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AMBIENT VIBRATION TESTING, DYNAMIC IDENTIFICATION AND MODEL UPDATING OF A HISTORICAL BUILDING. CHAPEL OF THE WÜRZBURG RESIDENCE (GERMANY)

Pablo Pachón[1], Víctor Compán[2], Javier Fdo. Jiménez Alonso[3].

[1] PhD Candidate. Department of Building Structures and Geotechnical Engineering. University of Seville (Spain). ppachon@us.es.
[2] Associate Professor. Department of Building Structures and Geotechnical Engineering University of Seville (Spain). compan@us.es.
[3] PhD Candidate. Department of Building Structures and Geotechnical Engineering. University of Seville (Spain), jfjimenez@us.es.

ABSTRACT

One of the main difficulties that can be detected in a historical building structural analysis is the high level of uncertainty associated with many factors affecting the behavior of the structure. Slight modifications of the mechanical properties of the structural materials, the soil-structure interaction or even the building construction process may be the cause of high changes between the results obtained from a numerical analysis and others estimated experimentally. Among the non-destructive techniques, the finite element model updating from the dynamic modal parameters identified experimentally, allows the adjustment of these models in order to obtain a more accurate estimation of behaviour of the structure. In the present paper, the implementation of this technique on the Chapel of the Würzburg Residence (Germany), one of the most important churches of the Central European Baroque has been presented. The experimental modal parameters have been estimated from the operational modal analysis of the signals measured at different points of the structure during an ambient vibration test. The correlation between the numerical and experimental modal parameters after the updating process is adequate.

Keywords: Historic construction, Operational modal analysis, Model Updating., Würzburg Residence.

1. INTRODUCTION.

The chapel, purpose of this study, is integrated in the Würzburg Residence [1], a large construction belonging to the German Baroque, which was declared a World Heritage Site by UNESCO in 1981 (Figure 1). The construction of the Residence dates from the early eighteenth century when the Schönborn family decided to build a palace to relocate the Episcopate. Balthasar Neumann [2, 3] was its main work master for over thirty years.

Figure 1. Würzburg Residence (Germany).

In the different phases of the design of the chapel, it was positioned in different places until Balthasar Neumann moved it to the south-east of the Residence (Figure 2). Its design was consulted, in Paris, to Robert de Cotte and Gabriel Germain Boffrand, with prestigious recognition and extremely knowledge about this kind of buildings. The first of them is responsible for the design of the main staircase, determined by a great interested vault, not only by its paintings, but also by its structural solution and constructive proposal.

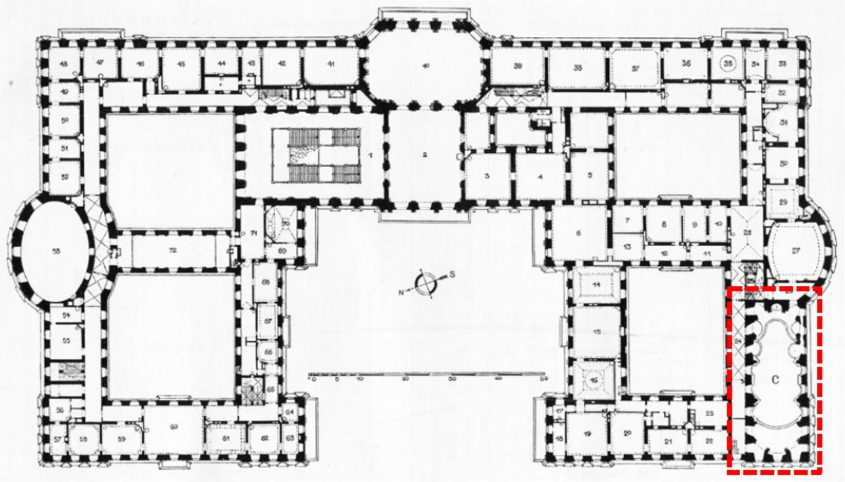


Figure 2. Localization of the chapel in the plan of the Würzburg Residence.

2. ARCHITECTURAL CONFIGURATION.

The architectural configuration of the chapel presents a spatial view with a clear longitudinal character, being composed of three main longitudinal cells connected by two other lateral ones (Figure 3). The walls are very slim with a15.2 m of height and 1.50 m of thick, and a high percentage of voids, greater than 50% of the surface of the facade.

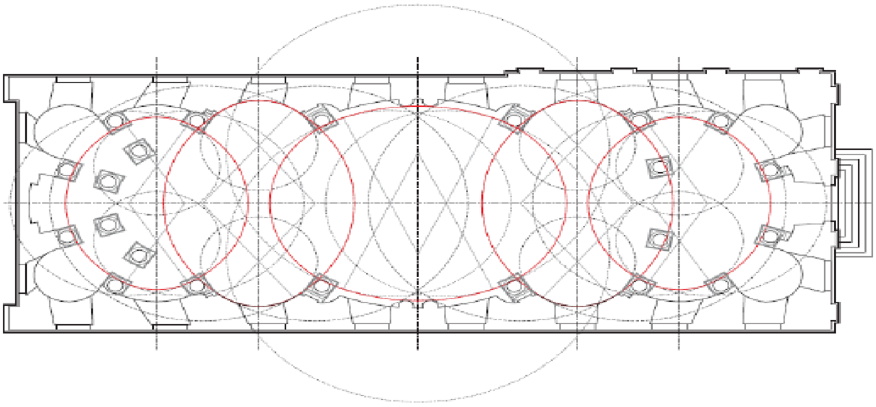
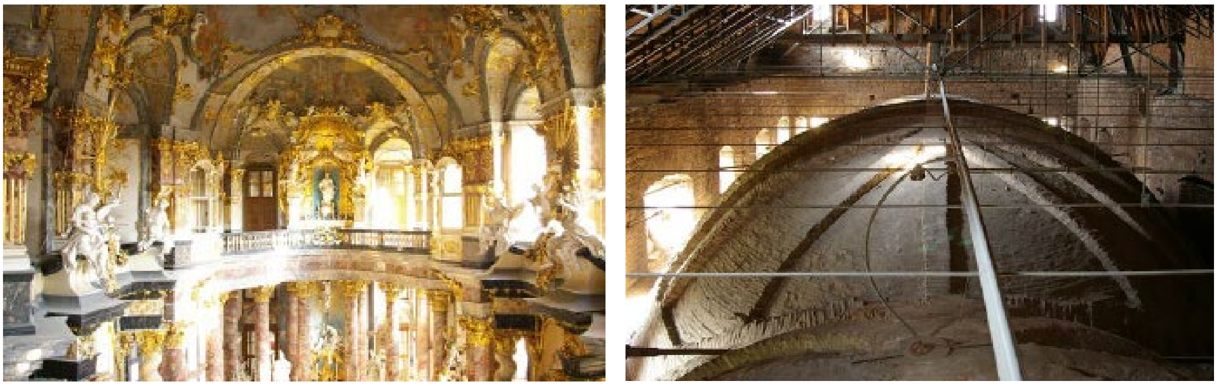


Figure 3. Study of the trace of the Chapel of the Würzburg Residence.

The domes are masonry surfaces of bricks with 30 cm of thick, grown in a single lawyer, reinforced at its base by increasing the thickness till 45 cm. The reinforcement is also presented in the radial ribs reaching a section of 45x45 cm (Figure 4). In the construction process of the domes, the nerves are built alongside the rest of the sheet.



a)

b)

Figure 4. a) Interior and b) exterior view of the Chapel of the Würzburg Residence.

3. AMBIENT VIBRATION TEST.

For the definition of the ambient vibration test a preliminary numerical modal analysis has been performed using the Ansys software. Due to the complexity of the shape, a 3D brick element (8 nodes per element) has been used to define the structural model of the chapel. In order to focus the study to the dome, the effect of the lateral walls has been determined, in a simplified way, through two spring elements whose stiffness corresponds to the flexural rigidity of the wall in the considered direction. In the same way, the following material properties have been considered for the constituents materials: E (MPa) = 2000; ν= 0.2; ρ (Kg/m3)= 1700 and k_h=1000 kN/m [4]. The horizontal stiffness of the walls has been determined considering that these elements have been made with the same material than the rest of the chapel and assimilating their behavior to a cantilever. Finally, a numerical modal analysis of the structure has been developed to estimate the numerical natural frequencies of the chapel (Table 2). The first three numerical vibration modes have been shown in Figure 8. The effect of the lateral walls has been simulated dividing the structure in four zones, the wall 1 and 4 corresponding to the lateral domes and walls 2 and 3 corresponding to the main dome.

The above finite element modal has been used to localize the more adequate position for the reference accelerometers, the points with more modal displacements for the first considered vibration modes (Figure 8), being located the intersection between domes and in the lateral sides of the main dome (Figure 5).

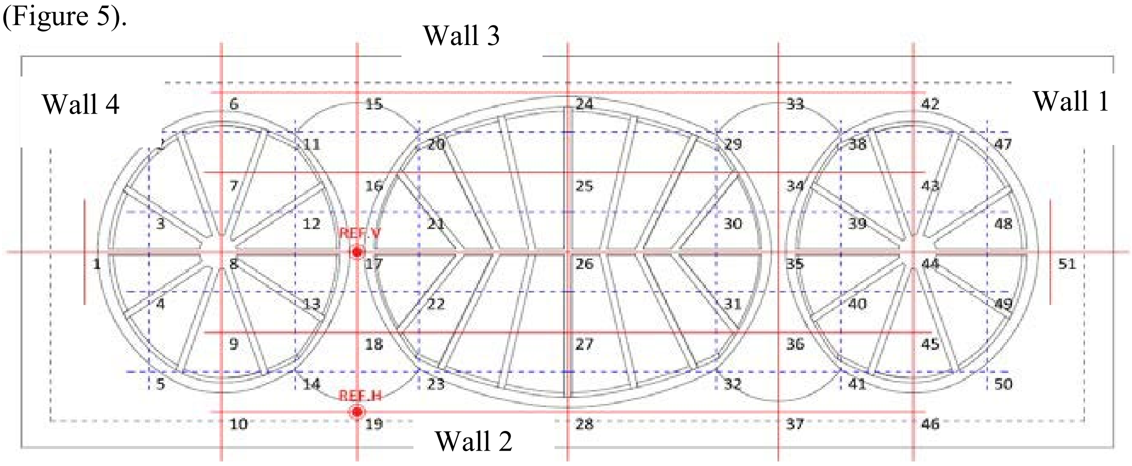


Figure 5. Localization of the accelerometers (17 and 19 references).

The monitoring of the structure (Figure 6) has been made using a data acquisition central (Granite) and eight uniaxial accelerometers (Episensor) of the Kinemetrics company. The accelerometers (6 mobiles and 2 references) have been located according to Figure 5. At each point, the accelerometers have been placed in the three spatial directions (vertical, lateral and longitudinal). Twenty-six measurements have been made using the eight accelerometers in each series and 10 minutes of duration per each series.

a) b)

Figure 6. a) Data acquisition central, computer equipment and b) force balanced accelerometer

4. OPERATIONAL MODAL ANALYSIS.

The above recorded measured were processed by two operational modal analysis methods, one in frequency domain (Figure 7), Enhanced Frequency Decompostion (EFDD) and one in the time domain, Subspace Stochastic Identification (SSI). Both methods [5, 6] are implemented in the Artemis software.

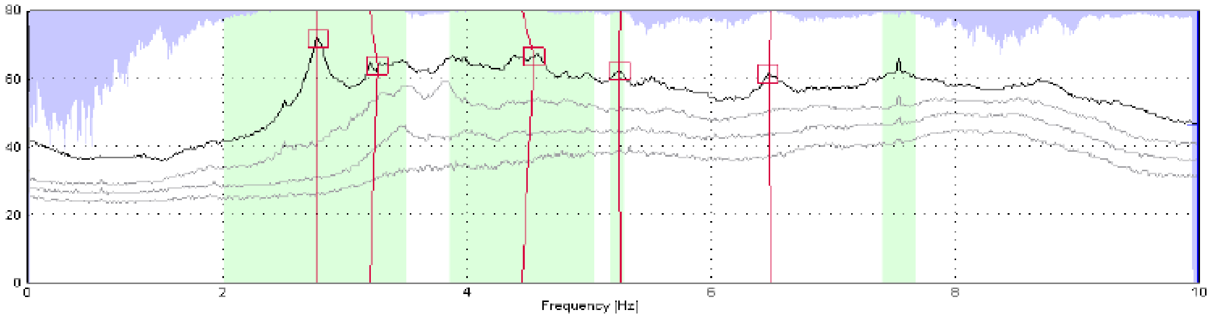


Figure 7. Response spectrum. Identification of the modal parameters by EFDD method.

Both methods identify five vibration modes, inside a frequency range 0-10 Hz. The obtained results and their MAC ratios are shown in Table 1.

Table 1. Experimental identification of the modal properties.

Vibration Mode	Natural Frequency [Hz]			M.A.C.
	EFDD	SSI	Δf [%]	
1	2.769	2.764	0.18	0.99
2	3.210	3.285	2.28	0.83
3	4.446	4.539	2.04	0.80
4	5.249	5.262	0.24	0.90
5	6.481	6.481	0.00	0.81

In order to carried out an estimation of the correlation between the numerical and experimental modal parameters, the relative differences between the natural frequencies and the modal assurance criterion ratios (M.A.C) have been obtained for the first three identified vibration modes (Table 2 and Figure 8). Only the first three vibration modes have been considered due to the local character of the fourth and fifth identified vibration modes.

Table 2. Numerical/Experimental vibration modes.

Vibration Mode	Natural frequencies [Hz]		Δf [%]	M.A.C.
	Numerical	Experimental (SSI)		
1	3.362	2.764	21.63	0.93
2	3.431	3.285	4.44	0.77
3	3.988	4.539	12.13	0.29

Despite the use of a very detailed finite element model, the errors between the experimental and numerical modal parameters are really high, being necessary to make an adjustment of the finite element model of the structure in order to guarantee that the numerical model was able to model adequately the behavior of the structure.

Analyzing Figure 8, the first and third experimental vibration modes show a lateral deflection behavior, while the second vibration model corresponds to a longitudinal deflection of the chapel. In that last case, the relative displacement of the different measured points is not so marked so the goodness of the results is not good enough to consider these coordinates in the finite element model updating process of the chapel.

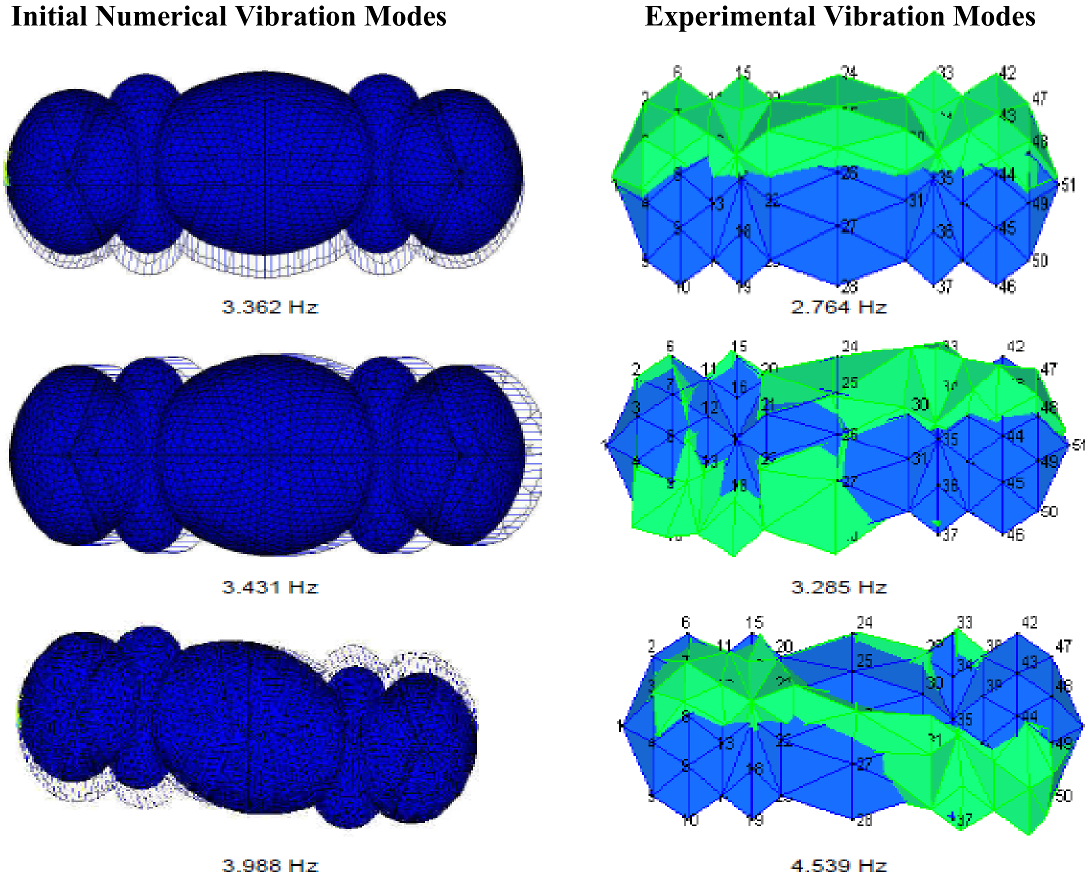

Initial Numerical Vibration Modes **Experimental Vibration Modes**

Figure 8. Numerical versus experimental vibration modes.

5. FINITE ELEMENT MODEL UPDATING.

The easiest way to perform a finite element model updating is minimizing the relative differences between the numerical and experimental results [7]. The equation created with this aim is usually defined by the formulation of a least square problem. This function must be optimized by a global optimization algorithm. In order to assess the goodness of the updating process the correlation among the natural frequencies, vibration modes and M.A.C. ratios are obtained. The acceptance criterion of this last ratio has been established in values upper than 0.90.

An especial care must be taken in the selection of the identified parameters, so they must be sufficiently reliable to avoid problems in the convergence of the iteration method. On the other hand, the grid of measures must be dense enough to avoid spatial aliasing problems associated with the determination of the M.A.C. ratios [8].

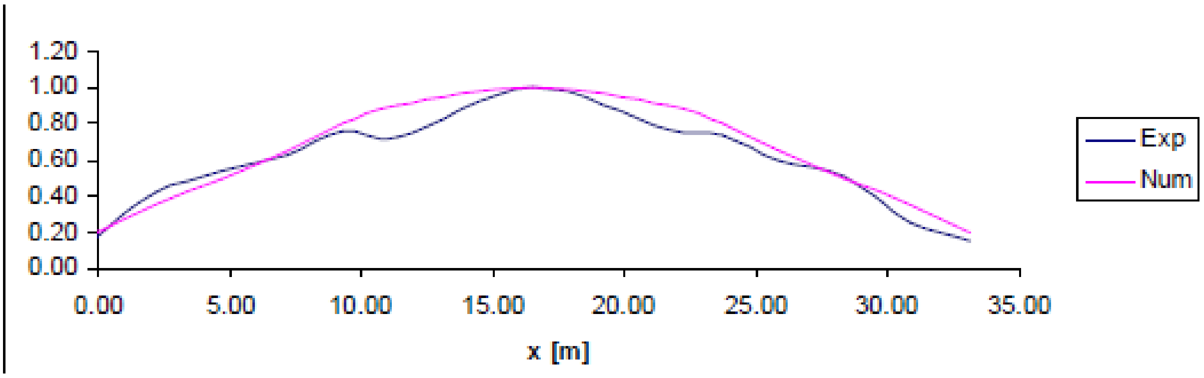
Normally, the finite element model updating process begins with a previous manual adjustment of the natural frequencies in order to facilitate the optimization process of the least square problem given the high singularity of the objective function. In this case, given the relative differences between the numerical and experimental natural frequencies obtained from the preliminary numerical analysis and the likeness between the numerical and experimental modal shapes, this phase has been neglected during the present updating process. Secondly, the physical parameters of the structure that influence more the dynamic behavior of the structure must be selected. A sensitivity study has been performed among the possible parameters [8], being selected the seven physical parameters described in Table 3. The selection of more parameters would make more difficult the physical understanding of the updating process. Finally, the finite element model updating has been performed through the implementation of the optimization algorithm in the Matlab software [9].

Table 3. Range of variation of the physical parameters selected.

Parameters	Minimum	Updated	Maximum
Young’s Modulus dome [MPa]	1000	1650	4000
Young’s Modulus ribs [MPa]	1000	1610	4000
Young’s Modulus starting wall [MPa]	1000	1670	4000
Long. stiffness wall 1&4 [kN/m]	200	410	2000
Lat. stiffness wall 2&3 [kN/m]	200	415	2000
Lat. stiffness wall 1&4 [kN/m]	200	1975	2000
Long. stiffness wall 2&3 [kN/m]	200	1506	2000

The objective function has been defined from the resiudes obtained from the diferences between the numerical and expeirmental natural frequencies corresponding to the first three vibration modes and the normalized modal coordinates of the two lateral vibration modes (Figure 9). The convergence proces has been improved creating.so experimentally so numerically, vectors with the mean values of the modal coordinates, obtained from eleven sections made on the structure in the longitudinal direction. These sections are correlated with the grid defined during the ambient vibration test. According this cristerion, the objective fucntion has been defined by 25 residues (3+2x11), optimized through the implementation of a global optimization algorithm, genetics algorithms, using a population of 1000 vectors, and being reached the minimum after 50 iterations.

Updated versus experimental first vibration mode



Updated versus experimental third vibration mode

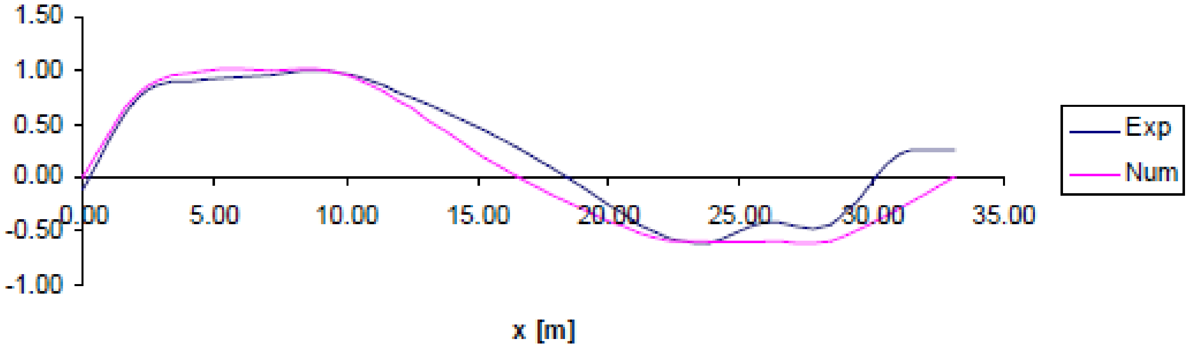


Figure 9. Correlation between the first and third numerical and experimental vibration modes.

6. DISCUSSION OF THE RESULTS.

The change of the physical parameters (Table 3) suggests certain reduction of the stiffness of the modelled materials according to the deterioration and cracking level of this kind of constructions. This stiffness reduction is especially marked in the case of the lateral walls, very slender. The updating process improves the correlation between the numerical and experimental natural frequencies, reducing the relative differences between natural frequencies and increasing the values of the M.A.C. ratios (Table 4) through the change of the seven selected physical parameters. All the parameters show values inside an acceptable physical range, facilitating the adequate understanding of the updating process and validating the convergence of the optimization method used. On the other hand, for the development of further studies, given the magnitude reached by several parameters, it is possible to reduce the number of physical parameters in the finite element model updating process.

Table 4. Updated/Experimental vibration modes.

Vibration Mode	Natural frequencies [Hz]		Δf [%]	M.A.C.
	Numerical	Experimental (SSI)		
1	2.784	2.764	0.70	0.95
2	3.366	3.285	2.46	0.91
3	4.542	4.539	0.06	0.89

7. CONCLUSIONS.

The development of a finite element model of a historic construction based on the results of the material properties of local tests and the best technical judgment does not guarantee that this initial model allows estimating reasonably the modal parameters (natural frequencies and modal shapes) of the structure, even if the numerical model has a high level of details. The first three vibration modes of the Würzburg Chapel have been estimated by the application of the operational modal analysis methodology to the measurements made during an ambient vibration test. Comparing the experimental parameters and the initially ones, obtained from a numerical finite element model, high relative differences between natural frequencies and vibration modes were obtained. In order to reduce this differences a finite element model updating process has been carried out, modifying the value of seven physical parameters of the model. Alter the adjustment; the correlation between the numerical and experimental natural frequencies and the values of the M.A.C. ratios of the three selected vibration modes has been increased significantly. All the modifications of the physical parameters are inside a physically acceptable variation range, so the technical interpretation of the results is easy, the global success of the updating process is validated. The adjustment of the parameters suggests that the main variable that governs the dynamic behavior of the first three vibration modes of the chapel is the stiffness of the lateral walls, being its value lower than the considered initial value in the finite element model.

ACKNOWLEDGEMENTS

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