



Numerical Modelling and Structural Health Monitoring for Built Heritage Management: The Case of the Church of Santa Croce in Ravenna

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Abstract. The conservation of the built heritage represents nowadays a great challenge for the scientific community and for the heritage managers since historical buildings can typically face both seismic and climate related hazards. To increase the resilience and reduce the vulnerability of historical constructions, specific strategies and methodologies should be developed and applied. In the framework of the Shelter project, funded by the European Union's Horizon 2020 program, the Church of Santa Croce in Ravenna (Italy) was taken as a case study for the validation of such methodologies, involving a multidisciplinary approach. In this work, the structural behavior of the Church of Santa Croce was investigated through the development of a finite element model and the implementation of a Structural Health Monitoring system, with the possibility of accessing data in real-time. First, the historical analysis of the construction and slightly-destructive tests were carried out to investigate the constructive details, the state of damage, and the mechanical properties of the materials. After acquiring a detailed knowledge level of the construction, modal analyses and nonlinear static numerical simulations were carried out to assess the modal parameters and to reproduce the existing crack pattern. On the one hand, the numerical analyses supported the design of the monitoring system itself; on the other hand, a model updating was carried out to calibrate mechanical parameters not explicitly obtained through testing. The adopted methodologies and approaches are described in the paper, together with the results of the numerical simulations and preliminary results acquired from the monitoring system.

Keywords: Cultural heritage · Historical buildings · Vulnerability · Finite Element Model · Structural Health Monitoring

1 Introduction

Risks related to the effects of climate change and natural hazards are increasingly threatening the cultural heritage. In order to reduce the vulnerability of historical buildings, to promote their exploitation and foster their conservation, it is necessary to identify and develop intervention plans and protocols to improve the resilience of the buildings and of the areas in which they are located [1–3]. The European SHELTER project (Sustainable

Historic Environments holistic reconstruction through Technological Enhancement and community-based Resilience), financed by the Horizon 2020 Research and Innovation Programme, aims to establish cross-scale, multidimensional, data driven and community based operational knowledge framework for cultural heritage and conservation-friendly resilience enhancement and sustainable reconstruction of historic areas to cope with climate change and seismic hazard.

The multidisciplinary activities undertaken within the SHELTER project made it possible to analyze the main challenges identified in five case studies, representative of different cultural heritage construction typologies from small to large scale, for the validation of the proposed methodologies. The urban open lab identified in the Italian territory is the Church of Santa Croce and the surrounding archaeological site in Ravenna, which represent an area affected by subsidence, alluvial phenomena and seismic events.

In this framework, the present work focuses on the case study from a structural point of view and it is structured as follows. Introduction to the case study and the presentation of the knowledge path are given in Sect. 2 in order to investigate the constructive details, the state of damage, and the mechanical properties of the materials [4–6]. Section 3 presents the installed real-time monitoring system and the dynamic identification. In Sect. 4, modal analyses and nonlinear static numerical simulations were carried out to calibrate the mechanical parameters used as input in the numerical simulations and to assess the vulnerability of the church, trying to reproduce the existing crack pattern. Finally, Sect. 5 collects the main conclusions of this work.

2 The Case Study: Church of Santa Croce in Ravenna

The Church of Santa Croce is located in the city center of Ravenna (Italy) within an archeological site inscribed as UNESCO cultural property since 1996 (Fig. 1). The area in which the Church is located is characterized by subsidence phenomena which, together with the conformation of the site itself, determines the constant presence of water. The area is therefore prone to sudden flood, especially in case of heavy rainfall, which have become increasingly frequent due to climate change. Currently, a drainage system allows the site to be maintained in a dry condition.

2.1 Knowledge Path

In the framework of the safety evaluation of existing historical buildings, the knowledge of the construction is one of the most important aspects, to be achieved prior to the execution of numerical analyses and to the design of relevant interventions [4–6]. In order to plan the monitoring activities and to model the Church of Santa Croce, a specific knowledge path was followed, as described in the following sections.

Historical Analysis. The initial configuration of the Church of Santa Croce, built around 450 BC, was more complex with respect to the current one (Fig. 1). Through the collection of information about the origin of the construction and its evolution over time [7–9], it was possible to determine the chronological sequence of the main modifications occurred in the past centuries (Fig. 2). After centuries of demolitions and partial reconstructions, at the end of the XX century, the timber roof was rebuilt after a fire and

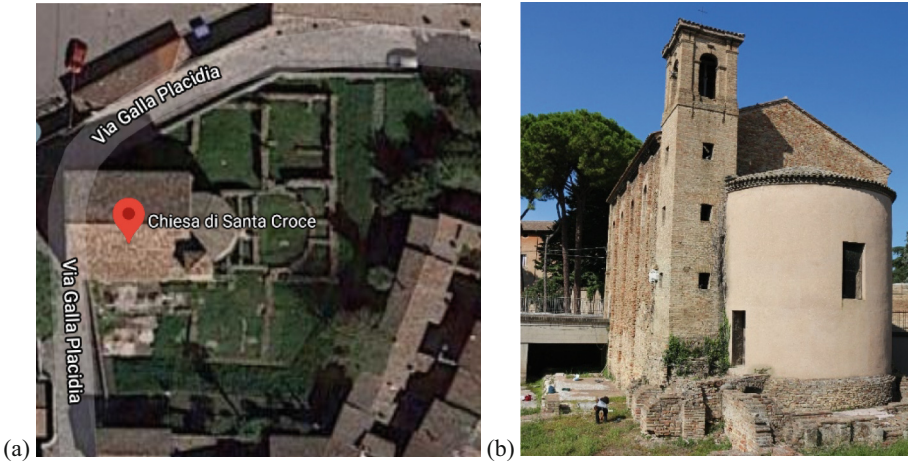


Fig. 1. Church of Santa Croce: (a) plan view from Google Maps, (b) south-east view.

strengthening interventions were carried out on the apsis, with reinforced plaster, and on the foundations.

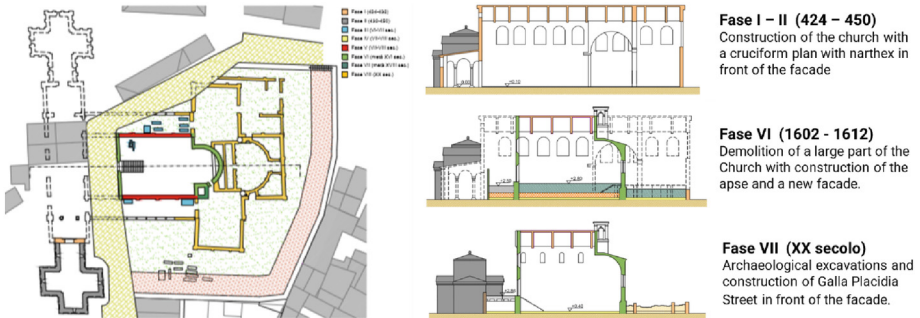


Fig. 2. Evolution of the configuration of the Church of Santa Croce.

Geometry and Details. A survey of the Church of Santa Croce was carried out to precisely describe its geometry and identify the structural elements and details. The vertical structural elements are double-leaves masonry walls, composed of several masonry typologies, due to the evolution of the construction through the centuries, all made by bricks and poor lime-based mortar. The roof is composed by timber trusses and wooden beams supported by a reinforced concrete corbel built at the top of the longitudinal walls and the apsis arch. The access to the Church is located on the west side, on Galla Placidia street, running close to the façade in the XX century, at a higher level with respect to the Church's floor.

Regarding the state of damage of the Church, the survey of the crack pattern was carried out (Fig. 3). Major cracks were located in correspondence with the connections

between orthogonal walls, on the southern wall and in correspondence with the apsis, both at the roof level and at the base. Moreover, a severe problem highlighted during the on-site inspections was the detection of the groundwater level higher than the floor level of the Church, leading to problems related to capillary rising damp and, more in general, to the presence of water on the site.

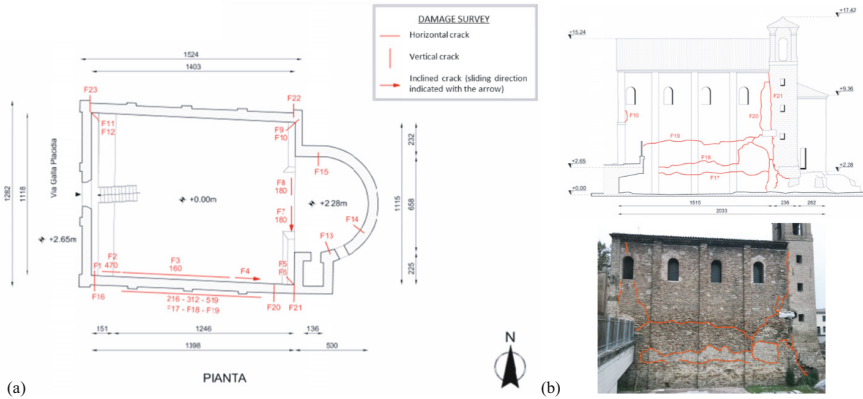


Fig. 3. Damage survey: (a) plan view, (b) southern wall.

On-Site Experimental Campaign. Given the historical character of the Church of Santa Croce, non-destructive and minor-destructive on-site tests were conducted with the objective of identifying the structural details and evaluate material properties to be used in the numerical simulations. In more details, the following investigations were carried out: (i) endoscopies to detect the wall stratigraphy, (ii) sonic tests to evaluate the homogeneity of the masonry walls and the presence of cracks/defects, and (iii) sampling of bricks and mortar for the determination of their compressive strength. The test locations are reported in Fig. 4.

Endoscopies, conducted on the southern and western walls, having a total thickness of 62 cm, allowed to evaluate the walls stratigraphy which is entirely composed by clay bricks and lime-based mortar. Within the thickness, it was not detected the present of a disorganized core.

Sonic tests may be performed according to different methodologies, mainly distinguished as direct and indirect sonic tests [10, 11]. Considering the features of the construction and the possibility to easily access both wall sides or one side only, in the present work both methodologies were adopted: one direct sonic test and three indirect sonic tests were performed. The tests were conducted using two piezoelectric probes, positioned on opposite sides of the walls (direct tests) or on the same side (indirect test), considering the testing points represented in Fig. 5a. In more detail, for indirect sonic tests, the emitting probe was positioned in correspondence of the testing point “0”, while the receiving probe was progressively moved in correspondence with the other testing points (1–16). For the direct sonic tests, the two probes were positioned in the same testing point on the opposite sides of the wall. By knowing the time of flight, which is the

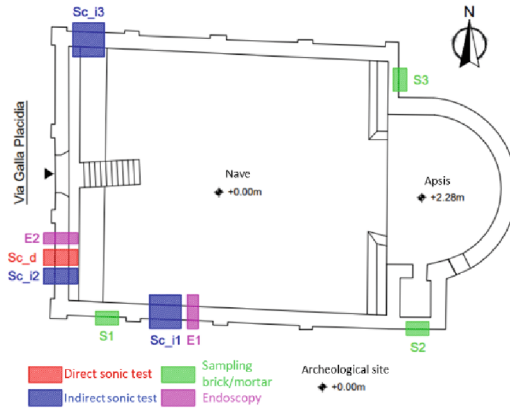


Fig. 4. Plan view with indication about the test locations.

time the sonic waves take to travel, and the distance within the probes, it was possible to evaluate the wave velocity, that can be directly related to the material quality. The results of an indirect sonic test are presented in Fig. 5b, where the velocity contour plot was obtained by interpolating the results obtained at the different testing points. In Fig. 6, the comparison between the sonic wave velocities obtained for all the tests is presented. It is possible to observe that lower values of the wave velocities were obtained for the indirect sonic tests and this can be explained by the irregularities detectable on the wall surfaces, mainly due to damages and degradation of the mortar joints.

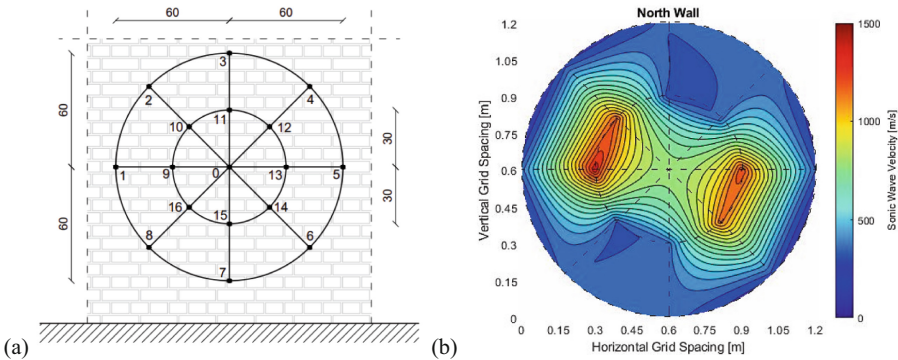


Fig. 5. Sonic tests: (a) location of testing points, (b) representative map of wave velocities for the indirect sonic test Sc_i3.

Concerning the determination of material properties, 7 bricks and 2 mortar joint samples were extracted from different masonry portions. Due to the quality and state of conservation of the mortar, it was not possible to extract a larger number of undamaged samples. The obtained samples were then tested in the laboratory. In more detail, bricks were cored to obtain specimens having a unitary aspect ratio, which were then subjected

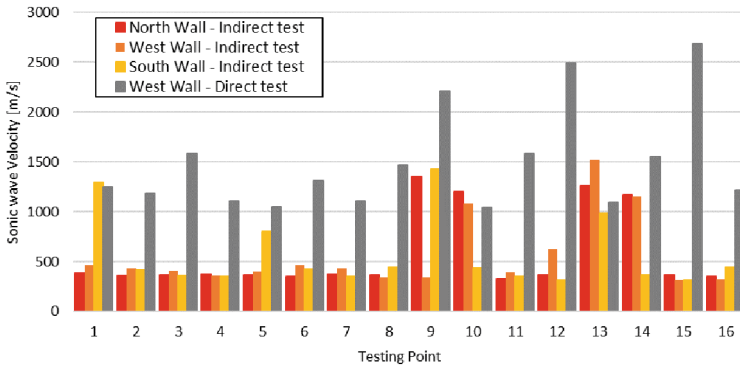


Fig. 6. Sonic test results.

to uniaxial compression test [12], obtaining an average brick compressive strength equal to 11.1 MPa. Double punch tests [13] were performed on the mortar joint samples, for the evaluation of the mortar compressive strength, resulted equal to 2.6 MPa. By knowing the compressive properties of the constituent materials, the masonry compressive strength was estimated by using the Eurocode 6 formula, obtaining 3.2 MPa.

3 Structural Health Monitoring System

3.1 Real-Time Monitoring System

On the basis of the knowledge acquired about the state of conservation of the Church of Santa Croce, a proper design of the monitoring system was carried out by first identifying the typologies of the sensors to be adopted. Considering the subsidence problems and the pre-existing cracks detected through the damage survey, the following sensors were chosen: (i) 5 linear potentiometers, with a gauge length of 50 mm, to measure the opening of main cracks, (ii) 2 biaxial clinometers (measurement range of $\pm 5^\circ$, resolution equal to 0.001°) to measure rotations of the longitudinal walls, (iii) 5 level meters (measurement range of ± 40 mm, sensitivity equal to 0.01 mm) to monitor vertical displacements of the walls, and (iv) 6 uniaxial accelerometers for the dynamic identification. They were all installed inside the Church in the positions reported in the plan view of Fig. 7. A web dashboard was also developed for the real-time visualization of the data registered by the acquisition system. The data were transmitted to the web platform through wireless protocols.

The structural monitoring began at the end of April 2021 and is currently in operation. The data registered by potentiometers, clinometers and level meters from April 2021 to December 2022 are presented in Fig. 8. In general, it can be observed that the only crack for which a consistent opening is registered is the crack in correspondence with the potentiometer P5, positioned at the base of the apsis, where the access to the crypt is located. Angle variations registered by the clinometers are comparable for the two longitudinal walls. Concerning vertical displacements, even if a global trend cannot be identified, consistently with the fact that the external walls of the church are not

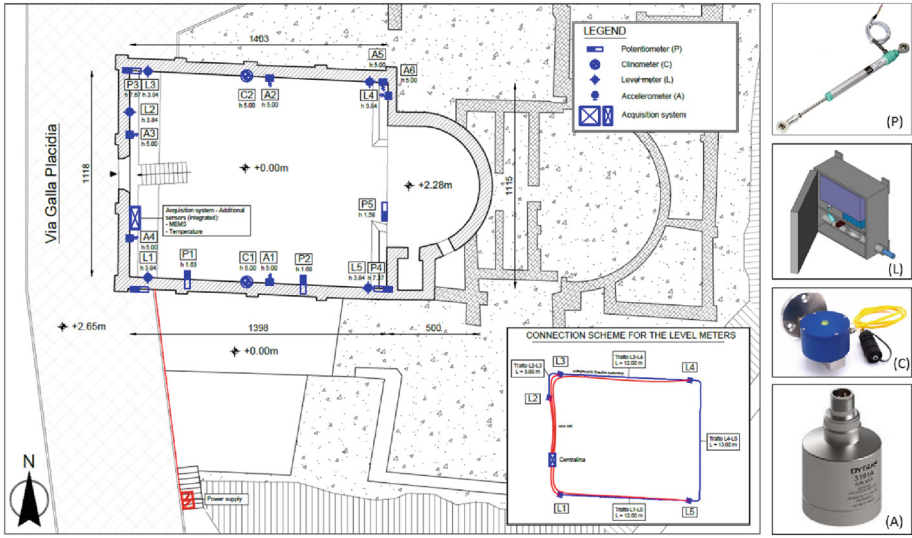


Fig. 7. Monitoring system: type and positions of the sensors.

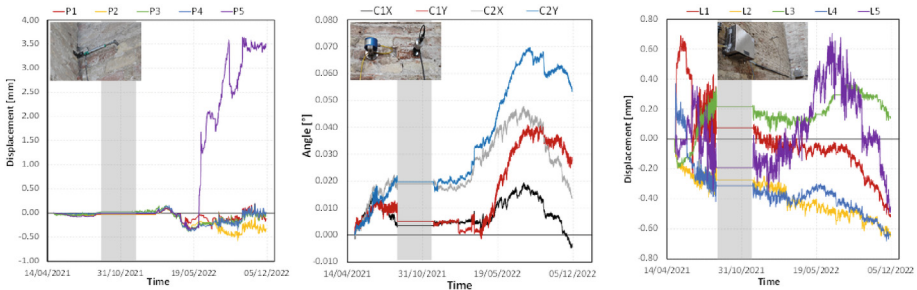


Fig. 8. Real-time monitoring data from April 2021 until December 2022 (grey area: no data due to flooding of the Church).

adequately connected in correspondence with the corners, it is possible to notice that, at the end of 2022, a negative increment of the displacements is registered by all the level meters. The grey area indicated in the graphs of Fig. 8 represents a period of time in which the monitoring activities stopped due to the fact that the Church was flooded as a result of severe thunderstorms and of the malfunctioning of the drainage system.

3.2 Dynamic Identification

As previously described, uniaxial piezoelectric accelerometers (sensitivity of 10 V/g and measurement range of ± 0.5 g) were also installed, for a limited period of time, to perform ambient vibration tests for the dynamic identification of the construction. They were positioned at a height of 5 m from the base of the Church (Fig. 7). Ten different registrations obtained under dynamic excitation induced by ambient vibrations

were considered. For each registration, signals were acquired with a frequency equal to 200 Hz for a total duration of 100 s. The dynamic characteristics of the structure were identified by means of the Enhanced Frequency Domain Decomposition (EFDD) method [14], which is based on a singular value decomposition of the Power Spectral Density (PSD) matrix to separate the contribution of each vibration mode. Once the singular value decomposition is performed, the Peak-Picking identification technique [15] can be adopted for the identification of natural frequencies. Considering the different registrations for each accelerometer, it was possible to identify recurrent ranges of resonance frequencies, leading to the identification of the first five natural frequencies of the Church as the average between the ones obtained for all the registrations. Moreover, modal displacement values were derived for each accelerometer and for each registration, then averaged with respect to the total number of registrations, to evaluate the mode shapes associated to the natural frequencies previously identified.

Results in terms of natural frequencies, periods and damping ratios of the first modes of the structure are reported in Table 1. They were used for the calibration of the numerical model, as will be explained in the following. Mode shapes are presented in Sect. 4, in comparison with the mode shapes obtained from the eigenvalue analysis.

Table 1. Natural frequencies, periods and damping ratios of the first five modes of the structure.

Mode	Frequency (Hz)	Period (s)	Damping ratio (%)
I	2.716	0.368	3.90
II	3.926	0.255	1.93
III	4.656	0.215	1.97
IV	5.618	0.178	1.89
V	6.847	0.146	0.84

4 Numerical Model

A 3D solid continuum finite element model (Fig. 9) of the Church of Santa Croce was developed by using the commercial software DIANA FEA v. 10.6. The geometry was defined on the basis of the geometric survey and of the on-site inspections previously described. The structural elements (masonry walls, apsis strengthened with reinforced plaster, reinforced concrete ring beam, timber roof elements) were modelled by adopting isotropic continuum models and quadratic brick elements. The elastic material properties are summarized in Table 2. It is worth mentioning that the elastic properties of the masonry were set by considering the values proposed by the Italian Building Code commentary [16] for poor-quality brick masonry. Indeed, information about the elastic modulus or the Poisson's ratio were not obtained during the on-site investigations.

The soil was modelled according to the Winkler model, i.e. by considering mutually independent springs of stiffness k , through boundary interface elements. Values concerning the mechanical characteristics of the soil were established on the basis of previous

surveys conducted in the area, i.e. investigation on the soil type and monitoring activities in which vertical displacements of the masonry walls were measured [7]. In more detail, to simulate the real behaviour of the foundations due to soil subsidence, different elastic stiffness constants were adopted under the masonry structural elements: 155.6 MPa/m for the façade, 155.5 MPa/m for the southern wall, 165.46 MPa/m for the northern wall, 45.1 MPa/m for the bell tower, and 151.7 MPa/m for the apsis. To reproduce the presence of the street adjacent to the main façade, a horizontal constraint was considered in the model to account for the restraint to horizontal translations provided by the street itself.

As observed during the damage survey, the walls were not properly connected in correspondence with the corners of the building. For this reason, quadratic interface elements were introduced at the connection between orthogonal walls. The stiffness parameters of these elements, i.e. one normal component (k_z) and two shear components (k_x and k_y), were calibrated by considering the results obtained during the dynamic identification process, as described in the following.

The loads considered during the analyses were the ones related to the self-weight of the structural and non-structural elements.

Table 2. Material properties adopted in the FE model.

Material	Young's modulus E [MPa]	Poisson's ratio ν [-]	Mass density w [kN/m ³]
Masonry	1800	0.2	18
Timber	9000	0.2	7.5
Reinforced concrete	32000	0.2	25

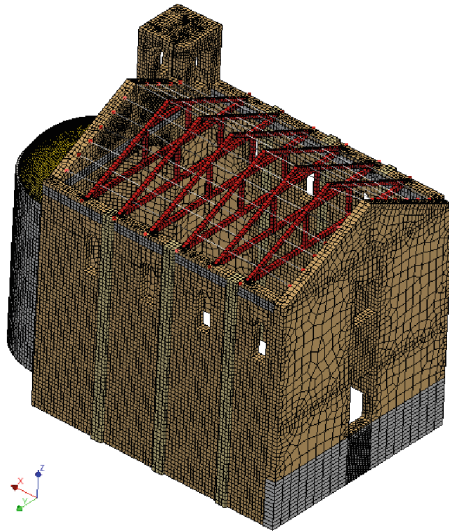


Fig. 9. Finite Element Model of the Church of Santa Croce.

4.1 Eigenvalue Analysis

The dynamic behaviour of the church was investigated by performing an eigenvalue analysis on the 3D FE model with the objective of calibrating the stiffness parameters of the interface elements inserted in correspondence with the walls connections. With this purpose, a modal analysis was initially carried out on a model in which infinite stiffness values were assigned to these interface elements. As expected, natural frequency values much higher than the experimental ones were obtained. Subsequently, the stiffnesses were calibrated by using the experimental frequencies as a reference: first the normal stiffness k_z was calibrated, then the shear stiffnesses k_x and k_y were varied until convergences with the experimental data. Eventually, the stiffness values obtained were: $k_z = 0.6 \text{ N/mm}^3$ and $k_x = k_y = 0.06 \text{ N/mm}^3$.

In Fig. 10, a comparison between the experimental and numerical first vibration modes is presented. Values of the displacements were taken from the FE model considering the points where the real accelerometers were placed during the dynamic testing, then normalized and amplified. As it can be seen, a quite good agreement was obtained between the experimental results and those from the calibrated model, demonstrating the reliability of the model itself.

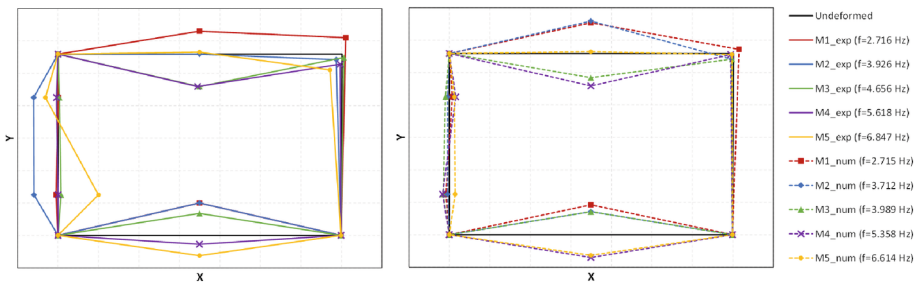


Fig. 10. Comparison between numerical and experimental mode shapes.

4.2 Nonlinear Analysis

In addition to the eigenvalue analysis, a nonlinear analysis was also performed with the aim of simulating the existing cracking scenario. In order to model the nonlinear mechanical behaviour of the masonry, the Mohr-Coulomb plasticity model was adopted, with cohesion and angle of internal friction equal to 0.075 MPa and 0.38 rad, respectively. The dilatancy angle was set to zero and cohesion or friction hardening were not considered. A tension cut-off was set at 0.05 MPa. Adopted values of the mechanical properties were set according to indications available in the Italian Building Code commentary [16] for existing masonry buildings and based on preliminary parametric analyses. The nonlinear static analysis was performed by applying the dead loads in 10 subsequent load increments. The regular Newton-Raphson method was used to solve the nonlinear problem. The results of the nonlinear analysis are presented in Fig. 11 for the last load step, i.e. total dead load applied, in terms of vertical displacements (Fig. 11a), in-plane

principal stresses (Fig. 11b), vertical plastic strain (Fig. 11c), and normal stresses at the interfaces (Fig. 11d).

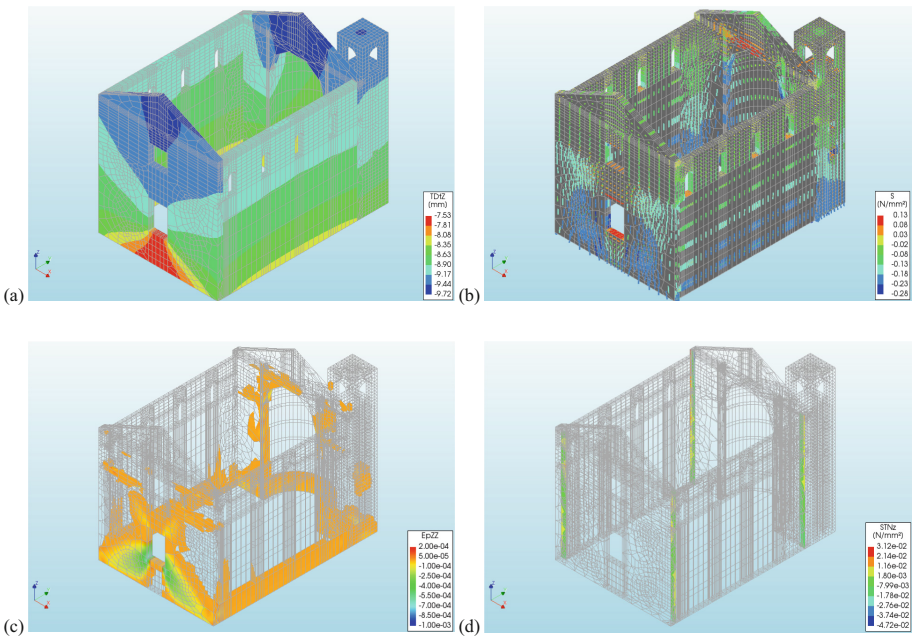


Fig. 11. Results of the nonlinear analyses: (a) vertical displacements, (b) in-plane principal stress components, (c) vertical plastic strains, (d) interface normal tractions.

It can be noticed that the most stressed masonry portions are located below the opening on the main façade, in correspondence with the apsis and, in general, in the lower portions of the masonry walls. Plastic strains can also be observed at the connection between the bell tower and the southern wall and between the bell tower and the apsis. Even if the presented results cannot precisely describe the crack pattern, it is worth mentioning that these locations are the ones in which most of the pre-existing damage was concentrated (Fig. 12). Due to the presence of the Galla Placidia street, it was not possible to investigate cracks in the masonry portion below the opening of the main façade. Along the interface elements at the corners, it can be observed that positive normal relative displacements are detected in many points, thus indicating the opening of cracks in those positions.



Fig. 12. Real damage pattern: (a) connection between the bell tower and the southern wall, (b) connection between the street and the southern wall.

5 Conclusions

In this work, a methodology which can be applied for the evaluation and monitoring of the state of conservation of existing buildings belonging to the cultural heritage was presented. The information related to the knowledge of the construction, to be achieved with historical analyses, on-site surveys and investigations about structural details and material properties, adopting non-invasive techniques, represent a key factor for the subsequent phases and, more specifically, for the accurate design of a Structural Health Monitoring system and for the numerical modeling.

The possibility to access monitoring data in real-time through a web dashboard was investigated and developed to provide a tool for the technicians, who can have the possibility to receive updated information about the monitored entities and to intervene in case of problems or specific events which might be dangerous for the historical building. Moreover, the information obtained through the monitoring system could be useful for the numerical model updating. The numerical model is, indeed, essential for the study of the safety of the building, e.g. against seismic events, and it should be the closer as possible to the reality. Within this perspective, the monitoring activities will continue in the following months, providing a basis for the definition of maintenance protocols supporting decision making processes.

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