

MODAL IDENTIFICATION OF THE SAN FRANCESCO CHURCH IN PISA, ITALY

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Abstract. *The preservation of Cultural Heritage assets from natural and man-made disasters is of great importance for communities because of their architectural and social value. Lack of any hazard-resisting design, material typology and degradation due to ageing strongly affect the behaviour of Cultural Heritage assets. In this context, Structural Health Monitoring systems can help stakeholders to control the behaviour of heritage constructions, to improve the estimation of their residual life expectancy and to optimize maintenance and retrofitting interventions. This paper presents the preliminary results of the modal identification of the transept of San Francesco church in Pisa. An experimental campaign aimed at measuring the structural response under environmental vibrations was performed, and Operational Modal Analysis was applied to quantify modal properties (frequencies and mode shapes). Data were then used to calibrate the elastic parameters of a refined numerical model. Issues and practical considerations related to the design and installation of dynamic monitoring systems for complex masonry constructions (such as the one under investigation) were derived to provide practitioners with practical guidance.*

1 INTRODUCTION

Cultural Heritage (CH) assets represent a relevant economic resource because of cultural tourism, but their intangible value is also of primary importance since they play a fundamental role in fostering a community's sense of place and belonging. For these reasons, preservation of heritage constructions is a matter of primary importance, though current conservation efforts are too often limited to emergency measures, and designed without a comprehensive intervention plan [1].

In this context, Structural Health Monitoring (SHM) [2] systems can help stakeholders control the behaviour of heritage constructions, while improving the estimation of their residual life expectancy and optimizing maintenance and retrofitting interventions.

Numerical models are commonly used as a tool to assess structural health of CH assets and to predict the buildings response to environmental conditions. Typical CH assets are characterized by the lack of any hazard-resisting design, materials of unknown properties and diffused degradation due to ageing. For this reasons, epistemic uncertainties regarding materials, geometry and boundary conditions [3, 4] strongly affect Finite Element (FE) model results.

Ambient vibration-based modal identification techniques are then key to record and derive information for both model parameter calibration and structural control. Being non-destructive, such techniques perfectly meet the well-known minimum intervention and reversibility criteria for CH assets [5]. Through dynamic identification, vibrational properties of the structure (natural frequencies, modal shapes and damping coefficients) can be deduced and compared to the ones obtained from numerical models [6, 7, 8].

In this paper we present the first steps towards the definition of a robust SHM system for masonry CH assets [10]. The San Francesco church in Pisa, Italy (Figure 1) was chosen as a case study, and dynamic measurements were performed to evaluate the response of its bell tower and transept to ambient vibrations.

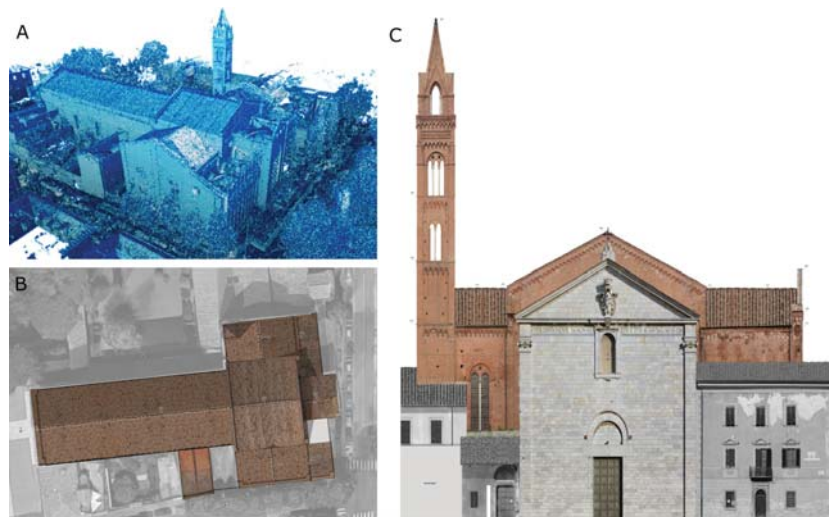


Figure 1: A) Point cloud survey; B) planimetry; C) façade of the San Francesco church.

The results were elaborated through Operation Modal Analysis (OMA) techniques [9] and used to identify natural frequencies and mode shapes. A preliminary dynamic identification of the bell tower alone provided first estimates for the constitutive parameters of the masonry walls. A FE model of the entire church was then built in order to preliminarily choose relevant

mode shapes involving the transept, and to design sensor positioning. After the experimental campaign, the same model was used to perform a manual mode-matching between numerical and experimental results.

2 THE SAN FRANCESCO CHURCH IN PISA

The construction of the San Francesco church in Pisa dates back to the 13th century, and was executed under the direction of architect Giovanni di Simone [11]. It follows the traditional Franciscan canon of sobriety and humbleness, avoiding frescoes and limiting the use of marble to the façade (of later construction), preferring exposed brick on the exterior and painted plaster on the interior.

Its geometry (the nave measures 70.5 m x 17.7 m) makes it the second largest church in the city, after the Cathedral of Pisa. Its peculiarity is a “hanging” masonry tower, resting at a height of 12 m above ground level on two limestone cantilevers embedded in the north transept walls. The dynamic behaviour of the bell tower was already investigated during an experimental campaign in March 2019 by a research group from the University of Pisa lead by Prof. De Falco. The campaign’s results are briefly recalled in the following.

A massive restoration work of the San Francesco church is currently underway, thus enabling the self-standing scaffolding system to be used during the dynamic experimental campaign herein presented. It is worth noting that the scaffolding system (Figure 2) is designed to have no contact with the structural system, so that it does not affect dynamic observations. Thanks to this, a diffuse network of sensors over most of the church’s transept, including the highest portion of the walls, could be installed, thus obtaining significant data for modal identification.

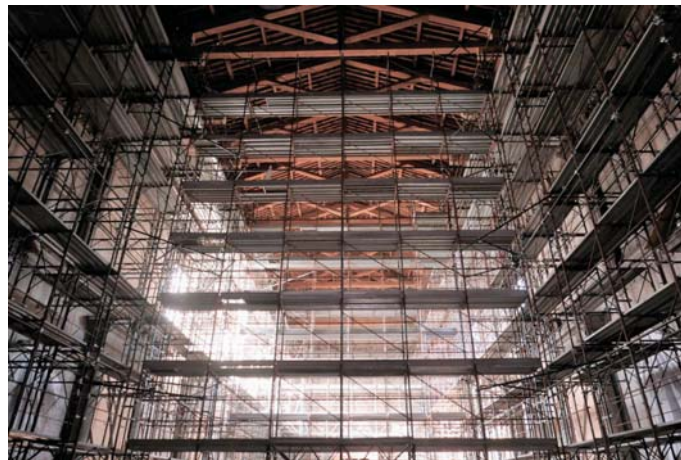


Figure 2: Self-standing scaffolding system in the nave.

Plans of renovation also envisage the complete removal and restoration of the roof and of the supporting truss structures. This will allow a new experimental campaign to be performed in order to better evaluate the effect of roofing on the overall vibrational behaviour of the building.

3 EXPERIMENTAL CAMPAIGN ON THE BELL TOWER

On the 30th March 2019, an experimental campaign was performed on the San Francesco bell tower in order to identify its modal properties. Accelerometers and velocimeters were placed at different positions along the tower’s height (Figure 3), measuring its response to ambient

vibrations. Natural frequencies and mode shapes were derived using the software LMS Test.Lab 8 [12] to perform digital signal processing and to apply the PolyMax algorithm [13] to the data. The first three identified frequencies correspond to two flexural modes (1.10 Hz and 1.32 Hz) and a torsional one (3.55 Hz). Flexural modes are roughly aligned with the main diagonals of the bell tower's cross section.

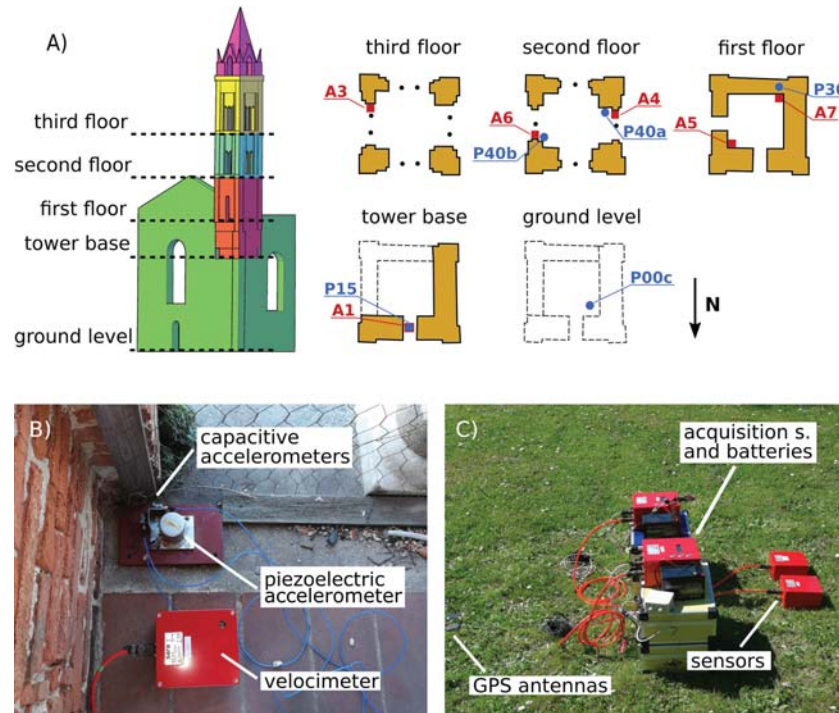


Figure 3: A) Sensor positioning along the bell tower. Accelerometers are indicated with the letter A, velocimeters with the letter P; B) employed sensors; C) velocimeter acquisition system.

A FE model was developed during this phase to simulate the masonry bell tower together with a limited portion of the neighbouring church walls (Figure 10). Experimental results were used to update the value of the elastic material properties of the model. The first three natural frequencies and mode shapes were matched with numerical ones (Figure 4) by varying the values of the Young's moduli of bell tower and church. Good accordance (less than 5% difference) between experimental and numerical data was finally reached for values of 1800 and 1300 MPa for the bell tower and church, respectively.

4 EXPERIMENTAL CAMPAIGN ON THE TRANSEPT

4.1 Instrumentation and acquisition

After the dynamic identification of the bell tower, an experimental campaign was carried out on the church's transept during December 2019 and January 2020. A network of accelerometers was used to record the building's response to ambient vibrations. Nine monoaxial capacitive accelerometers (*PCB DC capacitive accelerometers – Model 3701G3FA3G*) and six monoaxial piezoelectric accelerometers (*PCB ICP accelerometers – Model 393C*) from the Structural Laboratory of the University of Pisa were employed. Technical characteristics of the sensors are summarized in Table 1. Data were recorded and pre-processed through an acquisition system

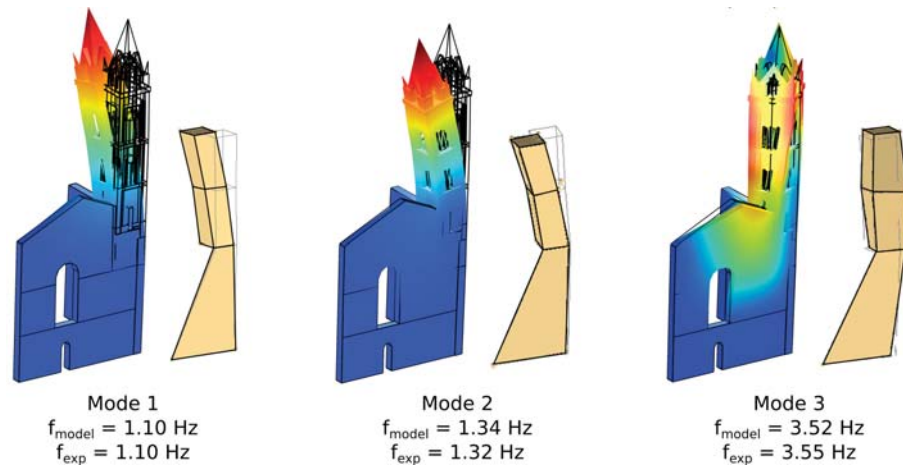


Figure 4: Mode matching for the bell tower.

(*LMS Scadas Mobile*) controlled by a dedicated application (*LMS Test.Lab 8*). Figure 5 shows the employed sensors and acquisition system.

<i>PCB DC capacitive accelerometers model 3701G3FA3G</i>	
Average sensitivity @ 30 Hz	1000 mV/g
Average eigenfrequency	540 Hz
Frequency range ($\pm 5 \%$)	0 to 100 Hz
<i>PCB ICP piezoelectric accelerometers model 393C</i>	
Average sensitivity @ 100 Hz	1000 mV/g
Average eigenfrequency	5.3 kHz
Frequency range ($\pm 5 \%$)	0.025 to 8,00 Hz

Table 1: Technical characteristics of the employed sensors.

The sensors were assembled to create two- or three-directional measurement stations by fixing them to rigid metallic plates. Four different device configurations were adopted to perform three 30 minutes records with a sampling frequency of 256 Hz and 8-second average time windows.

Sensor layout was determined beforehand based on the results of a preliminary numerical model. Two main necessities had to be assessed:

1. to identify the modal properties of all reachable transept portions;
2. to gain insight regarding the influence of roof and supporting trusses on the vibrational behaviour of the connected walls.

Figures 6 and 7 show sensor positions, and Table 2 summarizes the configurations with the corresponding instrumented positions. Sensors in positions 1, 6, 8, 14 and 25 were used for each configuration, in order to be able to merge data from the different acquisitions.

Connection between sensors and acquisition system was achieved through cables ranging in length between 50 and 100 m on account of the church's geometry. This required careful



Figure 5: Instrumentation. A) Piezoelectric accelerometer; B) capacitive accelerometer; C) piezoelectric two-directional measurement station; D) acquisition system; E) control station on top of the scaffolding.

POSITION	1	2	3	4	5	6	7	8	9	10	11	12	13
Configuration 1	•	•	•	•	•	•	•	•	•				
Configuration 2	•	•				•	•	•		•	•	•	•
Configuration 3	•					•		•			•		
Configuration 4	•					•		•					

POSITION	14	15	16	17	18	19	20	21	22	23	24	25	26
Configuration 1	•											•	
Configuration 2	•	•										•	
Configuration 3	•					•			•	•	•	•	•
Configuration 4	•		•	•	•	•	•	•				•	

Table 2: Sensor positions used for the different measurement configurations. In boldface reference positions.

planning in the design of the experimental campaign, to make sure that as few accelerometers as possible had to be moved between a configuration and the following. Nevertheless, logistics often required long procedures, resulting even more complex since operations were carried out on the scaffolding.

Cable length, together with some electrical dissipations which may also have interacted with the scaffolding system, could have been the cause of issues concerning some of the sensors during measurements. This was particularly true in the case of capacitive accelerometers, which required an external power source and for which tripolar power cables were used. Some of the

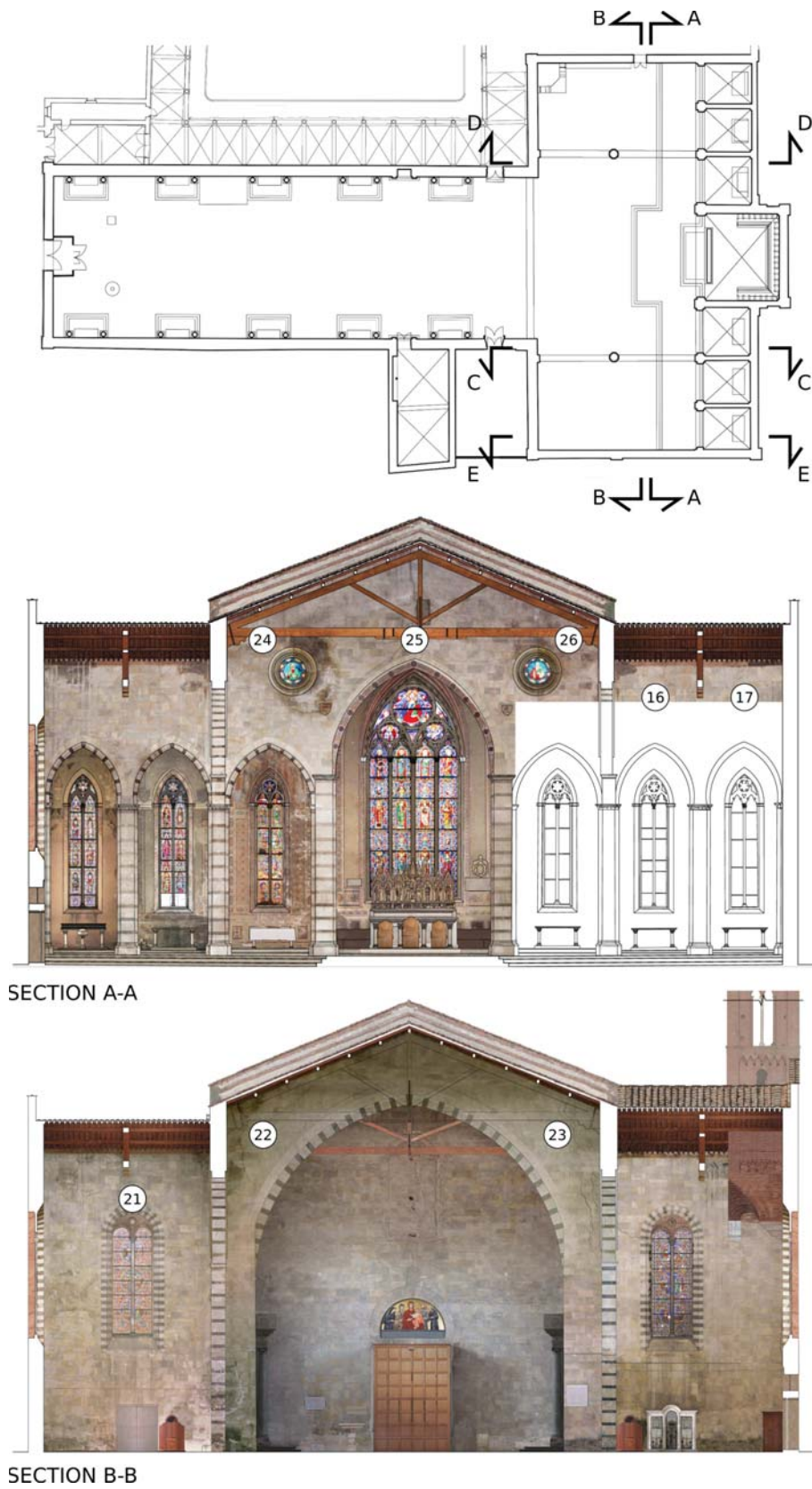


Figure 6: Sensor positioning. Church plan, section AA (east transept wall) and section BB (west transept wall). White portions were impossible to photograph.

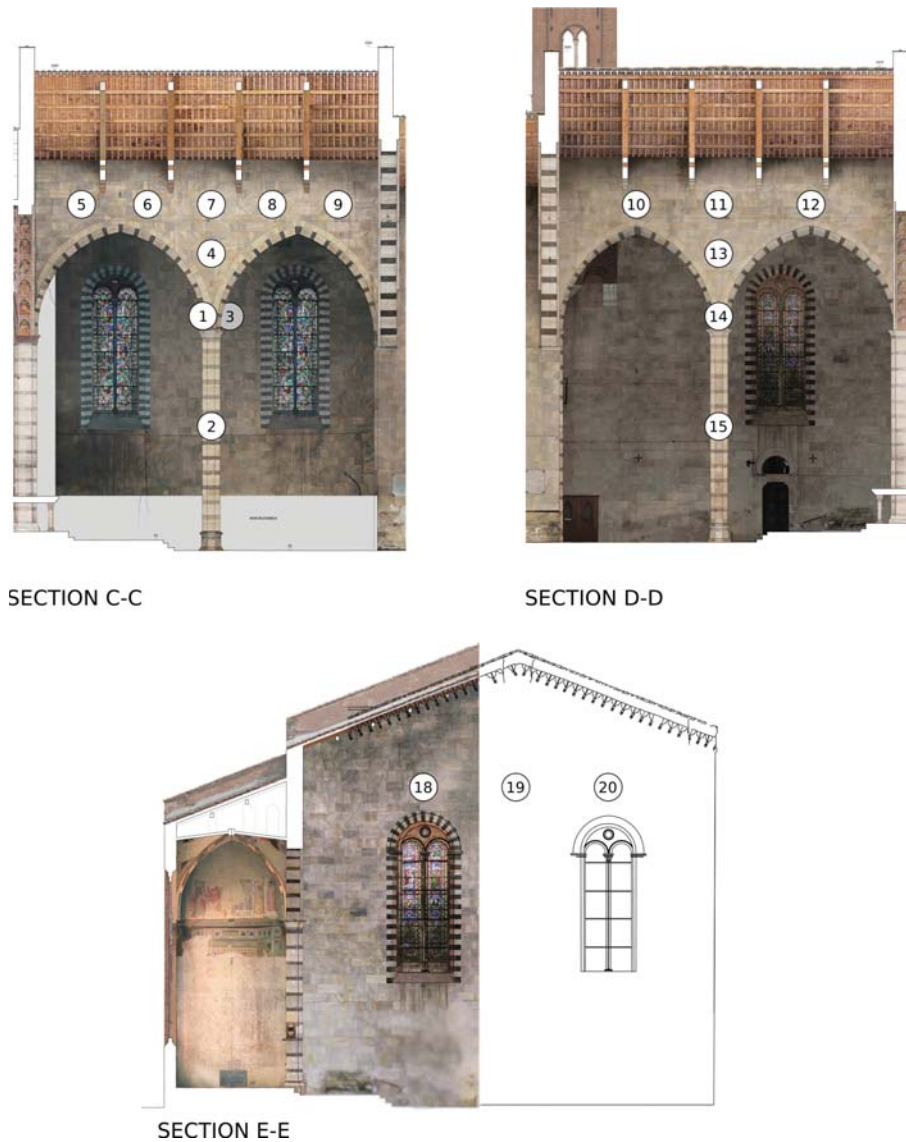


Figure 7: Sensor positioning. Section CC (south partition wall), section DD (north partition wall) and section EE (south transept wall). White portions were impossible to photograph.

longer cables, when used for sensors located closer to the acquisition system, had to be partially stored on cable reels. This may have worsened signal quality through induced electro-magnetic effects. Future testing may benefit from the use of piezoelectric accelerometers only, or from the use of capacitive accelerometers with better insulated cables.

4.2 Data elaboration and discussion

Data from accelerometers were processed using the software LMS Test.Lab, computing the Power Spectral Density function with Hanning windowing at 16768 spectral lines and 10% overlap. To perform a preliminary identification of peaks in the transept's frequency response, selected signals in the frequency domain were grouped based on sensor position: north and south partition walls and east, west and south transept walls. Figure 8 shows the resulting PSDs. Here, the different lines correspond to signals from accelerometers mounted on one wall, and measuring in orthogonal direction. Peaks have been identified through manual peak-picking.

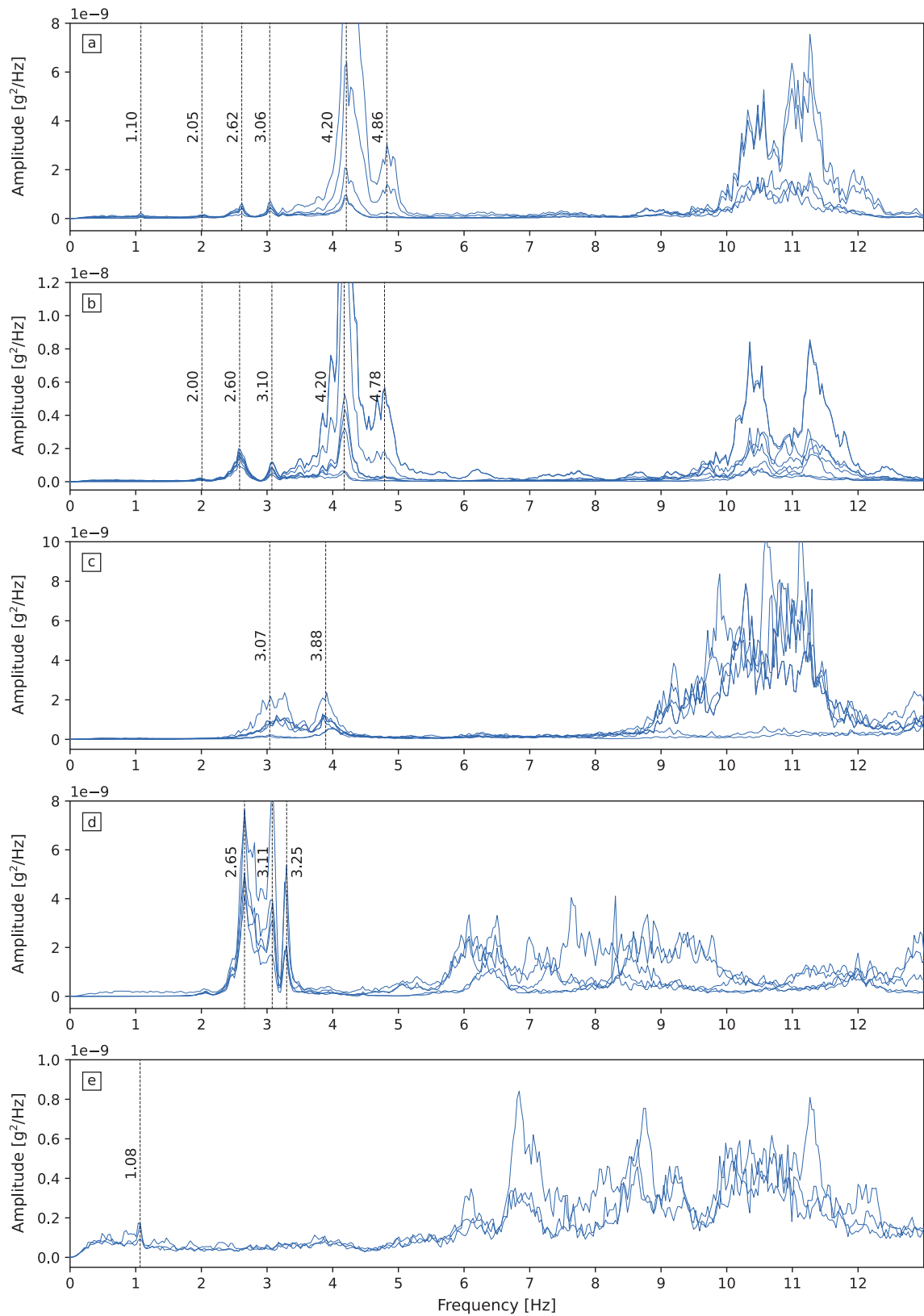


Figure 8: Power Spectral Density of signals recorded from sensors on different transept portions. a) North partition wall; b) south partition wall; c) east transept wall; d) west transept wall; e) south transept wall.

Some observations can be derived:

- frequency responses from the north and south partition walls are very similar. This could be expected since their geometry is roughly the same, even though boundary conditions differ significantly. The north wall is in fact contiguous to the bell tower and to an external vaulted cloister, while the south portion of the transept is free along its height and borders with adjacent roads.
- A peak corresponding to approximately 1.10 Hz can be recognized in the frequency responses of the north partition and west transept walls, and is absent from the response of other walls. This suggests that the first natural frequency of the bell tower, corresponding to its first flexural mode, was identified.
- The vibrational behaviour of the east transept wall is, as expected, quite different from the other walls. This is due to its being horizontally braced by several vaults that cover the altar and the chapels.
- The west transept wall is occupied for the most part by an archway that separates the transept from the nave, as can be seen in Figure 6. Unfortunately, the scaffolding system did not reach the arch's keystone, so that sensors were placed in positions very close to orthogonal walls. The frequency response shown in Figure 8 is detrimentally affected by the lack of sensors in the higher portion of the wall.

The PolyMax algorithm was applied to each single measurement run in order to identify natural frequencies which peaks may have been ignored during manual peak-picking, and the relative partial mode shapes. The results were then combined in LMS Test.Lab to construct global mode shapes, and a multi-run matrix was constructed, grouping together corresponding peaks from different runs (Table 3). Figure 9 shows the mode shapes identified with the PolyMax algorithm, on a simplified 80-point geometry of the church's transept. The northern portion is not shown, since it was not subjected to measurements.

	Configuration 1 [Hz]	Configuration 2 [Hz]	Configuration 3 [Hz]	Configuration 4 [Hz]
Mode 1		1.06	1.08	
Mode 2	2.01	2.00	2.00	
Mode 3	2.62	2.60	2.61	2.58
Mode 4	3.09	3.10	3.06	3.07
Mode 5			3.27	3.51
Mode 6	4.19	4.19	4.19	4.19
Mode 7	4.90	4.87	4.88	4.84
Mode 8	6.19	6.04	6.04	5.98
Mode 9			7.78	7.58
Mode 10	10.07	9.64	10.00	9.84
Mode 11		10.20	10.28	10.20
Mode 12	11.31		11.64	11.57

Table 3: Experimental natural frequencies of the transept.

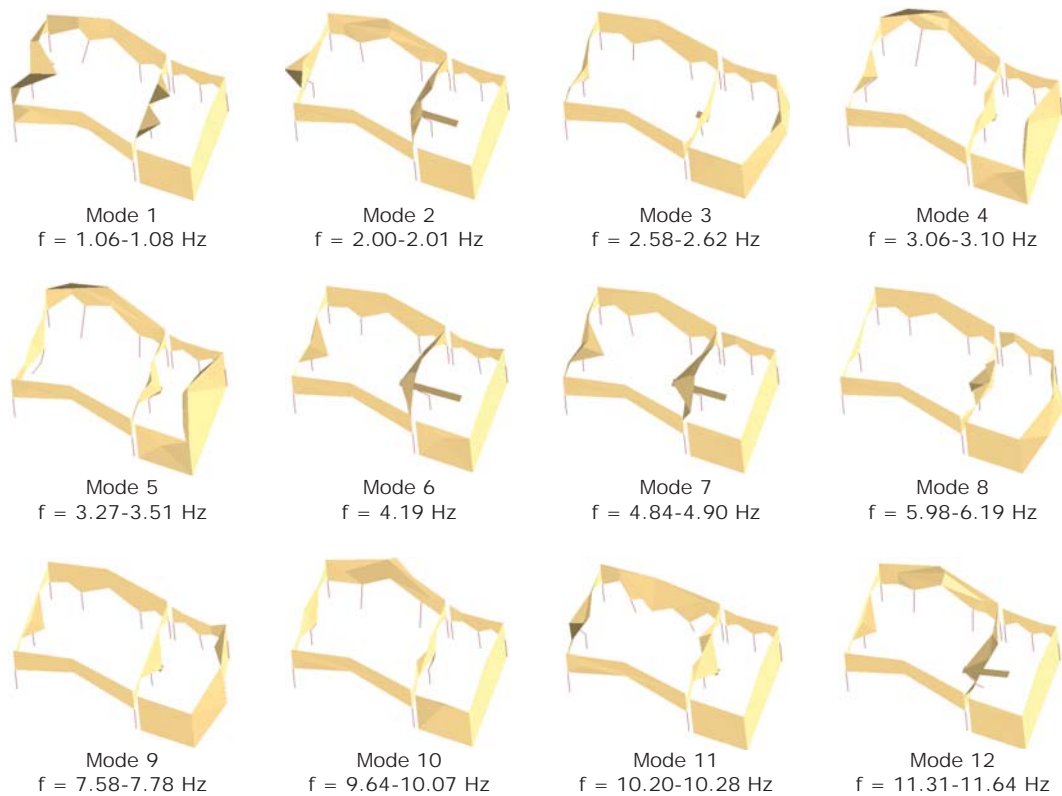


Figure 9: Experimental transept mode shapes extracted with PolyMax algorithm.

The identified mode shapes did not provide useful information regarding the influence of roof and supporting trusses. In particular, at this stage no conclusive answer can be given to the question regarding the eventual rigid-link effect exerted by the roofing system: while some of the mode shapes (e.g., modes 1, 2 and 4) show the two partitioning walls moving in phase, others (e.g., modes 6 and 7) clearly show them moving in opposition of phase. Further measurements, concentrating on the trusses' supports, will help to shed light on the matter.

5 FINITE ELEMENT MODEL

A FE model of the San Francesco church in Pisa was developed using the software Comsol Multiphysics 5.5 [14]. The church's geometry was obtained from a refined point cloud, resulting from a survey fieldwork with laser scanner (Figure 1A). The point cloud was imported in AutoCAD [15] and interpolating solids were defined to assembly the entire geometry of the church.

In Comsol Multiphysics, tetrahedral finite elements with Serendipity quadratic shape functions were used to define a mesh composed of 572991 elements, with maximum dimension set at 1.00 m (Figure 10). A cloister and part of the monastery are contiguous to the northern transept and nave walls (Figure 6). Their presence was considered using displacement boundary conditions to simulate the restraints they exert on the church. Since no conclusive observations could be made regarding the role of the roofing system in the dynamic characterization of the transept, trusses were included in the model because this was thought to represent the most "natural" choice. At this stage, values of Young's moduli for the church's and bell tower's masonry were estimated to be 1300 MPa and 1800 MPa respectively, in accordance with the previous

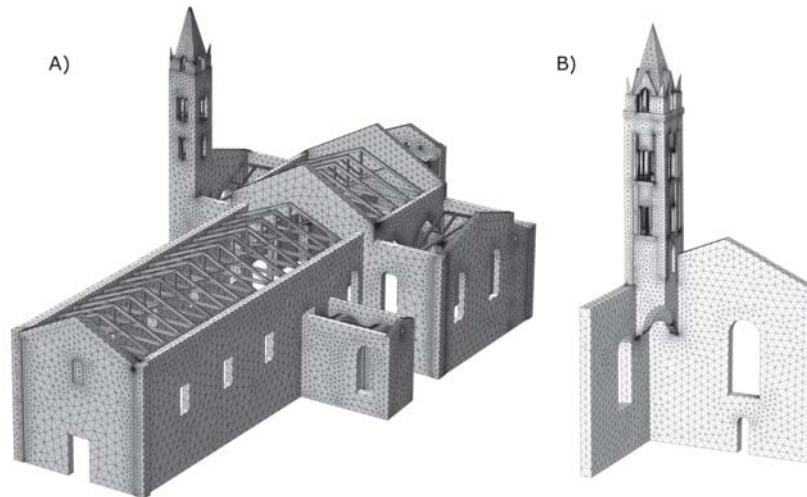


Figure 10: FE models. A) The church; B) preliminary model of the bell tower.

dynamic identification of the bell tower. An automatic updating procedure will be the object of further research work.

Modal analysis resulted in more than 150 mode shapes in the frequency range from 0 to 12 Hz, while only twelve were derived from data analysis (Table 3). Most of the former correspond to natural frequencies of the portions of the church which were not instrumented and therefore not identified, such as the nave and the altar chapels. Sensors used during the acquisition may have not recorded vibrations relative to mode shapes that were not triggered with enough energy by ambient noise.

Mode-matching was performed, and good accordance between experimental and numerical data was reached for some of the modes. Figure 11 shows modal shapes for modes 1, 2, 3 and 7 (according to numbering used in Table 3). Results of the FE model are compared with experimental data. The large number of numerical mode shapes, however, and the presence of many modes with very similar frequencies suggest the necessity to employ an automatic mode-matching procedure such as the Modal Assurance Criterion (MAC) [16]. For this reason, masonry constitutive parameters were not updated using experimental modal information in this case. This will instead be the topic of future research work.

6 CONCLUSIONS

This paper presents preliminary results of the modal identification of the San Francesco Church in Pisa, which is the first step towards the development of a robust SHM system for masonry CH assets. The church's bell tower and transept were subjected to dynamic testing, and operational modal analysis enabled the identification of a limited number of vibrational modes and frequencies. A FE model, preliminarily used to design instrumentation layout, was employed to perform mode matching between experimental and numerical mode shapes, using values for material constitutive parameters resulting from a previous experimental campaign on the bell tower. This first effort allowed us to expand our knowledge regarding practical problems and difficulties arising from performing dynamic testing on a complex structure such as the San Francesco church. Further experimentation will concentrate on specific substructures of the church, and on a dedicated investigation regarding the vibrational influence of roof and supporting trusses.

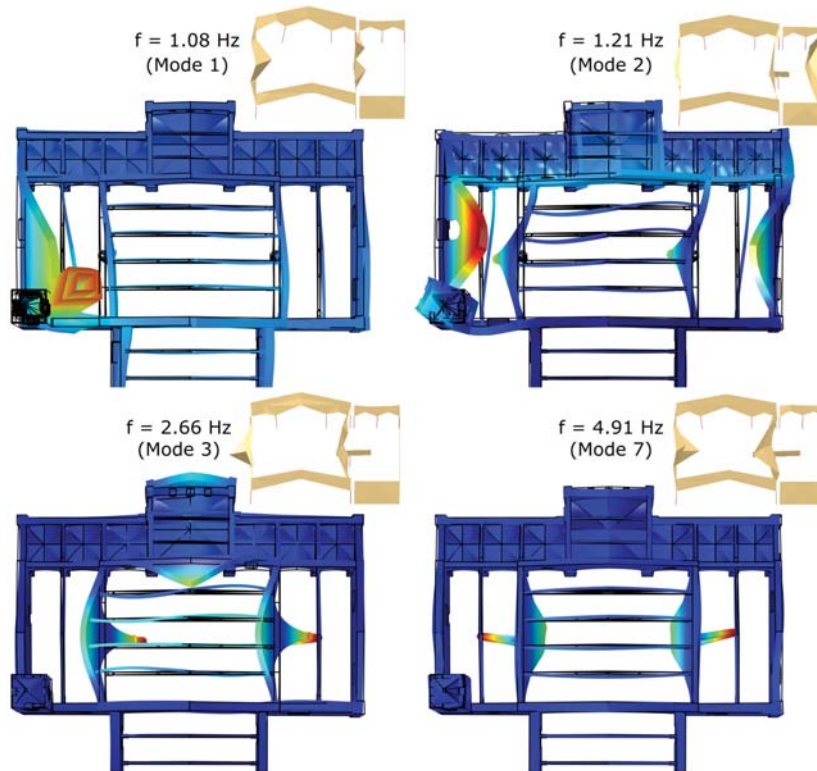


Figure 11: Mode shapes and natural frequencies from the FE model are shown and compared to mode shapes from the experimental campaign.

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