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Modal characterization and NDTs of a historical church in Noto

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Abstract

Assessment of historical buildings is now a matter of fundamental importance in civil engineering and researchers have been long working to find the best investigation strategies and trying to limit their invasiveness as much as possible. Among other investigation techniques, modal characterization (or dynamic identification) has been gaining popularity due to its non-destructiveness for its ability to capture the behavior of the real structure. Combined with more traditional non-destructive-tests (NDTs) or semi-destructive-tests (SDTs), a complete view of the state of health of the structure can be obtained. The present work illustrates the experimental activities carried out on an historical church in Noto (Italy) with the aim to determine modal parameters of the main masonry structure, with an important focus on its façade. NDTs and SDTs were used to identify the main material properties, which were then implemented on a detailed Finite Element (FE) model. Finally, numerical results were compared with the experimental ones in order to ensure a good simulation of the real structural behavior.

1. Introduction

Recent earthquakes occurred in Italy have shown how historical masonry buildings, and especially churches, are often highly vulnerable against seismic actions. In fact, post-earthquake investigations on many masonry churches

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have revealed that these structures may experience severe damage even when they are hit by medium-intensity accelerations, due to their intrinsic inability to resist against horizontal actions (Canuti et al., 2021; Hofer et al., 2018). Some of the reasons behind such poor performance under seismic actions can be summarized as it follows: peculiar geometrical features, i.e. tall and slender walls without any transverse connection, the presence of large openings, the absence of rigid floors, etc., that favor the occurrence of local mechanisms rather than an overall response (Zizi et al. 2021). In addition, structural complexity due to subsequent morphological transformation in time (Puncello et al., 2022), poor material properties, construction technologies and deterioration phenomena can also induce a bad conservation of the structures (Illampas et al., 2020).

Most of the Italian masonry churches represent an important percentage of the overall national and international architectural heritage, and for this reason strategies for their maintenance and monitoring should be pursued. Specifically, large efforts should be paid to reduce their seismic vulnerability, and for this reason, seismic safety should be first evaluated in order to later identify optimal retrofitting solutions (De Matteis et al. 2020). Historical analysis, in situ-surveys, damage scenarios, in-situ tests (destructive DT, semi-destructive SDT and non-destructive tests NDT), structural analysis and seismic assessment are fundamental parts of the knowledge-based approach to these kind of structures (Caprili and Puncello, 2019). In this context, among the non-invasive diagnostic tools, the characterization of the dynamic properties through ambient-vibration tests (AVTs) and operational modal analysis (OMA) becomes a helpful step to describe the real response of a structure under an external excitation. Experimental dynamic identification techniques can be usefully adopted to experimentally detect natural frequencies, modal shapes and damping coefficients, with the final aim to calibrate finite element (FE) models (Ramos et al., 2013). Lastly, long-term structural health monitoring (SHM) systems have been recently increased their popularity to fully capture the behavior of a structure in time, through the continuous collection of vibration data (in case of vibrations-based systems), as well as static data, e.g., strains, cracks opening, displacements, tilts (in case of mixed static-vibrations-based systems). SHM is often applied for damage-identification and damage-localization scopes. Some relevant applications are worth to be mentioned, e.g., the Consoli Palace in Gubbio (Kita et al., 2019), the Milan Cathedral (Gentile et al., 2019), the Anime Sante Church in L'Aquila (Russo, 2013).

In this work, we analyzed as case-study the Madonna del Carmine Church, located in Noto, Sicily. The city of Noto, placed in the southeastern part of Sicily, is characterized by a high seismic hazard with relevant historical events. Noto was completely destroyed by the catastrophic earthquake occurred in January 1693, that affected the old city and caused over 60,000 victims (Piatanesi and Tinti, 1998). After such event, the new city was build a few miles downstream from the beginning of the 1700. The Madonna del Carmine Church is believed to have been built between the 1730-1750. Further on, other relevant seismic sequences rumbled through the new city of Noto in 1727, 1780, 1818 and 1848, possibly damaging the structure in some of its parts. Some interventions were carried out in time too, modifying the original structure, and with the construction of other buildings in continuity with three of the main sides of the structure. The church has been subject to an experimental campaign based both on NDTs and SDTs to evaluate the main geometrical features, the connections between the different structural elements, masonry types, material properties and the eventual presence of active deterioration phenomena. A preliminary seismic safety assessment based on the identification of potential collapse mechanisms was carried out through limit analysis, identifying the façade as the most vulnerable part of the structure. Then, a refined numerical FE model was developed and further used to analyze the dynamic behavior of the structure, where the experimental results of the main geometrical and material properties were included. A FE model updating was lastly performed based on to the results of an experimental dynamic identification campaign.

2. Case-study description

The Madonna del Carmine Church is a masonry building belonging to the XVIII century. The structure consists of irregular perimetric stone walls clamped at the corners, a system of non-load-bearing decorative vaults, and a relatively recent wooden roof. The façade reaches a height of about 24 meters, has an arched shape with walls characterized by varying thickness along the height. The floor plan is characterized by a single three-apsidal hall and the presbytery is raised above the floor of the nave. The layout is a strongly elongated, irregular octagon, to which three semi-cylindrical volumes are aggregated, with a lower height than the central body, two at the transverse axis and one at the end of the longitudinal axis. An elongated pavilion vault with an octagonal base covers the central nave, the side apses are

covered by vaulted ceilings, and connected to the central body through arch structures. Figure 1 shows the floor and longitudinal section layout of the Madonna del Carmine Church.
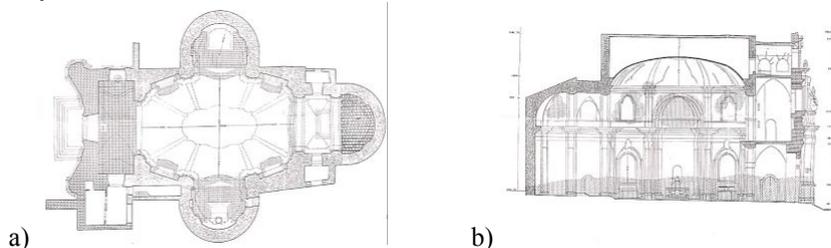

a)   b)

Fig. 1: Madonna del Carmine Church: floor plan (a) and longitudinal section (b).

2.1. Point cloud survey

The complex geometry of the church makes manual survey very difficult and imprecise. For this reason, a photogrammetric survey was carried out, which was then used to obtain the correct 3-dimensional geometry of the structure, further used to derive high-precision drawings and structural models. Figure 2 shows the survey stations and the final 3D view of the Point Cloud Model (PCM), obtained adopting Autodesk Recap Pro software.
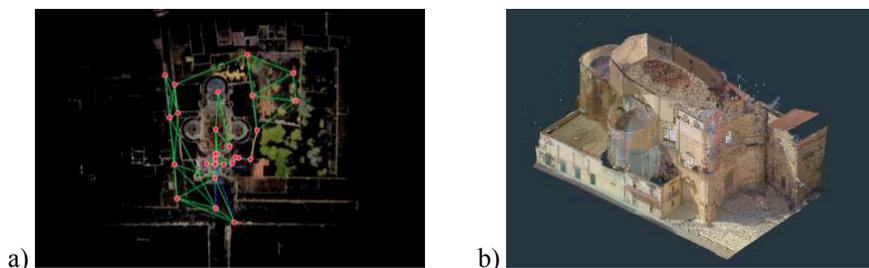

a)   b)

Fig. 2: Madonna del Carmine Church: photogrammetric survey stations (a) and PCM view (b).

2.2. Preliminary FE model

A simplified FE model was created using the MidasGen software, with the aim to design the experimental campaign, focusing efforts on the structural elements subject to higher tensional regimes. In detail, structural walls were modeled using bi-dimensional elements (plate), simplifying their geometry and using an average thickness values, even for those elements with a variable one. The wooden roof was assumed inadequate to guarantee a rigid diaphragm at the top of the structure, therefore it was modeled only in terms of additional mass applied to the vertical structure. The initial material properties were assumed based only on a typological recognition of masonry type based on tuff, according to the Italian Building Code, assuming the lowest knowledge level. Figure 3 shows a 3D view of the preliminary simplified FE model, together with the main modal shapes and relative natural frequencies identified.
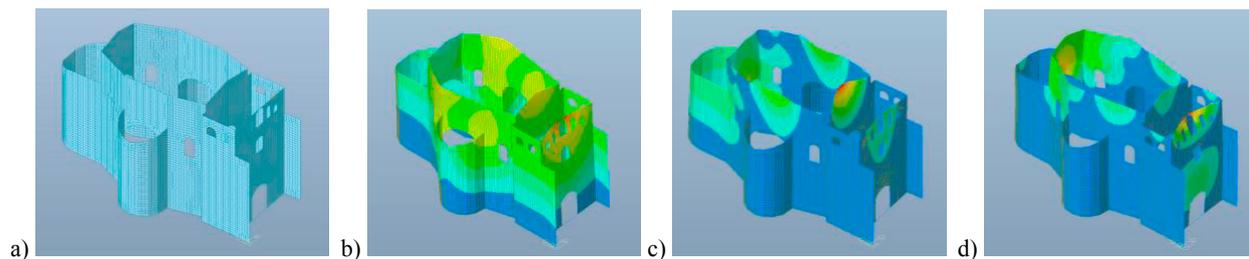

a)   b)   c)   d)

Fig. 3: 3D view of preliminary FE model (a) and main vibration mode shapes involving the presbytery: 2.49 Hz (b), 4.24 Hz (c) and 5.69 Hz (d).

3. Experimental campaign

The experimental campaign aims to increase the level of knowledge on geometrical and material properties, and to analyze the experimental dynamic behavior of the church, mainly focusing on the façade and the presbytery macroelements, for which results from a limit analysis of collapse mechanisms has identified lowest collapse multipliers. Such portions of the church can be the mostly affected in case of earthquake occurrence, as highlighted by results obtained from the preliminary FE model. In addition, the diffused deterioration detected during a first visual inspection, consisting in large humidity spots and mortar joints deterioration can contribute to worsen the capacity of such macroelements.

3.1. Semi-destructive and non-destructive tests

A set of complementary SDTs and NDTs were carried out, other than visual inspections to characterize the quality of the masonry. The main tests were: flat jacket tests (FJ), both single and double, pulse velocity tests (PS), and endoscopies (PE). Some masonry cores, together with the extraction of mortars from the joints were also carried out to reconstruct their composition and evaluate the presence of possible deterioration mechanisms. Figure 4 shows the location of the tests carried out.
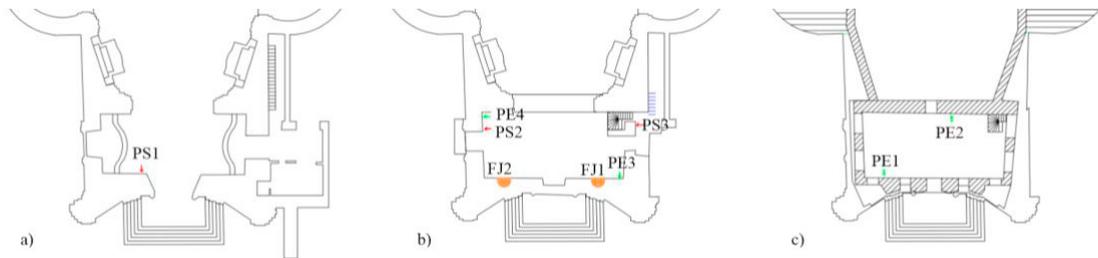

Fig. 4: Positions of the flat jacket (FJ) tests, pulse velocity (PS) and endoscopies (PE).

3.2. Modal characterization test set up

The test consists in measuring the accelerations on the structure subject to ambient vibrations only, thus Operational Modal Analysis (OMA) techniques were used to obtain the main modal parameters of the church. A set of 15 uniaxial accelerometers with a sensitivity of 10,000 mV/g was used in two different configurations, illustrated Figure 5.
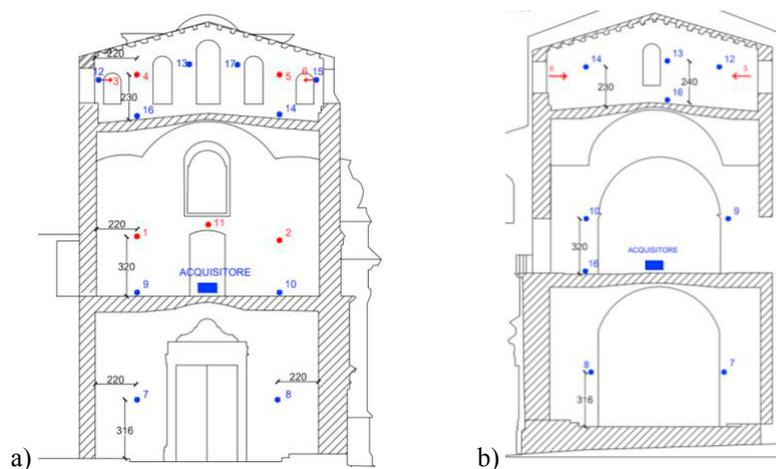

Fig. 5: Test setups and sensors location for the experimental dynamic identification: façade (a) and inner wall parallel to the façade (b).

Some accelerometers were maintained in a fixed position between the two setups (in red) while others (in blue) were repositioned between the two setups. The dot mark indicates that the direction of the accelerometer is perpendicular to the sheet, while the arrows are used to indicate a different direction. The sensors were anchored mechanically on the masonry walls, at different height, in the horizontal direction to capture the main out-of-plane modes, i.e., overturning and vertical flexure. The vibrations of the structure were recorded for about one hour for each set-up, with a sampling frequency of 200 Hz.

4. Experimental results and model calibration

4.1. Single and double flat jacks test

Flat jack tests were carried out in the main façade in two positions at an average height of 1.3m from the ground, in both the single and double mode. Such tests had the twofold aim of detecting the state of local stress present in the masonry, by measuring the variation in the stress state after the cut realization in an orthogonal direction to the wall, and also of determining the axial and transverse deformability modules for each degree of stress applied. The main results in terms of local stress $\sigma_{in\,situ}$, peak stress σ_{peak}, Elastic modulus E_m and Poisson's coefficient v_m are listed in Table 1.

Table 1. Experimental results from FJ tests.

Test ID	Test mode	$\sigma\,in\,situ$ (MPa)	$\sigma\,peak$ (MPa)	E_m (MPa)	v_m (-)
FJ1 – S	Single	0.26	-	-	-
FJ2 -S	Single	0.26	-	-	-
FJ1 – D	Double	0.26	0.77	1200	0.17
FJ2 -D	double	0.26	0.86	1100	0.28

4.2. Cores, endoscopies and mortar characterization

Five cores were extracted from the façade and their transverse walls to identify the type, homogeneity and quality of the masonry. Cores have different height, varying from 400 to 800 mm, depending on their location. After a first thickness of 35-40 mm of plaster, almost a homogeneous layer of biocalcarenite stones was detected (Figure 6a); however, almost in all cases, at about 30-40 cm from the external face, a reduction of the porosity and compactness was visible.

Three other openings were created to evaluate the level of connections among the walls, especially between the façade and the transverse ones. In these corners of the structure, masonry was not homogeneous, there was an absence of any courses or bands, and only some small squared-shape blocks could be recognized (see Figure 6b), avoiding their function as a key. Accordingly, the connections among the walls cannot be completely ensured.

a)   b)

Fig. 6: Inspection of a core from the façade (a) and inspection at a corner between the façade and the transverse wall (b).

Concerning the endoscopies, they were useful to investigate the presence of discontinuities and voids inside the masonry and were carried out in variable depths from the bottom to the top of the main façade from more than 110 cm to about 50 cm due to a significant reduction of the wall thickness in height. Further, no heterogeneity in the masonry types were detected.

Lastly, a petrographic and X-Ray diffractometric analysis of the mortar extracted from some joints were carried out, allowing to establish that the mortar is a lime-cement-based one, the aggregates are mostly siliceous, where vulcanites, quartz and feldspates can be recognized.

4.3. Sonic pulse velocity

The travel time and waveform characteristics of low frequency stress wave can be used to estimate masonry quality (Bindemitteln, 1986). An instrumented hammer generated the stress wave with an attached accelerator to record the input pulse while a piezoelectric accelerometer with a sensitivity of 10,000 mV/g was used as a receiver. Input pulse and received waveform was recorded using 100 kHZ sampling frequency. Tests were conducted using the direct path method in which the hammer hit and accelerometers are in line with one another on opposite sides of the masonry element.

Due to limited accessibility to both sides of the walls pulse velocity test were carried out in limited portions of the masonry being on 40x40 cm and 60x60 cm. A 5x5 base grid with 10 cm and 15 cm spacing (respectively for 40x40 cm and 60x60 cm investigated portions) was used for the pulse input and recording. The results showed pulse velocities mainly in the range of 800-1200 m/s with peaks up to 1800 m/s in line with a poor to medium quality masonry. Results are graphically shown in Figure 7.
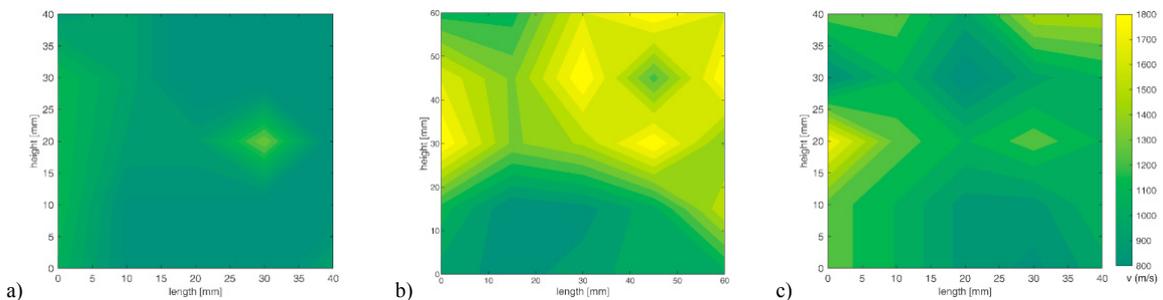

Fig. 7: Pulse velocity test results. PS1 (a), PS2 (b) and PS3 (c).

4.4. Experimental modal results

OMA technique was carried out based on the time series recorded during the in-situ experimental campaign through the use of the ARTeMIS Modal software. Data processing strategies were both Frequency Domain Decomposition (FDD) and Enhanced FDD (EFDD) techniques (Brincker et al., 2007). Before the analyses, data were pre-processed by performing operations like de-trending and verification of Gaussian data fitting (data should resemble white noise).

Accelerations from each set-up were analyzed separately. Concerning the first one, it was designed to analyze the façade modes. The resulting singular values plot is shown in Figure 8a, which reveals a first peak at 3.76 Hz, and a second one at 5.88 Hz. According to the modal shapes from the FDD (later shown in Section 4.5), the first frequency can be associated to the façade overturning mechanism, whereas the second deals with its vertical flexure. It is worth recalling that the results from FDD and EFDD analyses almost coincide in the analyzed cases.

Figure 8b shows instead the singular values plot for the internal wall, behind to the façade, that is characterized by a first frequency of 3.71 Hz (very close to that of the façade overturning), and the second frequency is at 6.88 Hz. Modal shapes allow to confirm also in this case that the same mechanisms identified before apply.
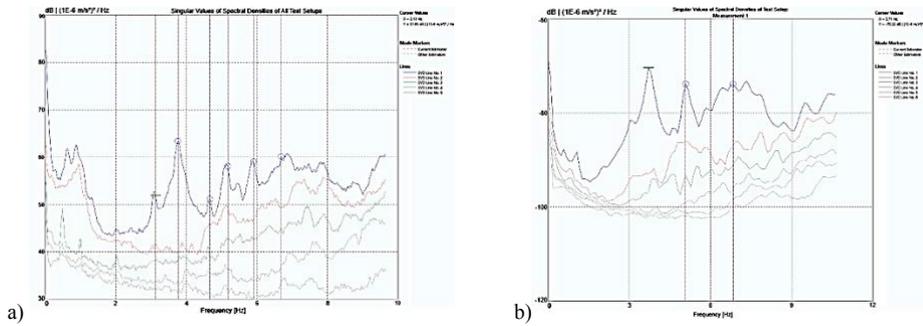
Fig. 8: Singular values plot from ambient vibration: (a) setup 1, (b) setup 2.

4.5. FE model updating and results discussion

After the in-situ experimental campaign, the preliminary FE model was updated to a more detailed one using MidasFEA NX software. Structural walls were modeled using 3D elements with geometry derived from the point cloud survey. Material properties were updated using the double flat jacket tests results reported in section 4.1

The following step consists in the comparison between the natural frequency values and corresponding modal shapes experimentally derived from the post-processing of the recorded time-series and those numerically derived from both the preliminary and updated FE models, for both the façade and the internal wall behind the façade. Table 2 lists the frequency values obtained from FDD modal analysis of ambient vibration acquisitions and from FE models (preliminary and calibrated). Percentage errors between experimental and numerical data are reported in brackets. Results have highlighted a good estimate of almost all the natural frequencies with the updated FE models, with a slight underestimation of the global stiffness of structure, except for the first out-of-plane mode of the inner wall.

In terms of modal shapes, Figure 9 compares qualitatively the first two modes identified for the façade, that allow clearly to correlate the first frequency to an overturning mechanism of the whole wall, and the second frequency to a vertical flexure. The same modes are obtained at the corresponding frequencies in the updated FE model.

Table 2. Comparison among the experimental and numerical frequencies, percentage error in brackets

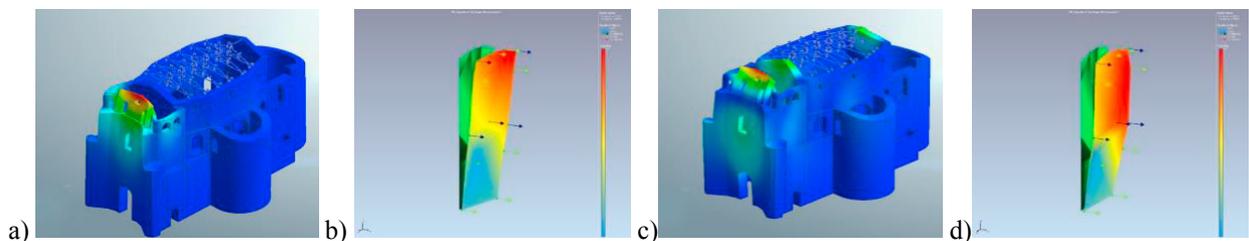| Mode	Wall	Setup	FDD	FE model preliminary	FE model updated
1st	Façade	1st	3.76	2.49 (-34%)	3.46 (-8%)
2nd	Façade	1st	5.88	5.69 (-3.2%)	5.85 (-0.01%)
1st	Inner	2nd	3.71	4.24 (14.3%)	4.05 (+9%)
2nd	Inner	2nd	6.88	6.78 (-1.5%)	6.62 (-4%)

Fig. 9: Comparison between numerical and experimental mode shapes. first (a, b) and second (c, d) façade modes.

5. Conclusions

The paper presented the results of an experimental campaign based both on NDTs and SDTs to evaluate the main geometrical features, the connections between the different structural elements, masonry types, material properties and the eventual presence of active deterioration phenomena on the Madonna del Carmine Church in Noto. The results were used to evaluate the overall health conditions of the structure and to calibrate a FE model based on the experimental modal characterization of the structure. Based on the results the following conclusions can be drawn:

- Cores, endoscopies and sonic pulse velocity test were used to evaluate the relative quality of the masonry, the presence of discontinuities, voids and to evaluate level of connections among walls.
- Single and double flat jacks were able to identify local stresses, being 0.26 MPa, and main masonry mechanical properties showing an elastic modulus and poisson coefficient varying between 1100-1200 MPa and 0.17 and 0.27, respectively.
- The numerical modal frequencies of the final detailed FE model show a very good estimate of the experimental ones with errors varying between 0 and 9% significantly reducing the initial error of the preliminary model (34%).

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