2019 IMEKO TC-4 International Conference on
Metrology for Archaeology and Cultural Heritage
Florence, Italy, December 4-6, 2019

The Non-smooth tale of "Apennine Churches" stroked by the Central Italy Earthquakes of 2016

Angela Ferrante[1], Ersilia Giordano[1], Francesco Clementi[1], Gabriele Milani[2], Antonio Formisano[3]

[1] *Department of Civil and Building Engineering, and Architecture, Polytechnic University of Marche, via Brecce Bianche, 60131, Ancona, Italy, a.ferrante@pm.univpm.it, e.giordano@pm.univpm.it, francesco.clementi@staff.univpm.it*
[2]*Department of Architecture, Built Environment and Construction Engineering, Polytechnic of Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy, gabriele.milani@polimi.it*
[3]*Department of Structures for Engineering and Architecture, University of Naples "Federico II", Piazzale Tecchio 80, 80125 Naples, Italy, antonio.formisano@unina.it*

Keywords: Masonry Churches, Damage Assessment, Discrete Element Method, Non-Smooth Contact Dynamics Method

Abstract – The dynamic behavior and the seismic vulnerability of different masonry "Apennine Churches", dramatically damaged by the last shocks sequence of 2016 that occurred in Central Italy, have been studied in this paper by means of advanced 3D numerical analyses with the Discrete Element Method (DEM). Thus, a discontinuous approach has been used to assess the dynamic properties and the vulnerability of the masonry structure, through large deformations regulated by the Signorini's law, concerning the impenetrability between the rigid bodies, and by the Coulomb's law, regarding the dry-friction model. The major purpose of this study is to highlight that relevant data on the real structural behavior of historical masonry can be provided through advanced numerical analyses. The comparison between the results of the numerical simulation and the survey of the existing crack pattern of the churches permitted to validate the used approach. Finally, from the results and conclusions of these cases study, it is possible to affirm that the used methodology can be applied to a wide variety of historical masonry structures in Europe.

I. INTRODUCTION

The damage assessment of historical masonry buildings is one of the most difficult tasks to be investigated in structural mechanics, since this kind of structures are commonly heterogeneous, with complex geometries, irregularities and absence of a box behavior due to defective connections between different structural parts, in particular walls and floors, that often play a fundamental role. However, the knowledge of the dynamical behavior is crucial for a reliable seismic vulnerability assessment, which became more and more important due to recent catastrophic earthquakes that stroked Italy in the last few decades (Umbria-Marche 1997–1998, Abruzzo 2009, Emilia-Romagna 2012, Marche-Lazio-Umbria-Abruzzo 2016) [1–5]. The Centre of Italy and mainly the Marche Region have suffered two major earthquakes in October 2016, causing widespread damage, especially on the historical structures. The epicenter of the second one stroked Norcia, Visso, Arquata del Tronto, Accumoli and Amatrice, and a lot of damages to cultural heritage were done also in the cities of Tolentino, San Severino, Camerino.

A peculiar structural type characterizes the stock of analysed churches in the area of Central Italy hit by the seismic sequence of 2016. These structures, namely "Apennine Churches", are distinguished by the poor quality local materials with which were often built, i.e. limestone masonry walls that in most cases are unplastered and bound by poor mortar. Furthermore, these buildings were based on simple architectural forms, typically much smaller than traditional Italian ones, with a maximum length of 30 m and a width less of 15 m. In many cases, the specific church configuration is characterized by a small single nave and a bell tower or a two-dimensional element.

To investigate the mechanical behavior of masonry structures, commonly finite element methods are utilized, often including very sophisticated constitutive laws taking into account post-elastic behaviors and damage [6–14]. These methods, while being very appealing, do not focus on the possible non-smooth nature of the dynamic response, which can come sliding and impacting between different blocks, and situation that is common just before and during the collapse.

Moreover, the ancient masonry structures can be considered as discontinuous structural systems, which are composed of units (e.g. bricks, stones, blocks, etc.), bonded together with or without mortar. Thus, for a numerical model to adequately represent the behavior of a real structure, both the constitutive model and the input material properties must be selected carefully by the modeler to take into account the variation of masonry properties and the range of stress state types that exist in masonry structures [15–18]. For this reason, the dynamics of ancient masonry structures are investigated in this study numerically by means of the Non-Smooth Contact Dynamics method (NSCD) which is implemented on a distinct element code [19–22]. In particular, the NSCD method has been applied to advanced numerical models to survey the dynamical behavior of the ancient masonry churches subject to strong non-linear dynamic actions and the modalities of progressive collapse mechanisms. Consequently, these characteristic masonry structures inside the epicentral area of the Centre Italy shocks of August and October 2016 has been discretized in very detailed 3D models. These models have been achieved through rigid blocks bounded together by points of contacts, which follow the Signorini's law, about the impenetrability condition, and the Coulomb's law, relative to dry-friction [23]. Thus, this approach pointed out discontinuous dynamics of the structures, allowing to explore it.

Figure 1. External and internal views of the Church of Santissimo Crocifisso

To limit the length of the paper, only the results concerning the case study of the church of Santissimo Crocifisso in Pretare, municipality of Arquata del Tronto in the province of Ascoli Piceno (Marche region, central Italy), in Figure 1, are here reported with the discontinuous approaches, in order to address comparison between the numerical and the real damages, and, at the same time, to confirm the powerful of the model.

II. HISTORICAL DEVELOPMENTS OF THE CHURCHES

The church of Santissimo Crocifisso is located in Pretare, a little village of the Marche Region, heavily hit by the Central Italy 2016 earthquakes.

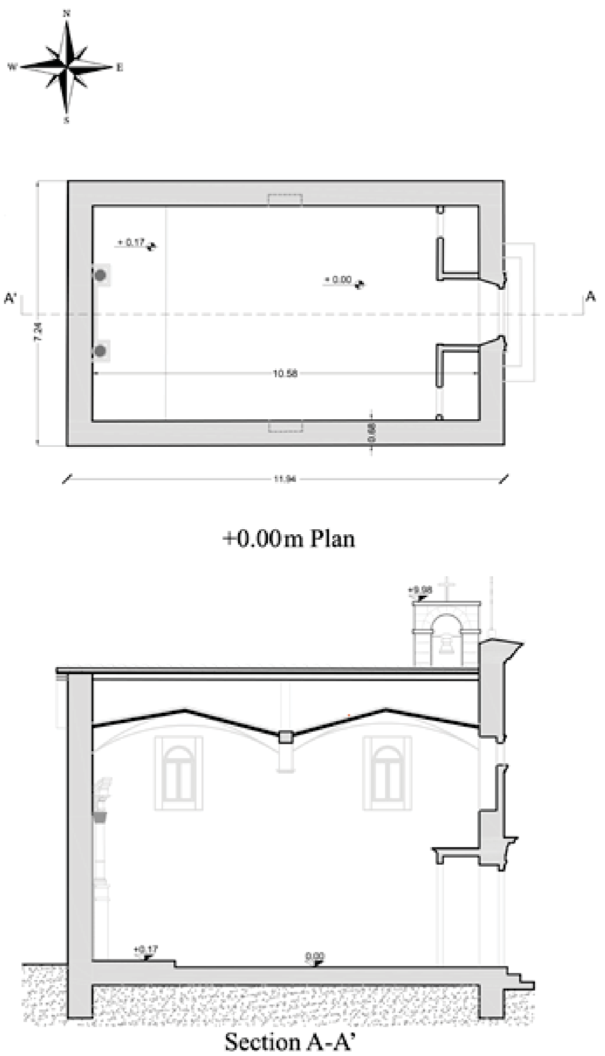

Figure 2. The plan and the transversal section of Santissimo Crocifisso's Church

The earliest evidence of this historical masonry structure dates back to the XV century and, in the beginning, it was an oratory. Thereafter, in the past, it was used only few times and it was always left in bad condition [24]. Between the XVII and XIX century, the church was partially restored and, then, in 1906 it was completely renovated, with the construction of the concrete bell-gable. Between the 1950 and 1960 other interventions were executed and, for a short period of time, the building was utilized as theater. The front façade is formed by unplastered stone of calcareous origin and it has a regular feature, characterized by a travertine stone entrance and an arched window above it. The church was seriously damaged by the quake of 1997, which led to the structural instability and several cracks, that compromised also the frescoes. Between years 2014 and 2015 the seismic retrofitting was executed by means of the scuci-cuci method of the masonry walls and, also, introducing a steel curb on the principal façade and a reinforcement of the camorcanna vaults. In this period the niches were reopened and a new wood roof was built.

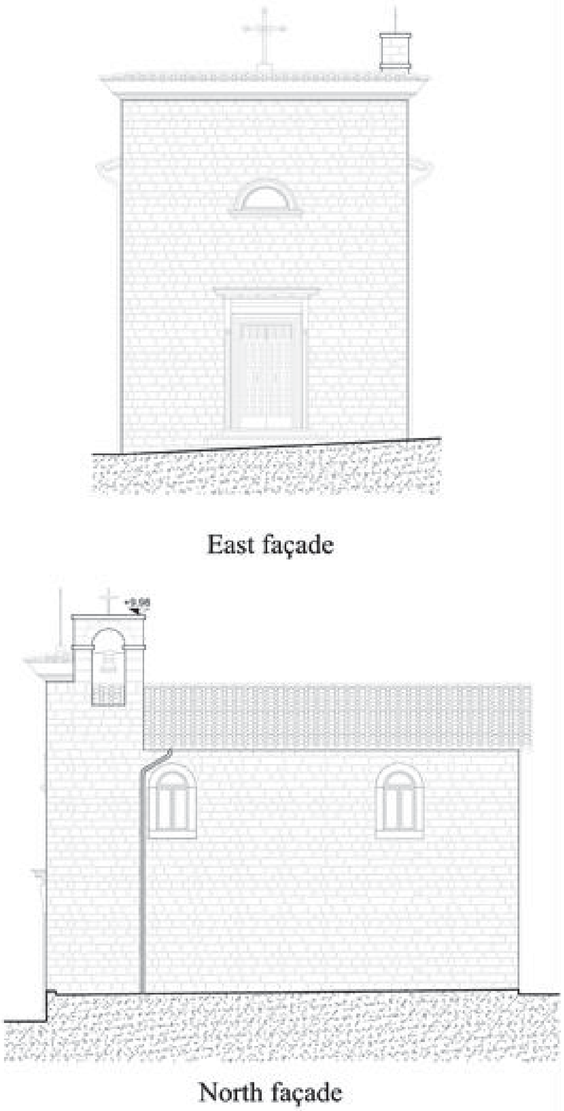

Figure 3. The west and south facades Santissimo Crocifisso's Church

The church has a single nave and the main dimensions are 11.94 m of length and 7.24 m of width and a maximum height of 9.98 m (see Figure 3 and Figure 3). The local calcareous stone is used to have a wall's thickness equal to 0.68 m. Moreover, the nave is cover by two cross vaults of camorcanna and the structure of the church's roof is made of wood trussed. Lastly, on the Northside of the church there is a bell-gable that sustains a bell weighing at least 30 kg.

III. DAMAGE OF THE CHURCH AFTER THE CENTRAL ITALY EARTHQUAKES OF 2016

The last main shocks sequence has seriously damaged Central Italy and especially the churches. These structures, for their particular geometry, are very vulnerable during a seismic event. As is highlighted in Figure 4, the Church of Santissimo Crocifisso in Pretare has reported diffuses failures. The major cracks have appeared in the upper part of the main façade (Figure 4a) and the lateral walls (Figure 4b), due to the absence of connection between them, and in the central part of the principal façade, between the opening and the entrance. Similarly, in the back façade (Figure 4c) there are deep failures due to the missing of the connection with the lateral walls and the in-plane cracking.

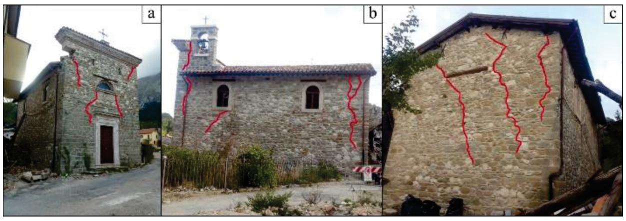

Figure 4. Cracks of Santissimo Crocifisso's Church after the seismic sequence of 2016 on the main façade (a), the north façade (b), the back façade (c)

IV. THE NON-SMOOTH CONTACT DYNAMICS METHOD

Between the discrete element methods, there is the NSCD method, which is characterized for three main points: (i) the non-smooth contact laws are directly integrated inside it, (ii) an implicit integration scheme is implemented and (iii) structural damping are not considered into it. Furthermore, the NSCD method requires some simplifications on the building of models. First of all, the bodies are assumed entirely rigid and, secondly, the contact laws between blocks are determined by the Signorini's impenetrability condition and by the dry-friction of Coulomb. Thus, these relations on the contacts involve the perfectly plastic impacts, hence without bounces as a consequence, i.e., a null value of the restitution coefficient in the Newton law. According to it, there is the main advantage of the limited computational complexity derived by the simple modelling of the impacts. Afterward, another relevant benefit due to the perfectly plastic impact is related to the dissipation of energy, which explains the damages of the material and the micro-cracks of the stones after the collisions and, additionally, supports the numerical integration and its stability from a computational point of view. Finally, in these models, the dissipated energy is determined by the involvement of the friction and it doesn't consider the damping effects, which instead are essential for the continuum models. The nonlinear behavior of different damaged churches is investigated with a real 3D model.

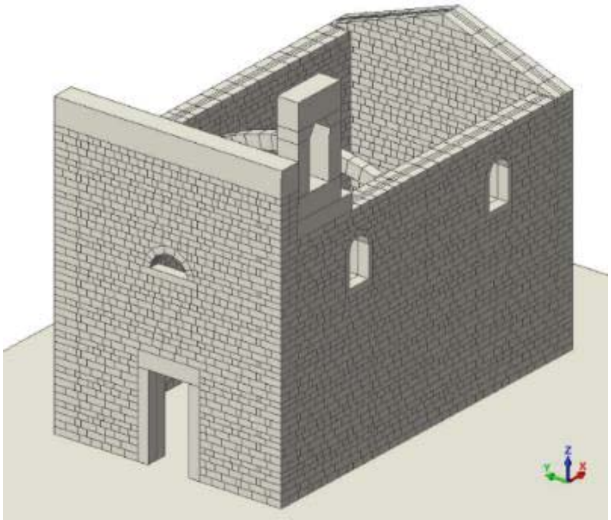

Figure 5. 3D model of the church of Santissimo Crocifisso

For this purpose, the LMGC90© code is used, due to its ability to compute the interaction of a large number of bodies, based on the NSCD method, assessing also the seismic vulnerability of the structures [25]. As visible in Figure 5, very detailed models have been created, considering the presence of some past retrofitting interventions, to better analyse the local and global mechanisms, their influence within the surveyed churches.

V. NUMERICAL RESULTS

The main results of the nonlinear dynamic analyses are reported in Figure 6 and in Figure 7 with a direct comparison with the real damage.

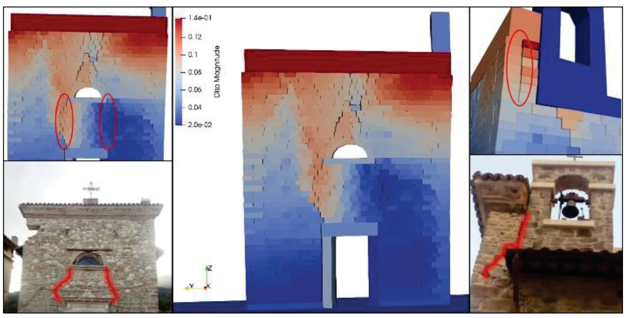

Figure 6. The failure mechanism of the main façade of the Church of Santissimo Crocifisso

It has been applied for this purpose the three main shocks of the seismic sequence of 2016 in the Centre of Italy. The strong motions used in the nonlinear analyses were recorded near the epicenter of the quakes and they are considered in sequence in the simulations, to investigate cumulated damage. Hence, a good match between the real and the numerical damages are reported for the main and the back façades.

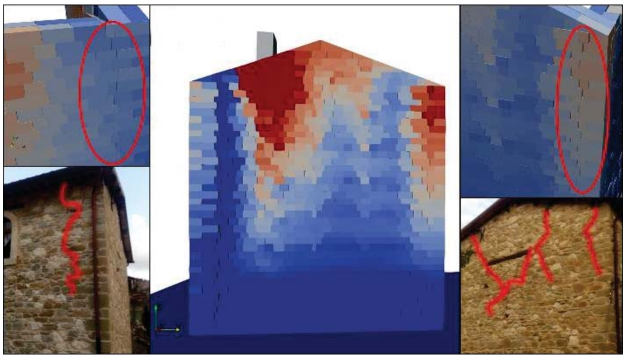

Figure 7. The failure mechanism of the West façade of the Church of Santissimo Crocifisso

Accordingly, the numerical results have given a deep insight into the seismic vulnerability of this damaged structure, confirming several possible failure mechanisms, and providing the necessary information for possible consolidation strategies and reconstruction.

VI. CONCLUSIONS

The results obtained for an "Apennine Churches" stroked by the Central Italy seismic sequence are here briefly reported and summarized, underline the high vulnerability of this type of structure, especially at the upper level. To a complete comprehension of the mechanical response of such complex ancient structures to seismic loading, pointing out the same portions most damaged during the seismic actions, it has been used a discontinuous approach and the NSCD method, implemented in the LMGC90©. It combines modelling simplicity and great predictive capabilities. Its simplicity comes from the following fundamental simplifying assumptions: (i) block rigidity; (ii) simple contact laws between blocks; (iii) absence of any damping. As a result, the mechanical behaviour of the masonry structures is influenced by only the friction coefficient, relative to the existing materials and which assumes the values relative to the current configuration of the analysed churches. This is a significant consequence for modelling ancient buildings, since the determination of the mechanical properties of these masonries is always uncertain and variable. Despite its simplicity, the model can predict a large variety of dynamical behaviours of the historical structures and their seismic vulnerability. Depending on the values assigned to the friction coefficient, different failure mechanisms may be found. Indeed, in this case study, the values of the friction represented the actual situation of the masonry walls and thus has been possible to obtain coherent collapse mechanisms and good matching with the real observed damages. Finally, the sensitivity of the results to the input parameters, a consequence of the model non-smoothness, is pointed out. This character is also present in real structures. Indeed, small irregularities in buildings (especially ancient buildings) affect the seismic response in a visible way. However, the overall behaviours (failure mechanisms) of the analysed macro-elements only gradually changes with parameters. For instance, if the friction coefficient is considered, the overturning mechanisms become gradually prevailing over sliding mechanisms, as the value of the friction coefficient increases. This will be surveyed in future papers and represents the main development to understand the existing ancient structures. Sensitivity to data is less evident in the standard FEM continuum models and represents a further distinguishing feature of the proposed approach.

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