INSTITUTO SUPERIOR TÉCNICO
Universidade Técnica de Lisboa

# MODELING AND MONITORING OF THE DYNAMIC BEHAVIOR OF THE ATLANTIC PAVILION ROOF

**Maíra Feijó Ledesma**

Dissertation presented for the degree of Master in

**Civil Engineering**

**EXTENDED ABSTRACT**

**September, 2010**

## ABSTRACT

The main purpose of the work presented in this Dissertation is to develop a tridimensional numeric finite element model of the Atlantic Pavilion Roof, as well as to conduct dynamic tests to identify its dynamic characteristics and to consider these in the calibration of the numerical model, adjusting the computed values to the identified ones.

**Keywords**

Glued laminated timber roof, finite element modeling, dynamic monitoring, ambient vibration tests, modal identification, dynamic behavior.

## 1. INTRODUCTION

To maintain Civil Engineering constructions with an adequate level of structural safety it is important to have systems to monitor or keep track of their structural condition throughout their lifetime, so that it is possible to establish, in due time, the appropriate rehabilitation or strengthening interventions, preventing undesired accident situations. This is precisely the main purpose of structural health monitoring, which can be accomplished using different methodologies, whether based on inspections and measurements performed periodically or involving the permanent installation of equipments, including the automatic data acquisition and processing.

The development and application of dynamic monitoring systems for Civil Engineering structures is the main purpose of the research project “Dynamic Monitoring for Structural Safety Assessment” supported trough the National Program for Scientific Equipment Renewal promoted by FCT. The work presented in this Dissertation, submitted to attain the degree of Master in Civil Engineering, was developed within the framework of that research project.

This Dissertation, entitled “Modeling and Monitoring of the Dynamic Behavior of the Atlantic Pavilion Roof”, presents some important contributions for the objectives of the Dynamic Monitoring System of the Atlantic Pavilion Roof, that is being developed within the framework of the above mentioned research project. Essentially, the development of a tridimensional numerical finite element model of the roof, the identification of its dynamic characteristics from the data obtained in ambient vibration tests performed as part of this work and the consideration of those modal properties in the calibration of the finite element model, adjusting the computed values to the identified ones. This Dissertation is therefore, an initial phase of the development of the referred dynamic monitoring system, essential to its actual implementation and to achieve its objectives.

## 2. DESCRIPTION OF THE ATLANTIC PAVILION

The Atlantic Pavilion Roof is a glued laminated timber structure, composed by 16 transverse frames, with a depressed arch shape, longitudinally spaced by 9.00 m, and variable geometry due to the irregular shape of the roof, named as frame 2 to frame 17, see Figure 1. It also has 4 longitudinal frames, with a semi-arch shape, two of them located in the Nose and the other two in the Back of the roof, named as frames LL. Each frame is supported by pinned steel bearings resting on a concrete foundation. The transverse frames are connected in the longitudinal direction by glued laminated timber bars that, in their greater majority, are pinned, at their ends, in one or both directions.

The transverse frames have spans that vary from 52.00 m to 114.50 m and a height, in relation to the arena, that goes from 28.20 m to 41.56 m. Their element with greater cross section has a constant width of 0.405 m and a height that is different from frame to frame, with values from 1.28 m to 2.10 m.

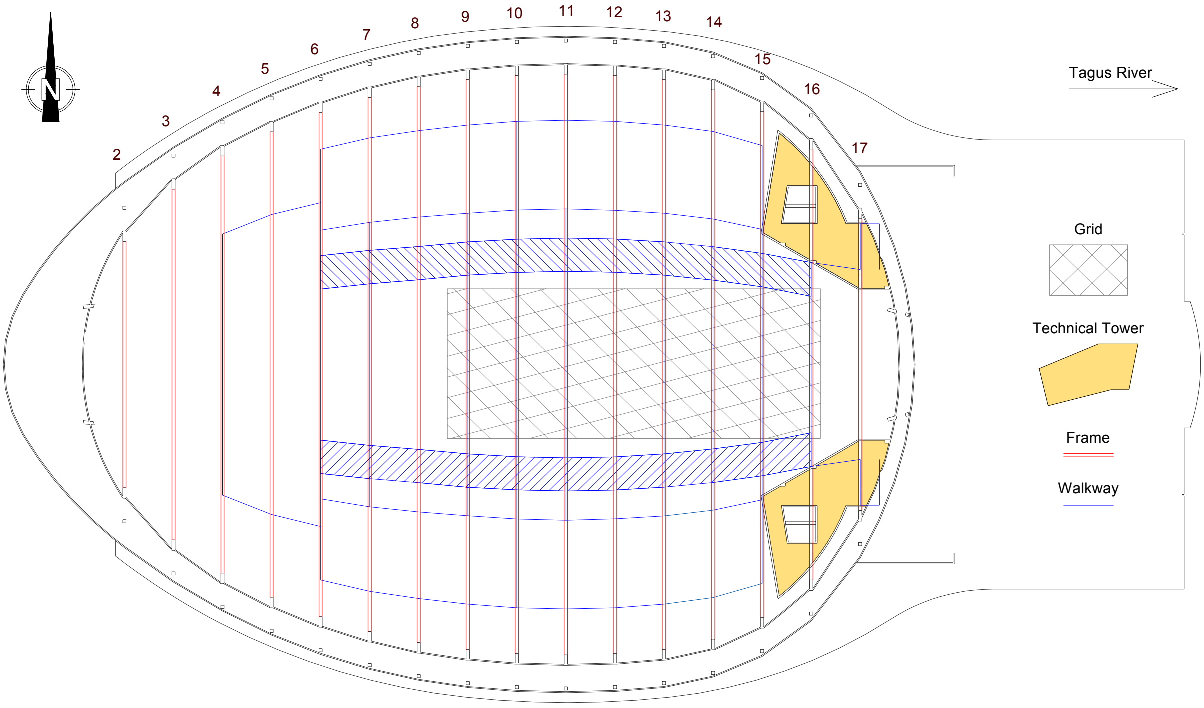


Figure 1 – Plan view of the Atlantic Pavilion Roof

## 3. MODELING OF THE STRUCTURAL BEHAVIOR

The structural behavior of the Atlantic Pavilion Roof was modeled using a tridimensional numerical finite element software, SAP2000 [1]. The model was developed with the main purpose of computing the dynamic characteristics of the structure, which were going to be compared with the ones experimentally identified.

### 3.1. Data collection for the development of the model

The data collection for the development of the finite element model was a laborious task, due, in great part, to the complexity of the structure being modeled. Furthermore, the detailed analysis of the design elements showed that several changes were introduced in the structure during its construction and many of them weren't clearly specified in the final design documents. This gathering of information was therefore carried out using several resources, namely, the Design [2], the reduced scale physical model, photos taken during the construction [3], visits to the Pavilion, several talks with LNEC's DE/NEM and the meeting with Mr. Jean-Paul Perrin that was involved in the roof construction works.

## 3.2. Model description

The definition of the finite element model was carried out based on the data collection previously presented. The model was developed using the several tools available in the software, in order to overcome the difficulties encountered in modeling an irregular structure as the Atlantic Pavilion Roof is. In this manner, 29 groups of elements were defined with the purpose of organizing them in sets of common properties or locations, since the irregularity of the structure didn't allowed the simple creation of plans with the orthogonal reference coordinates (*grids*). When working with the model elements, their selection was also made considering the properties of their cross section or material.

The two materials that constitute the structure, the glued laminated Spruce timber from class GL24h and the steel, were considered in the model with the properties presented in Table I.

Table I – Material properties

| material | E (GPa) | $\nu$ (-) | $\gamma$ (kN/m$^3$) |
|---|---|---|---|
| glued laminated timber | 11.6 [4] | 0.35 | 4.606 [2],[5] |
| steel | 200 | 0.30 | 77 |

In the developed model, the Atlantic Pavilion Roof is simulated with beam elements, for which a total of 113 distinct cross sections were defined, with 103 of them corresponding to timber elements and the other 10 to steel elements.

The pinned bearings at the base of the frames were simulated imposing restraints to the degrees of freedom of the corresponding joints of the model.

The developed finite element model has a total of 7256 joints, 11308 beam elements and 96 restraints to model the bearings. A total of 334 body constraints are also defined, imposing a relationship between the degrees of freedom of several joints. The model has therefore a total of 38300 independent degrees of freedom.

Frame releases were considered at the extremities of the 3031 beam elements that interconnect the transverse frames, to simulate the behavior of their metallic connections. Depending on the type of connection, one or both rotations, corresponding to the two bending moments (*M22* and *M33*), were considered to be free.

In the computation of the dynamic characteristics, besides the mass of the structural elements, the mass of other non-structural components was also considered, namely the mass corresponding to the weight of the technical walkways (1.55 kN/m), the air conditioning equipments (1.00 kN/m), the suspended metallic structure (grid) (420 kN), the windows that exist in frames 6 to 14 (0.50 kN/m) and the remaining dead loads – Spruce timber boards, thermal isolation and zinc cladding plates (0.274 kN/m$^2$). The additional masses were distributed in order to reproduce their correct location, with the linearly distributed values placed at the middle line of their location.

The development of the finite element model is quite important for the dynamic monitoring system, namely, as a help in the interpretation of the experimental results that are going to be obtained. It must be emphasized that a model of the Atlantic Pavilion Roof, as the one that was developed within this Dissertation, a global tridimensional model, has never been developed before, whether in the Design stage or after the construction. However, for this Dissertation, it was considered that the development of the model wouldn't be sufficient, since that work should be complemented with the model calibration based on the dynamic characterization tests results.

A graphical representation of the finite element model is presented in Figure 2 where different colors represent distinct materials (blue for timber and red for steel).

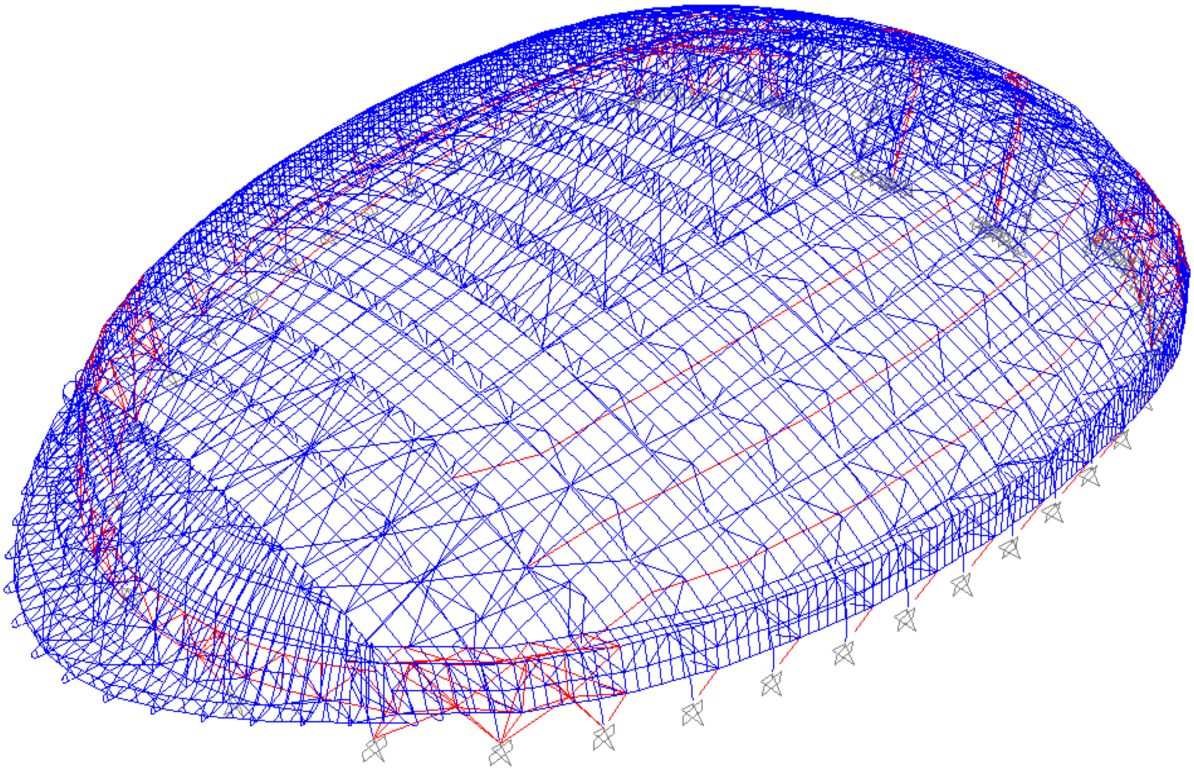


Figure 2 – Perspective view of the finite element model of the Atlantic Pavilion Roof

The numerical results obtained with the developed model are presented in chapter 6, where they are compared with the results of the experimental modal identification.

## 4. EQUIPMENTS USED IN THE DYNAMIC MONITORING

The equipments used in the dynamic monitoring of the Atlantic Pavilion Roof can be subdivided in permanent equipments (permanently installed to perform, in the future, the real time monitoring of the structure) and temporary equipments (provisionally installed to, in combination with the permanent ones, obtain an improved spatial refinement in the dynamic characterization tests, in order to be able to carry out a good identification of an initial state of the structure and a calibration of the finite element model).

The permanent equipments include:

- *EpiSensor* accelerometers from *Kinemetrics*, 14 uniaxial (ES-U2) and 1 triaxial (ES-T);

- 1 combined temperature and relative humidity sensor with an appropriate radiation shield from *Adolf Thies GmbH;*
- 1 *WindSonic* ultrasonic anemometer from *Gill Instruments*, whose installation wasn't yet carried out but is anticipated to be performed soon;
- data acquisition system from *Gantner Instruments,* including 1 *e.gate DP* module and *e.bloxx* modules with 19 bits analog to digital conversion, 15 of the *A1-1* type and 1 of the *A1-4* type;
- 1 industrial computer from DIGITAL-LOGIG, model *MICROSPACE* PCV855;
- 1 *TRACO POWER* uninterruptable DC power system (UPS) with a 300 W power supply, model TIS 300 – 124 UDS, and a battery, model TIS 24 – 70 AP;
- 5 *TRACO POWER* 24 W DC / DC converters, model TCL24-112DC 24W;
- several accessories, including protection boxes and cables.

The temporary equipments include:

- 12 uniaxial (ES-U) *EpiSensor* accelerometers from *Kinemetrics*;
- 4 power supply and signal conditioning units, developed at the LNEC's Scientific Instrumentation Centre (CIC), for the ES-U accelerometers;
- 1 laptop computer;
- data acquisition system from *Gantner Instruments,* including 1 *e.pac DL* module and *e.bloxx* modules with 19 bits analog to digital conversion, 4 of the *A1-1* type and 3 of the *A1-4* type;
- steel plates to support the accelerometers and cables.

The ES-U, ES-U2 and ES-T accelerometers were configured for a sensitivity of 20 Volt/g and since the *e.bloxx A1* modules can read ±10.0 Volt signals, the minimum acceleration amplitude that can be measured with the installed system is 1.907 μg.

The data acquisition was performed with software developed in *LabView* [6].

# 5. DYNAMIC TESTS AND MODAL IDENTIFICATION

The main purpose of the dynamic tests performed in the Atlantic Pavilion Roof was the experimental evaluation of the global dynamic characteristics of the structure. They were carried out on May, 20 and 21, 2010, and consisted in the measurement of ambient vibrations, induced in the structure, essentially, by the effects of the wind, but also by the traffic of vehicles in the vicinity of the structure and by the organizing and cleaning works that were being done inside the pavilion. The acceleration records obtained in the tests were analyzed using a stochastic modal identification method [7] to identify the dynamic characteristics of the roof.

## 5.1. Testing procedure

Since there was the intention of doing a good identification of the natural vibration modes shape, the dynamic tests involved acceleration measurements in a total of 27 points, located in the 9 frames with larger span and height. The permanent equipments were used in 15 of those points and the temporary equipments in the other 12 points. In each of the systems, the accelerations were recorded independently but almost simultaneously. In terms of the techniques usually adopted in ambient vibration tests and modal identification, the adopted procedure corresponds to perform two independent set-ups with three reference points. The sampling frequency used in the tests was 833.33 Hz and the obtained acceleration records have a total duration of 1 hour.

Table II and Figure 3 show the instrumented points and the orientation of the accelerometers installed in the roof, highlighting in red the 3 accelerometers that served as references for the temporary equipments.

Table II – Instrumented points in the tests

| permanent equipments | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bx. 2 | | | Bx. 3 | | | **Bx. 4** | | | | | Bx. 5 | | | Bx. 6 | | |
| ch.1 | ch.2 | ch.3 | ch.1 | ch.2 | ch.3 | **ch.1** | **ch.2** | | | **ch.3** | ch.1 | ch.2 | ch.3 | ch.1 | ch.2 | ch.3 |
| a1V-P6<br>vert. | a2V-P6<br>vert. | a3V-P6<br>vert. | a1V-P8<br>vert. | a2V-P8<br>vert. | a3V-P8<br>vert. | **a1V-P10**<br>**vert.** | a2T-P10<br>trans. | a2L-P10<br>long. | **a2V-P10**<br>**vert.** | **a3V-P10**<br>**vert.** | a1V-P12<br>vert. | a2V-P12<br>vert. | a3V-P12<br>vert. | a1V-P14<br>vert. | a2V-P14<br>vert. | a3V-P14<br>vert. |

| temporary equipments and reference ones | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit. 1 | | | Unit. 2 | | | **Bx. 4** | | | Unit. 3 | | | Unit. 4 | | |
| ch.1 | ch.2 | ch.3 | ch.1 | ch.2 | ch.3 | **ch.1** | **ch.2** | **ch.3** | ch.1 | ch.2 | ch.3 | ch.1 | ch.2 | ch.3 |
| a1V-P7<br>vert. | a2V-P7<br>vert. | a3V-P7<br>vert. | a1V-P9<br>vert. | a2V-P9<br>vert. | a3V-P9<br>vert. | **a1V-P10**<br>**vert.** | **a2V-P10**<br>**vert.** | **a3V-P10**<br>**vert.** | a1V-P11<br>vert. | a2V-P11<br>vert. | a3V-P11<br>vert. | a1V-P13<br>vert. | a2V-P13<br>vert. | a3V-P13<br>vert. |

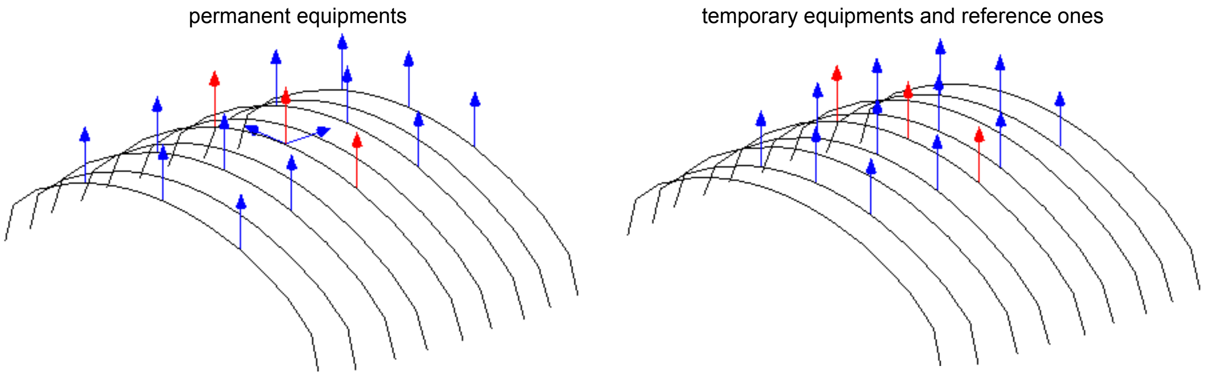


Figure 3 – Instrumented points in the tests

## 5.2. Presentation and analysis of the experimental results

### 5.2.1. Temperature and relative humidity

As previously referred, the permanent equipments, installed in the Atlantic Pavilion Roof, include a temperature and relative humidity sensor, so that in the dynamic tests that were performed, those two quantities were measured. It should be noted that, for the purposes of the dynamic monitoring system, it is important to know the ambient conditions at the time of the dynamic tests considered for the initial characterization of the structure that is presented in this Dissertation. Therefore, during the period of the ambient vibration measurements considered for the modal identification that will be presented, the average temperature was 36.0 ºC and the average relative humidity was 27.5 %.

### 5.2.2. Preprocessing of the acceleration records

Before the application of an output-only modal identification method, the acceleration records were preprocessed with the following operations:

- mean removal and detrending;
- high pass filtering at 0.1 Hz with a 1 pole Butterworth filter;
- low pass filtering at 6.67 Hz with a 8 poles Butterworth filter;
- decimation from the frequency used in the tests to 16.67 Hz.

### 5.2.3. Identification of the dynamic characteristics

The identification of the dynamic characteristics of the Atlantic Pavilion roof was performed with the enhanced frequency domain decomposition method (EFDD) [8] implemented in the software *ARTeMIS Extractor* [9]. For that purpose, the spectral density functions of the acceleration records were estimated considering samples with 1024 values, which correspond to a frequency resolution of 0.0163 Hz in the spectral density functions estimates. From the singular values and vectors decomposition of the matrices of those functions, singular values spectra were obtained, whose analysis is one of the important steps of the EFDD method.

Figure 4 shows the spectra of the first two singular values of the spectral density functions matrix that were estimated with the vertical accelerations recorded in the roof. The values of the identified vibration modes frequencies are also included in that figure.

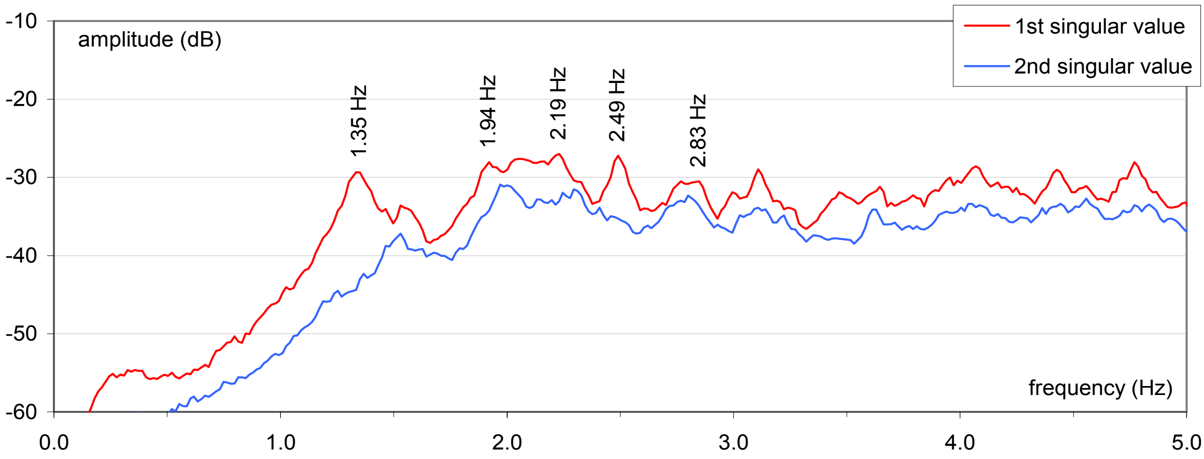


Figure 4 – Spectra of the first two singular values of the vertical accelerations spectral density functions matrix

The EFDD method procedures were applied to the amplitude peaks detected in the singular values spectra. With such approach, 6 vibration modes of the structure were identified, whose frequencies (f), type of mode and damping ratio (ξ) will be presented in 6.2.

# 6. MODEL CORRELATION AND CALIBRATION

## 6.1. Model calibration and updating

The calibration and updating of the model was started after the first measurements, which were taken after the installation of the permanent equipments. In fact, from the analysis of those initial records it was possible to obtain a first estimate for the frequencies of the first modes. The difference between these values and the computed ones, were the motivation to carry out a verification of all the data considered in the model. Some aspects needing improvement were then detected and after their correction, a model already closer to the experimental values, was obtained, which is however named as the initial model.

The final calibration of the model was concluded based on the results of the dynamic characterization tests. This calibration was performed on the initial model, resulting in a calibrated model, where the mounting joints in the main beams of the transverse frames were modeled as elastic connections, a detail that was not considered in the initial model.

## 6.2. Model correlation

The correlation of the identified dynamic characteristics with the computed ones was checked using different ways to establish a comparison between the two sets of results, namely: the comparison of the frequency values presented in a table; the graphical comparison of the computed frequencies with the identified ones; the graphical representation of the mode shapes; 45° plots [10] where the computed modal components are compared with the identified ones; the MAC coefficient [11]; and the COMAC coefficient [10].

Table III shows the values of the frequencies and respective damping ratios identified from the dynamic characterization tests data. The frequencies computed with the developed finite element model, before and after its calibration, are also presented in that table, so that a comparison of the results can be easily done.

Table III – Frequency and damping of the vibration modes

| nº | type of mode | identified values | | computed values | |
|---|---|---|---|---|---|
| | | EFDD method | | initial model | calibrated model |
| | | f (Hz) | $\xi$ (%) | f (Hz) | f (Hz) |
| 1 | vertical | 1.35 | 4.9 | 1.59 | 1.44 |
| 2 | longitudinal | 1.58 | 1.7 | 1.67 | 1.57 |
| 3 | vertical | 1.94 | 0.7 | 2.37 | 2.07 |
| 4 | vertical | 2.19 | 1.6 | 2.48 | 2.15 |
| 5 | vertical | 2.49 | 1.0 | 2.59 | 2.35 |
| 6 | vertical | 2.83 | 0.4 | 3.23 | 2.93 |

The graphical comparison of experimental and computed frequencies is shown in Figure 5. As can be seen, there is a significant improvement in the results after calibration of the model, which became to have a better overall agreement between the computed and identified frequencies.

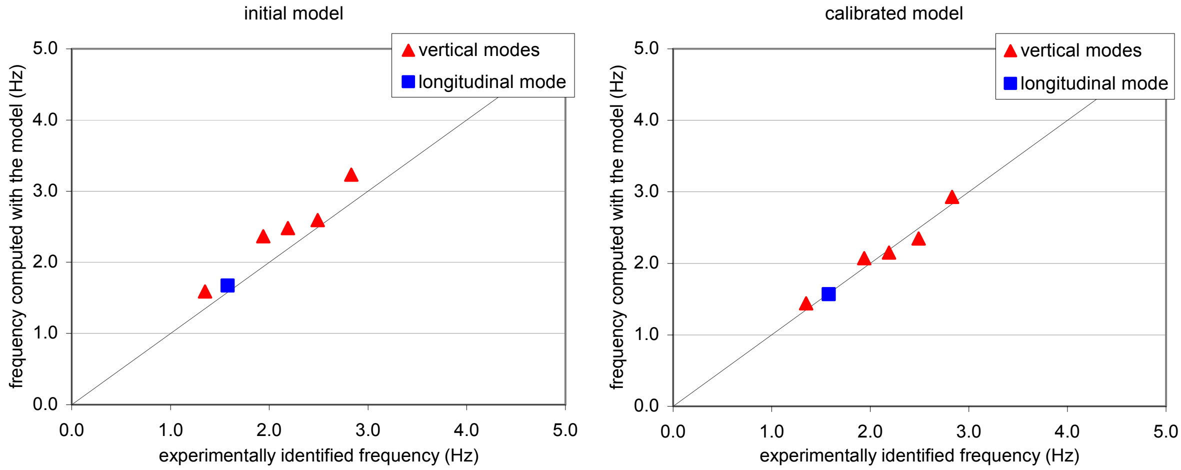
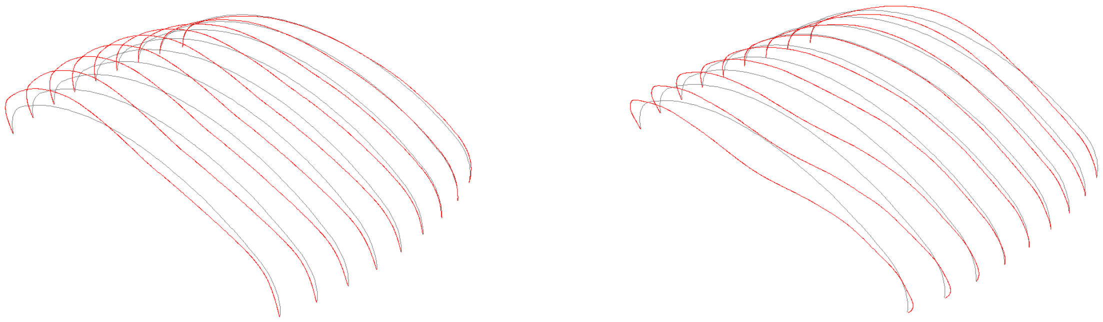


Figure 5 – Correlation between the experimental and computed frequencies

The mode shapes identified with the EFDD method, for the first two vertical modes, are presented in Figure 6, where they are compared with the mode shapes computed with the model.

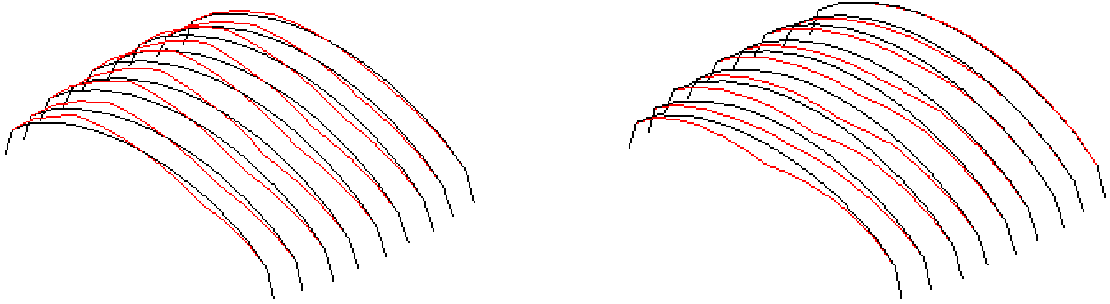
**1st vertical mode**
computed with the initial finite element model
(f = 1.59 Hz)

**2nd vertical mode**
computed with the initial finite element model
(f = 2.37 Hz)



identified with the EFDD method
(f = 1.35 Hz, $\xi$ = 4.9 %)

identified with the EFDD method
(f = 1.94 Hz, $\xi$ = 0.7 %)



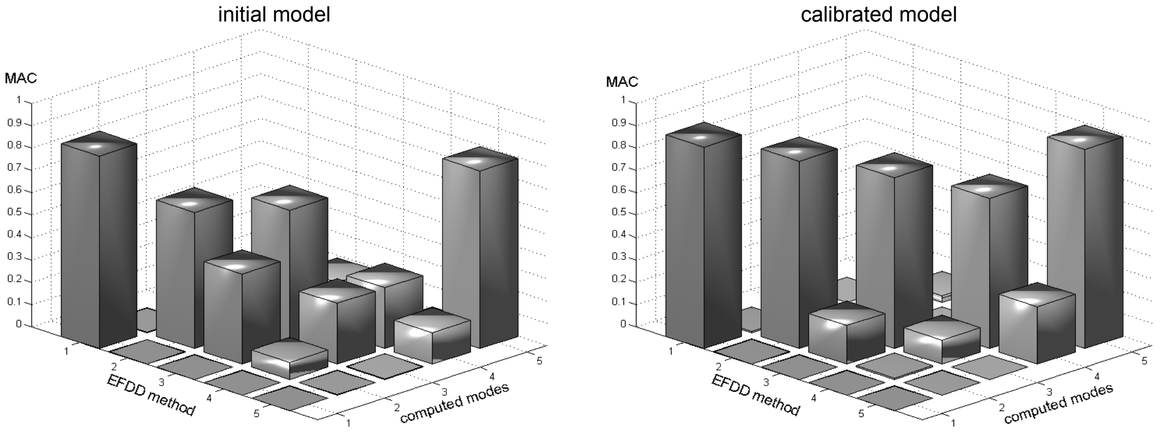
computed with the calibrated finite element model
(f = 1.44 Hz)

computed with the calibrated finite element model
(f = 2.07 Hz)

Figure 6 – Mode shapes of the first two identified vertical modes

Throughout the comparison of the mode shapes identified with the EFDD method and the ones computed with the finite element model, before and after its calibration, which were exemplified in Figure 6, it becomes evident that the calibration performed on the finite element model, improved the computed results when compared with the experimental ones. As it was previously referred, the frequencies computed after the model calibration are much more closer to the experimental ones, but the mode shapes also have a favorable change in comparison with the experimental mode shapes.

Figure 7 shows the MAC coefficient [11] matrices computed, respectively, with the initial and calibrated model, representing those matrices as 3D bar plots in a perspective view. The elements in the main diagonal of the MAC coefficient matrix, became much closer to 1 with the calibration performed on the model, showing the significant improvement of the finite element model.


initial model

calibrated model

Figure 7 – MAC coefficient matrices for the vertical modes

# 7. CONCLUSIONS AND FUTURE DEVELOPMENTS

## 7.1. Conclusions

The identified dynamic characteristics are in good agreement with those computed with the model, after calibration, both in terms of frequencies and of their respective vibration modes shapes. Thus, it can be considered that the developed finite element tridimensional numerical model is reasonably well validated. It was therefore accomplished, in a satisfactory manner, the purpose of making an initial characterization of the structure, which is important for the future development of the Dynamic Monitoring System of the Atlantic Pavilion Roof.

## 7.2. Future developments

In order to complement the results already achieved with this Dissertation, there is the intention to proceed with the implementation of the Dynamic Monitoring System of the Atlantic Pavilion Roof and fulfill the objectives of the research project “Dynamic Monitoring for Structural Safety Assessment”. This will involve the development of software for continuous processing of the measured data, including automatic modal identification, evaluation of vibration levels, characterization of wind and analysis of its effects in the structure and evaluation of the safety conditions of the structure and, eventually, detection of situations of structural damage.

# Bibliographic References

[1] CSI – SAP2000 *Integrated Software for Structural Analysis and Design*, version 12.0.1, 2008.

[2] Skidmore, Owings & Merril, Inc. (SOM) – *Lisboa EXPO 98 Atlântico, Pavilhão Multiusos de Lisboa S.A.*, Projecto de Execução, drawings and other design elements, on paper or computer files, 1995 and 1997.

[3] Photos of the construction and assembly of the Atlantic Pavilion Roof obtained at the LNEC's DE/NEM, 1997.

[4] NP EN 1194 – Timber structures. Glued laminated timber. Strength classes and determination of characteristic values, 1999.

[5] EN 350-2 – Durability of Wood and Wood based products. Natural durability of solid wood. Part. 2: Guide to natural durability and treatability of selected wood species of importance in Europe, 1994.

[6] National Instruments – *LabView Version 8.5.1 Reference Manuals*, National Instruments, 2008.

[7] Rodrigues, J. – *Identificação Modal Estocástica – Métodos de Análise e Aplicações em Estruturas de Engenharia Civil*, PhD Thesis, FEUP, 2004.

[8] Brincker, R.; Ventura, C.; Andersen, P. – *Damping Estimation by Frequency Domain Decomposition*, IMAC XIX, Kissimmee, USA, 2001.

[9] SVS - Structural Vibration Solutions – *ARTeMIS Extractor* Handy, Release 3.5, Denmark, 2005.

[10] Heylen, W.; Lammens, S.; Sas, P. – *Modal Analysis Theory and Testing,* Department of Mechanical Engineering, K. U. Leuven, Belgium, 1997.

[11] Allemang, R. J.; Brown, D. L. – *A correlation Coefficient for Modal Vector Analysis,* IMAC I, Orlando, USA, 1982.