Dinamic identification for structural analysis of Santa Ana church in Seville

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ABSTRACT: Santa Ana Church (1.266) is one of the main milestones in the heritage of Seville for being the first Christian church built outside the city walls and on the other side of the river, after the Reconquest of the city. The singularity of the geometry of its vaults together with its execution in brick and stone masonry make complex to determine the properties of materials. The impossibility of characterizing these materials by means of destructive tests leads to the application of other non-destructive technologies that allow us to approach the behavior of the numerical models to the reality performed.

This paper tries to determine the mechanical properties of the materials that constitute the structure of the church of Santa Ana, which are brick and stone masonry, through analyzing its dynamic behavior with environmental vibration techniques and modal operations analysis (OMA). After having carried the campaign out using the methods of modal identification in the stochastic subspace and in the frequency domain, four vibration modes are obtained that adjust to the modal behavior of the current building, within a frequency range between 2 and 4 Hz.

Initially, and thanks to new techniques such as photogrammetry, it has been possible to develop a finite element model (FEM) to analyze the structure with theoretical parameters of its materials.

With this model and through the environmental vibration technical it is possible to conclude with the suitability of the application of a non-destructive method in heritage buildings to extract the mechanical properties of the materials that constitute its structure through its dynamic behavior.

1 INTRODUCTION

Santa Ana church in Seville (*Figure 1*) is the first Catholic Church built in the city after the conquest (*Figure 2*). Its location outside the wall of the city makes the building work both as a Catholic temple and as a fortification because of having been built near the Boats Bridge and the Aljarafe zone.

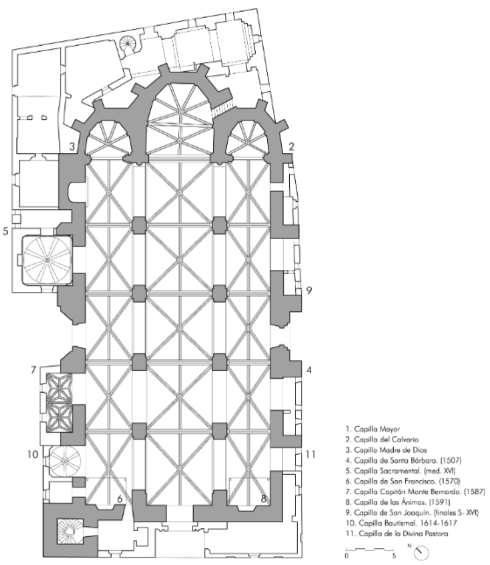


Figure 1. Santa Ana Church. Author's drawing

Figure 2. Author's Sketch

The primitive building has influences from Cordoba and Burgos. It has 34 long rods, the central space is bigger than the laterals and the proportional relation between its spaces is around $\sqrt{2}$ (Figure *4*). This proportional relations and the plane roof built due to possible battles make the vaults to be at the same height, and their geometry by imposition surfaces gets a better structural behavior. The primitive plant is shown without any indication of the existence of a crossing, and it has three naves separated by pillars that, in height, become pointed arches closed by a false triforium where the nerves of the vaults begin. Longitudinally, the vaults are crossed by a spine as it occurs in the Cistercian tradition. [6]

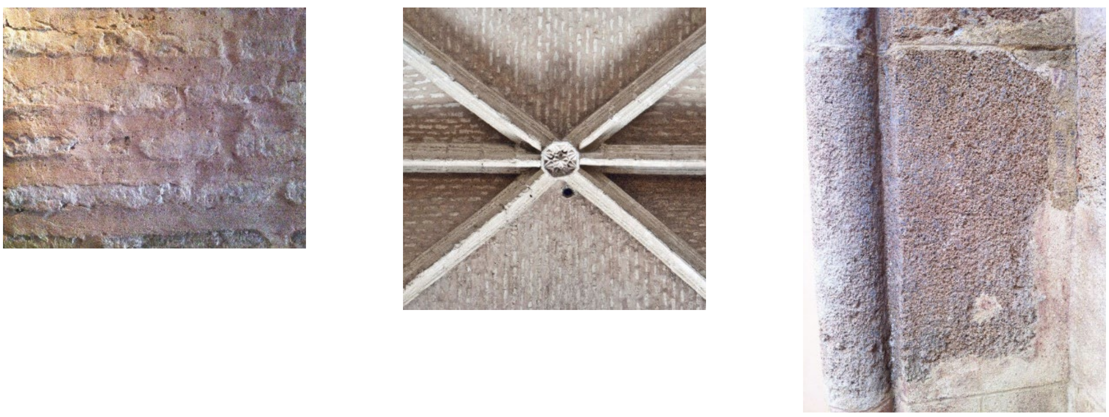


Figure 3. Brick and Stone Masonry

The main building was built in brick and stone masonry, whose mechanicals properties are difficult to define for being non-homogenous and isotropic materials. Determining these mechanicals properties is going to be one of the main objectives in this work.

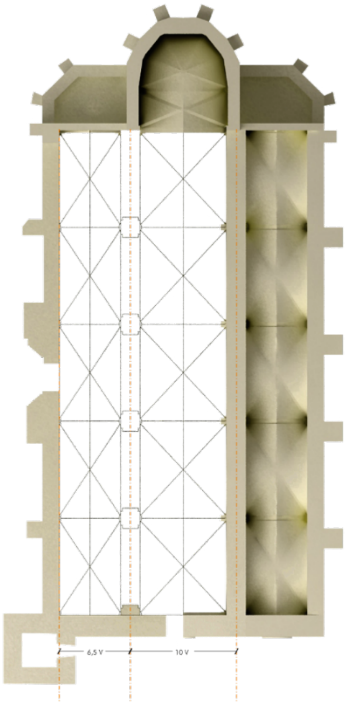


Figure 4. Proportion Relationships. Author's drawn

Figure 5. Vaults image

After the primitive construction, the building had numerous additions [6, 16], with the construction of small chapels that are annexed to the Epistle and the Gospel Naves. The tower suffered some interventions.

From a structural point of view, we analyze those constructions that could condition the building behavior, depending of its dimensions and its disposition in the main building. These little Chapels could work as buttresses of the main building.

We analyze the most important little Chapels [15]:

- 1.507. Santa Bárbara Chapel. In the fourth section of the Epistle Nave between the buttresses of the primitive building. (Figure *7*).

- Mid. s. XVI. In the second section of the Gospel Nave there is the Sacramental Chapel, built with square plant and cover with a hemispherical dome. (Figure *7*).

- 1.587. Captain Monte Bernardo Chapel. In the last Gospel Nave section, built in a rectangular floor and covered with a Terceletes Vault. (Figure *7*).

- Saint Joaquin. End of s. XVI. It is identical to the Santa Barbara Chapel and it is located in the second section of the Epistle Nave. (Figure *1*)

- 1.614-1.617. The Baptismal Chapel is located in the last section of the Gospel Nave (Figure *1*).

- In the last Section of the Epistle Nave, it is located the Divina Pastora Little Chapel. There is not information about its construction but it is possible to have been built around the year 1.865. (Figure *1*)

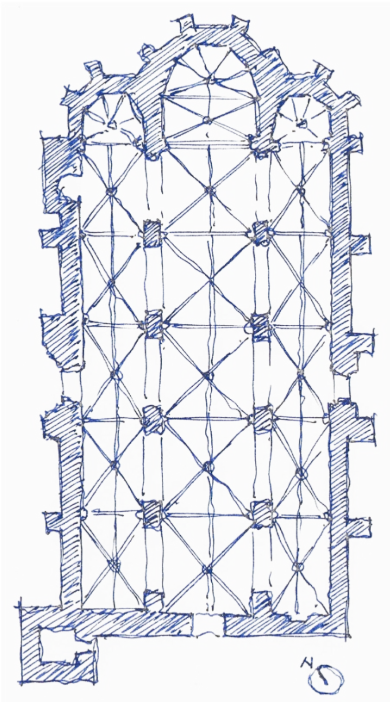


Figure 6. Primitive Building. Author's Sketch

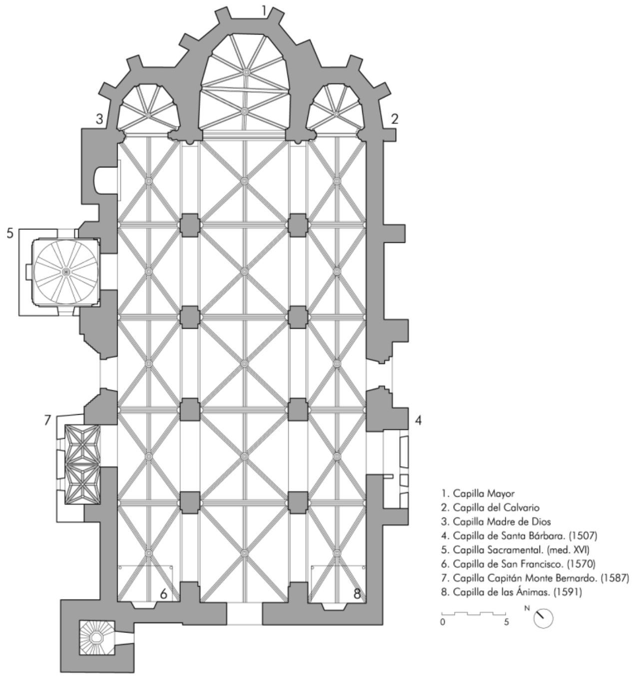


Figure 7. Building Evolution. Author's drawn

2 OBJECTIVES

Traditionally, the classical theory of masonry buildings establishes premises or hypothesis to their study, such as the zero tensile strength of the masonry, low-tension levels and the impossibility of slippage failure between elements [4, 5]. This analysis is limited to force lines that work in a flat element without analyzing the behavior in others than where the actions are acting. Another aspect considered is the safety of these buildings, which is established based on their geometry regardless of size [2]. For this work, numerical calculation models based on the finite element method (FEM) have been used. With this method, it is possible to analyze singular masonry structures such as Santa Ana Church, considering a three-dimensional behavior in which actions contained in a plane can give a response in another plane. Stresses and deformations higher than the elastic limit of the material can be considered to adjust the behavior with the current model.

This work pretends to characterize the mechanical properties of the building's masonry by an experimental campaign to determine the dynamic properties of the building from the application of environmental vibration tests and modal identification of its structure (OMA). This type of technique is presented as a useful tool in the study of heritage buildings. It allows, through non-destructive techniques, to analyze the building without interrupting its operation during the realization of the tests [12].

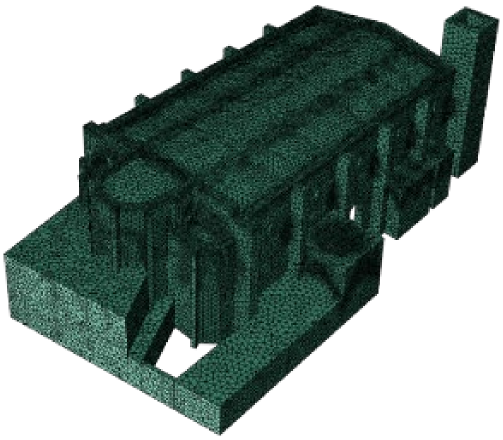


Figure 8. Finite Elements Model

Figure 9. Accelerometers

From a numerical model (Figure *8*) get using the finite element method (MEF), we try to establish a relationship between the behaviors with real model for its validation. This work will let us to do an advanced analysis to evaluate the structural damage and with so, calibrate the initial finite elements model.

As previously mentioned, the primitive building has suffered multiples additions and interventions through the construction of several Chapels next to the original building. The connection of these chapels to the main building is unknown and therefore the behavior of the actual building working as a whole could be questioned. Currently, there are no symptoms which show that the constructions could be disconnected from the main building (cracks or fissures), so the behavior could be considered as a whole. However, and considering the results that we have obtained, if these discontinuities could exist (micro breakage), they would not modify the dynamic results obtained based on the dynamic behavior analyzed.

The continuity and discontinuity could be analyzed as an Ultimate Limit State (ULS). The experimental campaign studies the dynamic behavior as a Service Limit State (SLS). After the first experimental campaign, the results show that it is possible to considerate the whole building as a unique structure due to the low level of excitation. In future campaigns, we will try to do an advance analysis with accelerometers located on the little Chapels' roofs.

3 METHODOLOGY

In order to get the experimental dynamic properties of the church, we need to previously make a finite element model (Figure *8*). In order to do so, we make a traditional draw of the building and use photogrammetric software (Figure *10*) to get the geometrical properties (vaults and nerves). We use Agisoft Photoscan [11] to elaborate the points cloud digital model. In order to do so we used a Laser Rugby 640G for levelling references targets and a Nikon D5000 for taking several photos in order to define the digital model. Once we have the digital model, we have to scale it to take measurements of the columns, nerves and vaults in order to define the numerical model geometry.

Figure 10. Photogrammetric Job

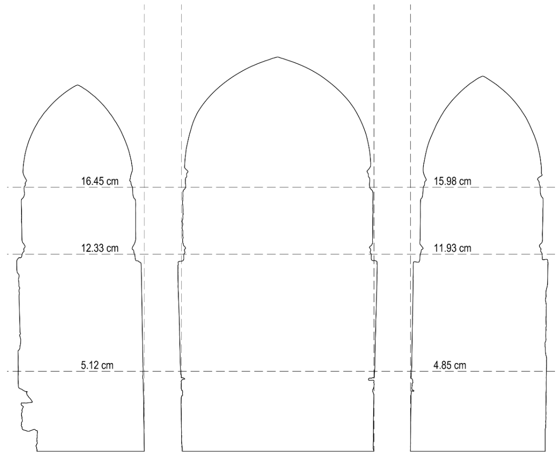


Figure 11. Columns Displacements

Before elaborating the numerical model, is necessary to do a geometrical one. In order to do this, it was necessary to work with Autocad and Rhinosceros softwares to generate complex geometries supported on photogrammetric works results.

Based on the geometric model and using Ansys ICEM to generate the finite element mesh, it is possible to analyze the structure with the ABAQUS CAE 6.13 [15]. In this software, the material properties are defined using solid elements for walls, columns, nerves and vaults, as well as shell elements to describe the Little Chapels. The references of these materials were taken from specific bibliography. (Augenti 2012)

These are the parameters considered:

Table 1. Mechanical Properties

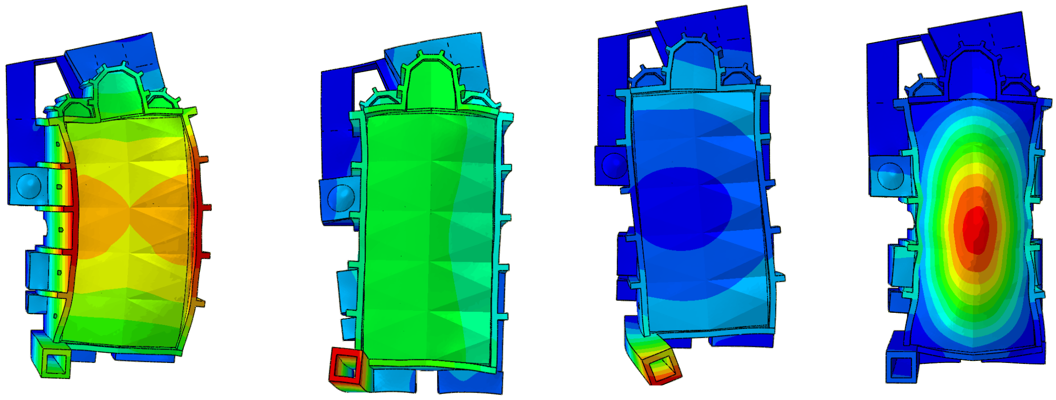
	ρ (N/m³)	E (N/m²)	n (N/m²)	s_c (N/m²)	s_t (N/m²)	G_f (N/m²/m)
Stone Masonry	1.900	3e+09	0,2	4,0e+06	0,1e+06	18
Brick Masonry	1.800	1,5e+09	0,2	1,5-3,0e+06	0,1e+06	18
Filled Material	800	3e+08	0,3	-		

ρ: Density E: Young's Modulus. ν: coeff. Poisson. σ_c: compression stress. σ_t: tensile stress. Gf: Damage Energy

Once the numerical calculation model has been elaborated from the data obtained in the photogrammetry, we carry a campaign out by placing uniaxial and triaxial accelerometers on the roof, that provide us dynamic information of the building. These accelerometers were placed in the greater modal displaced points [12, 13], which were previously determined with the numerical model from the distribution of masses and stiffness of the building with an initial material properties in order to do the initial calculation (Figure 12).

$$f_n = \sqrt{\frac{K_n}{m}} \qquad (1)$$

f_n= natural frequency
K_n= structural stiffness
m= mass

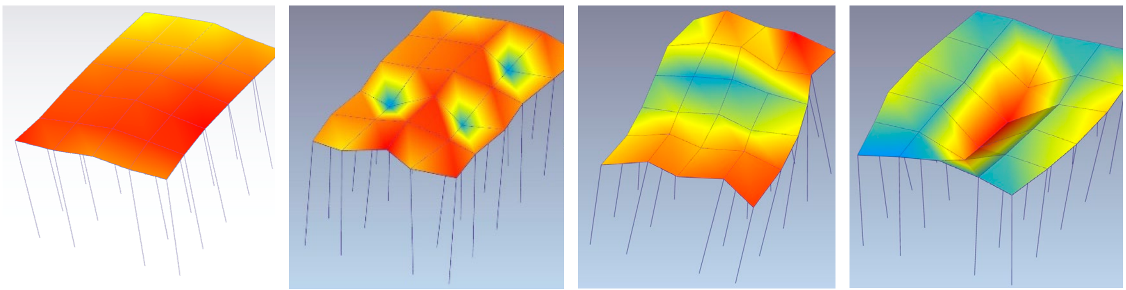


Mode 01 Mode 02 Mode 03 Mode 04

Figure 12. Main Vibration Modes

The position of the accelerometers [13] is determined thanks to an initial analysis of the maximum modal displacements using the numerical calculation model. With this, it is possible to start the experimental campaign. The vibration tests were carried out with environmental loads due to the complexity to generate forced loads in a singular structure like the one of our study.

With the results, the data are processed with the Artemis software [14]. Through the methods of Modal Identification of Improved Decomposition in the Frequency Domain (EFFD) and Identification in the Stochastic Subspace (SSI) *(Figure 14)*, four modes of building vibration were identified *(Figure 13)*.



Mode 01 Mode 02 Mode 03 Mode 04

Figure 13. Vibration Modes Detected with Artemis Software

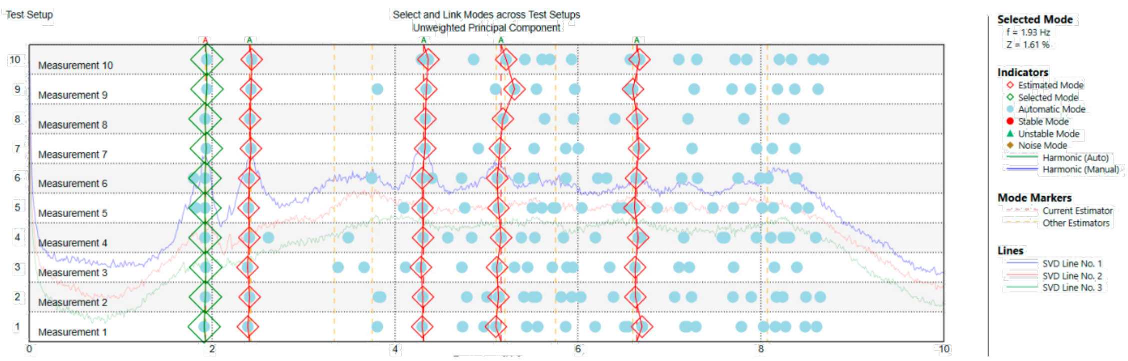


Figure 14. Identification of Modal Parameters in the stochastic subspace

4 CONCLUSIONS

Thanks to this method, we have obtained four natural modes of vibration of the building similar to the modal behavior of the numerical model, getting frequencies with relative errors over the 5% [8]. This allows us for updating the numerical model in order to adjust the mechanical properties of the materials.

MODE Nº	ARTEMIS	ANALYSIS FEM	
	(Hz)	FRECUENCY (Hz)	%
1	1,929	2,0251	4,75%
2	3,336	3,2034	4,14%
3	3,750	3,6543	2,62%
4	4,315	4,0872	5,57%

The presented method can be considered as a non-destructive highly technique for the dynamic evaluation of heritage buildings with masonry materials.

The knowledge of the dynamic behavior of the building through OMA allows us to evaluate the building against earthquakes with the elastic response spectrum in the numerical model.

After analyzing the frequencies results obtained in relation to those extracted from the numerical model, it is verified that the modal forms of both numerical and real models are similar. This fact will allow us to obtain a model calibrated in frequency and modal forms updating the mechanicals properties of their materials. With this, it is just possible to analyze the building structural behavior.

In futures works it will be possible to extend the experimental campaign with more strategical measuring points on the little Chapels roofs that will allow us to advance in the knowledge over the possible connections or disconnections between the main building and these Chapels, and their influence on the dynamic behavior of the whole.

We are currently using the updated numerical model to evaluate the structural behavior in a linear and non-linear domain.

Photogrammetry allows us to determine displacements values in the columns (Figure *11*) by using software to edit the points cloud and define complex geometries such as the one we are studying.

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