Dynamic Identification and Finite Element Model calibration of the Santa Ana church in Seville

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ABSTRACT

Dynamic identification plays a crucial role in understanding the behaviour of heritage structures, which often present significant uncertainties in their structural properties. Among available techniques, Operational Modal Analysis (OMA) has proven to be a particularly useful non-destructive tool for determining the dynamic characteristics of these buildings. It provides insights into the global behaviour of the structure and supports the calibration of finite element models (FEM) for vulnerability assessment purposes. This study focuses on the dynamic identification campaign conducted on the Church of Santa Ana in Seville, Spain. As a significant example of historical constructions in southern Spain, the church presents complex structural and material characteristics that pose challenges for numerical modelling. The research details the OMA campaign, including sensor placement, measurement configurations, and data processing challenges. The collected experimental data were used to calibrate a model of the church, refining material properties and boundary conditions to achieve an accurate representation of its dynamic response. The combination of dynamic identification and numerical calibration allowed the assessment of essential aspects of the structural behaviour that were not easily detectable through simple visual inspection on-site, such as the quality of the connection between macroelements and the influence of the vaults' infill. The results provide valuable insights into the reliability of OMA for heritage buildings and its role in facilitating accurate structural analysis.

Keywords: Heritage buildings, masonry structures, dynamic identification, finite element model, model calibration

1. INTRODUCTION

The assessment of heritage structures presents unique challenges due to often limited knowledge on their geometry, structural details and material characteristics [1]. Traditional methods for evaluating the mechanical properties, which rely on destructive testing, are generally unfeasible for heritage buildings

due to conservation constraints. In contrast, non-destructive techniques (NDTs) allow for material characterization without causing damage. However, these methods primarily provide localized information and may not fully capture the global structural behaviour.

Operational Modal Analysis (OMA) is a non-destructive technique that overcomes these limitations by offering a comprehensive assessment of a structure's dynamic response based on ambient vibration data. Unlike traditional forced vibration tests, OMA relies on environmental excitations, making it particularly suitable for historical buildings, where operations should be minimally invasive [2]. The modal parameters obtained through OMA, including natural frequencies and modal shapes, are crucial for understanding the overall structural behaviour. Moreover, this data is essential for the calibration of finite element models (FEM), reducing the high level of uncertainty due to the limited knowledge and complex nature of heritage buildings. These models serve as predictive tools for assessing structural integrity and evaluating vulnerability, allowing for designing minimal yet effective interventions when needed.

Despite its advantages, the application of OMA to heritage structures presents several challenges. The low signal-to-noise ratio, the presence of almost independent macroelements often leading to local closely spaced or coupled modes, and the partially known actual conditions can complicate modal identification. Additionally, structural discontinuities, material heterogeneity, constructive phases and alterations further complicate the interpretation of results during the FEM calibration process.

This study focuses on the dynamic identification of the Church of Santa Ana in Seville, Spain. The research emphasizes the planning and execution of an OMA campaign and its role in FEM calibration. The paper discusses the challenges associated with dynamic characterization and numerical modelling, providing insights into the applicability of OMA for heritage structures. The findings contribute to the ongoing development of non-destructive methodologies for structural assessment and offer a framework for improving the reliability of numerical models in heritage conservation efforts.

2.   SANTA ANA CHURCH

The Church of Santa Ana in Seville, built in the 13th century, following the Christian conquest of Seville, was the first church in the city constructed entirely from the ground up, rather than being adapted from a former mosque. Its location outside the city walls, on the banks of the Guadalquivir River, gave it a defensive character, as the area was still prone to attacks [3]. The church exhibits a blend of Gothic and Almohad influences, characteristic of the Mudejar style, and has undergone several modifications over the centuries, incorporating Renaissance and Baroque elements [4]. Many of these interventions were driven by structural damage caused by natural disasters, particularly earthquakes in 1356 and 1755 [3].

The church features a rectangular layout with three naves and a main apse. The central nave is taller and wider, although the roof is relatively flat and accessible through the tower, due to its defensive purpose (Figure 1a) [5]. The masonry is predominantly made of brick. Stone was used for critical structural elements such as vault ribs, arches, and areas requiring additional strength, like the lower section of the tower and the chancel connection. The ribbed vaults covering the naves rest on pointed arches supported by regularly spaced columns, and an upper gallery is integrated within the walls (Figure 1b). Little information is available on the vault filling. It is estimated that a structural infill exists up to mid-height, with the remaining space filled with lower quality material. A later intervention introduced a concrete slab over the passable roof, though details on its construction are limited.

Figure 1. Santa Ana Church: (a) aerial view; (b) interior, main altar.

3. DYNAMIC IDENTIFICATION

The OMA campaign of the church was conducted in September 2022. A total of 35 measurement points were instrumented, 22 on the roof of the nave (+14.4m to +16.4m above the ground level), three in each lateral apse (+12.0m), one in the central apse (+15.4m), four in the tower on two levels (+15.4m and +20.5 m) and two points in the galleries of the longitudinal arcades (+12.0m), which were accessed through manholes in the roof. Due to accessibility limitations, the upper level of the tower was not included in the campaign.

The available equipment consisted of five force balance triaxial accelerometers (KINEMETRICS ES-T, 0.01 to 200 Hz bandwidth, 155 dB dynamic range, 10 V/g sensitivity). To cover the 35 points to be measured, nine setups were defined, maintaining one accelerometer as reference and moving the others, as presented in Figure 2a. The accelerometers were connected to a 36-channel data acquisition system with an analogue-to-digital converter (Obsidiana 36X model), Figure 2b. For each acquisition, a sampling rate of 200 Hz and a duration of 20 minutes were set.
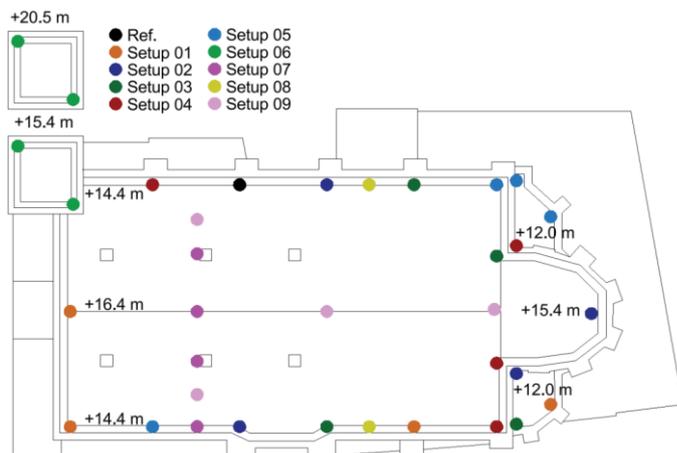
Figure 2. Ambient vibration test: (a) plan view of the accelerometer locations and setups; (b) acquisition system.

To process the data obtained from the test, two models were defined for a clearer insight into the dynamic behaviour of the building. The first model focused on a global analysis of the structure, including all the measurement points except the two located in the galleries of the longitudinal arcades. The second model focuses on the analysis of a single transversal section, including a total of 7 measurement points, comprising setup 07 and the sensors from setup 09 corresponding to the transversal section (Figure 2a).

The data was processed using ARTeMIS software [6]. The identification of the modes was challenging as not all the peaks were clearly distinguishable, and automatic identification was only possible for two modes. The singular values graph, employed for the identification of the global model according to the Frequency Domain Decomposition (FDD) algorithm, is presented in Figure 3.
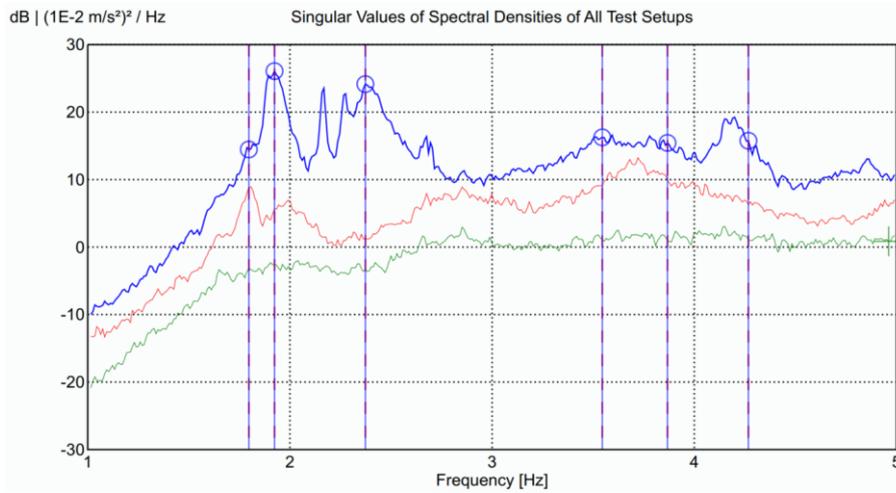

Figure 3. Experimental identification by the FDD method considering all the setups.

For a better identification, the singular values graph of each setup and the Power Spectral Densities (PSDs) of individual channels were analysed separately, along with the 2D model of the nave section. As a result, six modes were identified. The first mode is exclusive to the tower and was clearly detected by the tower sensors (Figure 4a). The second mode, although primarily involving the tower, also affects the nave, and can be clearly identified, as well as the third mode, which involves both the tower and the nave in a similar way. The three higher frequency modes were more complex to identify, especially mode six due to a lag in the frequency domain between the signals from one sensor and the others in different setups. Figure 4b shows some examples of channel signals that identify the frequencies of these modes more clearly. The final modes considering the entire campaign were chosen based on these additional analyses and the complexity of the modal shapes around these frequencies.
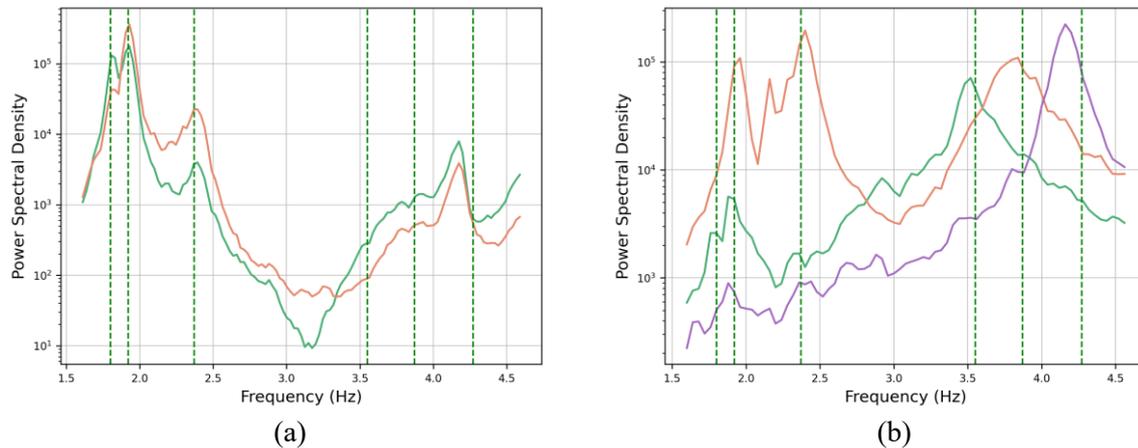

| (a) | (b) |

Figure 4. PSD graphs of representative sensors: (a) one tower top node in both horizontal axes; (b) three nodes on the nave. Green longitudinal, orange transversal, purple vertical.

The six modal shapes identified from the global model are presented in Figure 5. The first two are diagonal bending modes of the tower, with close frequencies of 1.80 and 1.92 Hz. The lower-frequency mode follows a diagonal between two free corners and does not affect the nave, while the higher-frequency mode follows a diagonal connecting one free corner to the nave, inducing nave movement. The third mode (2.37 Hz) combines a transverse bending shape of the nave with a tower bending mode, almost parallel to the façade, moving in counterphase with the nave. The fourth mode (3.55 Hz) involves the longitudinal movement of the nave, with minimal tower participation, while the fifth mode (3.87 Hz)

corresponds to a torsional motion of the nave, where the side not in contact with the tower shows the highest displacement, similar to the third mode. Finally, the sixth mode (4.27 Hz) is a vertical mode of the nave's roof.
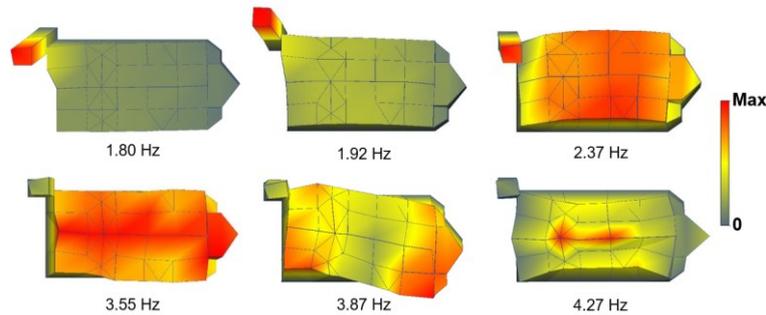

Figure 5. Six experimental vibration modes of the global model.

Figure 6 presents the modal shapes identified for the second model, including two translational modes in the plane of the portico, one translational mode perpendicular to the 2D structure, a torsional mode, and a vertical mode of the roof. The first tower mode was not detected. All other modes were identified, though the fifth mode (3.81 Hz) was more difficult to identify due to limited movement. The extracted natural frequencies and modal shapes are in good agreement with the results of the global mode.
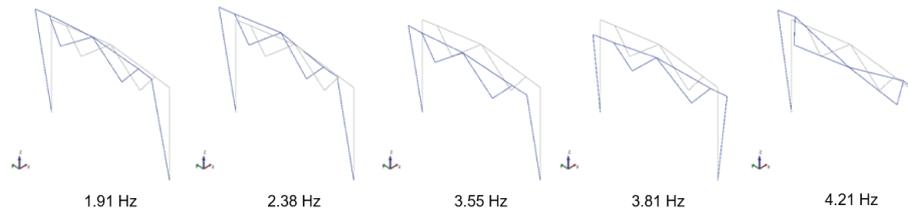

Figure 6. Five experimental vibration modes of the portico model.

4. NUMERICAL MODEL AND CALIBRATION

The first step in the definition of the finite element model (FEM) is the modelling of the geometry of the structure. This geometry is obtained from existing drawings and in situ measurements, enhanced with information obtained from a photogrammetric model. Material properties were defined on the basis of detailed visual inspection, literature review and sonic tests [7]. The software chosen for the definition of the numerical model of the building was Abaqus CAE [8]. After modelling the geometry in a CAD program, it was imported into the calculation program and meshed, using cubic elements.

Following the definition of the initial FEM, the modal properties derived from the dynamic identification test are used to calibrate the model. This methodology involves updating the values of a set of variables to align the numerical and experimental dynamic responses [9] [10]. To achieve this, a preliminary sensitivity analysis was conducted to assess the influence of the variables on the numerical estimation of the dynamic properties. Typically, the parameters associated with the greatest uncertainty are selected as variables, such as Young's modulus of materials and/or boundary conditions. The variables involved in the calibration are presented in Figure 7.

For the connection between the nave and the tower, which were initially considered to be fully connected, a contact interaction was modelled through a surface-to-surface contact in Abaqus software. In the normal direction, a linear pressure-overclosure relationship was defined, with the contact stiffness defined as the calibration variable. In the tangential direction, a rough friction formulation was applied, preventing relative sliding between the connected surfaces. This allowed the calibration of the first two modes. The third mode is also sensitive to this connection, particularly in generating out-of-phase vibration between the tower and the nave, although it is also influenced by the masonry properties of the vertical elements – a dominant factor also for the fourth and fifth modes.
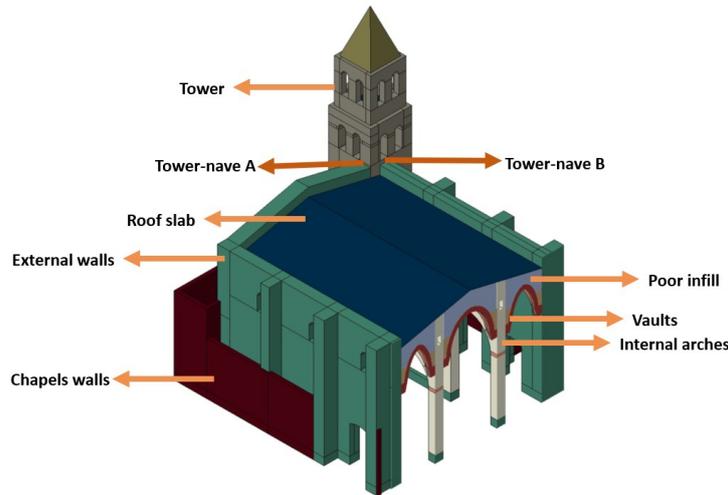
Figure 7. Elements of the model involved in the calibration.

In the sixth mode, the slab and the poor infill play a significant role, having some influence on the third mode. The definition of these two elements was challenging due to the lack of information. The slab was estimated to be 10 cm thick and was modelled as being connected to the internal faces of the perimeter walls and the upper faces of the internal arches. The poor infill was modelled as a solid element connected to the slab and vaults, but disconnected from the vertical elements by a geometric setback of 1 cm. The calibration parameter for these elements was the Young's, modulus whose values were highly affected during calibration, especially for the poor infill. Table 1 shows the final updated values of the variables.

Table 1. Variables of the FEM model calibration process. Initial and updated values.

Element	Variable	Initial value	Updated value
Tower (Tw)	Youngs's modulus [MPa]	1500	1150
Ext. walls	Youngs's modulus [MPa]	1500	1150
Int. arches	Youngs's modulus [MPa]	1500	1150
Vaults	Youngs's modulus [MPa]	1500	1300
Poor infill	Youngs's modulus [MPa]	25	110
Roof slab	Youngs's modulus [MPa]	25000	35000
Chapels walls	Youngs's modulus [MPa]	1500	1000
Tw-nave A	Connection [MPa m]	connected	14
Tw-nave B	Connection [MPa m]	connected	10
Tw-chapel A	Connection [MPa m]	connected	100
Tw-chapel B	Connection [MPa m]	connected	100

The calibration process was carried out manually, carefully adjusting the values of the variables and calculating the eigenvalue for each singular modification, resulting in a process involving numerous iterations. Including six modes in the calibration adds complexity, as improving the calibration of one mode can negatively affect another. To address this, a balance must be struck between prioritising frequency accuracy and modal shape alignment, ensuring the best overall calibration.

In the initial model, although the first six modes globally correspond to the six modes identified during the experimental campaign, the sequence of modes was not preserved, and several frequency values exhibited a significant margin of error, as shown in Figure 8. The main discrepancies in frequencies, which lead to a change in the order of the modes, correspond to the two modes of the tower and the vertical mode of the roof. For the tower modes, a reduction in frequency was required, which was achieved by decreasing the stiffness of the connection to the nave and chapels, thus increasing flexibility for this element. This adjustment establishes the correct order of the first three modes. In the case of the roof, where the poor infill and slab were identified as the variables most influencing this element, the frequency was calibrated by increasing the Young's modulus values of these two components, thereby

producing a stiffer roof. This increase in frequency shifted the initial mode 4 to mode 6, which then properly ordered the last three modes.
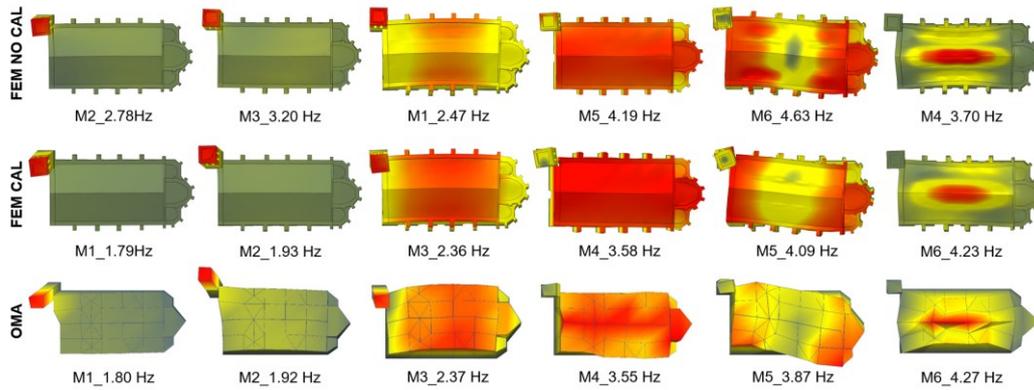

Figure 8. Dynamic properties comparison of the experimental and numerical models, initial and calibrated (CAL).

The comparison of the modal shapes presented in Figure 8 qualitatively demonstrates the agreement between the numerically predicted modal properties and the experimental results. Furthermore, the results are evaluated in terms of the relative error of the natural frequencies and the modal assurance criterion (MAC), as outlined in Table 2. In terms of frequency, it can be observed that, except for mode 5, the updated values show a maximum error of 1%, indicating a high correlation. For mode 5, the frequency was reduced from 4.65 Hz to 4.09 Hz, though it was challenging to get closer to the experimental value of 3.87 Hz. This mode is influenced by numerous variables, and further refinement would have resulted in greater errors in the other modes. Therefore, the calibration of the remaining modes was prioritized, provided that acceptable values for mode 5 were maintained. Regarding MAC comparison, the first four modes exhibit significantly good agreement. While the two modes with higher frequencies present a similar shape at a qualitative comparison, they show lower MAC values. Modes at higher frequencies generally exhibit more complex behaviour and pose greater challenges for identification during data processing in the experimental campaign. This complexity could justify the lower MAC values observed. Nevertheless, the calibration of these modes can still be considered reliable.

Table 2. Experimental and numerical frequencies and MAC comparison.

| Mode | Frequency | | | MAC |
	Experimental [Hz]	Numerical [Hz]	Error [%]	
1	1.80	1.79	-0.4	0.96
2	1.92	1.93	0.3	0.89
3	2.37	2.36	-0.5	0.97
4	3.55	3.58	1.0	0.91
5	3.87	4.09	5.7	0.61
6	4.27	4.23	-0.9	0.53

5. CONCLUSIONS

This study has focused on the dynamic identification of the Church of Santa Ana in Seville based on the OMA campaign. During the data processing, it became evident that identifying certain modes, when considering the global response from all sensors, presented significant challenges, specifically the local mode of the tower and the three higher-frequency modes.

To address this limitation, a thorough and detailed analysis was carried out, focusing on the individual signal from each setup and channel in order to identify the modes as reliably as possible. Additionally, a second, simplified model of a section of the nave was defined. This approach enhanced the accuracy of mode identification, contributing to a more precise evaluation of the structure's dynamic response.

Regarding the numerical model, the results obtained from preliminary inspection and non-destructive testing allowed for initial numerical modal shapes sufficiently close to those identified during the experimental campaign, despite certain discrepancies in frequency values. The subsequent calibration of the frequencies and modal shapes yielded highly satisfactory results, resulting in a remarkably accurate numerical model. This provides an essential insight into relevant aspects of the structural response, including the connection between the tower and the nave and the characteristics of the nave's infill. The updated model constitutes a solid foundation for conducting further analyses of the seismic vulnerability of the structure, marking a significant step toward proper and informed conservation.

ACKNOWLEDGEMENTS

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