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Cultural Heritage and earthquake: the case study of San Francesco's church in Amandola (Central Italy)

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***Abstract* – Italy is a high seismic risk country. Since 1900 more than 30 earthquakes with magnitude greater than Mw=5.8 occurred, and the last one is the Central Italy seismic sequence. It heavily hit the regions of Marche, Umbria, and Abruzzo causing many deaths, injuries and extensive damages on the cultural heritage. This paper analyses the church of San Francesco in Amadola, located in the Marche region that has been considered condemned for the severe damages reported after these earthquakes. The church is globally analyzed by the application of nonlinear static analysis on a Finite Element Model where the nonlinearity of masonry is taking into account with a proper constitutive law. The study wants to prove how global analysis combined by the local analysis can reproduce the behavior of this structure during a quake, showing that it can repeat the real damages produced by earthquakes.**

I. INTRODUCTION

The last seismic sequence that occurred in central Italy hit a large area; it included four regions Marche, Umbria, Lazio, and Abruzzo. The sequence had three principal shocks with a range of magnitude between the Mw=5.8 and Mw=6.5; the latter has been, for its intensity, the stronger recorded in Italy after 1980. It is only the latest of a long line of strong seismic sequence that has been damaged Italy, like the earthquakes of Umbria-Marche (1997), Abruzzo (2009) and Emilia-Romagna (2012) which caused numerous structural collapses and the loss of human lives. In that scenario there is the subject of this paper, the San Francesco church (**Errore. L'origine riferimento non è stata trovata.**), it is located in a little village of Marche region, in the province of Fermo, i.e. Amandola. The church was badly affected by the last Central Italy earthquakes, indeed, as already seen in the other event the historical structures, especially churches and towers [1–6], are not able to resist the horizontal forces for their particular geometry and manufacturing methods. This must not discourage because an adequate structural analysis with subsequent interventions design can increase their capacity and protect the Italian historical heritage [7, 8]. This study focused on the first step to save the historical structures, the structural analysis, this has been done using a 3D Finite Element software where linear and nonlinear static analysis has been adopted to study the seismic response of the monastery. As other researchers have shown [9]–[12], we want to stress once again as these types of analysis can reproduce the effect of the quakes on the historical structures so be a good starting point for seismic retrofitting.

II. HISTORICAL DEVELOPMENT

The church was built between 1313 to 1352, and the Romanesque façade was finished only in 1430. During the XVII century, both church and monastery have been renewed, in this time also the shape of belfry changing with the construction of pinnacle. The complex has been hit by the 1997 Umbria-Marche earthquake that caused many damages.

The church has a Romanesque style, and it is evident from the simple façade and the few decorations outside. Solomonic columns and a gable (dated back to 1429) decorate the gate. The church has an only nave with a polygonal apse, on the right side of the presbytery, there is the Annunciation's chapel where can admire pictures decoration of the second half of 1400. The church is famous for a precious wood Christ dating back to the end of 1200. The complex also has a monastery that in the years was turned first in a school and after in a museum. The monastery had a rectangular cloister built in the same time of the church and renewed on the first years of the XVII century, on the lunettes are visible frescoes of 1635 that show the life of San Francesco.

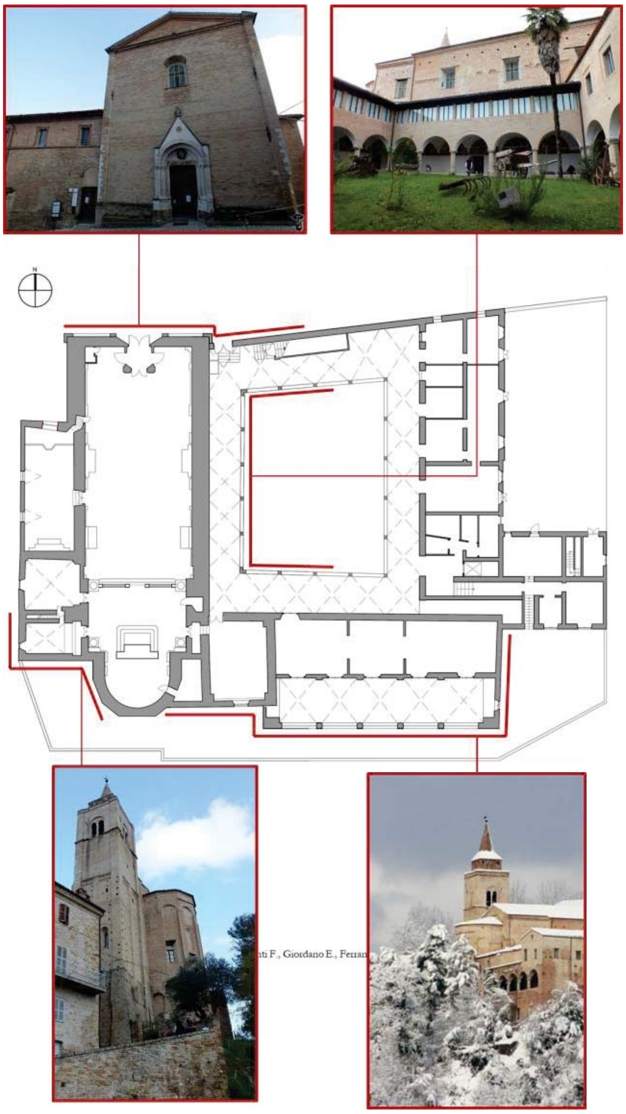

Fig. 1 "San Francesco Church" in Amandola (Central Italy)

III. GEOMETRY SURVEY

The monastery is composing of a church and a convent. The main dimensions of church nave are 30.93 m length and 14.36 m width; it ends with the polygonal apse that has a maximum width of 6.89 m, depth of 5.67 m and a maximum height of 21.43 m. The brick masonry wall's thickness is in a range between 1.70 m (lateral walls) and 0.80 m (apse walls). The structure of the church roof is made of steel truss. On the West side of the church, there is a square bell tower with dimensions of 6.45x6.45m2 and a maximum height of 39.45 m, and it terminates with a pinnacle of 5.25 m high. On the West near the bell tower, there is the chapel of Annunciation with a dimension of 5.50x5.02 m^2 and a little rectangular church of 13.24 m long and 4.68 m width. On the East there is the convent, it is an assembly of rectangular and square buildings that cover an area of 1298 m^2, the major has a square plant of 30.00 m of side, it has two floors with a medium-high of 8.74 m. In the center, there is a rectangular cloister of 14x20 m^2; it is composed of two orders of arches that rest on squat hexagonal columns. On the Southside, there is a rectangular structure of dimensions 29.65x11.52 m^2 with three floors; the maximum height is 20 m. On the East, there is a little building with two floors with a plant of 10.50x9.84 m^2 and a high of 7.50 m. The entire structure is built in masonry bricks (

). the cloister is made up of rigid floors.

IV. DAMAGES OF 2016-'17 CENTRAL ITALY SEISMIC SEQUENCE

The last central Italy earthquake hit the church, already after the first quakes of 24th August 2016 the church was closed. The church reported many damages, especially on the bell tower and on the lateral chapels. The bell tower lost the upper part of the pinnacle after the 24th August seismic shock. After the 30th October 2016 earthquake, the last section of the tower was damaged with shear cracks on the South wall. The chapels on the West side of the monastery show the activation of out of plane mechanisms. Also, the cloister was severely damaged by the quakes. The structure shows extensive damages on the brick cross vaults of the cloister and on the Southside. This building also shows shear cracks, and the activation of North façade overturn (FIG. 3).

V. THE NUMERICAL MODEL

The conventional simplify methods are limitedly effective in the study of the cultural heritage, therefore an accurate

3D Numerical Model (NM) has been realized using Midas FEA© software. The use of this NM has allowed us to reproduce the geometry of the entire building paying particular attention to the walls' thickness and the principal openings, to fit the shape carefully it was necessary to use solid tetrahydric meshes with 4 nodes. **Errore. L'origine riferimento non è stata trovata.**a shows the FEM model of the San Francesco church that consists of 73433 nodes, 246646 solid elements, and 213708 d.o.f. The rigid floors of the cloister are modeled with rigid links. To reproduce the creation and the evolution of the cracks the Total Strain Model implemented in the software has been used, based on a smeared cracks model [13, 14], for which the definition of compression, tension, and shear constitutive laws are required. In this work the Hordijk law is used in tension, the parabolic law in compression and a linear law in shear [15]. (Fig. 4b, Fig. 4c)

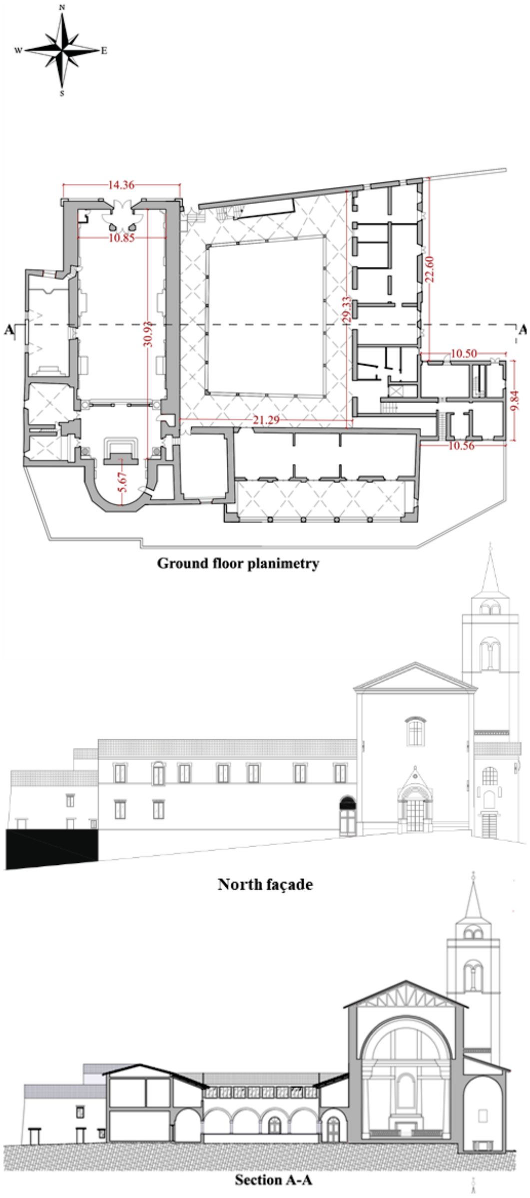

Fig. 2 Geometric configuration of "San Francesco Church" in Amandola (Central Italy)

Fig. 3 External cracks on bell-tower and apse a), internal cracks on a wall of the cloister b)

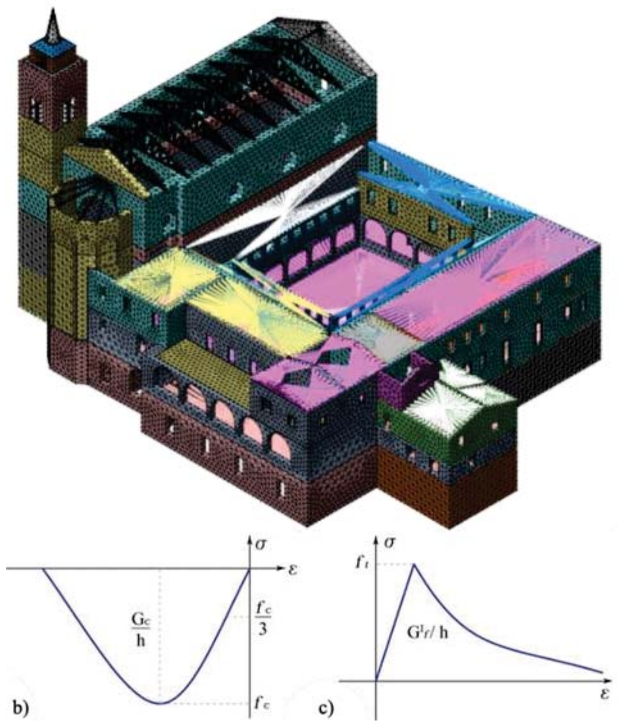

Fig. 4 a) Finite elements model of "San Francesco Church" in Amandola (Central Italy); b) Parabolic compression constitutive law; c) Hordijk tension constitutive law.

VI. PRELIMINARY RESULTS OF NUMERICAL ANALYSIS

To begin with, the structure was subjected to linear dynamic analysis in free vibration to identify the most significant modal forms and frequencies. The analysis showed that the modes with greater participant mass, mode 5 (Meff = 29.91%) and mode 12 (27.70%), are both in a northerly direction and involve respectively the tympanum of the façade and the cusp of the bell tower. In a southerly direction, instead, the mode that moves the greater mass quantity is 7 (Meff = 22.55%), it involves the upper part of the longitudinal walls of the nave and the upper part of the bell tower. As can be seen, the presence of rigid floors prevents movements out-of-plane in the area of the cloister. The dynamic behavior was compared with the accelerating spectra recorded during the earthquake in Central Italy, both with respect to the recordings of the Amandola station (AM05, blue and red lines) and with respect to those of the epicenters (Campli CMI, Forca Canapine FCC, and Amatrice AMT, gray lines). In Fig. 5 it can be seen how the modes with the greatest participating mass, which have a period between T = 0.149 sec and T = 0.217 sec, are close to the acceleration peaks in the case of Amandola and instead, are on peaks in the case of epicentres, thus justifying their current state of damage and stressing that, if the structure had been in the epicentres, the damage to these elements would have been greater.

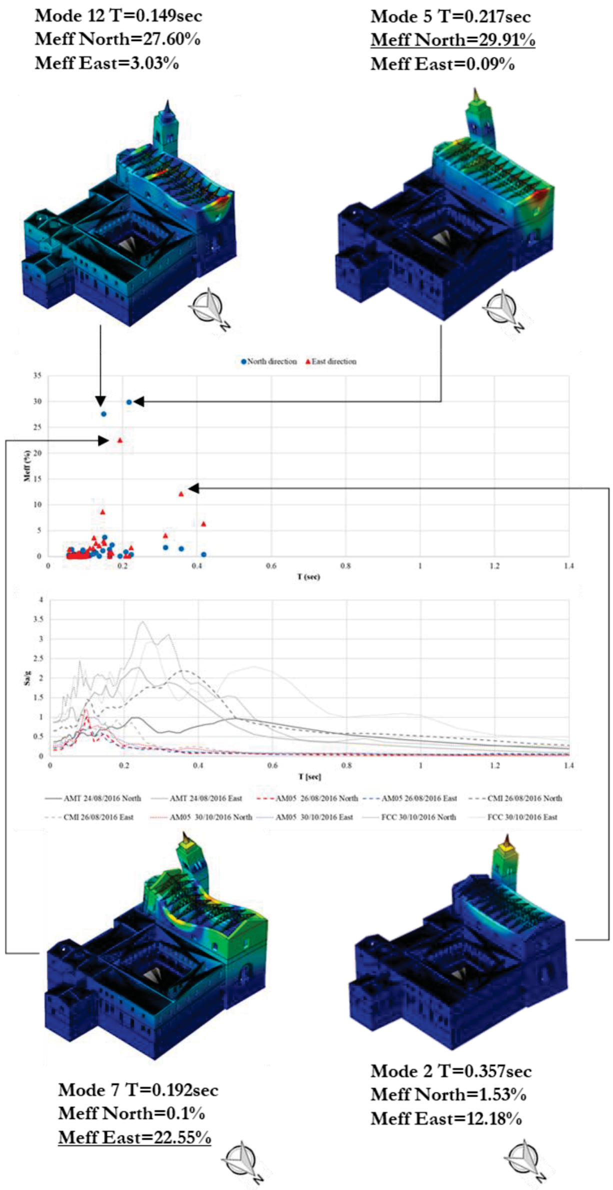

Fig. 5 Distribution of the main modal forms and comparison with the pseudo-acceleration response spectra of the Central Italy earthquake (gray in the epicentres recordings and in color those of Amandola)

After modal analysis Push-Over was performed As specified by the Italian Code two type of transversal loads should be used to study the seismic capacity [16, 17], i.e. proportional to the structural masses (Push-Mass) and to the main modes (Push-Mode) both applied on the structure subjected only to the gravity loads [18], [19]. The nonlinear static analysis has the limitation of not depict the dynamic variation due to the materials' degradation, leading to an overestimation of the masonry capacity [20]. In this paper is not reported, in order to limit the length, the dynamic identification of the monastery [21–26], and the model validation has done comparing the numerical results with real damage exhibited after the 2016 seismic sequence. The main results are reported in Fig. 6, where a good comparison between the real and the numerical damages is summarized for the portico cross vaults and the main façade.

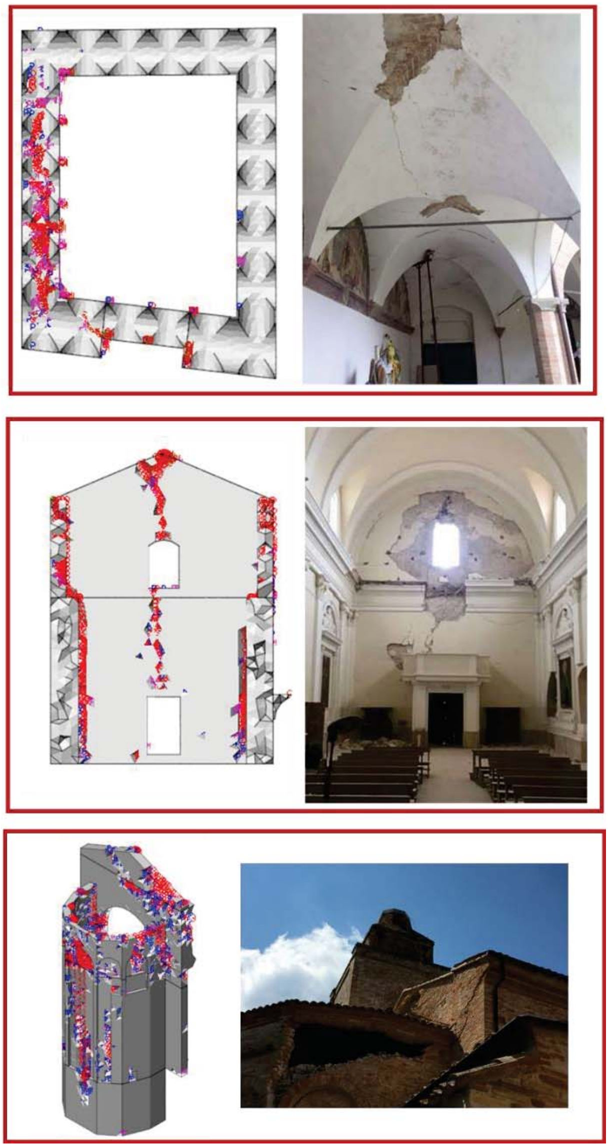

Fig. 6 Damages on the cross vaults, main façade and apse of "San Francesco Church" in Amandola (Central Italy)

VII. CONCLUSION

This type of structures for their geometry and complexity should be studied using different types of analysis that ranging from simple (kinematic limit analyses with pre-assigned failure mechanisms) to moderate/severe (FE non-linear static/dynamic analyses) so permit a sensitivity study. The paper wants to underline that, also with its limitations, the nonlinear static analysis can be a good compromise, since it can reproduce the real damages observed on the San Francesco's monastery after the Central Italy Earthquake sequence and it is able to identify the critical macro-elements that usually active a failure mechanism. This type of analysis has the advantages of less computation time, and it does not require many knowledges at the user

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