate of 2.5Hz.

The acquisition software was developed using LabView [5] to synchronize the data loggers which are connected using TCP-IP communication protocols and a daily report is emailed to a remote system using a General Packet Radio Service (GPRS) based mobile data service.

Level 0	Level 1	Level 2	Level 3



Initials for Signals' identification: L(1)(2)(3)(4)	(1)Level number (2)Type of signal: R – strain gauge Rosette Acc – accelerometer B – strain gauge in bolt Inc – inclinometer	(3)Strain gauge direction in rosettes V – vertical tower axis H – horizontal along section perimeter D – diagonal	e.g. **L2R21D**: **L**evel **2**, **R**osette **21**, strain gauge in **D**iagonal direction

Table 1 – Sensors' location and identification.

4 SYSTEM CALIBRATION

The calibration of the system has two main topics, namely the transformation of the signal into physical quantities and the zeroing of the signal. The first one is specific to the equipment and only the second will be discussed in this document as a way to interpret the obtained strains.

The start of the recording was done after the assembly of the tower, with a normal function of the wind turbine and with a certain wind speed and so the measured strains are not an absolute value but is relative to the moment of the initialization.

In Figure 2 the measured parameters are presented. The component related to the self-weight can be accurately estimated using numerical methods knowing the tower geometry and turbine manufacturers data. The component of the gauge calibration error must be dropped out considering a very low wind speed and the system was zeroed with a wind speed of 4.62 m/s.

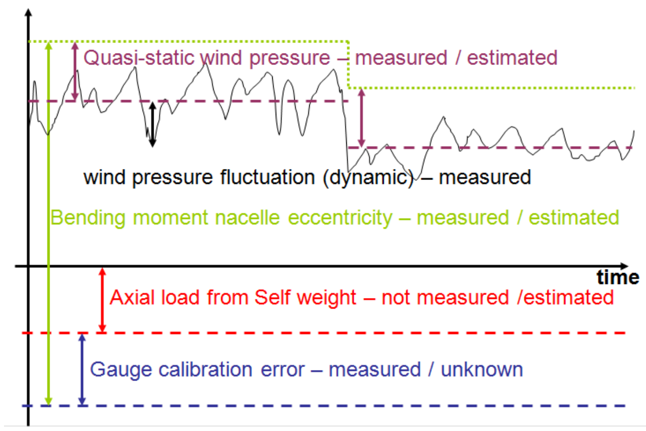


Figure 2 –Strain history at an arbitrary location and its decomposition in static or quasi-static components and dynamic component.

The bending moment due to the nacelle eccentricity (0.725 m) was also included in the measurements and it was dropped out from the measurements by performing a full rotation of the nacelle (360º) with increments of 20º and registering both the obtained strains as well as the environmental conditions.

Knowing all the presented components, it was then possible to obtain values for the strains that accurately represent the static and dynamic effect of wind pressure on the turbine blades and on the tower.

5 ACCELERATION MEASUREMENTS AND MODAL IDENTIFICATION

5.1 Modal extraction from measurements

In this monitoring a preliminary modal identification was performed before the operation starts. The three accelerometers at the top of the tower (level 3) and two at each of the levels 1 and 2 were used. The acceleration measurements for modal extraction were made during the idle state of the turbine.

Table 2 summarizes the obtained results for the modal parameters. Some difference may be expected between the fore-aft and the side-to-side natural frequencies of the tower. However, it is to be noted that the accuracy of the measurements tends to be of the same order of that difference.

		Mode			
		1	**2**	**3**	**4**
Frequency (Hz)	Measured	0.340	0.343	2.767	2.794
	Updated FE model (Es=300MPa; e=1.0m)	0.345	0.345	2.751	2.751
Damping (%)		1.32	0.96	0.13	0.23
Mode type		Bending Nacelle direction (x-x)	Bending Transversal to Nacelle direction (y-y)	Bending Nacelle direction (x-x)	Bending Transversal to Nacelle direction (y-y)

Table 2: Natural frequencies, modes and damping.

5.2 Finite element model identification

A tower model was developed using the software LUSAS [4] considering quadratic thick shell elements with 8 nodes and using the tower geometric properties. The reinforced concrete foundation was also included in the model as well as the soil-foundation interaction. The FE model uses 3D solid continuum finite elements for the concrete foundation and linear springs for the contact with the soil.

The model parameters used for model updating were: i) the mass of the tower, ii) the stiffness of the springs simulating the soil-structure interaction and iii) the vertical eccentricity of the turbine's centre of gravity.

Concerning the vertical eccentricity of the nacelle, the reason for including it was that the exact value of the eccentricity was not given in the design documents of the wind tower. The final model considers E_s=300MPa and 1.0 m vertical eccentricity for the centre of gravity of the nacelle relative to the top of the steel tower. Results for the natural frequencies and mode shapes are shown in Table 2.

6 STRAIN

6.1 Shell

As it was referred, the strains measured in the shells were acquired at two different frequencies, depending on the characteristics of the correspondent data logger. The measurements recorded with the data loggers with dynamic recording capabilities with frequencies up to 100Hz had to be decimated for a frequency of 2.5Hz in order to allow a comparison of all data.

In order to visualize the evolution of the shell stresses depending on wind speed, the maximum tensile and compressive stresses were computed from the measured time series segmented in periods of 10 seconds. These extreme values are plotted in Figure 3 against the corresponding 10-seconds mean wind speed. Maximum stresses are achieved between 10 and 14 m/s wind speed decreasing to a steady state level for higher wind velocities. This effect is due to the regulation of pitch angle for higher wind speeds, that is, the blade angle varies in order to decrease the tower loading while maintaining the production rates ([6] and [7]).

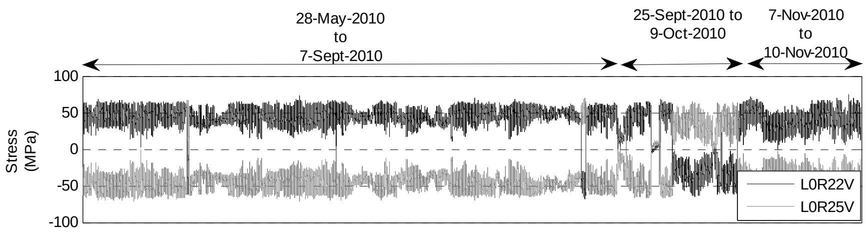


Figure 3 – Time signals obtained during Phase II with trigger based on wind speed greater than 14m/s.

At each measurement point three stress directions are measured. Therefore, the principal stresses can be computed and are presented in Figure 4 for levels 0 and 1. The highest principal stresses occur for wind speeds of about 12 m/s with maximum values of about 130 MPa.

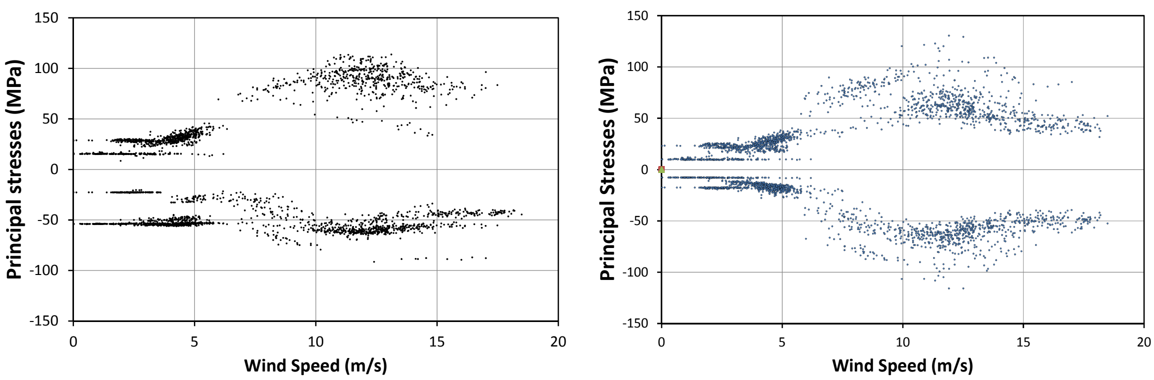


Figure 4: Principal stresses in the shell at levels 0 and 1 plotted against 10-seconds mean wind speed.

6.2 Bolts

The flange connections monitored in the current work are connected using pre-stressed bolts. Due to that fact, the stress fluctuation observed in the monitoring of the bolts strain gauges readings are a lot smaller than the readings on the tower shell, as presented on Figure 5.

The presented readings shows a negative value of the bolts force representing a loss pre-stress from the starting point of the readings until the measurement time.

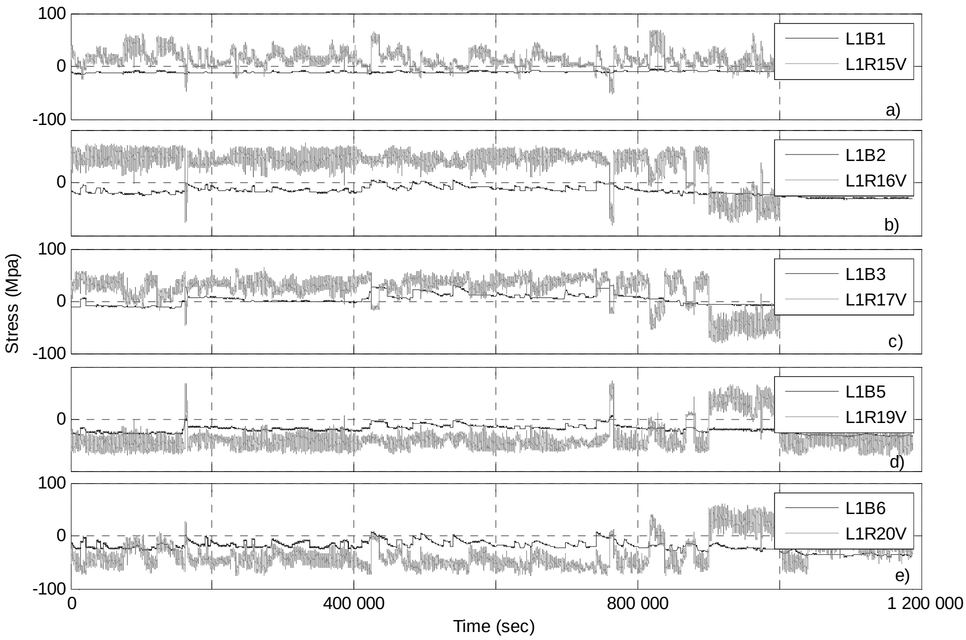


Figure 5 – Comparison of stresses in bolts (dark curves) with vertical stresses in shell at level 1 during the second measurement period.

The unsteady behaviour observed in some bolts is justified by the difference in time occurred between some periods of readings but can also be connected to some adjustments made in the neighbour bolts pre-stress. When all the instrumented bolts present an increase of tension, this can be correlated with the maintenance work performed in the tower that includes retightening of the bolts, as presented in Figure 6.

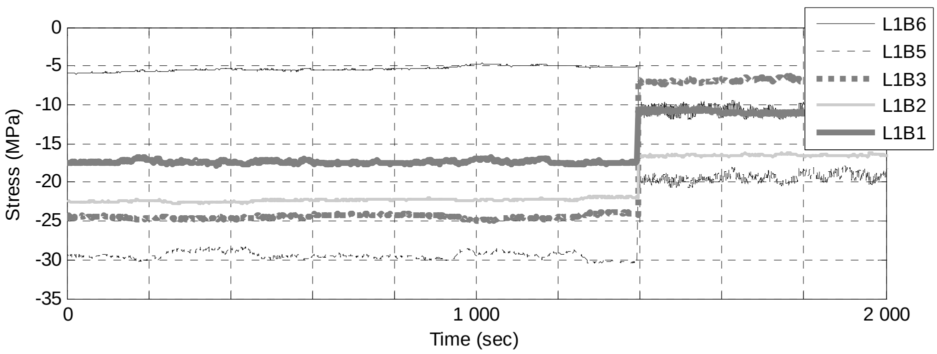


Figure 6 – Stress increase in the bolts due to retightening.

6.3 Fatigue spectra

Fatigue spectra were calculated for the shell vertical stresses using the rainflow method and the number of cycles was linearly extrapolated for a 20 years lifetime (20x365 days). The obtained spectra is presented in Figure 7, were a comparison between the measured spectra and the ones provided by the tower manufacturer and the EN1993-1-9 [8] for fatigue detail category 71 is also presented.

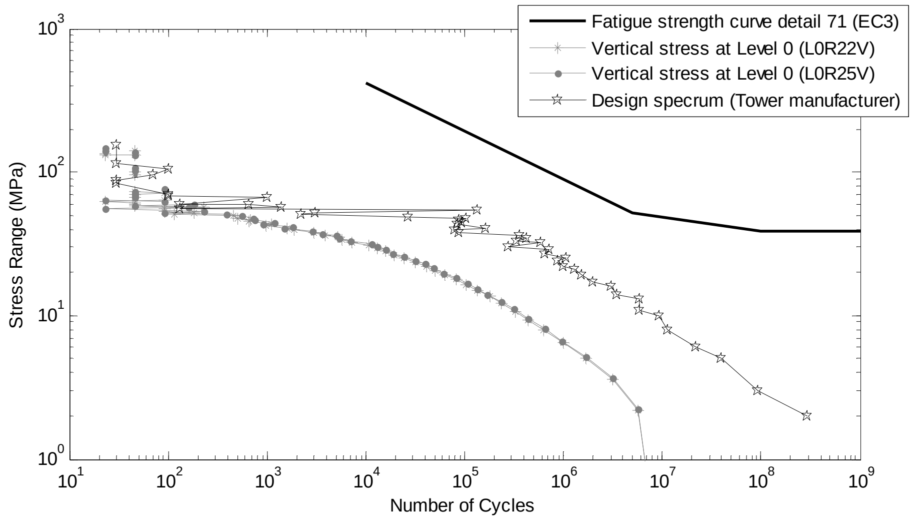


Figure 7 – Comparison of measured fatigue spectrum extrapolated for 20 years lifetime with design spectrum and strength curve obtained from EN1993-9 for detail 71.

7 DYNAMIC BEHAVIOR

7.1 Accelerations

The dynamic response of the wind tower is mainly due to the turbine rotation and is therefore almost periodic. In order to avoid excessive vibrations it is recommended that the lowest natural frequencies must be kept away from the rotational and/or blade-passing frequencies and their harmonics.

It can be observed in Figure 8 that the three lower peaks are observed in the range 0 Hz to 1 Hz and several other peaks are identified up to 3 Hz. The first peak in the spectrum corresponds to the rotational frequency of 0.25 Hz. The wind turbine manufacturer gives operating limits of 0.13Hz and 0.25 Hz, for the lower and upper rotor speed, respectively. The upper limit is attained for average wind speeds around 12 m/s, which is in the range of wind speed for which recording of the monitored signals is activated. The second spectral peak is at frequency 0.34 Hz and corresponds to the first and second natural frequencies of the tower. The damping ratio measured during operation in these modes is 1.12%, close to the value obtained in the modal identification. The third peak in the spectrum corresponds to the blade passing frequency of 0.75 Hz.

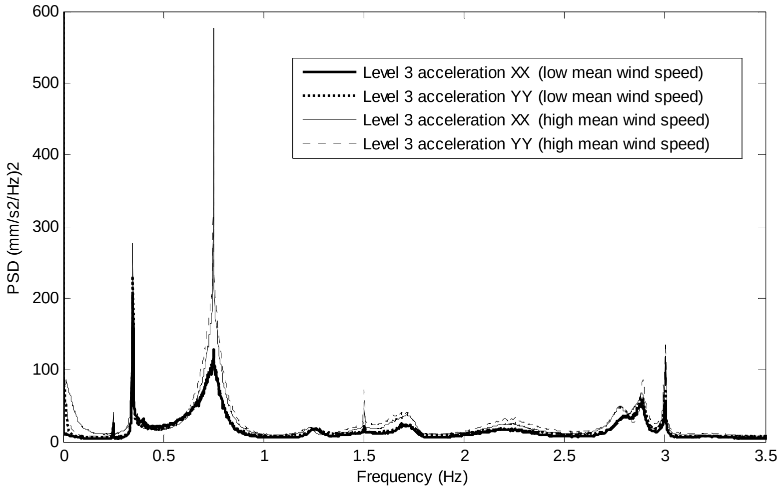


Figure 8 – Power spectral densities of the acceleration at the tower level 3 obtained during operation.

7.2 Displacements

It is not established any general limits, by the design guidelines, for the displacements of the tower however there are some recommendations for the displacements that must guarantee a proper functioning of the tower such as no mechanical interference between blade and tower may occur.

The rotations at levels 2 and 3 are obtained directly from the inclinometers. Displacements can be obtained from integration of the accelerations, although only the dynamic part of the signal can be obtained as presented in Figure 13. Integration error was controlled through Baseline Correction and Filtering.

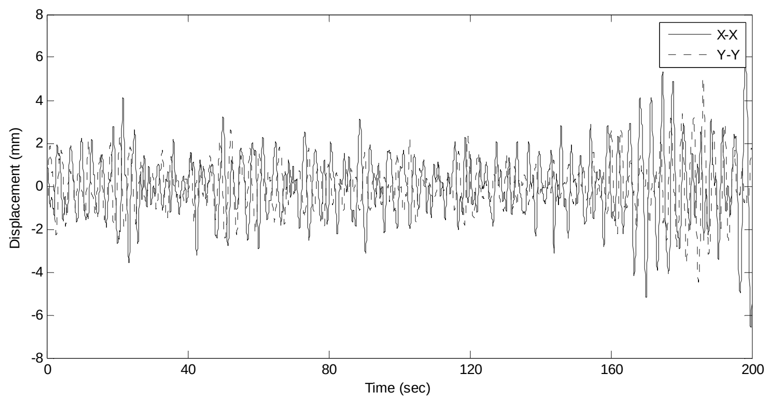


Figure 13 – Typical time window of horizontal displacements at level 3 in x- and y-direction obtained from time integration of filtered accelerations using a highpass Butterworth filter above 0.2 Hz.

8 CONCLUSIONS

The monitoring system installed is able to measure strains in three directions of 26 points of the inner surface of the tower shell and in 18 pre-stressed bolts. Additionally, accelerations in three levels of the tower, inclinations at two levels and the inner temperature are measured. Calibration of the equipment was performed and preliminary measurements were used for consistency analysis of the data. A finite element model was developed and updated through modal identification performed before the turbine started production.

As expected, stress variations along the tower height are low, since the cross section varies in diameter and thickness along the height, corresponding to an optimized structural solution.

The strains measured on the cylinder shell (vertical, horizontal and inclined) vary with wind speed, increasing up to a wind speed of about 12 m/s and decreasing beyond that. This is typical of pitch regulated towers and is due to the pitch rotation of blades in order to maintain a constant production without overloading the tower. The stress variation inside the pre-stressed bolts is low and therefore almost independent of the wind speed.

The spectra obtained for the shell stresses at level 0 section were extrapolated to twenty years lifetime. They are clearly below the design spectra as expected, except for the higher stress ranges.

Dynamic response is evaluated through the acceleration spectra. It is clear that no resonance occurs in the tower in the range of identified natural frequencies.

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