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SEISMIC ASSESSMENT OF CULTURAL HERITAGE: NONLINEAR 3D ANALYSES OF "SANTA MARIA DELLA CARITÀ" IN ASCOLI PICENO

Francesco Monni[1], Francesco Clementi[1], Enrico Quagliarini[1], Ersilia Giordano[1] and Stefano Lenci[1]

[1]Department of Civil and Building Engineering, and Architecture, Polytechnic University of Marche
Via Brecce Bianche, 60131, Ancona, Italy
f.monni@univpm.it, francesco.clementi@univpm.it, e.quagliarini@univpm.it, S.lenci@univpm.it

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Abstract. *In this paper a masonry church is analysed in order to assess its seismic vulnerability with respect to the actual state of conservation, including past retrofitting. The case study is the "Santa Maria della Carità" church, located in Ascoli Piceno, a small town of Marche region, in the Centre of Italy, where two major earthquakes occurred in August and in October 2016, causing widespread damage. The church has a large historical, architectural value because is one of the most important example of the Barocco age in the region, and contains a lot of precious paintings of local artists. Moreover it has also a social value for the city of Ascoli Piceno, because it is the only one that is opened to the devotees for every moment of day and night. Stroked also by the L'Aquila earthquakes (2009) the church was subjected to a retrofit intervention (2010), in order to obtain a better "box-like behaviour". Churches are usually characterised by a high seismic vulnerability due to their structural and geometric configurations, heterogeneous and deteriorated materials. These structures have very large and high external walls without internal orthogonal walls: the space thus created is often covered by some thin vaults or thrusting arches. In this work using an advanced FEM approach (a 3D nonlinear solid numerical model has been used to evaluate the seismic capacity) the structure has been studied to establish its significant deficiencies, in order to obtain a clear understanding of the structural behavior. The results should be useful to design a reliable strengthening intervention, but they could be also extrapolated to the wide variety of historical churches, and generalized for a wide masonry building category.*

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1 INTRODUCTION

The seismic vulnerability assessment of historical constructions with great architectural value, like churches, is of strategic importance considering the richness of the European and Italian architectural heritage [1,2]. The earthquakes that hit Italy last years (L'Aquila 2009, Emilia Romagna 2012, Centre-Italy 2016) confirmed the high vulnerability of this type of structures [3–5], and also the recent advances in structural assessment of this building typology confirm the centrality of the matter [6,7]. Churches are usually characterized by very large and high external walls without internal orthogonal walls: the space thus created is often covered by some thin vaults or thrusting arches. Due to the lack of a rigid intermediate horizontal diaphragm and a lack of walls interlocking, historic churches often show the absence of "box-like behavior": these monumental buildings cannot be reduced to any standard structural scheme, and this makes difficult to evaluate their seismic reliability.

In this paper is presented the case study of Santa Maria della Carità church, firstly hit by L'Aquila earthquake (2009) and closed after this seismic event. The church was re-opened after a retrofitting (2010) but it was successively re-closed, as a precaution, in August 2016 due to the Marche-Umbria-Lazio-Abruzzo earthquakes.

After a first phase dedicated to a deep knowledge of the building (to determine exactly the historical building evolution, crucial for this kind of studies [8]) a structural assessment was developed.

Using advanced numerical tools to perform nonlinear three-dimensional (3D) analyses, possible failure mechanisms of the structure, when subjected to an earthquake and to establish the significant deficiencies of the structure was investigated, to capture the aspects to be considered in future restoration interventions.

2 THE CASE STUDY: "SANTA MARIA DELLA CARITÀ" CHURCH

The church of Santa Maria della Carità in Ascoli Piceno has a significant historical and architectural value: it is one of the most prominent example of the Barocco age in the Marche Region and contains a lot of valuable paintings of local artists (Fig. 1). Moreover, it has also a social value for the city of Ascoli Piceno, because it is the only one opened to the devotees all time in the day and night [9]. The construction age is not known, the first proof of the existence of a little church, grow up at 1306, can be found in a parchment. Later, since the early years of the 16th century to 1583 the building has been partially demolished and re-built, in several steps, in the same place, modifying basically the facade with the tympanum raising and front doors opening. Further to this intervention the nave has been covered with a masonry vault and has been connected by a triumphal arch with the apse, built at the same time. Therefore, iconographical documents attest the presence of a pre-existing bell-tower on the different side respect to the actual. So, the triumphal arch was built during the 16th century, but the actual bell-tower was built only at the end of 17th century, after almost one hundred years [10,11]. The church has a unique nave of 12.93 m wide, 23.15 m long and has a maximum height of 16.5 m, it ends with a rectangular apse 6.55 m wide, 8.30 m long and a height of 11.95 m (Fig. 2). The apse is inside the sacristy, who have two floors, and it has a maximum height of 15.90 m. In the sacristy, there is also the bell-tower: it has a square shape with side 4.31 m and has a maximum height of 27.80 m. The thickness of walls is variable between 2.21 m (piers of the nave) and 0.91 m (walls of the nave). The bearing structure are made of stone masonry, the main façade, characterized by three front doors, has ornaments with classical pattern (columns, tympanum, cornice) and the masonry layer is constituted by white travertine, the nave is covered by a brick elliptic vault (like the apse zone) with lunettes that create small ornamented niches jointing with the columns included inside walls. Also in Santa Maria della Carità, like many other Italian churches, the triumphal arch separates nave area from the apse. It is inserted in a masonry panel, with an elliptically shaped opening has a thickness of about 1.2 m. The church walls have different masonry materials (i.e., brick, travertine, stone, etc.), in the walls of the nave there is two distinct type of masonry in elevation, this can be explained by the different age of edification. At a height of 11.08 m there is travertine block, and up there is irregular stone.

Figure 1. The main façade of the church (left) and view of the internal space (right).

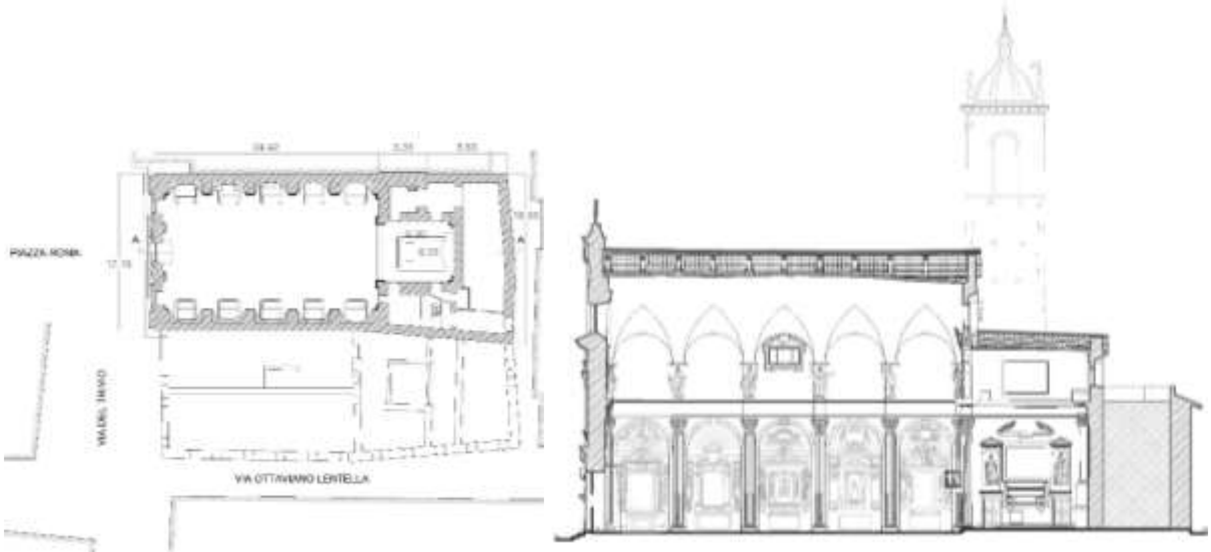


Figure 2. Floor planning (left) and section (right) of the church.

3 STRUCTURAL MODEL

In this work, the nonlinear damage behavior of the masonry is considered within a continuum mechanics theory, based on a smeared crack approach [12,13] where the cracks are not described one by one but are instead continuously spread within the body and affect (reduce) the medium stiffness, a concept that offers a variety of possibilities, ranging from fixed single to fixed multi-directional and rotating crack approaches. Here, the distinction lies in the orientation of the crack, which is either kept constant, updated in a stepwise manner or updated continuously [14]. Due to the limited data required, the smeared crack models are practice-oriented

[15]. The panels were modeled with solid tetrahedron elements with 4 nodes, and optimized regular mesh was used for discretization. The nonlinear behavior of the masonry panels of the historical complex is represented by a Total Strain Crack Model based on fixed stress–strain law concepts available in Midas FEA©. In this way, the cracks are fixed in the direction of the principal strain vectors being unchanged during the loading of the structure. The tension/compression behavior of the masonry was modelled by the constitutive laws reported in Figure 3.

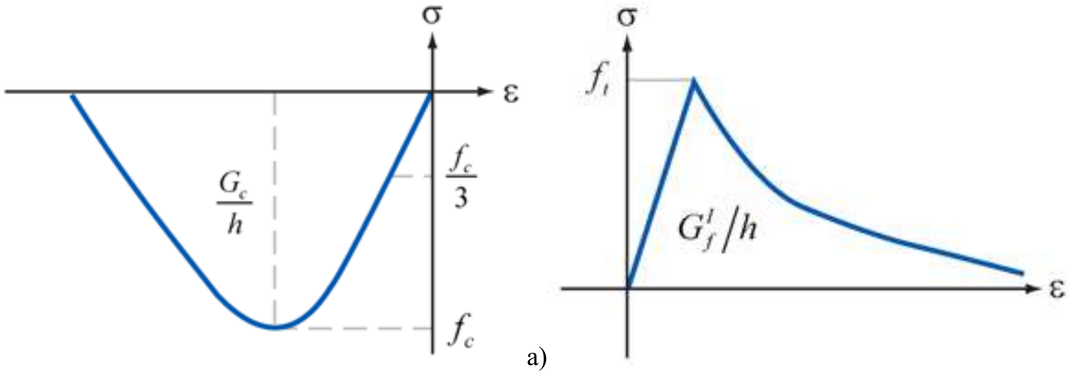


Figure 3. Stress–strain constitutive relations used for the simulation: a) masonry uniaxial compression; b) masonry uniaxial tension.

About materials properties, the masonry mechanical parameters used in the model (from in situ survey and from Italian Codes for existing masonry buildings [16,17]) are reported in Table 1.

	fc [MPa]	ft [MPa]	γ [N/mm3]	E [MPa]	ν	Gc [N/mm]	Gf [N/mm]	Confidence Factor (CF)
Squared block stone masonry thin joins								
KL1	5.33	0.53	0.000022	3840	0.3	3.74	0.04	1.35
Squared block stone masonry								
KL1	4.44	0.44	0.000022	2800	0.3	3.29	0.03	1.35
Solid bricks and lime mortar masonry good mortar								
KL1	2.67	0.27	0.000018	2250	0.3	2.30	0.02	1.35
Disordered rubble stone masonry								
KL1	0.74	0.07	0.000019	870	0.3	0.94	0.01	1.35
Solid blocks and disordered rubble stone masonry								
KL1	1.25	0.12	0.0000194	1677	0.3	1.35	0.01	1.35
Squared block stone and disordered rubble stone masonry thin joins								
KL1	1.24	0.12	0.00002	2202	0.3	1.35	0.01	1.35

Table 1. Mechanical characteristics of the main elements.

The shear retention factor (β) gives the shear stiffness after cracking, which can be a constant (low) value between 0 and 1, or a value depending on the crack opening. Here, a constant value equal to 0.05 was adopted like requested in [18].

The Numerical Model (NM) has been built to reproduce the geometry of the structures, focusing on the variations in wall thickness, on geometrical and structural irregularities, and on wall connections. Finally, the major openings in the buildings have been reproduced. The NM consider a complete separation between the church and the annex, since as previously said, the annex could have been built later than the church. About the diaphragm stiffness (a choice that could significantly affect the overall response [17]), they have been considered as flexible floors, in fact the hypothesis of rigid floors may be unrealistic in case of existing buildings (e.g. historical masonry structures), where various ancient constructive technologies (i.e. timber floors and roofs, structural brick or stone vaults) can be found for floor and roofing systems. The NM consider the contribution of the retrofit intervention executed in 2010 (after the L'Aquila eartquake of the year 2009).

After meshing, the final 3D NM is shown in Fig. 4, it counts 17136 nodes, 59632 solid elements and 49827 degrees of freedom (d.o.f.). Nonlinear static analyses (i.e., pushover) reported in the next sections have been performed assuming a rigid ground foundation (fixed base model) and the following parameters have been adopted during the analyses:

- Maximum number of iterations of load increment: 200;
- Maximum analysis number of sub-steps: 1500;
- Minimum analysis number of sub-steps: 5;
- Initial load factor 0.01.

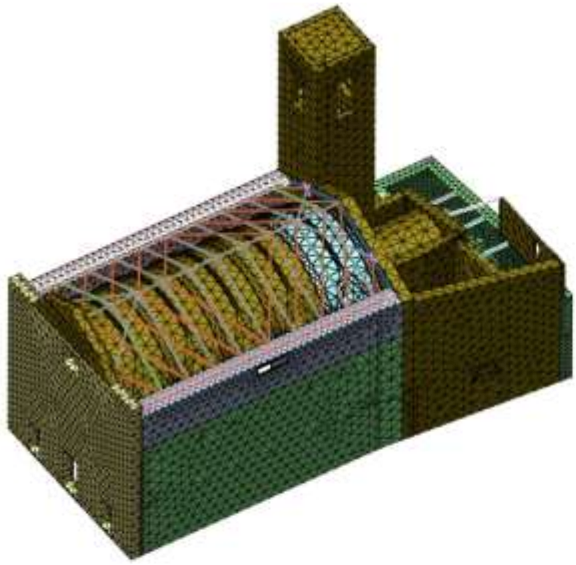


Figure 4. Numerical Model of the church.

4 NONLINEAR STATIC ANALYSIS: CONSIDERATIONS AND RESULTS

The seismic behavior has been analyzed by using a nonlinear static analysis method: under conditions of constant gravity loads a monotonically increasing horizontal loads have been applied using a pushover analysis [19]. Based on this method, the effects of the seismic loads have been evaluated by applying two systems of horizontal forces perpendicular to one another, not acting simultaneously. The first load distribution is directly proportional to the masses of the structures (PushMass) on each floor; the second load distribution is proportional to the main mode in the considered direction (PushMode). These two load distributions could be considered as two limit states of the building capacity.

It is noteworthy to point out that a conventional pushover is assumed in the study, i.e. loads applied to the building do not change with the progressive degradation of the structure that occurs during loading. This means that the conventional pushover does not account for the progressive changes in modal frequencies due to yielding and cracking on the structure during loading [20,21]. Hence, the hypothesis of invariance of static loads could cause an overestimation in the analysis of the masonry building seismic capacity especially when a non-uniform damage on the buildings or a high level of cracking are expected. However, also in its conventional form, the pushover provides an efficient alternative to expensive computational nonlinear dynamic analyses and can never the less offer useful and effective information on the damage state that the building can develop under seismic loads [21]. The main capacity curves obtained by nonlinear static analysis are reported in Fig. 5.

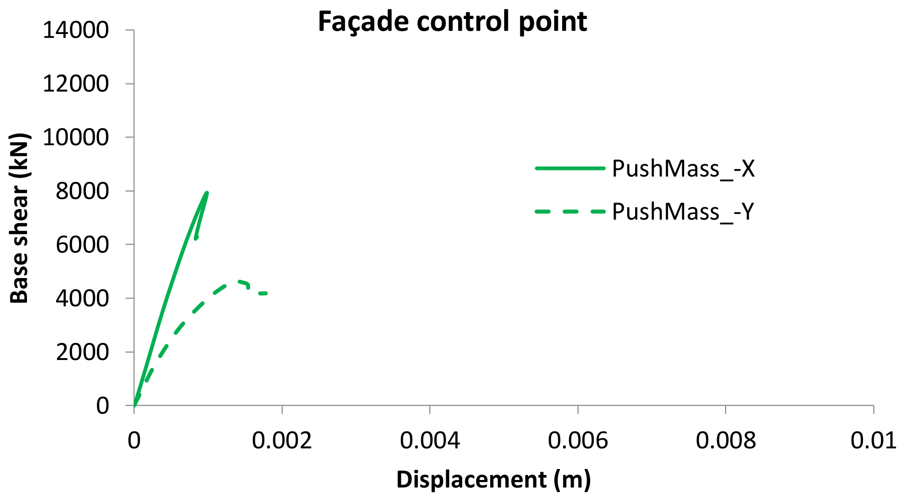
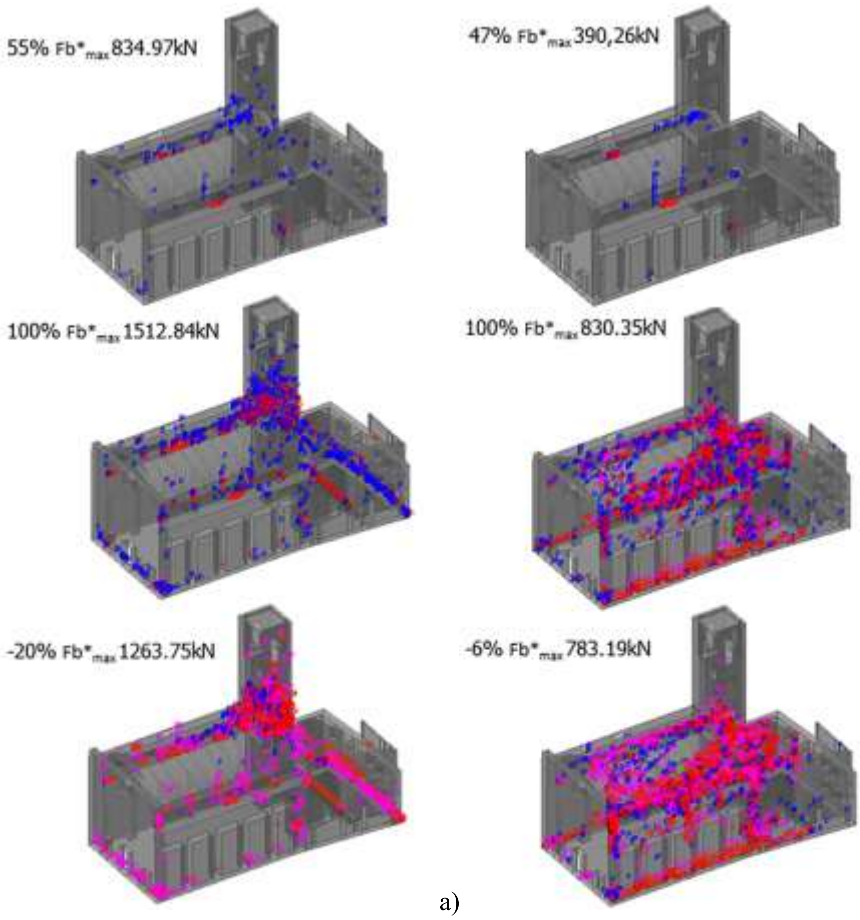


Figure 5. Capacity curves for the 3D NM.



a) b)

Figure 6. Cracking patterns obtained from Pushover analysis: uniform load –X (a), and –Y direction (b).

The X-Direction have a brittle behaviour. Meanwhile, in the Y-Direction a more ductile behaviour is observed. Analysing the damages for increasing values of the transversal load, as reported in Fig. 6a, can be seen that the cracking evolution is concentrated around the tower near the connection between the triumphal arch and the nave walls, but when the load acts along Y-Direction (Fig. 6b) more diffuse damages appear in the main vault and on its connection with the nave walls.

To summarize the seismic performances of the church, the Seismic Risk Index I_R is used:

$$I_R = \left(\frac{T_{R,c}}{T_{R,D}}\right)^{0.41} \tag{1}$$

It might be worth to remind that $I_R > 1$ corresponds to a safe structure, $I_R < 1$ corresponds to an unsafe building on the standard of the new constructions [22]. The $T_{R,C}$ in Eq. (1) is the return time of the seismic action that produces, for the requested SLSD, the non-respect of the inequalities $d^*_{max} \leq d^*_u$ (d^*_{max} is the demand, and d^*_u is the capacity in the equivalent s.d.o.f. system [23]). In the case of “Santa Maria della Carità” church the index has a value of 0.35.

5 CONCLUSIONS

To provide a contribution on the topic of the seismic vulnerability of Italian building heritage the behaviour of a study case, the “Santa Maria della Carità” church, has been analysed under earthquake loading. For this purpose, a 3D NM of the church has been set up and a nonlinear analysis has been developed. The seismic analyses allow to obtain a screening of the most vulnerable elements of the structure, which are the eccentrically tower and the main vault. This information can be used to design local and global retrofitting works. It is believed that the results obtained with respect to the seismic assessment of this case study could be extrapolated to the wide variety of historical churches, and generalized for a wide masonry building category.

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