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Dynamic Identification and FE Updating of S. Torcato Church, Portugal

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NOMENCLATURE

ω Natural frequency value
φ Mode shape vector

ABSTRACT

San Torcato Church is located near the city of Guimarães, Portugal. The construction of the church started in 1871 and completed in recent years. The church combines several architectonic styles, like Classic, Gothic, Renaissance and Romantic. This “hybrid” style is also called in Portugal as “Neo-Manuelino”. At the moment, the church has significant structural problems due to soil settlements of the main façade. Cracks can be observed in the main and lateral facades. The cracks are visible from the outside and inside of the temple. The bell-towers are leaning, and the arches in the main nave present vertical deformations. Non-stabilized phenomena are present in the structure. To stabilize the damage, a structural intervention is planned to occur soon and the church is already monitored to assist the intervention. The paper clearly presents the problem with emphasis to the dynamic analysis carried out before the structural strengthening, namely: the experimental tests with output-only techniques for frequencies, damping and mode shapes estimation, and FE model updating analysis.

1. INTRODUCTION

Before any intervention to a structure, identification of all structural properties and damage sources has a significant importance. Although numerical model analyses methods allow one to simulate various cases, estimation or assumptions of the structural properties are not easy. To alter these difficulties many non-destructive methods have being developed but the information of those techniques rather local or insufficient.

Experimental dynamic identification techniques, which are generally based on the acceleration records of a structure, allow us to obtain natural frequencies, mode shapes and damping coefficients. These data represent the dynamic response of a structure, as a result of its physical properties that are unknown or difficult to obtain.

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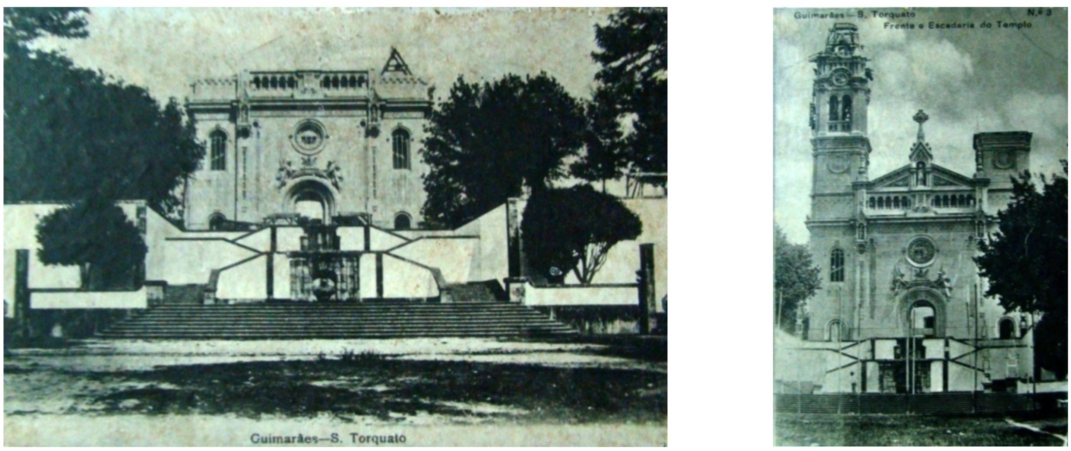
By this way, the real response of the structure under specified or unknown excitations can be used to calibrate Finite Element (FE) models.

In this context, modal identification tests were carried out on San Torcato Church to tune a FE model used for safety analysis. The work includes the experimental campaign for estimation the modal parameters (natural frequencies, mode shapes and damping coefficients) and procedures to tune accurately the FE model.

2. SAN TORCATO CHURCH

San Torcato Church is located in the village of St. Torcato, 7 km North from the city of Guimarães, Portugal. Construction of the church started in 1871 and completed in recent years. In Figure 1 early stages of the construction can be seen. The church combines several architectonic styles, like Classic, Gothic, Renaissance and Romantic. This “hybrid” style is also called in Portugal as “Neo-Manuelino”.



(a) (b)

Figure 1 - Early stages of the construction (San Torcato Museum): (a) mail façade without towers, and (b) the first tower construction.

Architectural plan shape of San Torcato Church exhibits a classical cross basilica scheme (Figure 2) with the main nave covered with a barrel vault, transept that is crowned with a dome in the middle and the apse part. Besides the main façade, two towers are located. Between towers and transepts, one story with low height was added to the church from both sides of the nave. Accesses to the towers are provided from inside those buildings.

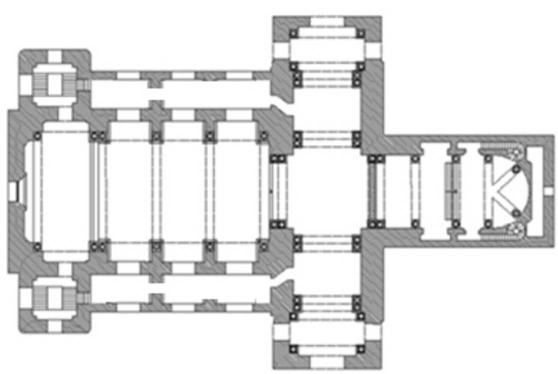


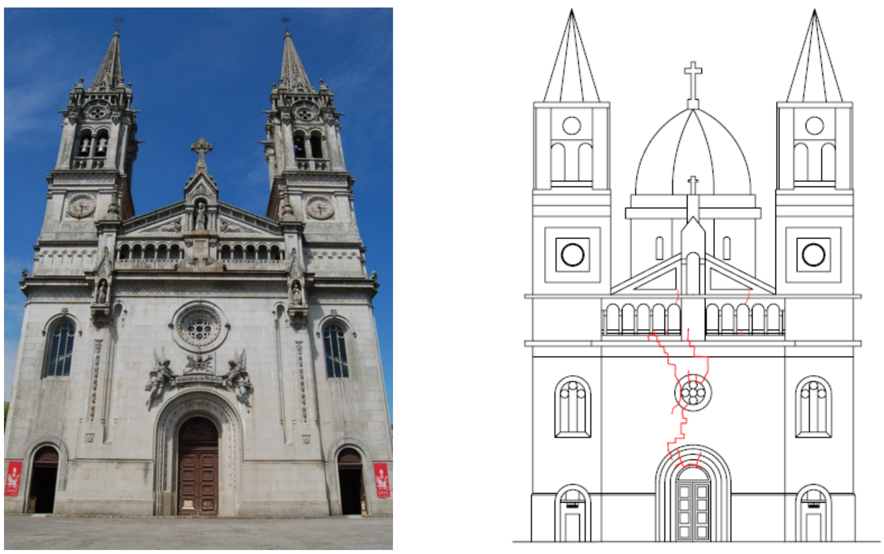
Figure 2 - Plan of San Torcato Church.

The nave of the church has 25 m length and 15 m width. The walls have 1.30 m of thickness. The nave is covered with a barrel vault which is supported by stone arches. The vault stands on stone columns that are supported with buttresses adjacent to body walls of the nave. At the transition with transept, main dome is carried by a masonry double arch.

The bell towers are located beside the main nave, adjacent to the facade. They have rectangular plan shape with 7.50 m in length and 6.20 m width, measured from outer surface. Load bearing walls of the towers are 1.45 m in thickness and have 32.70 m high until the belfry level. Belfry parts of the towers have two arched openings in all directions and have 8 m of elevation. The towers are covered with conical roofs.

Due to the construction long duration, structural techniques and materials vary within whole structure. The main façade, towers, lateral façades beside the towers and main nave are prior in construction phase and are made of granite stone with dry joints. The apse is combined with reinforced concrete walls after the springing level of the vault.

The significant structural problem of the structure is the crack pattern on the main facade due foundation settlements. The cracks than can be seen on the main façade, starting from the mid arch at the main entrance and goes through the rose window and reaches to the left and right corners of tympanum (Figure 3). The continuity of cracks inside the church and tilting of the towers indicates a settlement due to high stress level of towers and soft filling layer of soil.



(a) (b)

Figure 3 - Facade view of San Torcato Church and the damage pattern: (a) general view; and (b) damage map.

3. DYNAMIC IDENTIFICATION

3.1 Test Planning

In experimental modal analysis of San Torcato Church, 10 uniaxial PCB 393B12 model piezoelectric accelerometers with a bandwidth ranging from 0.15 to 1000 Hz (5%), a dynamic range of ±0.5 g, sensitivity of 10 V/g, 8 μg of resolution and 210 gr of weight were used. For data acquiring, a 16 channel Digital to Analogue Converter (ADC) was used (Figure 4).

(a) (b)

Figure 4 - Conventional equipments used for dynamic identification: (a) accelerometers; and (b) and data acquisition system.

For the expected frequency range, preliminary test results [1] were taken into account. The first four natural frequencies were ranging from 2 to 4 Hz. To select the measuring, mode shapes of the FE model previously studied for safety analysis was used.

Records were taken in 35 points within 9 test setups. Schematic layout of sensors is given in Figure 5. Reference accelerometers were decided to be placed at the top of the towers (two accelerometers in each tower in two perpendicular directions) because of their high amplitude and modal contribution in each mode. Towers and main facade had to be measured accurately as they have serious damages. Thus, the amount of measurement points was chosen dense in this area. The nave of the structure was decided to be measured in 13 points in the vault; at the supports and at the top. Transept was decided to be measured at the corners. In the apse part, two points were selected at the corners.

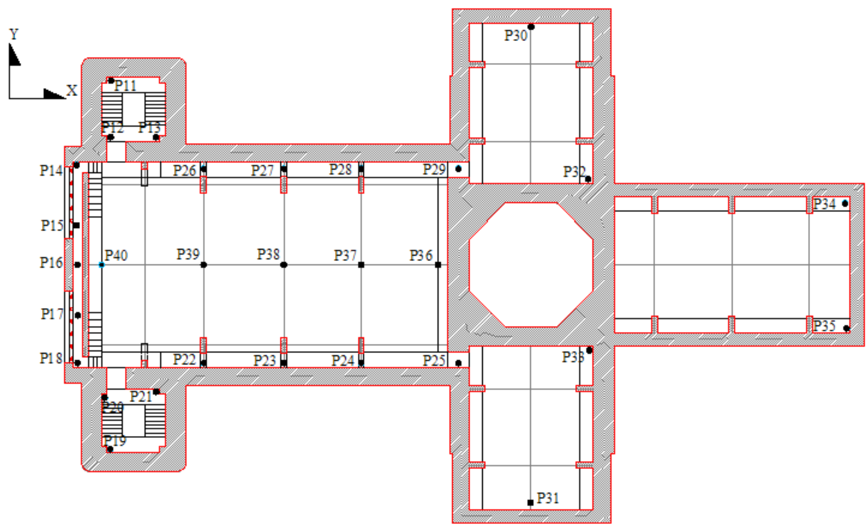


Figure 5 - Plan scheme of measured DOFs.

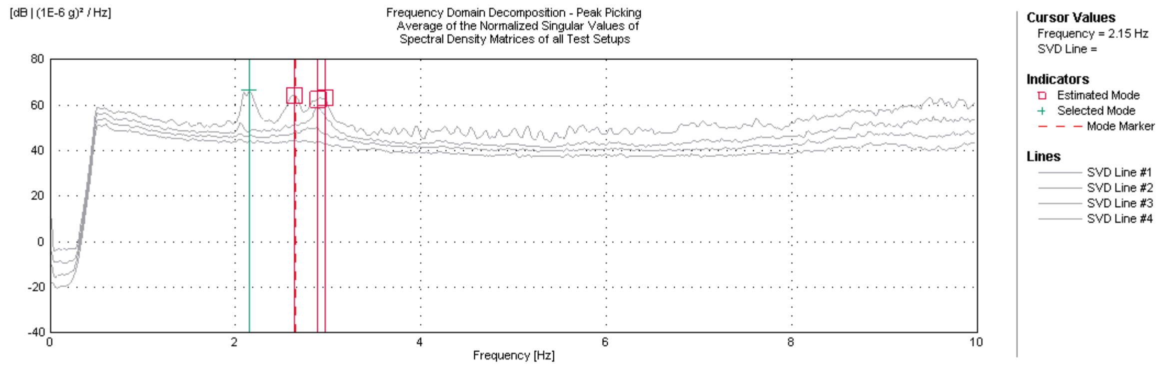
Accelerations were recorded with 200 Hz sampling rate for 10 minutes. Ambient vibration was used as excitation. The wind and traffic excitation was enough to obtain, at least, the first four modes for all structure.

3.2 Dynamic Results

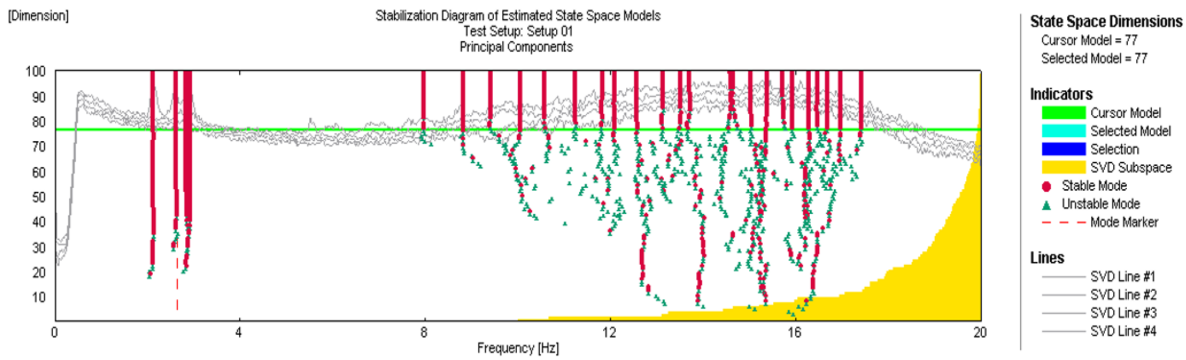
By using Frequency Domain Decomposition (FDD) [2] technique each mode is estimated as a decomposition of the system's response spectral densities into several single-degrees-of-freedom (SDOF) systems. For frequency domain analysis, the frequency range was between 0 and 2 Hz, with 1024 points window length, and with 66.7% overlap.

Frequency response graphs are very useful to interpret the data roughly. When the graphs are examined, in each setup, between 2 to 3 Hz clear peaks are identified (Figure 6a). In different setups some other peaks are visible in the range of 4 to 5 Hz. However, to be able to identify global frequencies, all the setups were processed together.

To compare the results with other frequency domain techniques, the Enhanced FDD [3] and Curve-Fit FDD [4] were used. Also the Stochastic Sub-Space Identification (SSI) method [5], based on the solution of state space matrices, was used to check the results. For the SSI analysis, SSI-PC (Stochastic Subspace Identification-principal component) method was used (Figure 6b). In Table 1 the frequency estimation of natural frequencies within the chosen methods is given.



(a)



(b)

Figure 6 – Estimation methos: (a) FDD method, and (b) SSI method.

Table 1: Comparison of frequency domain methods with SSI method

	FDD		EFDD		CFDD		SSI
	Frequency [Hz]	Error [%]	Frequency [Hz]	Error [%]	Frequency [Hz]	Error [%]	Frequency [Hz]
Mode 1	2.15	0.4	2.14	0.1	2.13	0.3	2.14
Mode 2	2.64	0.4	2.62	0.1	2.62	0.1	2.63
Mode 3	2.89	1.3	2.89	1.1	2.86	0.3	2.85
Mode 4	2.97	1.4	2.94	0.3	2.93	0.1	2.93

The estimated frequencies with all different methods gave very close results. Also the results of the previous dynamic analysis [1] which were carried out in towers and on the balcony in separated setups exhibit similar results, with the first four frequencies equal to 2.13, 2.60, 2.81, and 2.92 Hz for the North tower, and 2.13, 2.62, 2.85, and 2.90 Hz for the South tower.

Figure 7 presents the estimated mode shapes. In the first two modes it is observed translational modal displacements in X and Y directions. Third and forth mode exhibits torsion modes. Towers move diagonally in opposite directions while the nave is bending.

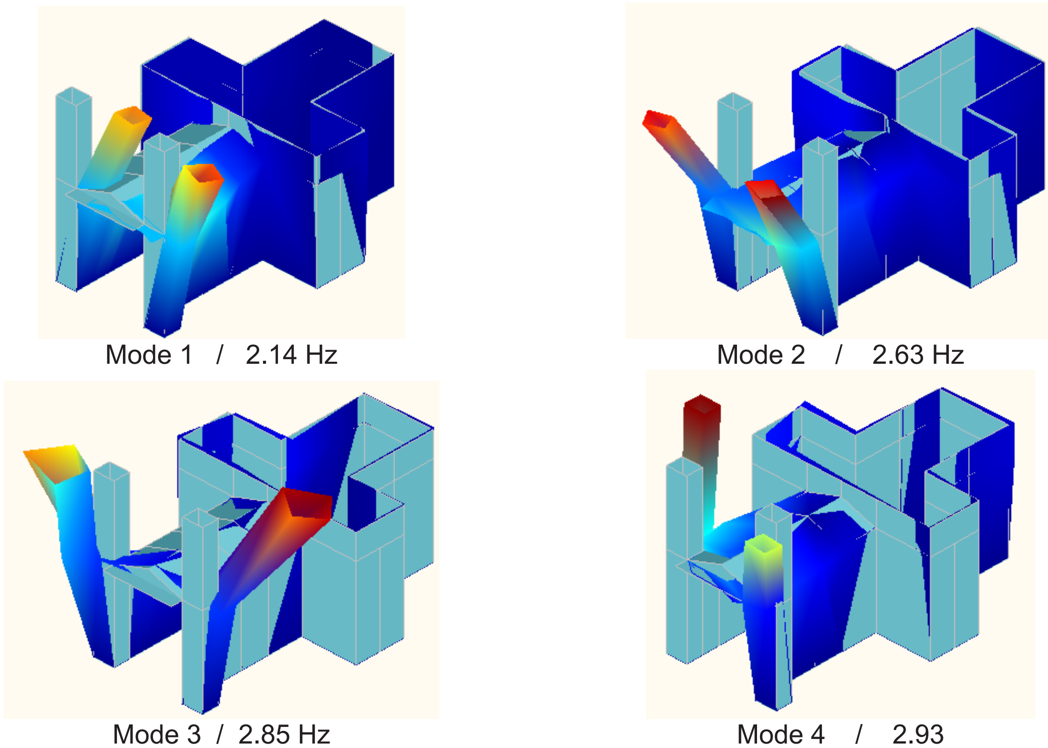


Figure 7 – Mode shapes of the structure

4. MODAL UPDATING

4.1 FE Model

The numerical model of San Torcato church was built for the static non-linear analysis. The model was built in iDiana Release 9.3 Software [6]. Only the nave, façade and towers were modeled.

The model was built with 20 nodes quadratic solid elements CHX60 and with 15 nodes quadratic wedge elements CTP45. The architectural details were neglected and only structural solid parts were modeled. Totally, the model has 3044 solid elements with 3153 DOF.

For soil structure interaction, 16 nodes quadrilateral interface elements CQ48 were used. Soil properties defined elastic and masonry elements were considered homogeneous in all parts of the structure (Figure 8).

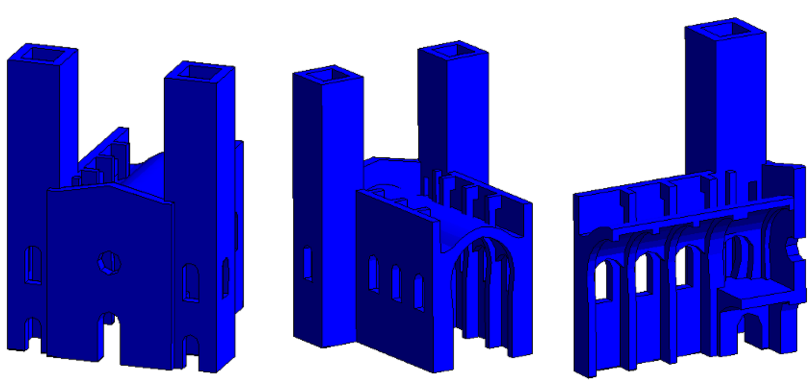


Figure 8 – 3D visualization of numerical model

The following hypothesis and assumptions were used in the model:

- Soil-structure interaction is defined with interface elements which allow definition of horizontal and vertical stiffness properties of soil. For the numerical assumption of the properties, a previous soil investigation results were used [1];
- Weight of the masonry assumed as 25 kN/m^3;
- The Poisson's ratio of the masonry defined as 0.2;
- Homogeneous masonry material was used in all parts of the structure;
- Due to incomplete model, the missing part of the structure was simulated by introducing interface elements at the intersection with transepts, to simulate the stiffness of the missing parts.

4.2 Model Updating

The finite element model updating procedure was carried out with four updating parameters with the initial values given in the Table 2. The Young's modulus of the masonry E_m, the normal stiffness of the first soil-structure region E_s, the normal and shear stiffness properties of interface elements at the missing part, E_{tn} and E_{ts}, respectively.

Table 2: Initial values for the updating parameters

E_m	15	GPa
E_s	3900	kPa
E_{tn}	Rigid	-
E_{ts}	Rigid	-

For the comparison between experimental and numerical data frequencies and modes shapes were used. The modes were compared by the Modal Assurance Criterion (MAC) [7]. The MAC is the most commonly used method to investigate the consistency of two different models. It depends on the correlation of modal vectors and varies from zero to one, depending on the consistence of the models. A MAC value equal to one indicates 100% match of both mode shape vectors. MAC is defined by:

$$MAC_{e,n} = \frac{\left| \sum_{i=1}^{n} \varphi_i^e \, \varphi_i^n \right|^2}{\sum_{i=1}^{n} \left(\varphi_i^e\right)^2 \, \sum_{i=1}^{n} \left(\varphi_i^n\right)^2} \qquad (2)$$

where φ^e and φ^n are the mode shape vectors, experimental and numerical, respectively.

The structural updating parameters and their effect on the updating results were first studied manually by comparing the frequencies and MAC values. The contribution of each parameter was studied independent from the other variables. To the best combination was chosen after several trials. The results of the starting point for the robust updating analysis are presented in Figure 9, in terms of mode shape comparison, according to the different parts of the structures, and the MAC and frequency comparison plot. The numerical model was too stiff according to the experimental natural frequencies.

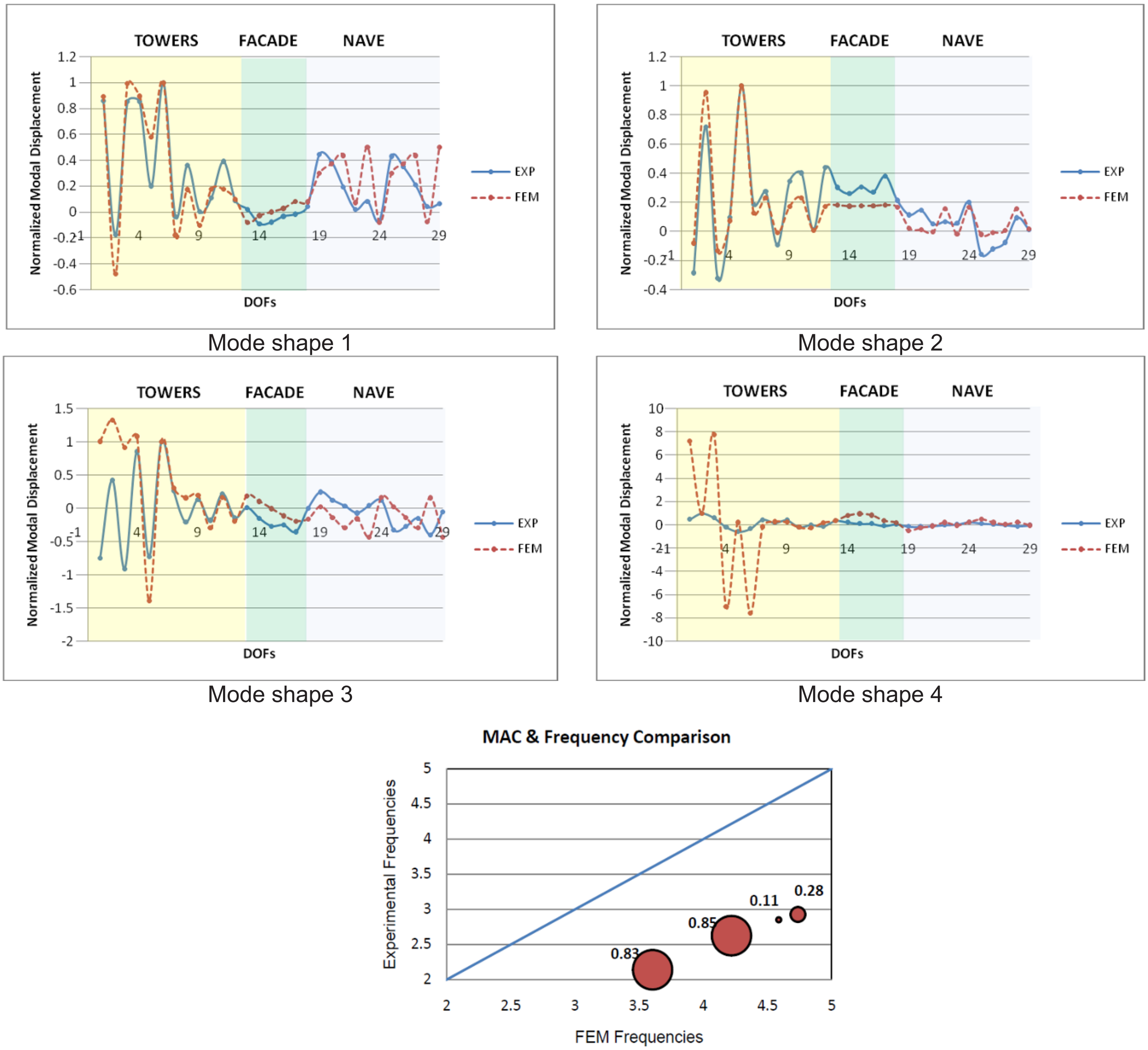


Figure 9 - Comparison between experimental and numerical results before robust updating analysis

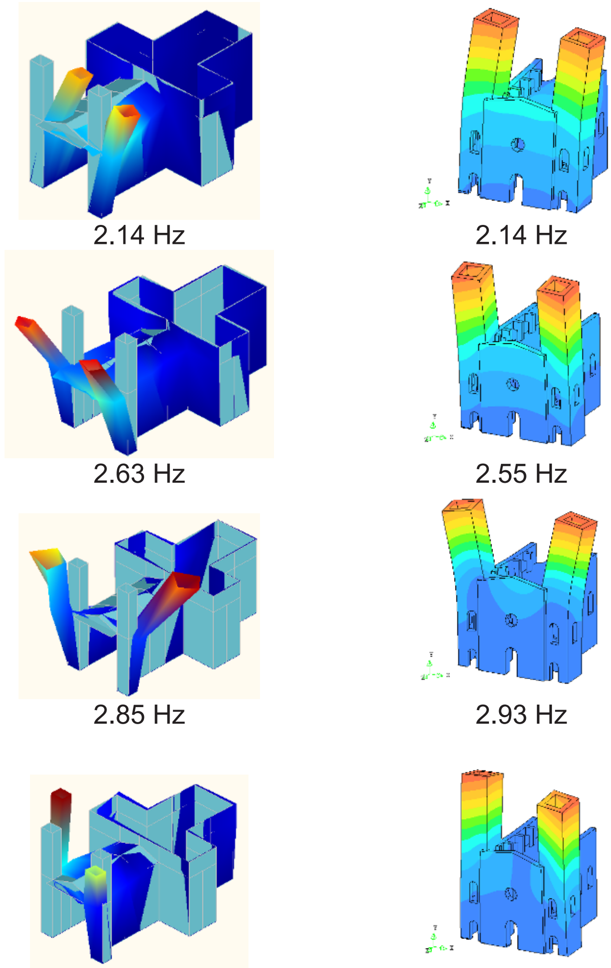
For the robust updating analysis, the Douglas-Reid method was used [8]. Lower and upper boundaries for the updating variables were defined according to engineering judgment. The updating results are presented in Table 3. The frequency errors are lower than 3% and the MAC values higher than 77%. The updated values for the structural parameters are consistent from the engineering point of view.

Table 3: Results of the robust updating analysis

Name	Optimum	Modes	ω_{exp} [Hz]	ω_{FE} [Hz]	ω Error [%]	MAC
E_m	5.642 GPa	1st (Transversal Y)	2.14	2.14	0.09	0.92
E_s	0.629 GPa	2nd (Longitudinal X)	2.63	2.55	2.86	0.86
E_{tn}	0.046 GPa	3rd (Torsional)	2.85	2.93	2.70	0.83
E_{ts}	21.591 GPa	4th (Torsional)	2.93	2.94	0.41	0.77

The mode shapes of the updated model exhibit high consistence with experimental mode shapes (Figure 10). In the first and second mode shapes (translational modes), no significant difference is observed between the modes. The third mode shape of the numerical model present similar behavior with experimental model, but when the north tower is examined, it can be seen that the torsion effect is higher than the numerical model. The forth mode shape also exhibit similar behavior, but the reason for having a low MAC value can be related with amplitudes of DOF's and the damage pattern which was not introduced in the analysis.

Experimental Results | FE Model



Mode 1: 2.14 Hz | 2.14 Hz

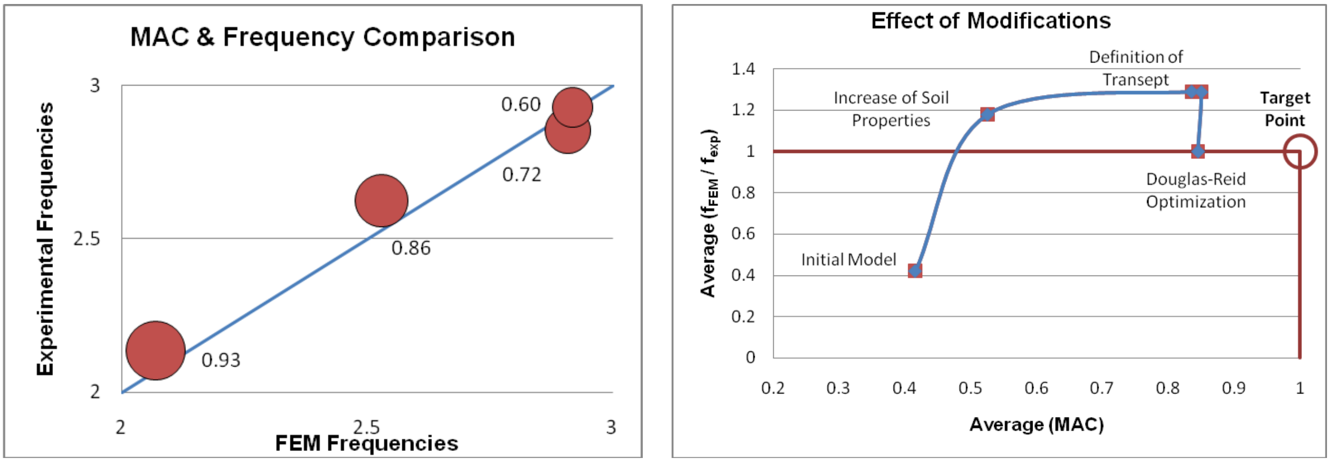
Mode 2: 2.63 Hz | 2.55 Hz

Mode 3: 2.85 Hz | 2.93 Hz

Mode 4: 2.93 Hz | 2.94 Hz

Figure 10 – Mode shape comparison

Figure 11a presents the MAC and frequency comparison plot, where now it can be seen that the frequencies are almost in the 45º line. Figure 11b shows the evolution of the results during the manual tuning and robust updating method. The effect of all the modifications is plotted by means of frequency ratio and MAC values. The final point presents a high contribution of the modifications relative to the starting point. However, the evaluation of results and still being far from the target point, which is desired to be one for MAC values and one for frequency. This indicates that the model needs of other modifications to achieve better results. Considering the crack's widths observed on the main façade, the simulation of the cracks by means of interface elements are advised for the next step.



(a) (b)

Figure 11 – Final updating results: (a) MAC and frequency comparison plot; and (b) evolution of the updating analysis.

5. CONCLUSIONS

The paper presents the modal identification analysis of San Torcato Church, together with one updating analysis of a FE model.

The data collected in the field was checked and processed with different methods. Due to the low level of excitation, only the first four global modes of the structure were estimated. The obtained results are high consistency with preliminary dynamic identification results, in terms of frequency and mode shapes.

A FE model, which was previously built for safety analysis, was updated by using manual and robust optimization procedures. Modifications were carried out on homogeneous elastic properties of masonry, elastic soil properties and stiffness parameters of the interface elements which were added to the model in order to simulate the missing part of the transept and apse. High consistence of the numerical model was obtained with manual modifications and non-linear algorithms, but further analysis considering the damage (cracks) should be carried out to achieve better results.

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