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CALIBRATION OF THE NUMERICAL MODEL OF A STAND IN DRAGÃO STADIUM BASED ON GENETIC ALGORITMS

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Abstract. *This paper is focused on the experimental calibration of the numerical model of a stand in Dragão stadium based in genetic algorithms. A finite element numerical model of a group of seating deck units including the connections between them and the connections with the stands, was developed. Also a dynamic test was performed in the South stand in order to characterize the local dynamic properties of a group of seating deck units, particularly its natural frequencies, modal configurations and damping coefficients. The experimental calibration of the numerical model was performed using an iterative method based on a genetic algorithm. The stability of a significant number of parameters, considering different initial populations, proved the robustness of the adopted algorithm in the scope of the optimization of the numerical model. Also the calibration results demonstrate a very good agreement between numerical and experimental modal responses and a significant improvement of the numerical model before calibration.*

1 INTRODUCTION

In recent years, the organization of sport events of international scale, especially in European countries, has launched new challenges in terms of rehabilitation and reconstruction of the existing football stadiums and in some cases, the construction of new stadiums.

The need to reduce the obstacles in front of the public forced the stadiums to be built using larger span and slender structural elements. This situation took the structures to be more susceptible to resonance phenomena, especially due to the proximity between the frequencies associated with the synchronized movements of the public with the natural frequencies of vibration of the structure [1].

The new functional requirements of sports facilities, especially those associated with the safety and comfort of spectators, have led to a growing interest of researchers for the study of dynamic effects induced by the public in this type of structures [1]. These studies usually involve performing dynamic tests and the development of numerical finite element models to support decision and typically calibrated based on experimental data [1].

In this context it should be noted the experimental studies carried out by Littler et al. [2] at Twickenham Stadium (United Kingdom), by Pavic and Reynolds [3] in the stadium of Bradford (United Kingdom) and Cigada et al. [4] at Giuseppe Meazza Stadium (Italy), and involving measuring the vertical acceleration of the stands, with and without spectators, using a permanent monitoring system. The results of these studies have revealed the importance of the presence of spectators for the dynamic properties of the stands, in particular the values of vibration frequencies and damping coefficients.

Most experimental studies have mainly focused on the global analysis of the dynamic behavior of the stands, neglecting the characterization of local vibration modes associated with seating deck units. Of the few studies identified it is important to point the work of Marques et al. [5] and Marovic et al. [6], which despite focusing on the evaluation of the dynamic response values of the seating deck units during sport events, they did not include the identification of its local modal parameters.

From the works developed by Lima Avila and Doz [7], Saudi et al. [8], Marques [5] and others, experimental modal information is used for calibration of numerical finite element models of the stands. The calibrated models have proved to be especially useful in the study of reinforcement interventions [8], in the design of vibration control systems [5], identification of structural damage [7] and for simulation of load scenarios different from those normally acting with the structure in normal operation.

This article focuses on the experimental calibration of a numerical model of seating deck units of Dragão Stadium. For this purpose, it is developed a numerical finite element model that aims to study the dynamic behavior of a seating deck unit and considers the influence of its connection with neighboring seating deck units. It is also performed the experimental characterization of a series of seating deck units of the south stand of Dragão stadium, in order to identify its local dynamic properties, particularly natural frequencies, mode shapes and damping coefficients. Finally, automatic calibration of the numerical model was performed using an iterative method based on genetic algorithms, which uses a computational interface between three programs (Autodesk Robot, Excel and Matlab), allowing the inclusion of a conventional structural calculation program in an optimization flow through specific API routines.

2 DRAGÃO STADIUM

Dragão stadium is located in the city of Porto (Portugal) and was built on the occasion of the European Football Championship in 2004. The stadium has a capacity of 50092 spectators and comprises four stands: south, west, north and east (Figure **1**a). The north and south stands consist of a single level, while the east and west stands consist of two levels, one lower and one upper.

Each stand is divided into structurally independent bodies separated by joints. The structure of each body of the stand is formed by a set of frames, spaced by 8.1 m, at the interior perimeter, and 10.5 m on the perimeter of the periphery. The seating deck units are supported by the raker beams that integrate these frames.

a) b)

Figure 1: Dragão stadium: a) global view; b) stands plan.

The seating deck units of the lower stands are T-shaped prefabricated elements in reinforced concrete (Figure **2**). The seating deck units are formed by a horizontal plate of thickness equal to 0.10 m and width equal to 0.80 m, which supports on a vertical rib with 0.15 m thickness and variable height between 0.48 m and 0.63 m, depending on the position of the seating deck unit in the stand frames.

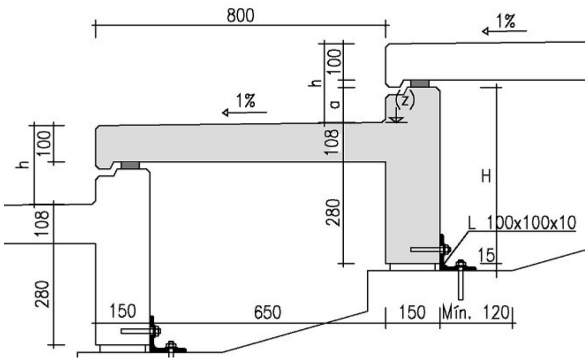


Figure 2: Seating deck units of Dragão stadium (lower stands).

In radial direction, the connection between the seating deck units is guaranteed, in an alternating solution, by rigid connections by means of 3 metal connectors type M20, and flexible connections through EPDM rubber pads. Towards its perimeter each seating deck unit is separated from neighbors by joints.

Each seating deck unit is supported in raker beams by means of a clamping device consisting of a steel angle L100×100×10 which is connected to the vertical seating deck unit rib and to the beam frame by means of two steel connectors type M12. Between the base of the rib of the seating deck unit and the stand beam there is a neoprene pad with 15 mm thick.

3 NUMERICAL MODEL

3.1 Description

The numerical finite element model of the seating deck units of the stands of Dragão stadium was developed using the commercial software Autodesk Robot Structural Analysis [9] (Figure 3a).

The numerical model comprises a set of 10 consecutive seating deck units, located on the south stand inside the area identified in Figure 1b, and aims the characterization of the local dynamic behavior of seat deck unit of row 14 considering the influence of its connection with neighboring seating deck units.

The horizontal plates and ribs of seating deck units in addition to the steel angle of the supports, were modeled by shell finite elements, while the remaining elements, in particular the steel connectors and the elastic supports between seating deck units and between the seating deck units and the stand frame, were modeled using beam finite elements. In Figure 3b is illustrated in detail the modeling of the links between seating deck units and between the seating deck units and the stand frame.

In the numerical model all the structural elements that constitute the seating deck units, were reproduced, in accordance with the design information. For simplicity all seating deck units were modeled with a span equal to 8.22 m corresponding to the span of the seating deck unit of row 14.

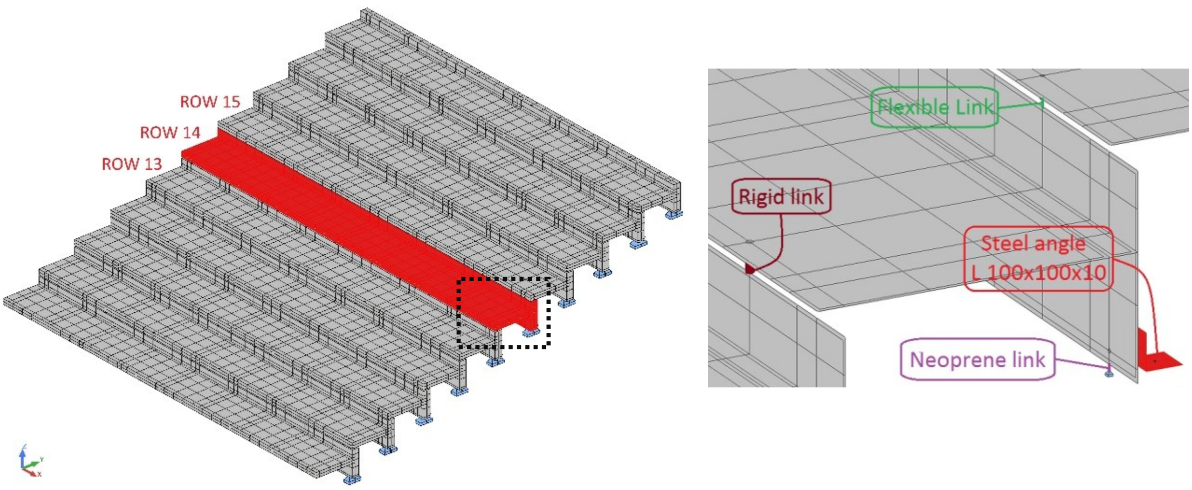


Figure 3: FE numerical model: a) global view, b) detail of modeling of the links between seating deck units and between the seating deck units and the stand

3.2 Geometrical and mechanical properties

Table 1 presents the most relevant geometric and mechanical parameters adopted in the numerical model of seating deck units, including its name, the value adopted and respective units. In addition, the upper and lower limits that will be used later in the calibration phase of the numerical model are also indicated.

Table 1: Geometrical and mechanical parameters of the numerical model of the seating deck units.

Parameters			Unit	Adopted value	Limits	
					Lower	Upper
E_c	Elasticity modulus of concrete		GPa	32.2	28.0	36.0
ρ_c	Concrete density		kN/m^3	25	--	--
E_{M20}	Elasticity modulus of steel in M20 connectors between seating deck units		GPa	210	150	250
$E_{S,0}$	Elasticity modulus of steel connectors between seating deck units and stand beams	Other rows	GPa	210	150	250
$E_{S,13L}$		Row 13 (left)				
$E_{S,13R}$		Row 13 (right)				
$E_{S,14L}$		Row 14 (left)				
$E_{S,14R}$		Row 14 (right)				
$E_{S,15L}$		Row 15 (left)				
$E_{S,15R}$		Row 15 (right)				
E_{EPDM}	Elasticity modulus of EPDM rubber pads between seating deck units		MPa	50	0	150
$E_{N,0}$	Elasticity modulus of neoprene layer between seating deck units and stand beams	Other rows	MPa	50	0	150
$E_{N,13L}$		Row 13 (left)				
$E_{N,13R}$		Row 13 (right)				
$E_{N,14L}$		Row 14 (left)				
$E_{N,14R}$		Row 14 (right)				
$E_{N,15L}$		Row 15 (left)				
$E_{N,15R}$		Row 15 (right)				

The value adopted for the elasticity modulus of concrete was defined on the basis of the results of a concrete ultrasonic test, since there was no design information about its mechanical properties. The results of this test allowed to estimate an average value of the dynamic elasticity modulus of concrete equal to 32.2 GPa with a coefficient of variation of 3.0%. The variation in this parameter limits were, however, extended to meet the fact that the ultrasonic test has been performed on a limited number of seating deck units due to accessibility constraints for the remaining seating deck units.

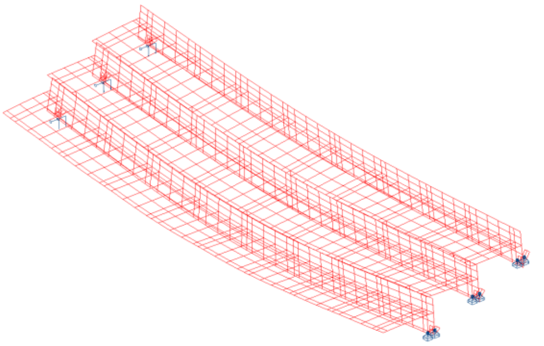
The definition of variation limits of the elasticity modulus of steel of the connectors between seating deck units and between the seating deck units and the stand beams allowed to meet some singularities observed *in situ*, in particular the use of a larger number of connectors than those provided in the design stage, the use of connectors of different diameter of the specified in design, and the loss of connection stiffness due to poor filling of the holes with a chemical component.

The definition of the limits of variation of the elasticity modulus of EPDM rubber pads and neoprene, in the connection between seating deck units and between the seating deck units and the stand beams, respectively, also allowed to meet situations observed *in situ*, namely, the deterioration or inexistence of supports, and the use of elastic supports in different materials of the specified design.

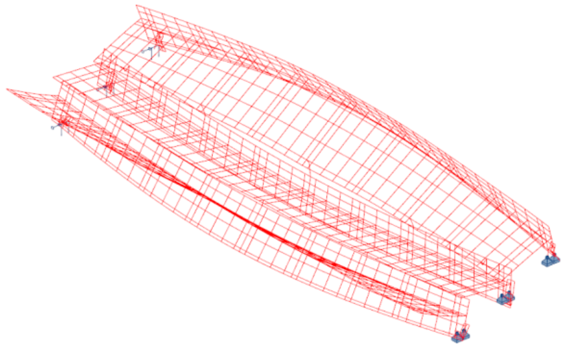
In the case of the elasticity modulus of steel of the connectors between the seating deck units and the stand beams, and the elasticity modulus of neoprene, distinct characteristics are defined for the supports located to the left and right on seating deck units 13, 14 and 15, and other seating deck units.

3.3 Numerical modal parameters

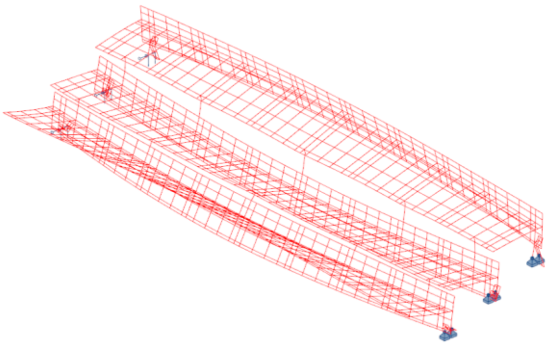
Figure 4 shows the values of the vibration frequencies of the main local modes of the seating deck units and the corresponding mode shapes obtained from the numerical model developed based on the adopted values of parameters listed in Table 1. Modes 1 and 5 essentially involve bending movements of the seating deck units. Modes 2, 3 and 4 mainly involve torsional movements of the seating deck units. In the mode shapes were only represented the seating deck units of rows 13, 14 and 15.



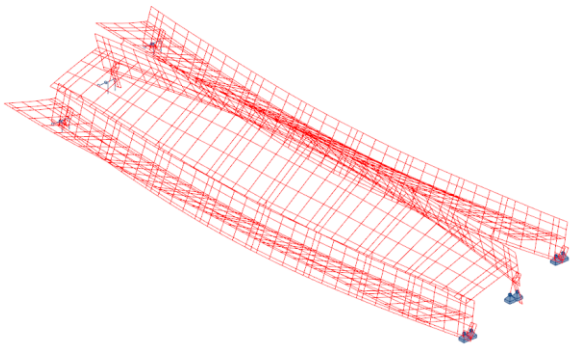
Mode 1 – f = 12.15 Hz



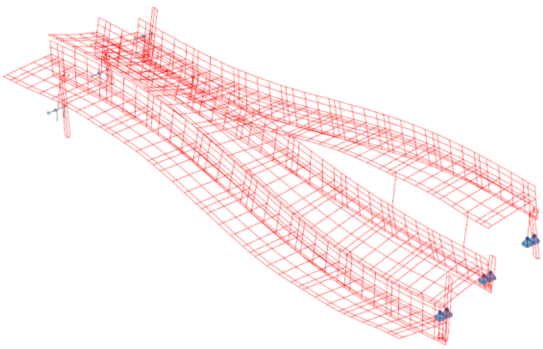
Mode 2 – f = 18.57 Hz



Mode 3 – f = 20.66 Hz



Mode 4 – f = 23.32 Hz



Mode 5 – f = 30.71 Hz

Figure 4: Numerical modal parameters.

4 DYNAMIC TEST

4.1 Description

The dynamic test aimed to identify the modal properties of the seating deck units, especially its natural frequencies and local vibration modes and the respective damping coefficients.

The test was conducted using a technique with fixed reference points and mobile measurement points, involving the use of 16 high sensitivity piezoelectric accelerometers, PCB 393B12 model. The accelerations were measured in the vertical (z) and radial (y) directions in a total of 49 measurement points located in the seating deck units of rows 8, 13, 14, 15, 18 and 28 of south stand.

Figure 5a illustrates the position of the accelerometers in the seating deck units. The ends of the seating deck units of rows 8, 14, 18 and 28 were instrumented in the vertical direction, in order to identify eventually global movements associated with the stand frames. In turn, the seating deck units of rows 13, 14 and 15 were instrumented in the vertical and radial directions in order to characterize the local movements of the seating deck units.

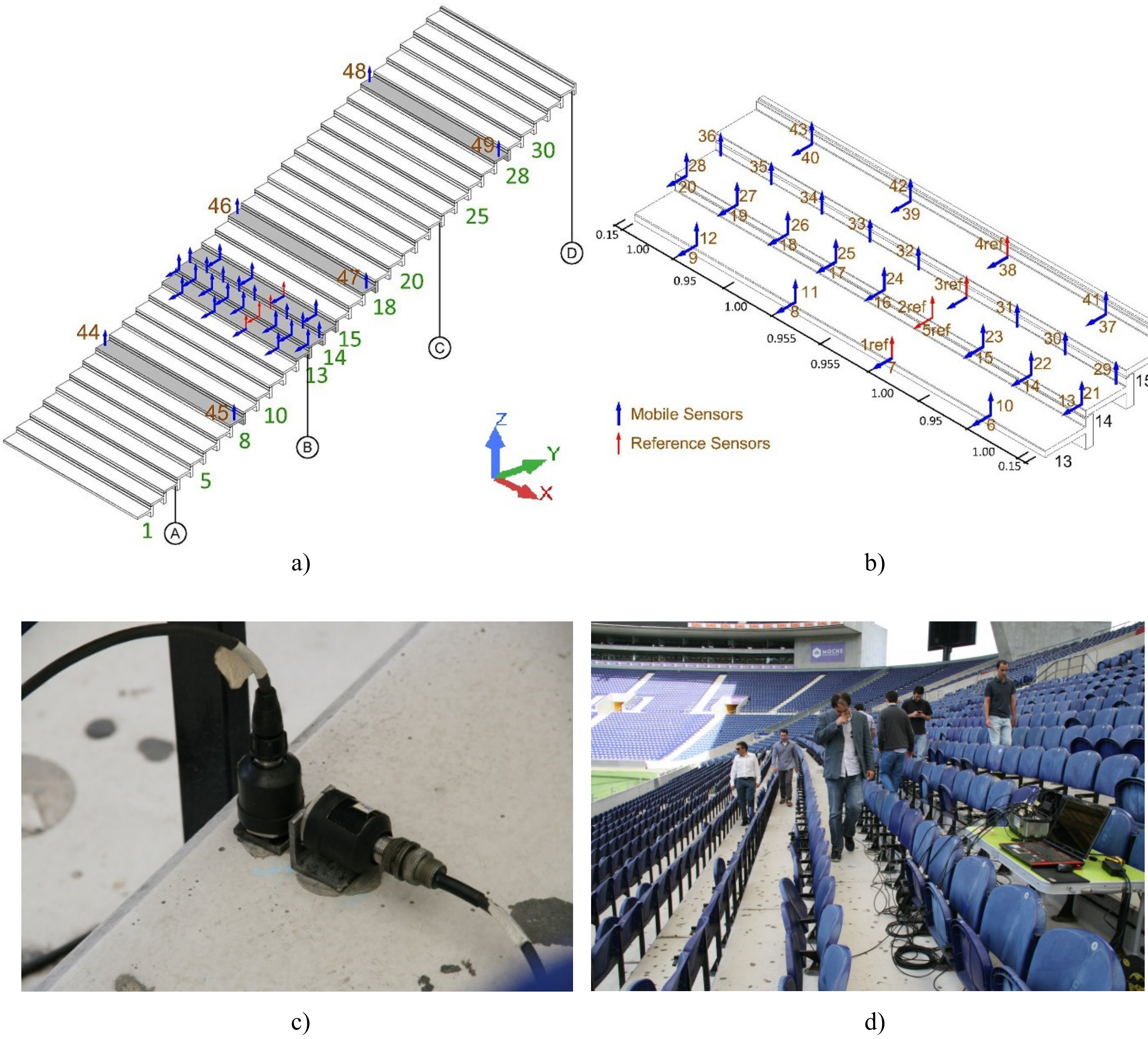


Figure 5: Dynamic test: a) measurement points (global view); b) measurement points of rows 13, 14 and 15; c) accelerometers; d) external excitation.

The reference transducers were located on the seating deck units of rows 13, 14 and 15 in positions 1, 2, 3, 4 and 5 (Figure 5b). Data acquisition was performed using NI cDAQ-9172 system, using four NI 9234 modules for IEPE type accelerometers. The time series were acquired with a duration of 5 minutes, with a sampling frequency of 2048 Hz, further decimated at a frequency equal to 256 Hz. The connection of accelerometers to seating deck units was performed by means of metallic plates and angles bonded to the concrete surface (Figure 5c).

The test took place under an external excitation ensured by the action of a group of individuals who performed jumps and walked randomly over time (Figure 5d).

4.2 Modal parameters identification

The identification of modal parameters was performed by the application of the Enhanced version of Frequency Domain Decomposition method (EFDD) using the commercial software ARTeMIS [10].

Figure 6 show the curves of the average and normalized singular values of spectral density matrices of all experimental setups, obtained by the EFDD method. Five local vibration modes associated with the seating deck units in correspondence with the 5 peaks indicated in the curve of the first singular value, were identified.

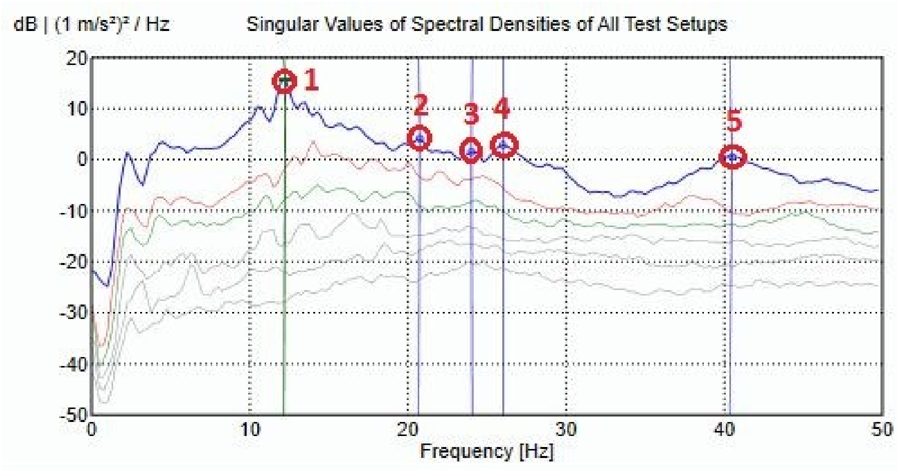
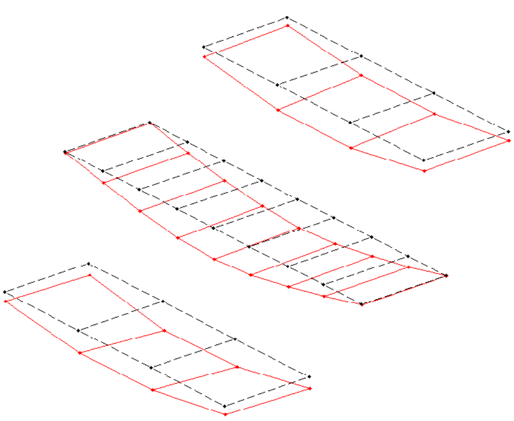
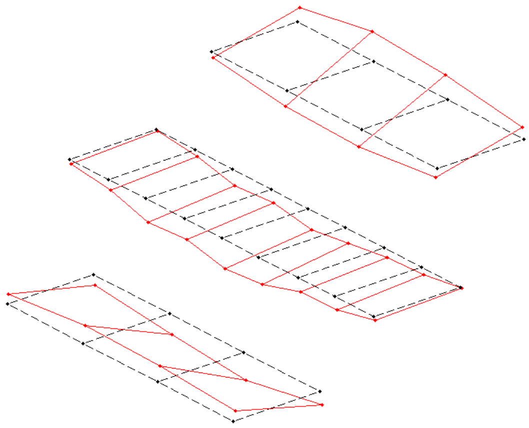


Figure 6: EFDD method: average and normalized singular values of spectral density matrices.

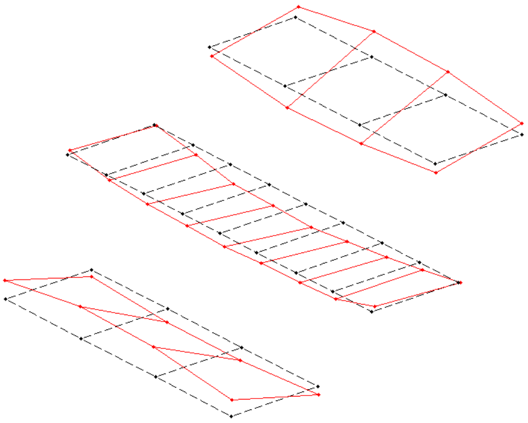
In Figure 7 are shown the mean values of natural frequencies and corresponding local modes of vibration of the seating deck units. The analysis of the modal configurations allows to identify movements associated with bending and twisting of the seating deck units with very good definition. In these modes of vibration the movements of the stand frames are negligible. Modes 2 and 3 are distinguished by the fact that the movement of the seating deck unit of row 14 involves transverse and vertical bending, respectively. The values of the damping coefficients vary between 1.11% and 2.53%.



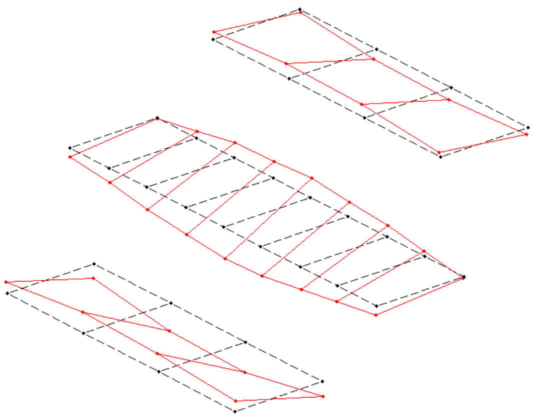
Mode 1 – f = 12.15 Hz
ξ = 2.53 %



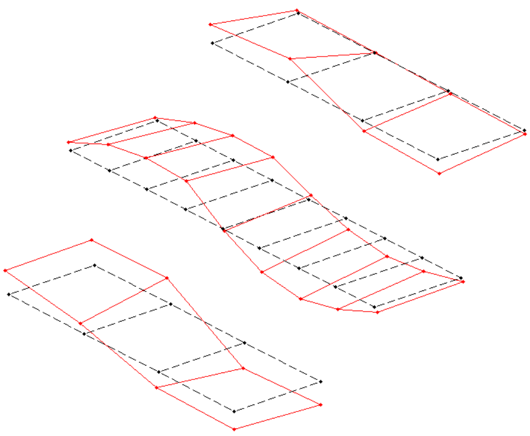
Mode 2 – f = 20.68 Hz
ξ = 1.36 %



Mode 3 – f = 24.06 Hz
ξ = 1.26 %



Mode 4 – f = 26.01 Hz
ξ = 1.26 %



Mode 5 – f = 40.35 Hz
ξ = 1.11 %

Figure 7: Experimental modal parameters.

5 CALIBRATION

The calibration of the numerical model of the seating deck units was based on the results of the dynamic test and involved performing a sensitivity analysis and an optimization based on genetic algorithms.

5.1 Methodology

Figure 8 presents a flowchart illustrating the iterative process of the numerical model calibration based on a genetic algorithm and involving the use of three softwares: Autodesk Robot [9], Excel [11] and Matlab [12]. A detailed explanation of the proposed methodology is presented in reference [13].

In the present work some improvements to the tool developed by Ribeiro et al. [13] which allowed to improve its versatility and computational efficiency, were introduced, in particular: i) the possibility of performing the numerical modeling of the structure in a conventional automatic structural calculation software, in this case Autodesk Robot; ii) the implementation of API routines from Robot software, in Excel environment, that enable an efficient interconnection of the numerical model to the optimization algorithm, namely for the extraction of numerical modal parameters, from Robot to Matlab, and for the introduction of new set of values of numerical parameters, from Matlab to Robot, and iii) the application of genetic algorithms based on existing routines of Matlab software.

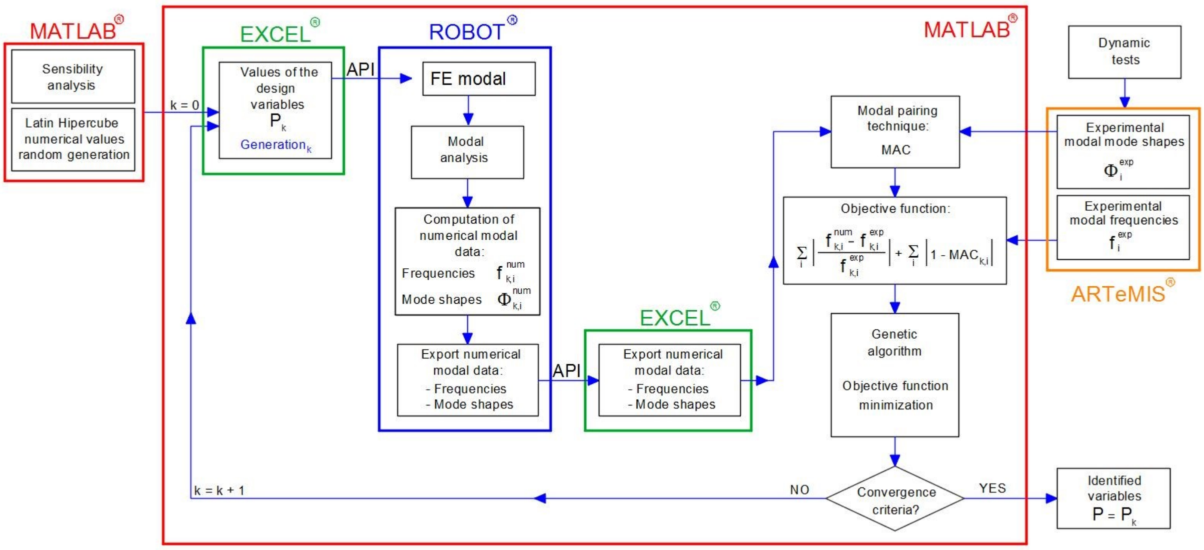


Figure 8: Flowchart of the calibration methodology of the numerical model.

5.2 Sensitivity analysis

The sensitivity analysis aims identifying the parameters that most influence the responses of seating deck units, particularly the natural frequencies and vibration modes, and which will be later included in the optimization phase.

Figure 9 shows the results of the sensitivity analysis using a Spearman correlation coefficients matrix [14]. The sensitivity analysis was performed using a stochastic sampling technique based on 1000 samples generated by Latin Hypercube method. The correlation coefficients situated in the range [-0.20; +0.20] were excluded from the graphical representation.

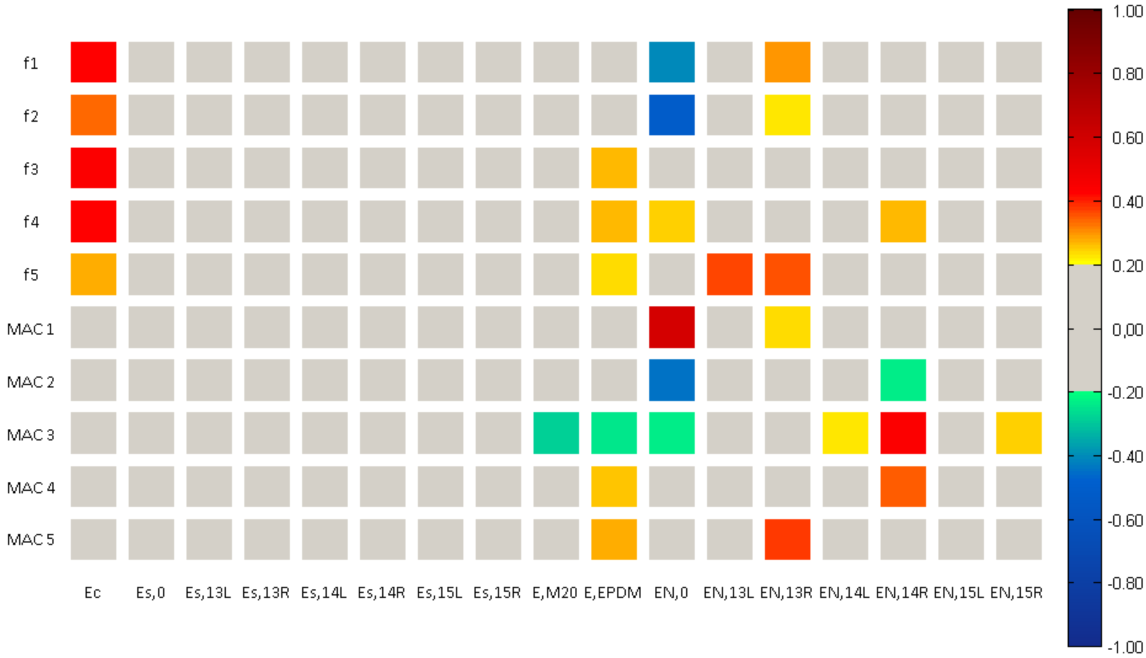


Figure 9: Spearman correlation matrix.

The correlation matrix shows that the elasticity modulus of concrete (E_c), elasticity modulus of steel in M20 connectors between seating deck units (E_{M20}), elasticity modulus of EPDM rubber pads between seating deck units (E_{EPDM}) and elasticity modulus of neoprene (E_N) of almost all the seating rows, are the parameters that most influence the modal responses.

5.3 Optimization

The optimization phase aimed to obtain the values of the numerical parameters that minimize the differences between the numerical and experimental modal parameters, and involves the definition of an objective function and the application of an optimization technique based on a genetic algorithm.

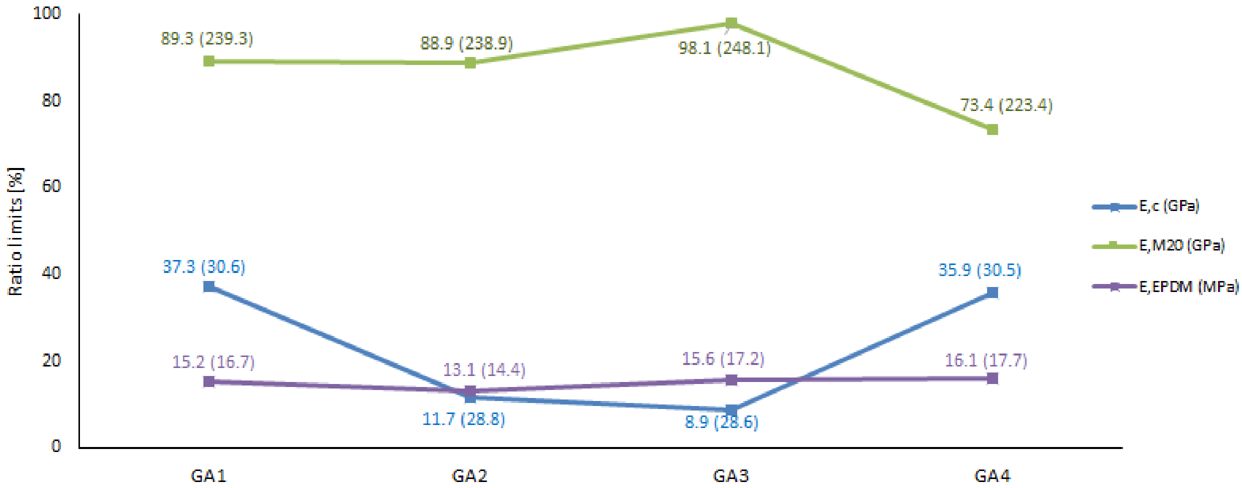
The objective function (f) comprises two terms, one related with the residuals of the vibration frequencies and other related with the residuals of MAC values:

$$f = a\sum_{i=1}^{5}\frac{\left|f_i^{exp} - f_i^{num}\right|}{f_i^{exp}} + b\sum_{i=1}^{5}\left|MAC\left(\varnothing_i^{exp}, \varnothing_i^{num}\right) - 1\right| \qquad (1)$$

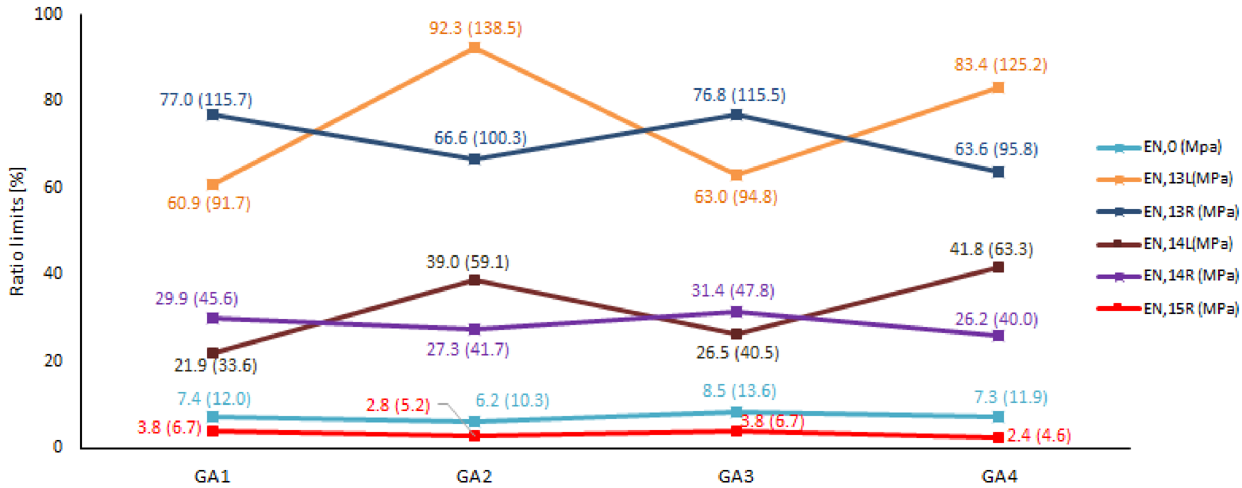
where f_i^{exp} and f_i^{num} are the experimental and numerical frequencies for mode i, ϕ_i^{exp} and ϕ_i^{num} are the vectors containing the experimental and numerical modal information regarding mode i, and a and b are weighting factors of the terms of the objective function assumed, in this situation, equal to 1.0.

The optimization model involves 9 numerical parameters and 10 modal results. The genetic algorithm was based on an initial population of 30 individuals and 100 generations, in a total of 3000 individuals. The initial population was randomly generated by Latin Hypercube method. In this algorithm was defined a number of elites equal to 1, a replacement rate equal to 5% and a crossing rate of 50%.

In Figure 10 are presented the ratios of the values of each numerical parameter in relation to the limits given in Table 1 for the independent optimization runs GA1 to GA4. A ratio of 0% means that parameter coincides with the lower limit and a ratio of 100% means that coincides with the upper limit. The global parameters and parameters related to the interfaces between the seating deck units are shown in Figure 10a, with the correspondent values indicated in brackets. The parameters of the interfaces of the seating deck units to stand beams are shown in Figure 10b.



a)



b)

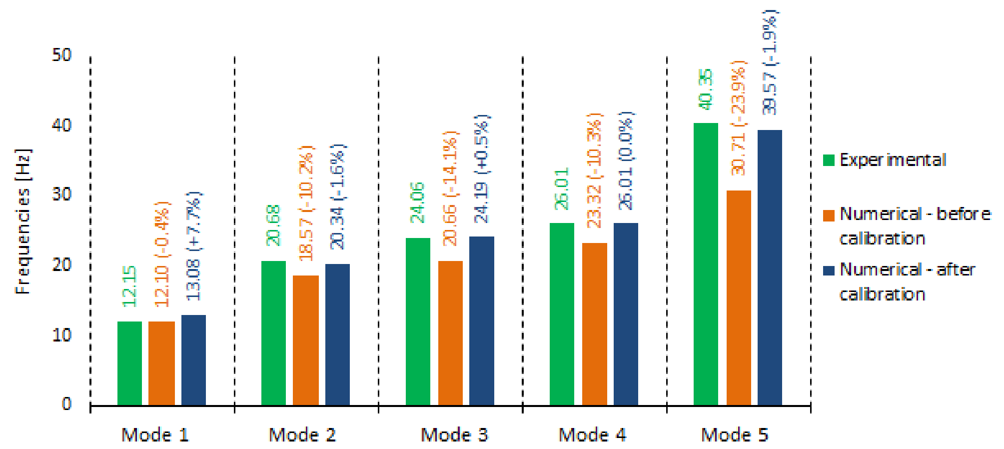
Figure 10: Values of numerical parameters obtained for optimization runs GA1 to GA4: a) global parameters and parameters of the interfaces between the seating deck units; b) parameters of the interfaces between seating deck units and stand beams.

The results help identifying as that the most sensitive parameter, the elasticity modulus of neoprene layer between seating deck units and stand beams of the other rows (E_N), which is the one exhibiting the lower variations, close to 3%. The elasticity modulus of EPDM rubber pads between seating deck units (E_{EPDM}) also has lower variations, in the order of 3%, possibly due to the fact that it has correlation with several modal responses. For the elasticity modulus of concrete (E_c) and the elasticity modulus of steel in M20 connectors between seating deck units (E_{M20}), which are less sensitive to the responses, estimates have higher variations and near 25%.

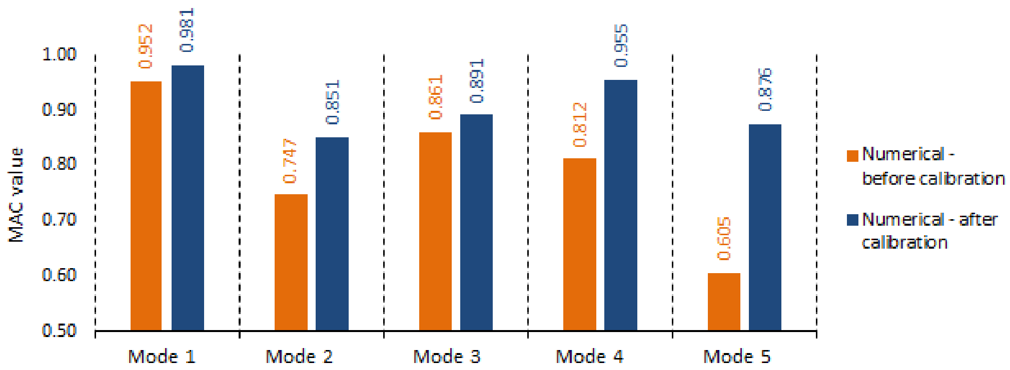
Regarding elasticity modulus of neoprene layer between seating deck unit and stand beams of row 13, at left (E_{N13L}) and right sides (E_{N13R}), the estimates show variations with opposite trend, that is, the increased stiffness of the left support is normally associated with a decreased stiffness of the right support and vice-versa. The same applies to the elasticity modulus of neoprene layer between seating deck unit and stand beams of row 14, at left (E_{N14L}) and right sides (E_{N14R}). This should be related to the fact that there are different combinations of these sets of parameters that lead to the same solution in terms of the optimization problem.

Figure 11a presents the experimental and numerical values of vibration frequencies before and after calibration, indicating the values of errors of numerical and experimental vibration frequencies, with reference to the values of the experimental frequencies. The numerical results after calibration refer to the optimization run GA3, which was the case that led to the lowest residue of the objective function. Figure 11b shows the MAC values before and after calibration.

The average error of the frequencies decreased from 11.8% before calibration to 2.4% after calibration. The average value of the MAC parameter increased from 0.795 before calibration to 0.911 after calibration.



a)



b)

Figure 11: Correlation analysis of experimental and numerical modal parameters: a) frequencies of vibration; b) MAC values.

6 CONCLUSIONS

This article focused on the experimental calibration of a numerical model of seating deck units of Dragão stadium.

The three dimensional finite element numerical model includes a series of 10 consecutive seating deck units. In the modeling special attention was given to the link between the seating deck units as well as the connection of the seating deck units to the stand beams.

The dynamic test carried out on a series of seating deck units of the south stand of the stadium allowed the identification of five local vibration modes, mainly involving coupled bending and torsion movements of the seating deck units, with frequencies ranged between 12.15 Hz and 40.36 Hz.

The results of the optimization of the numerical model of the seating deck units demonstrated a very good approximation with experimental results and a significant improvement in relation to the numerical model before calibration. On the other hand, the genetic algorithm allowed to obtain sufficiently stable estimates of a significant number of parameters, considering different initial populations, proving its efficiency and robustness.

The analysis of the values of numerical parameters after calibration allowed to established that: i) the optimal value of the elasticity modulus of steel in M20 connectors between seating deck units approached the upper limit, reflecting, possibly, a more effective link between the seating deck units in relation to the planned design; ii) the values of elasticity modulus of neoprene layer between seating deck units and stand beams have very different values depending on the seat deck unit and position on the seat deck unit, which corroborates the evidences of a visual inspection carried out *in situ*, which in some situations found the absence of supports, and in other situations the existence of supports performed with materials and thicknesses different from those specified in design; iii) the optimal value of the elasticity modulus of concrete approached its lower bound, standing in the range between 28.6 GPa and 30.6 GPa.

As future developments the authors intend to carry out the validation of the numerical model of seating deck units under the action of controlled movements of public based on dynamic analysis that include public-structure interaction and taking into account eventual nonlinearities of the dynamic system. For this purpose, it is planned to carry out a dynamic test under public action with the measurement of the forces applied by individuals and the responses in terms of accelerations of seating deck units.

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