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Dynamic Identification and Monitoring of St. Torcato Church

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Abstract The paper is related to the San Torcato Church, in Guimarães, Portugal. At the moment, the church has significant structural problems due to soil settlements. Cracks can be observed on the main and the lateral façades, the bell-towers are leaning, and the arches in the nave exhibit a failure mechanism with cracks and 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 follow 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, FE model updating analysis and dynamic monitoring.

Keywords: Dynamic identification, modal updating, dynamic monitoring

Introduction

San Torcato Church is located in a small village near Guimarães. The church started to be constructed in 1871 and was completed in 2008. The church has a classical basilica plan scheme combining several architectonic styles, like Classic, Gothic, Renaissance and Romantic. This “hybrid” style is also called in Portugal as “Neo-Manuelino”. Due to the long construction process, different materials were used. The walls are manly in granite masonry, but the apse and the main altar were constructed in reinforced concrete walls and covered with granite veneer walls. Thus the structure exhibits complexity both in material and structural levels.

By simply looking to main façade a significant crack can be observed. Starting from the key stone of the entrance door arch, the crack goes through the rose window to the roof, splitting the façade in two macro blocks, as it is represented in Figure 1. The crack pattern seen on the façade is also observed inside.

The leaning of the towers reveals that they are moving in opposite directions due to soil settlement. The hair cracks seen at the bottom of the towers might be related with the compressive stress concentration caused by eccentric loads.

A finite element model of the church was built in 2000. The model includes the main façade with the towers and the nave till the transept (parts with structural problems). A static non-linear analysis was carried out to assess the safety of the church. The soil stiffness was also considered in the analysis, based on the results of soil inspection tests. At that time, no experimental tests were carried out to characterize the material’s properties, so the adopted mechanical parameters were introduced based on experience gather with related works. However, the results of the FE model reproduces quite well the observed damage.

As the church is going to be strengthened soon, it was decide to update the FE model by a global dynamic identification analysis and to install two monitoring systems, one static and one dynamic.

Experimental Dynamic Tests

Test Planning In the experimental modal analysis of San Torcato Church 10 uniaxial 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 bits channel Digital to Analogue Converter (ADC) was used.

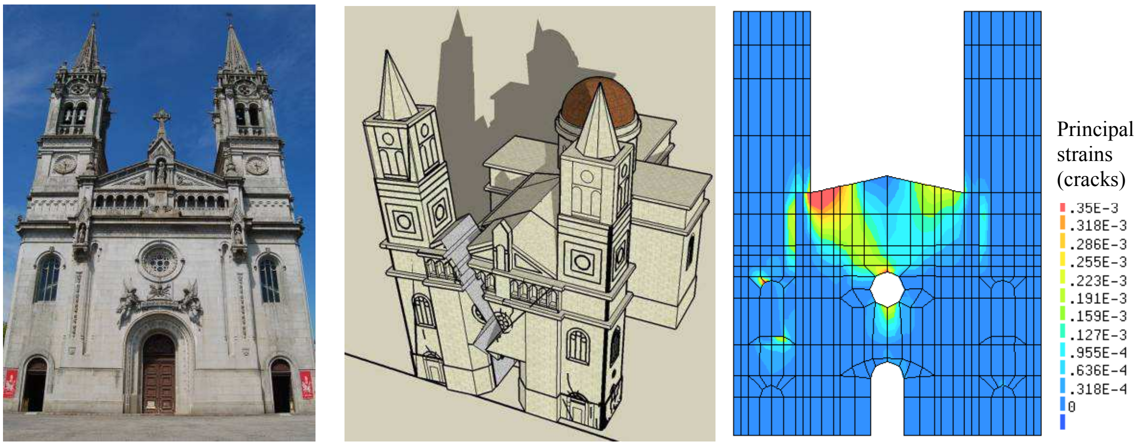

Figure 1 : Façade view, crack pattern representation, and numerical model with cracks

Records were taken in 35 points within 9 test setups. Schematic layout of sensors location is given in Figure 2. 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 façade had to be measured accurately as they have serious damages. Thus, the number and location of measurement points was chosen dense in this area.

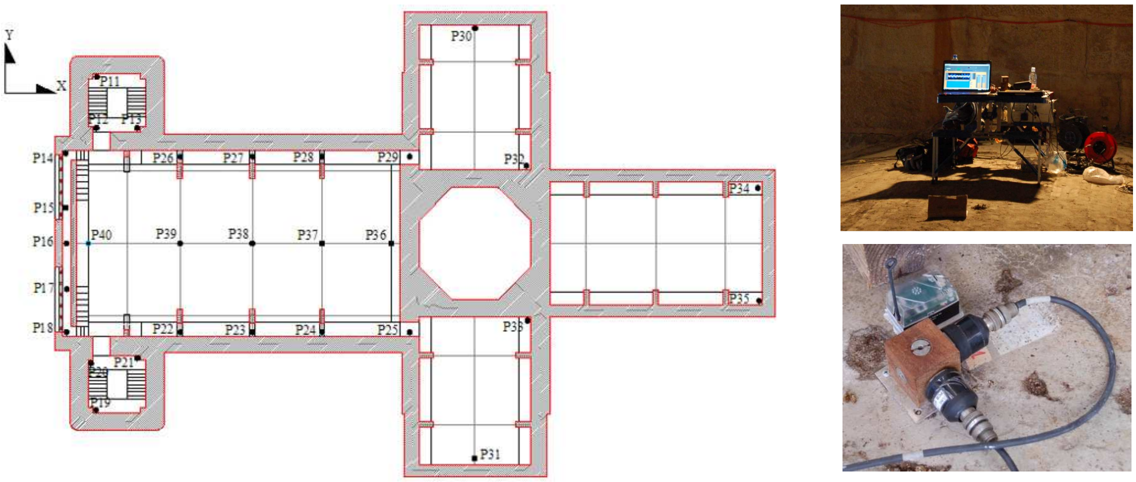

Figure 2: Plan scheme of measured DOFs, acquisition system and sensors

Dynamic Identification By using Frequency Domain Decomposition (FDD) technique (Brincker et al. 2000), each mode was estimated as a decomposition of the system's response spectral densities into several single-degrees-of-freedom (SDOF) systems.

To compare the results with other frequency domain techniques, the Enhanced FDD method (Rodrigues et al. 2001) and Curve-Fit FDD method (Jacobsen et al. 2008) were used. Also the Stochastic Sub-Space Identification (SSI) method (Peeters and De Roeck 2001), based on the state space formulation, was used to check the results. For the SSI analysis, SSI-PC (Stochastic Subspace Identification principal component) method was used (see Fig. 3). In Table 1 the frequency estimation according to each method is given and the error taking the SSI method as reference.

Modal Updating

Finite Element Model The model was rebuilt in iDiana Release 9.3 Software (TNO 2008). Only the nave, façade and towers were modelled. The model was built with solid elements and interface elements to simulate the soil structure interaction.

The following hypothesis and assumptions were used:

- 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 (Ramos and Aguilar, 2007);
- 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.

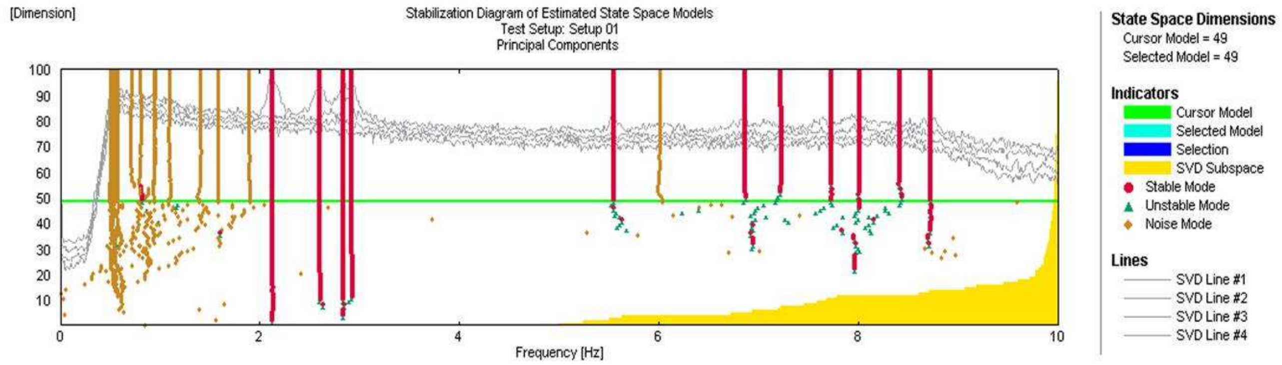

Figure 3: Estimation of frequencies with SSI method.

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	–0.50	2.14	<0.01	2.13	+0.50	2.14
Mode 2	2.64	–0.50	2.62	+0.50	2.62	+0.50	2.63
Mode 3	2.89	–2.00	2.89	–2.00	2.86	–0.50	2.85
Mode 4	2.97	–2.00	2.94	+0.50	2.93	<0.01	2.93

Modal Updating The FE updating procedure was carried out through a series of updating analysis. Here, only the last analysis with four updating parameters will be presented in detail. 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. The initial and the updated values are presented in Table 2.

Table 2: Initial Values for the updating parameters

Updating Parameters	E_m	E_s	E_{tn}	E_{ts}
Initial Values	15.00 [GPa]	3.90 [GPa]	0.10 [GPa]	100.00 [GPa]
Final Values	5.60 [GPa]	0.63 [GPa]	0.05 [GPa]	21.59 [GPa]

For the comparison between experimental and numerical results, frequencies and modes shapes were used. The modes were compared by the Modal Assurance Criterion (MAC) (Allemang, 2003). It depends on the correlation of modal vectors and varies from zero to one, depending on the consistence of the models. MAC value equal to one indicates 100% match of both mode shape vectors. MAC value is defined by:

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

where $\varphi^{\exp}$ and φ^{FE} are the mode shape vectors, experimental and numerical, respectively.

For the robust updating analysis, the Douglas-Reid method was used (Douglas et al., 1982). Lower and upper boundaries for the updating variables were defined according to engineering judgment. The updated results in terms of frequencies and MAC values are presented in Table 3. The mode shapes of the updated model exhibit high consistence with experimental mode shapes (see Fig. 4).

Table 3: Results of the robust updating analysis

	Modes	*Experimental* [Hz]	*FEM* [Hz]	*Error* [%]	*MAC*
1^{st}	Transversal (*y*)	2.14	2.14	<0.01	0.92
2^{nd}	Longitudinal (*x*)	2.63	2.55	3.04	0.86
3^{rd}	Torsion	2.85	2.93	2.81	0.83
4^{th}	Torsion	2.93	2.94	0.34	0.77

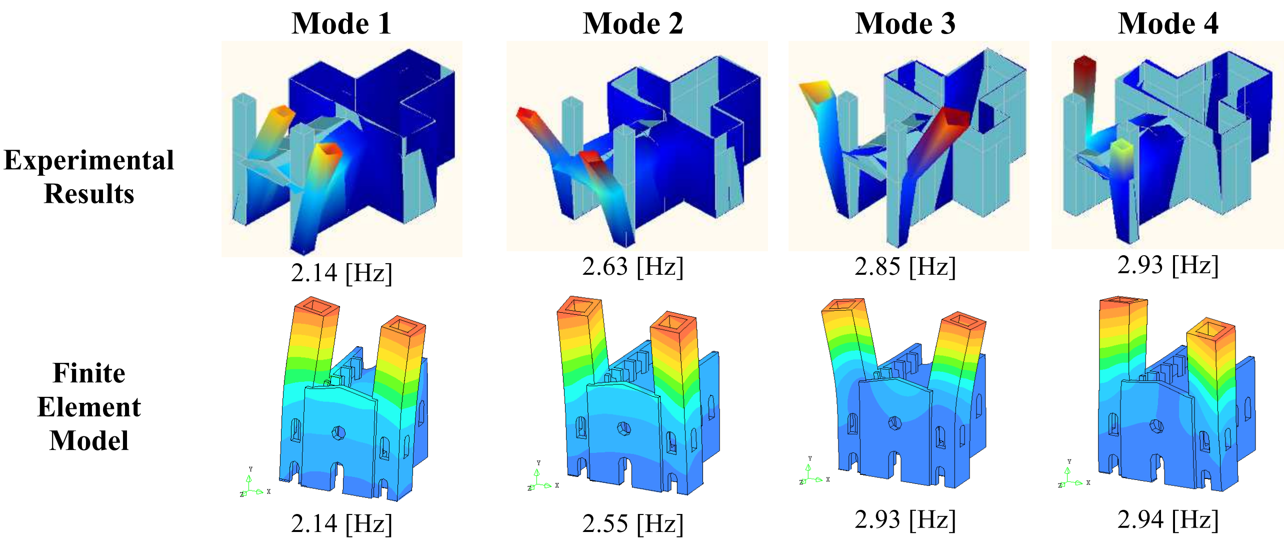

Figure 4: Mode shape comparison

Figs. 5-a and 5-b presents the MAC and frequency comparison plot of the initial model and updated model, respectively. The updated frequencies are almost on the 45º line, which corresponds to a good correlation. Fig. 5-c shows the evolution of the results during all the updating analysis. 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 are still far from the target point, which is desired to be one for MAC values and one for frequency ratio. This indicates that the model needs 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.

Dynamic Monitoring System

A continuous dynamic monitoring system was installed in the church starting from November 2009. This monitoring system was planned to be composed by four piezoelectric accelerometers, one portable DAQ unit, one Uninterruptible Power Supply (UPS), and one computer with embedded processador Pentium IV as remote station. A modem was included in the monitoring system to periodically send the processed data via GSM to a local FTP account. The accelerometers were located in two nodes in the towers of the church (one in each tower) for performing measurements in perpendicular directions. The central data acquisition station, as well as a scheme of the location of the measurement nodes is shown in Fig. 6.

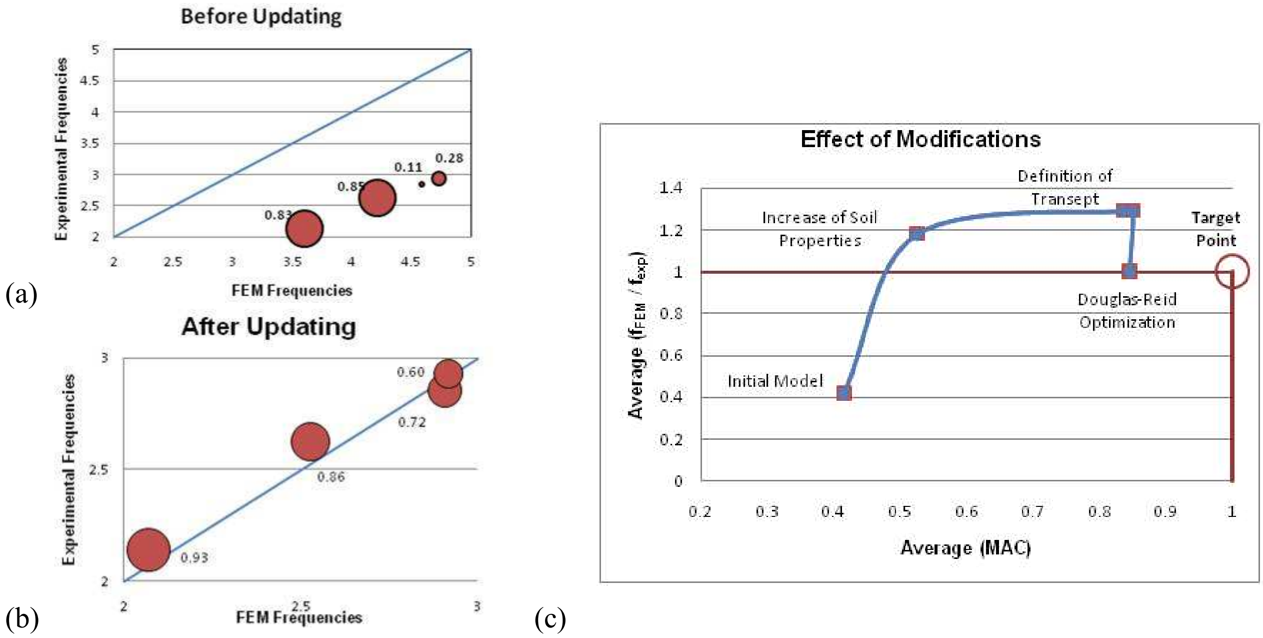

Figure 5: a-b) Comparison of the models before and after the updating processes and c) overall effects of modifications

Figure 6: Continuous Dynamic monitoring system setup. (a) Data acquisition station; and (b) measurement node

The time series recordings were remotely processed using an automatic feature extraction tool especially developed for this purpose. The results of the evolution of the first four natural frequencies of the structure are shown in Fig. 7.

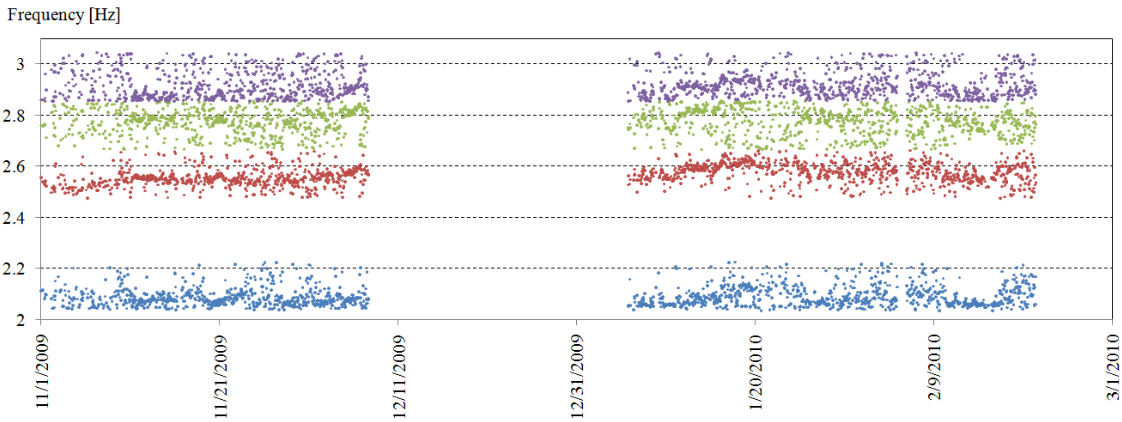

Figure 7: Evolution of the natural frequencies – St. Torcato church case of study

Conclusions

The paper presents how the dynamic global analysis carried out on San Torcato Church before the strengthening intervention can be useful to calibrate the numerical model. Modal parameters were accurately estimated with ambient vibration analysis. A FE model previously built for safety analysis was updated by using manual and robust optimization procedures. High consistence of the numerical model was obtained with non-linear optimization algorithms, but further analysis considering the damage (cracks) should be carried out to achieve better results. The church is currently being observed by continuous dynamic monitoring system which will be useful to evaluate the structural intervention.

References

[1] Allemang, J R (2003). "The Modal Assurance Criterion – Twenty Years of Use and Abuse." *Sound and Vibration* , 14-21.
[2] Brincker, R, Zhang, L, and Andersen, P (2000). "Output-only Modal Analysis by Frequency Domain Decomposition," in *Proceedings of ISMA25* 2.
[3] Douglas-Reid, BM, WH (1982). "Dynamic tests and system identification of bridges." *Journal Struct. Div., ASCE*,108, 2295-2312.
[4] Jacobsen, N J, Andersen, P, and Brincker, R (2008). "Applications of Frequency Domain Curve-fitting in the EFDD Technique."
[5] Peeters, B, and De Roeck, G (2001). "Stochastic System Identification for Operational Modal Analysis: A Review." *Journal of Dynamic Systems, Measurement, and Control*, 659-667.
[6] Ramos, LF, and Aguilar, R (2007). "Dynamic Identification of St. Torcato's Church: Preliminary Tests." Guimarães, Portugal, University of Minho, Technical Report, 30.
[7] Rodrigues, J, Brincker, R, and Andersen, P (2001). "Improvement of Frequency Domain Output-Only Modal Identification from the Application of the Random Decrement Technique."
[8] TNO (2008). "Displacement method ANAlyser", Version 9.3, Cd-Rom, Netherland.