

# Experimental Investigations and Numerical Simulations for the Seismic Assessment of a Masonry Building



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**Abstract** In Europe, a significant part of the existing building stock is composed by masonry structures, and, in many cases, these structures are located in seismic areas. They were built based on the empirical expertise of their constructors, and, therefore, are characterised by several construction solutions, different materials, and a high vulnerability to earthquakes. Moreover, during their long service life these buildings have been subjected to damage, degradation, and interventions to adapt them to the new performance demands. All these aspects make quite difficult the evaluation of the safety level of masonry structure, and several approaches are still debated for the definition of accurate numerical models for seismic assessment purpose. The present paper discusses the performed investigations and the defined numerical model for the evaluation of the safety level of a masonry structure characterised by two floors, by the presence of wooden roofs and masonry vaults at the first level, and by a pitched roof whose elements are made of wood. The building is located in a seismic area and is utilised as a church. The analysis of the documentation, the geometrical survey and the visual and experimental investigations have been utilised to define its level of knowledge, and to calibrate a numerical model for vulnerability evaluation.

**Keywords** Masonry structure · Level of knowledge · Vulnerability · Numerical model

## 1 Introduction

Our cities are characterized by the existence of a wide masonry building stock which is still in use and that, particularly in some Countries like Italy, represents an historical and monumental patrimony. This heritage must be preserved for several reasons, as testimony of the architectural evolution but also for the effects of its out of service on

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tourism and on the society, as in many cases these structures are utilized for public functions.

However, this patrimony due to its long service life is characterized by the effects of material degradation due to the environmental action, damage patterns induced by dynamic loads and/or foundation settlements, etc.

The seismic events of the last decades [1–4] underlined the high vulnerability of the masonry patrimony, that represents the largest part of the south Europe city centers, and the necessity of preserving this patrimony firstly to avoid human loss, and also the failure of historical testimonies.

Thus, the reliable evaluation of the current safety level of a masonry structure has reached increasing attention by researchers for the social and economic implications, but also for the difficulties connected to the definition of a complete and widely applicable approach to the analysis of these structures [3, 5–7]. In fact, due to the high variability of construction typologies, of the architectural style and mechanical characteristics, several approaches and applications are discussed in the technical literature.

The prerequisite for the evaluation of the current safety level of these structures against earthquakes and the design of possible effective interventions, is the acquisition of a good level of knowledge which is usually difficult to acquire due to the lack of documentation, the existence of changes of the original structure occurring over time, resulting from the necessity of adapting the structure to the new required performance, the occurrence of damage phenomena, etc.. In many cases these interventions are responsible of increasing the irregularity of the structure and their vulnerability to seismic actions.

Several techniques are available for the complete mechanical characterization of masonry structures, however the most reliable are too invasive and thus in many cases may not be adopted due to the necessity of preserving the structure, or are time-consuming and economically expensive.

Thus, in literature many researchers have proposed the use of the laser scanner for the acquisition of a reliable geometry [2, 8]. In [2] the geometrical survey by means of 3D Laser Scanner and the seismic vulnerability assessment of the baptistry of San Giovanni in Tumba located in Monte Sant' Angelo (Italy) is discussed. The paper shows the advantage of the Laser Scanner methodology, which is able to acquire a huge number of points within limited time intervals, allowing the definition of a complete and detailed 3D model. These characteristics justified the increase of the researchers' attention for the laser scanner with the aim of defining a refined 3D model of the cultural and historical heritage.

The present paper aims to highlight the relationship between a detailed survey, also including ad hoc chosen experimental tests, and the structural analysis of an irregular structure, by discussing in detail the procedure for the seismic vulnerability analysis of the S. Marco Evangelista Church in Bari (Italy). This structure has been chosen for its complexity and the presence of structural elements characterized by different behavior. It is discussed the acquisition of geometrical data by means of Laser Scanner, the seismic P-wave refraction method for soil characterization, the endoscopic tests to exactly evaluate the construction technology and geometrical

features of masonry structural elements, the compressive tests on drilled cores and the results of the structural analysis on a Finite Element (FE) model both for static and dynamic loading conditions. The paper is organized as follows: in Sect. 2 the examined Church is described, Sect. 3 discusses in detail the experimental campaign carried out to increase the knowledge level of the structure. In Sect. 4 the definition of the finite element model of the Church is described and the results of the seismic analysis are illustrated in detail.

## 2 The San Marco Evangelista Church

The San Marco Evangelista Church is located in Bari (Apulia, Italy), and is an isolated masonry palace surrounded by masonry walls (Fig. 1). The building has plan dimensions of 16 m  $\times$  23 m, a maximum height of 10.5 m and it comprises two levels and an attic.

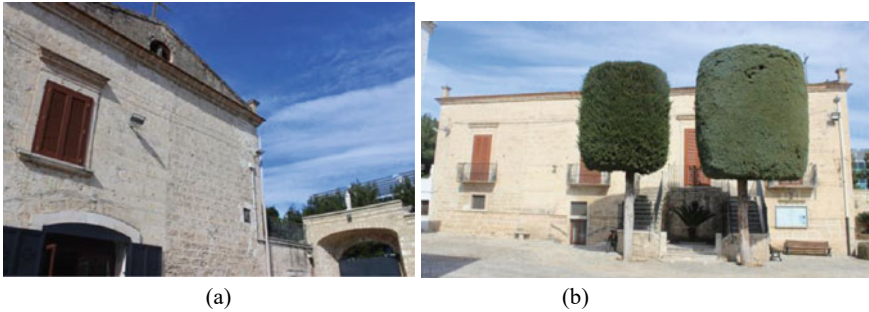
The San Marco Evangelista church was built during the VIII century and its original function was farmhouse. The visual inspection of the structure highlights that it was built in two periods, as two different materials can be recognized in the structure. In detail, the main nave of the church and the apse have been realized in the same period and with the same materials, while the remaining rooms are characterized by a more porous material, and it was reasonable built prior to the first cited part. This consideration is confirmed by the presence of an arch which is not coherent with the actual orientation of the floor, it can be hypothesized that in the original structure, which did not comprehend the actual nave and apse, the floors were oriented orthogonally to the actual direction, coherently with the distribution of the masonry walls, however, when the other parts of the structure were built, the floors were substituted and oriented differently (see Fig. 2). The Church presents cracks localized in the zones where the two materials are connected.

In the 1977 the town Council changed its function and established that the patronal rooms, the oil mill, and the stables were used for religious functions, then the bishop Ballestrero dedicated the structure to St Marco Evangelista.

Between the 1980 and the 1990, a retrofitting intervention was carried out on the structure consisting of the demolition of the floor located on the actual position of presbytery and subsequent reconstruction with a wooden floor.

**Fig. 1** View of the San Marco Evangelista Church in Bari (Italy)





**Fig. 2** a Frontal view of the East façade; b Frontal view of South façade of San Marco Evangelista Church

During the 1985 due to a tornado, the roof of the building was significantly damaged and, thus, the church was subjected to an extensive intervention during which the roof was rebuilt with a wooden pitched roof. The historical research has not given any information on the interventions during the period between the building construction and the 1980.

Observed from the outside, the building appears composed by two rectangular plan parts, orthogonal to each other. The first rectangular part is oriented East–West while the second part is along the North–South direction and connects the liturgical hall directly with the sacristy.

The liturgical hall is at the ground floor in two adjoining rooms, which originally were used as oil mills, and that have a characteristic “L” shape with the altar placed at an angle in order to guarantee most of the visibility. Each of the two rooms is characterized by round arches that support two lowered barrel vaults orthogonal to each other, whose intersection determines a groin vault.

All the rooms at the ground floor are characterized by exposed stone walls except for the altar, while the rooms on the first floor are entirely plastered.

The parish office and some classrooms for pastoral activities are located at the first level.

An internal masonry staircase, consisting of two ramps supported by a barrel vault, and an external masonry staircase located on the main façade allow the access to the first floor, while the attic can be reached only by means of the internal staircase.

The Church presents barrel vaults and floors realized by planks and timber beams.

The attic is characterized by a trussed wooden roof supported by the walls and by central masonry pillars. To reduce the span lengths of the ridge beam, wooden struts are installed in the vertical plane.

The entrance to the liturgical hall is located on the East side of the building where two openings of different sizes are placed: the first with a lowered arch allows the entry to the liturgical hall, the second, which is smaller than the first one, allows entry to the sacristy and ancillary rooms. On the longest façade of the building there is a secondary entrance that allows lateral access to the liturgical hall.

### 3 Experimental Campaign

The lack of documentation regarding the geometric and structural characteristics of the Church, has imposed a detailed geometrical survey and experimental tests to improve the knowledge level and to perform the subsequent seismic vulnerability assessment.

In detail, a series of laser scanning surveys have been planned for defining a reliable finite element model of the structure.

This methodology was chosen as it allows a complete description of the structure, overcoming the main limit of the “traditional” survey whose accuracy is dependent from the choices of the operator, that unavoidably must discretize the structure, and in this way, inevitably effects the accuracy of the numerical model.

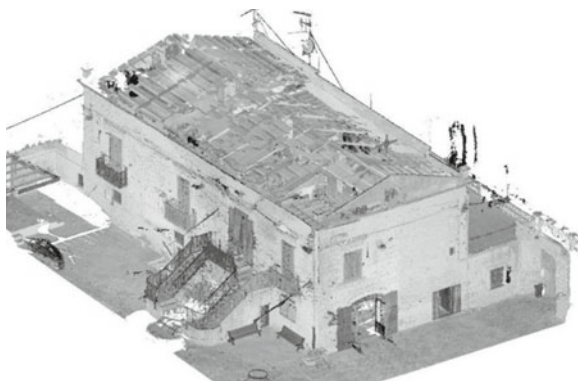
The use of 3D Laser Scanner provides a 3D point cloud data which allows the definition of a high-resolution geometrical model of the investigated structure. This objective is obtained by merging many acquisitions obtained by changing the position of the 3D Laser Scanner. The three-dimensional point cloud data are later analyzed by inserting boundary and connectivity conditions which allow to define a refined geometrical model.

The adopted 3D Laser Scanner is Leica HDS 6100 which is a continuous wave phase-based TLS characterized by an acquisition velocity equal to 127,000 pts/s, it allows a large field of view ( $360^\circ \times 270^\circ$ ), ensuring at the same time a low beam divergence and a good measuring accuracy (a standard deviation on a single acquisition equal to 3 mm at 25 m and 5 mm at 50 m).

To acquire a complete and very detailed three-dimensional model of the San Marco Church a total number of 23 scans were collected, which have been correlated to each other by a series of reflective targets.

At the end of the process, the resulting aligned model of the San Marco Evangelista Church shown in Fig. 3 has been obtained, which has an average root mean square error of the overall alignment around 2 mm.

**Fig. 3** Computer rendering of the 3D model of the San Marco Evangelista Church acquired by means of Laser Scanner



From the superimposition of the plans of the three floors, it is possible to deduce that the walls appear to have a continuity in elevation, the pillars of the attic, which support the wooden beams of the roof truss, are instead not perfectly aligned with under walls.

Moreover, endoscopic tests have been carried out to acquire detailed information regarding the stratigraphy and geometrical features of the walls and vaults. In detail, the Rigid micro Explorer was adopted which is a micro inspection camera with a diameter of 17 mm and a  $320 \times 240$  RGB resolution, placed at the end of the endoscopic cable, equipped with an entirely digital platform that allows to record images and videos with a resolution of  $640 \times 480$ .

The endoscopic tests have been carried out on 7 masonry walls and a vault. The tests show that the masonry walls at the ground floor are realized by tuff bricks organized on two leaves whose dimensions vary along the perimeter of the building, while the walls inside the church are realized by a single leaf of tuff brick. The latest typology is also observed at the first floor, except for the central wall which is a double- leaf wall in tuff bricks.

To evaluate the mechanical parameters of the materials, two cylindrical specimens were extracted by means Diamond core drill IM250H, with an external diameter of 80 mm and internal diameter of 74 mm, and the two cores have been subjected to compression tests (Fig. 4). The evaluated compression strength was equal to 1.88 MPa.

Moreover, with the final aim of estimating the mechanical characteristics of the walls and in accordance with the Italian Code [9] and the 2019 Guidelines [10], the Masonry Quality Index (MQI) [11–13] method was applied which makes use of a visual survey of the faces and the cross section of wall panel and proceeds by verifying if it obeys the “rules of the art”. The visual analysis makes use of 7 parameters (usually indicated as SM, SD, SS, WC, HJ, VJ, and MM). It is worth noting that the masonry quality influences differently the response to different actions, thus, the cited 7 parameters must be evaluated based on the acting loads. The seven parameters are:

1. MM Parameter—Quality of the Mortar/Contact between Masonry Units: the quality of mortar affects the transfer of stresses between masonry elements avoiding the concentration of stresses.

**Fig. 4** Compression test on a drilled core



2. WC Parameter—Level of Connection between Adjacent Wall Leaves/Headers: the global behavior of the wall, particularly the compressive and out-of-plane ones, are highly influenced by the headers connecting the wall leaves, because they allow the distribution of the gravitational loads on the whole wall transversal section.
3. SS Parameter—Shape of the Masonry Units: the use of perfectly cut elements affects the response to horizontal in-plane loads.
4. SD Parameter—Dimensions of the Masonry Units: this parameter is based on the observation that the static and dynamic behavior of the wall improves as the ratio between the brick length and the wall width increases.
5. VJ Parameter—Staggering of Vertical Mortar Joints: this parameter takes into account the effect on the wall static and dynamic behavior of stagger properties of vertical joints.
6. HJ Parameter—Horizontal Mortar Bed Joints: the presence of continuous and horizontal layers of mortar allows to better distribute the gravitational loads on the panel transversal section and improves the response under seismic actions.
7. SM Parameter—Mechanical Characteristics and Quality of Masonry Units: this parameter considers the brick mechanical properties and conservation state.

On such basis, the MQI must be evaluated for three different load conditions: vertical loading, horizontal in-plane loading and horizontal out-of-plane loading, the expression is the following:

$$MQI = m \times SM \times (SD + SS + WC + HJ + VJ + MM) \quad (1)$$

where  $m$  is a factor introduced to consider the influence of the quality of the mortar, which is assumed equal to 1 except for very-weak mortar, when it is set equal to 0.7.

Based on the MQI values, three different masonry categories are individualized, denoted by A, B, C whose behavior worsens from A to C.

The masonry walls of the San Marco Church have been classified as shown in Table 1, where NF stands for Not Fulfilled, PF for Partially Fulfilled, and F for Fulfilled (see Fig. 5), while the mechanical properties have been evaluated in accordance with the prescription of the Italian Codes for the squared softstone masonry.

To characterize the soil, on-site tests have been performed; in detail, the seismic P-wave refraction method has been adopted which evaluates the compression waves generated by a seismic source located at a known distance from the investigated site, this test was chosen as these waves are more clearly identifiable. In the seismic refraction survey, the transducers detect the refracted waves traveling at higher speeds. Knowing the first arrival times and the geophone-source distance, and by analyzing the curves of the first arrivals to each transducer (travel time), it is possible to determine the speed of the various layers and to produce a seismic stratigraphy to be correlated to the geological formations or discontinuities present in the investigated soil.

**Table 1** Evaluation of MQI for a masonry panel of the San Marco Evangelista Church

		Vertical loading (V)	Horizontal in-plane Loading (I)	Horizontal out-plane Loading (O)
MM	NF	0	0	0
WC	PF	1	1	1.5
SS	F	3	2	2
SD	F	1	1	1
VJ	PF	0.5	1	0.5
HJ	F	2	1	2
SM	PF	0.7	0.7	0.7
	QMI	5.25	4.2	4.9
Masonry category		A	B	B

**Fig. 5** Detail of a masonry panel for the evaluation of MQI

The method is based on the observation that the P-wave speed through a medium depends on the physical properties (i.e. rigidity, density, saturation) and degree of homogeneity of the material.

In the here examined case, the seismic P-wave refraction tests have been performed adopting a length of the survey line equal to 50 m, located parallel to the east façade of the Church.

The source of P waves was an instrumented impact hammer with a weight equal to 8 kg which hits vertically on an aluminum plate suitably placed on the ground, for the prevailing generation of rich high frequency P waves, with repeatable and directional waveforms.

The waves were acquired by means of 24 electromagnetic geophones with moving-coil characterized by a natural frequency equal to 4.5 Hz. The geophones were installed at a constant distance of 2 m and the frequency acquisition was set



equal to 256 Hz. To obtain a complete description of the soil, 8 different shot points were chosen: two located at the ends of the acquired line and the other 4 shot points in correspondence of the 5th, 10th, 15th and 20th geophone, respectively.

The data processing was carried out by means of software RAYFRACT [14].

In Fig. 6 the acquired seismogram for the case in which the shot point is at the start point of the survey line is shown, while in Table 2 the first arrival times of P-waves at the surface of the earth for each geophone are presented.

The results of the soil inspection are shown in Fig. 7 where a contour plot shows the acquired wave velocity profile at varying depth from the ground level (y axis) and along the survey direction (x axis). The plot shows that the subsoil consists of 2 basic seismic stratigraphic units from the ground level:

- The first seismic stratigraphic unit UsC (see Fig. 7) extends up to an average depth between 1.3 ÷ 2.8 m from the ground level with an almost stratiform structure. This seismic layer is characterized by  $V_p$  values ranging between 500 ÷ 900 m/s, with minimum values recorded at a distance along the survey direction greater than 22 m, while the minimum values are reached beyond the cited distance. The boundary, which divided this unit from the underlying seismic layer, appears clearly marked as it is characterized by very high gradient values.

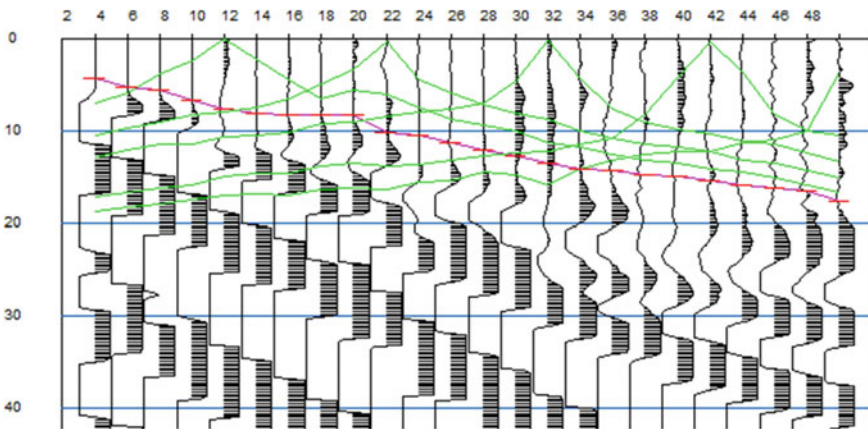


Fig. 6 Seismogram for the shot point at the beginning of the survey line

Table 2 Seismic P-wave refraction tests: first arrival times for each geophone with the shot point at the start point of the survey line

Geophone	1	2	3	4	5	6	7	8	9	10	11	12
[ms]	4.21	5.15	5.62	6.61	7.55	8.02	8.31	8.31	8.31	10.11	10.53	11.16
Geophone	13	14	15	16	17	18	19	20	21	22	23	24
[ms]	12	12.6	13.5	14.1	14.2	14.8	15	15.4	15.9	16.15	16.47	17.52

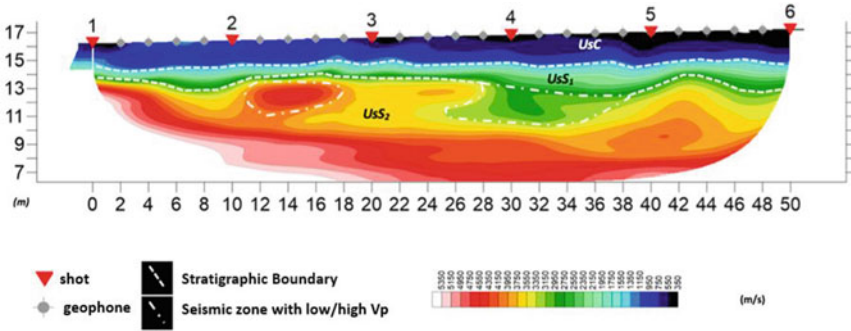


Fig. 7 Seismic stratigraphy: x axis distance [m] along the survey direction and y axis distance along the vertical direction [m]

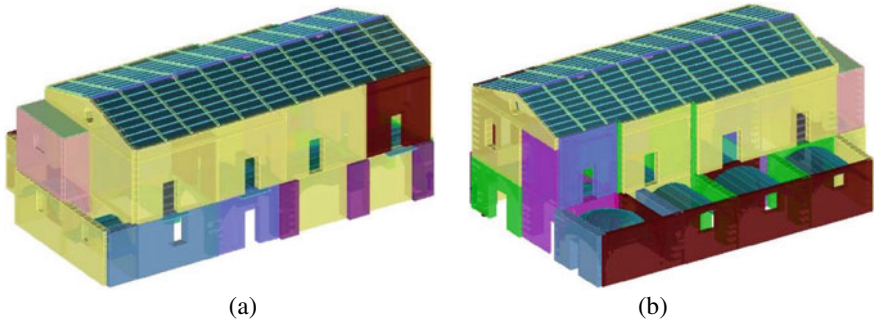
- The second seismic stratigraphic unit UsS (see Fig. 7) shows a clear increase in the detected speeds and an uneven distribution of the values. This unit can be further divided into 2 subunits: the first unit UsS<sub>1</sub>, characterized by a variable thickness ranging between 1.0 ÷ 2.0 m, reached the maximum values in the range of distance along the survey direction equal to 28–40 m. This zone manifests V<sub>p</sub> values ranging between 1450 m/s and 2400 m/s with values increasing with depth. The second seismic stratigraphic unit UsS<sub>2</sub> is characterized by V<sub>p</sub> values greater than 3300 m/s with an uneven distribution, moreover, at a depth of 7 m from the ground level, the V<sub>p</sub> values increase ranging between 4500 m/s and 5700 m/s.

In accordance with the experimental results and with the Italian Codes prescriptions [9, 10], the category A (Rock or other rock-like geological formation, including at most 3 m of weaker material at the surface) was assumed for the soil, while the topographic category was assumed equal to T1.

### 4 Numerical Model

To evaluate the safety level of the San Marco Evangelista Church, a reliable finite element model was defined based on the results of the experimental campaign and utilized to estimate the response to seismic action compatible with the seismic hazard of the zone. To this aim, a response spectrum analysis was carried out to assess the seismic vulnerability.

The numerical model assumes that the walls have a homogeneous stratigraphy whose thickness is imposed based on the endoscopic results. The vertical walls and the vaults have been modelled by means of 7338 shell elements, while the columns at the attic and the roof elements have been modelled through 861 beams, and the floors have been modelled by means of 502 elements which distribute the loads. The whole model is characterized by 7664 points; in Fig. 8 the 3D view of the model



**Fig. 8** 3D view of the finite element model of the San Marco Evangelista Church: **a** south view; **b** north view

is shown, the different colors are related to the adoption of different geometrical thicknesses.

The experimental compressive strength of tuff is equal to 1.88 MPa, and the experimental compressive strength of mortar is equal to 2.50 MPa, thus the characteristic compressive strength of masonry is obtained as follows:

$$f_k = K f_b^{0.7} f_m^{0.3} \tag{2}$$

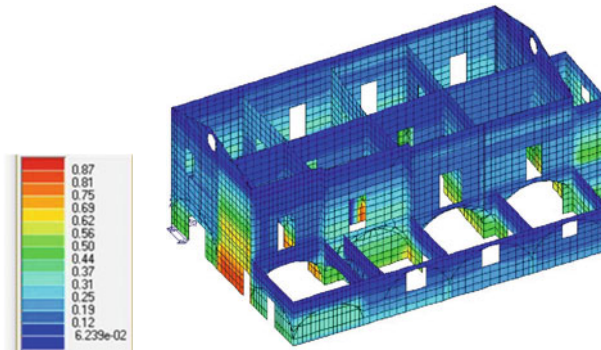
where  $K = 0.45$ ; thus,  $f_k = 0.92$  MPa.

The knowledge level is equal to LC3 with a confidence factor equal to 1 [9, 10], moreover, in accordance with such codes, the mechanical properties have been increased by a coefficient equal to 1.2, and the final mechanical parameters are shown in Table 3.

The analysis has been carried out by adopting a snow load equal to  $0.8 \text{ KN/m}^2$ , wind load  $0.65 \text{ KN/m}^2$ , moreover, for the wooden floors the structure’s self-weights have been set equal to  $0.08 \text{ KN/m}^2$  and non-structural permanent loads equal to  $1.00 \text{ KN/m}^2$ . The live load at the ground and first level has been set equal to  $2.00 \text{ KN/m}^2$ , and at the attic equal to  $0.5 \text{ KN/m}^2$ . The evaluation of self-weights of vault abutments has been carried out by considering the variation of the height along the vault, thus,

**Table 3** Mechanical parameters adopted for the FE model

Material	Young’s modulus [MPa]	Modulus $E_{0.05}$ [MPa]	Shear modulus [MPa]	Density [ $\text{kg/m}^3$ ]
Regular softstone masonry	2112	–	845	1580
Wood C18	10,500	5999	660	375
Glued laminated timber	11,500	9599	650	385



**Fig. 9** Results of the safety checks related to the axial forces and out-of-plane bending moment induced by static loading condition

different values of load have been adopted depending on the position of the considered shell element on the vault.

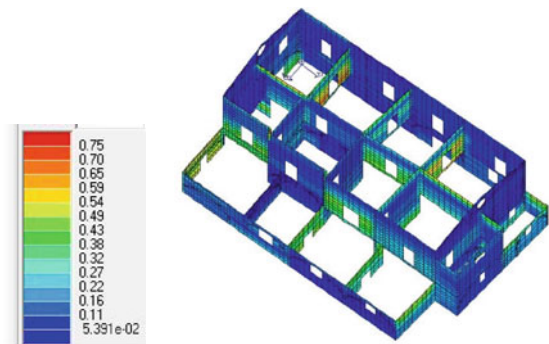
In the first step of the analysis, a static analysis has been carried out to estimate the safety level of the Church in the usual loading conditions. In Fig. 9 the plot of safety checks related to the axial forces and out-of-plane bending moment is shown.

In accordance with the Italian Building Codes [9, 10], due to the irregularities of the structure both in elevation and in plan, a behavior factor  $q = 2.25$  for the horizontal design spectra and  $q = 1.5$  for the vertical direction have been adopted.

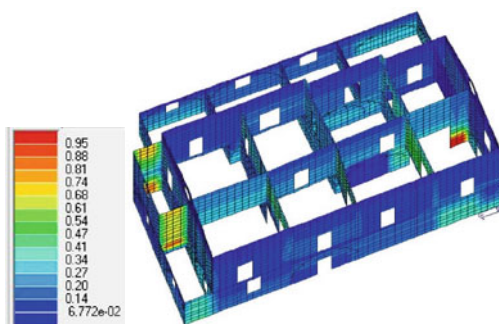
The response spectrum analysis has been carried out to evaluate the seismic vulnerability of the church. In Fig. 10 the plot of the safety checks related to the axial forces and in-plane bending moment due to the worst load conditions is shown, in this case the load combination considers the seismic action too.

For the same load combination, in Fig. 11 is plotted the results of the safety checks related to the shear action. It is worth noting that the structure is subjected to shear forces not compatible with its resisting capacities.

**Fig. 10** Results of the safety checks related to the axial forces and in-plane bending moment induced by the worst seismic load condition



**Fig. 11** Results of the safety checks related to the shear forces induced by the worst seismic load condition



## 5 Conclusion

The paper presents the survey and the seismic vulnerability evaluation of San Marco Evangelista Church in Bari (Italy), which dates back to the VIII century, having cultural value and that can be considered representative of the Italian historical patrimony.

Due to the irregularities both in plan and in elevation and the lack of information regarding the original configuration of the structure, an extensive campaign was carried out. The present paper has shown the benefits of the use of Laser Scanner methodology for defining the exact geometric configuration, and the relationship with the definition of an accurate finite element model. The experimental campaign allowed the detailed characterization of the masonry structural elements and of the soil.

The experimental analysis and the definition of an accurate numerical model highlighted that the San Marco Evangelista Church capacity may be lower than the demand when it is subjected to seismic actions, and that has an average vulnerability degree.

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