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On the dynamics of the civic clock tower of Rotella (Ascoli Piceno) severely damaged by the Central Italy seismic sequence of 2016

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ABSTRACT
A dynamic identification technique and the Non-Smooth Contact Dynamics method (NSCD) have been applied to the study of the seismic response of the ancient civic clock tower of Rotella, in the province of Ascoli Piceno, inside the epicentral zone of the last Centre Italy earthquakes of August and October 2016. According to this model, the masonry tower has been modelled as a system of rigid blocks, and since the contacts between blocks are governed by the Signorini's impenetrability condition and by dry-friction Coulomb's law, the tower exhibits discontinuous dynamics. The NSCD method has proved to be a powerful tool for investigating the dynamics induced by ground seismic accelerations. Indeed, the numerical results have given a deep insight into the seismic vulnerability of this medieval damaged tower, confirming several possible failure mechanisms.

1 INTRODUCTION

Bell and Medieval masonry towers are very widespread and they belong to the built heritage that must be preserved, especially in high-seismicity regions. As a consequence of their geometrical features, different masonry textures and mechanical properties, they exhibit quite different structural behaviours under horizontal loads. For this reason, accurate knowledge of dynamical parameters of such structures is paramount for any numerical advanced nonlinear dynamic analysis, 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) (Cavalagli, Comanducci, and Ubertini 2018; Krstevska et al. 2010; Milani 2013).

In October 2016, two major earthquakes occurred in the Marche region in the Centre of Italy, causing widespread damage especially on the historical structures. The epicentre of the second one stroked Norcia, Visso, Arquata del Tronto, Accumoli and Amatrice, and a lot of damages to cultural heritage were also done in the cities of Tolentino, San Severino, Camerino, and Matelica.

Hence, this work presents the dynamic characterization and the advanced numerical analyses of the ancient civic clock tower of Rotella, in the province of Ascoli Piceno (AP) in the Central Italy, in light of the structural damage caused by the quakes that struck it in 2016, plunging the area into chaos for several months (see Figure 1).

In the first part of the work, a dynamic identification technique for non-destructive evaluation of heritage structures is discussed with reference to the case study. Even though the positioning of the instrumentation of the monitoring system was conditioned by quite common operative problems, due to the limited accessibility of the structure, it was in any case possible to identify with a certain confidence the first three frequencies of the towers and their corresponding mode shapes.

Then, three advanced numerical models are used to have an insight into the modalities of progressive damage and the behaviour of the structure under strong dynamic excitations, namely a Non-Smooth Contact Dynamics method (NSCD), where the influence of the brick fragments of really small size elements are analysed using a full 3D detailed discretization.

This method 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 (Clementi et al. 2019; Ferrante, Clementi, and Milani 2019).

Figure 1. Views of the façades of the civic tower of Rotella.

In fact, the ancient masonry structures can be considered as discontinuous structural systems, which is composed of units (e.g. bricks, stones, blocks, etc.), bonded together with or without mortar. Thus, for a numerical model to adequately represent the behaviour 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 (Clementi et al. 2017; Maio et al. 2015; Alessio Pierdicca et al. 2016).

In the NSCD method, the tower is schematized as a system of rigid blocks, undergoing frictional sliding and perfect plastic impacts. The structure exhibited a complex dynamic behavior, because of the geometrical nonlinearity and the non-smooth nature of the contact laws, with a focus on the possible non-smooth nature of the dynamic response, which can come commonly just before and during the collapse.

2 THE CASE STUDY

2.1 *Historical development*

The Rotella (AP) civic clock tower goes back to the XI century, when it was the bell tower of the Church of Santa Maria della Pietà, which was extend in 1430.

In 1755 the tower collapsed after landslide movements, due to the erosive action of the Oste torrent. Later, after damages caused by the adverse weather conditions, in 1987 were executed the retrofitting interventions.

2.2 *Geometrical survey*

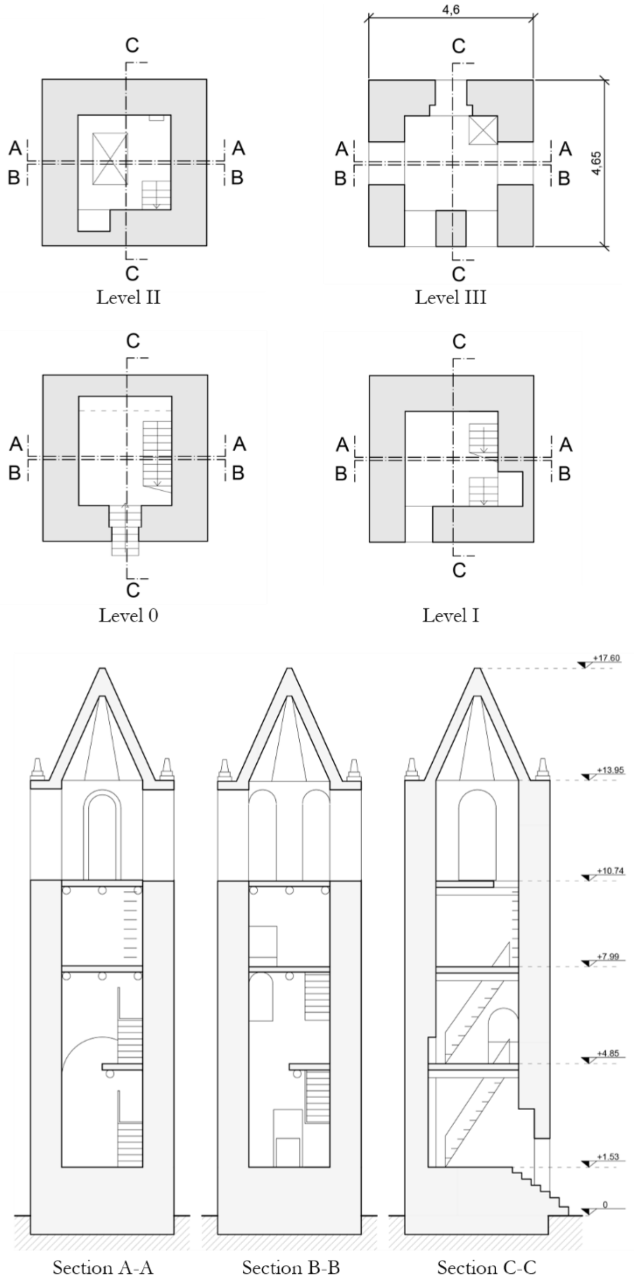

Figure 2. Geometric configuration of the Rotella (AP) civic clock tower.

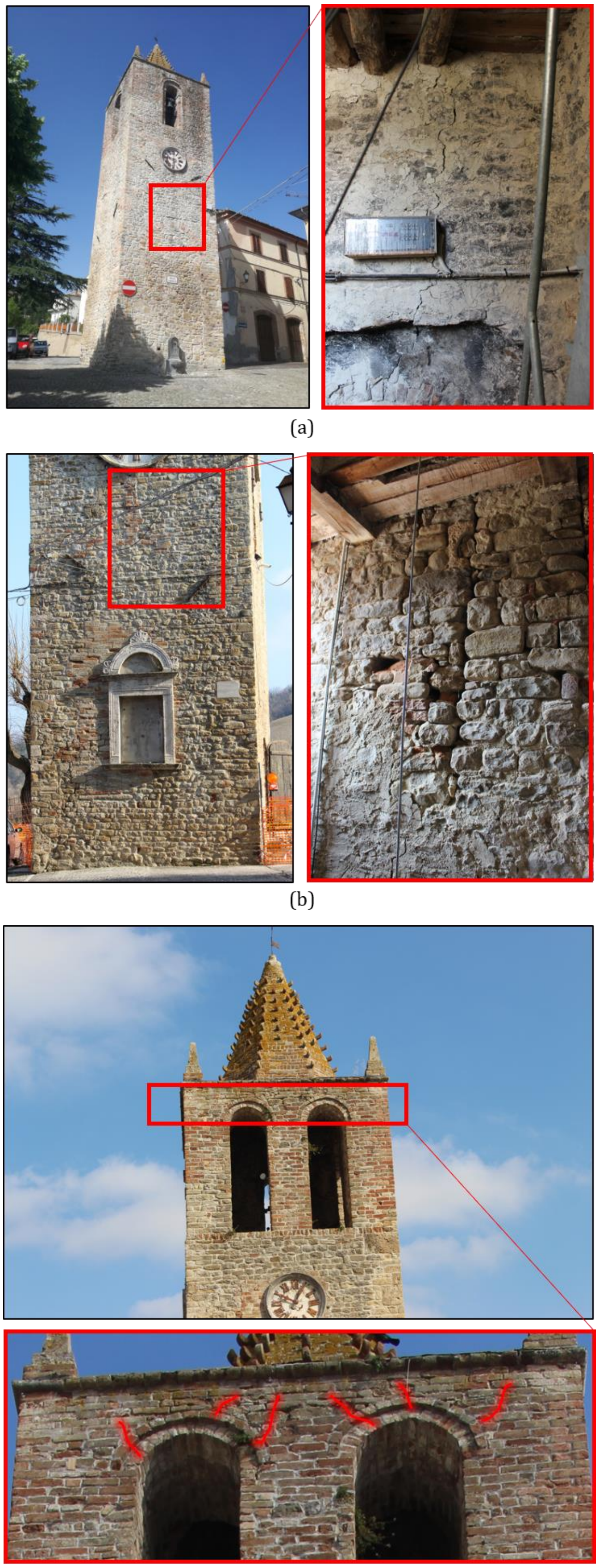

Figure 3. Views of the damages of the Rotella (AP) civic clock tower after the seismic sequence of 2016 of the North-East façade (a), South-East façade (b) and South-West façade (c).

The Rotella (AP) civic clock tower presents a sample regular configuration, with a rectangular plant of dimensions equal to 4.6m x 4.65m and a height of 17.60m. The three internal floors are made by wooden tables. Moreover, a masonry cone with an hexagonal base forms the cover of this vertical structure (Figure 2).

2.3 *The damages of the 2016 Central Italy earthquake*

The belfry has suffered serious damages after the Central Italy seismic sequence of 2016 and today it has the function of civic clock tower and it is the symbol of the municipality of Rotella.

The main damages are present on the cell bell, in the upper part of the vertical structure, characterised by the wide arched windows (see Figure 3).

3 DYNAMIC CHARACTERIZATION - AMBIENT VIBRATION SURVEY (AVS)

The method for vibration-based identification of modal parameters used in the presented work operates in the time domain, and it is based on a state-space description of the dynamic problem (Van Overschee and De Moor 1996) using the Covariance Stochastic Subspace Identification (SSI-Cov) algorithm.

Using the procedure described in (Peeters and De Roeck 1999), the modal parameters (frequencies, modal shapes and damping ratios) can be extracted by the Eigen-decomposition of the system matrix $[A]$. For the sake of brevity, the complete formulation is not included in the discussion.

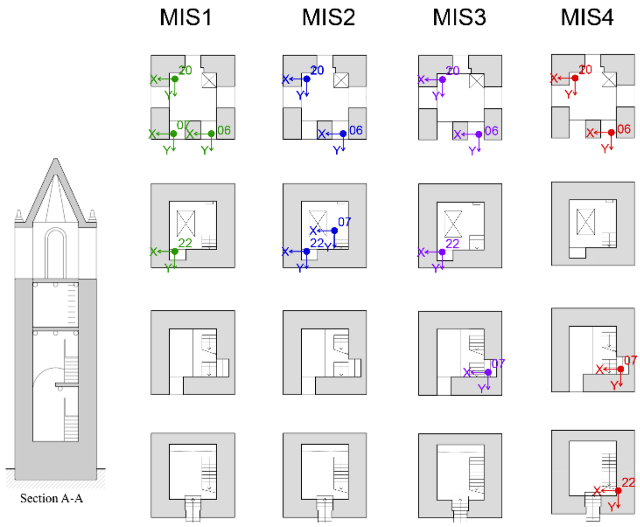

Figure 4. Layout of the accelerometers in the Rotella tower.

The AVS response of the tower was measured at different elevations (Figure 4) and with different acquisitions. The accelerometers were fixed directly in contact with the structural elements and parallel to the main directions of the belfry, in order to get both translational and torsional modes (Catinari F. et al. 2017; A. Pierdicca et al. 2016; Pierdicca et al. 2015).

Figure 5. Views of the used equipment for the AVS of the civic clock tower of Rotella (AP).

The experimental measurement was carried out using five tri-axial Piezo-MEMS accelerometers (see Figure 5) connected to a SincHub for the synchronization. The sensors featured a sensitivity of 1V/g, a frequency range of 0.8-100 Hz and a dynamic range of 120 dB. Each level was instrumented at least in two corners. At each corner, two high sensitive accelerometers, measuring in two orthogonal directions, were placed. Other couples of accelerometers were put in different positions at various levels to obtain more information about the dynamic behaviour of the whole tower.

Each measurement was recorded with a sampling frequency of 1024 Hz for a total duration of 60 minutes, resulting in 3.686.400 datapoints per channel. The record duration of 60 minutes should be long enough to eliminate the influence of possible non-stochastic excitations during the test (McConnell 2001).

The collected measurements were initially sampled at 1000 Hz. A factor of 40 decimated them before processing to have the final data of 12.5 Sample per Second (SPS) (Singh et al. 2014). The described procedure was used for each AVS.

The stabilization diagram obtained from the analysis of the collected data through Cov-SSI is reported in Figure 6. It shows the alignments of stable poles, for increasing order models, and it allows the determination of the *n* eigenvectors of dynamic matrix [*A*] which are representative of structural modes, and how many are instead purely numeric (due to their redundancy of calculation or noise). Then, it is possible to isolate the natural modes from the numerical ones by increasing the order of the model and checking the stability of the results. The stability of a pole is defined as follow:

- the estimated frequency is considered stable if it does not change more than 2%;
- the damping for different orders should not deviate more than 15%;
- the modal shape obtained by a certain order is compared to the same one obtained by a minor order by Modal Assurance Criterion (MAC) that must be at least equal to 90%.

The identified frequencies appear slightly spaced and local modes show only for values upper to the 3rd (Figure 6).

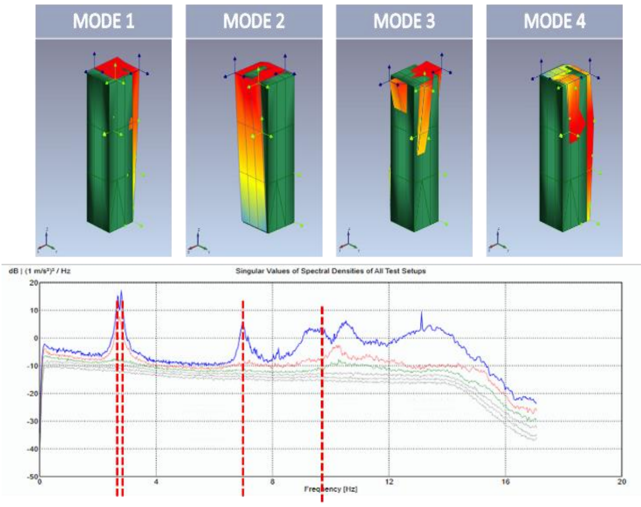

Figure 6. Stabilization diagram and experimental mode shapes of the civic clock tower of Rotella (AP) identified with Cov-SSI method.

4 THE NON-SMOOTH CONTACT DYNAMICS METHOD

The NSCD method belongs to the family of Discrete Element methods, distinguishing from the classical Distinct Element method for three differences: (i) it integrates the non-smooth contact laws directly, (ii) it uses an implicit integration scheme, and (iii) it does not account for any structural damping. It is important to stress the fact that the NSCD method is based on some modelling simplifications. The main assumption is that bodies are rigid, and their dynamics is governed by the equation of motion and by the frictional contact conditions. To describe the frictional contact laws, we must introduce some basic definitions. In the following, the notation adopted in (Jean 1999) is used (scalars, vectors, and tensors are explicitly declared, and italic letters are used for all of them). Given two arbitrary bodies B_i and B_j, let P_i and P_j (Figure 7a) be the points of possible contact on the boundaries of B_i and B_j, respectively, and let *n* be the outer unit vector, orthogonal to the boundary of B_i in P_i. We define $g = (P_j - P_i) \cdot n$ the gap between P_i and P_j (a dot means scalar product), $(\dot{u}_n, \dot{u}_t)$ the normal and tangential velocities of P_j with respect to P_i, and (r_n, r_t) the normal and tangential reactive forces of B_i on B_j.

The contact conditions are:

1. The Signorini's law of impenetrability (Figure 7b)

$$g \geq 0, r_n \geq 0, g r_n = 0, \quad (1)$$

which, in the case of contact $g = 0$, is equivalent to the following Kuhn–Tucker conditions (Moreau 1988)

$$\dot{u}_n \geq 0, r_n \geq 0, \dot{u}_n r_n = 0, \quad (2)$$

written in term of relative normal velocity.

2. The dry-friction Coulomb's law (Figure 7c) that governs the behaviour in the tangential direction

$$|r_n| \leq \mu r_n; \begin{cases} r_t < \mu r_n \rightarrow \dot{u}_t = 0 \\ |r_t| = \mu r_n \rightarrow \dot{u}_t = -\lambda \frac{r_t}{|r_t|} \end{cases}, \quad (3)$$

with μ the friction coefficient and λ an arbitrary positive real number.

If q is the vector of the system configuration parameters (unknown translations and rotations of each body), and p is the global vector of reaction forces, the equation of motion can be written as follows

$$M\ddot{q} = f(q, \dot{q}, t) + p, \quad (4)$$

where M is the mass matrix, and f is the vector of external forces.

The local pairs $(\dot{u}_n, \dot{u}_t)$ and (r_n, r_t) characteristic of each contact, are related to the global vectors $\dot{q}$ and p, respectively, through linear maps which depend on q. Since the contact laws (1) - (3) are non-smooth, velocities $\dot{q}$ and reactions p are discontinuous functions of time. They belong to the set of bounded variation functions, i.e. functions which, at each time, have finite left and right limits. Since the accelerations are not defined when the velocities are discontinuous, Equation (4) is reformulated in the integral form (Jean 1999; Moreau 1988), and it is solved numerically using a time-stepping approach, where t time is discretized into time intervals, and, within each time interval $[t_i, t_{i+1}]$, the equation of motion is integrated as follows

$$M(\dot{q}_{i+1} - \dot{q}_i) = \int_{t_i}^{t_{i+1}} f(q, \dot{q}, t)dt + \bar{p}_{i+1}, \quad (5a)$$

$$q_{i+1} = q_i + \int_{t_i}^{t_{i+1}} \dot{q}(t)dt. \quad (5b)$$

Where $\bar{p}_{i+1}$ is the impulse in $[t_i; t_{i+1}]$. The primary variables of the problem are the velocity vector $\dot{q}_{i+1}$ and the impulse vector $\bar{p}_{i+1}$ at the instant t_{i+1}. In the NSCD method, the integrals in (5) are evaluated by means of an implicit time integrator. The overall set of global Equation (5) and local contact relations (1) and (2), where the reactions are approximated by the average impulses in $[t_i; t_{i+1}]$, is condensed at the contact local level, and then they are solved by means of a non-linear Gauss–Seidel by block method.

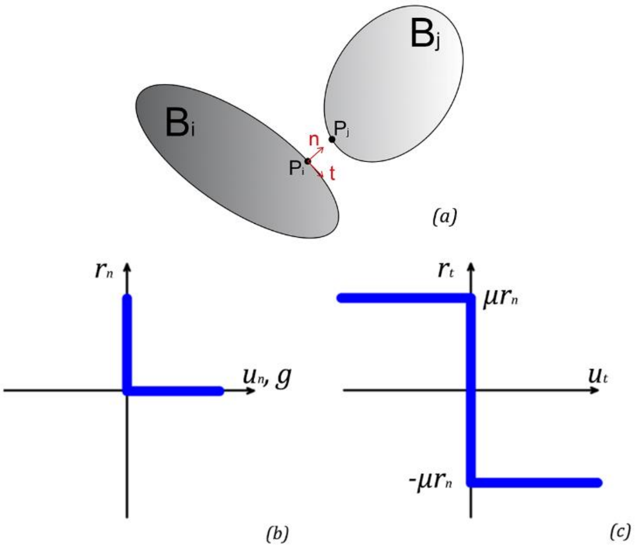

Figure 7. The interaction between two bodies (a) Signorini's law (b) Coulomb's law (c).

The relations (1) imply a perfectly plastic impact, i.e., the Newton law with restitution coefficient equal to zero. A perfect plastic impact law makes impossible to describe bouncing phenomena, and, furthermore, overestimates the energy dissipated during impacts. However, in case of systems of bricks or stones, the restitution coefficient has low values, and bouncing phenomena can be neglected. Since we are interested in the dynamical interactions between different parts of the fortress, we neglect blocks deformability. It follows that the numerical results obtained depict an overall picture of the fortress dynamics and describe the failure mechanisms of the whole structure, due to blocks rocking and sliding, but they do not describe the stresses and strain distributions within each block.

The values of friction coefficient μ range from 0.3 to 1.2, according to different combinations of units and mortars (Vasconcelos and Lourenço 2009). As a first attempt, we assume the value μ =

0.5 for the interface block/block of the external and internal leaf, μ = 0.3 for the infill and the interface between it and the leaf, and μ = 0.9 for the interface block/foundation to observe, mainly, the dynamics of the fortress without the structure-foundation interaction. Finally, we note that damping is not considered here and only friction and perfect plastic impacts dissipate energy.

The LMGC90© code is used, due to its ability to compute the interaction of a large number of bodies, based on the NSCD method, also assessing the seismic vulnerability of the structures (Dubois, Acary, and Jean 2018). As visible in Figure 8, very detailed models have been created to understand better the influence of local and global mechanisms within the analysed ancient civic clock tower and, where possible, the presence of some past retrofitting interventions is also considered.

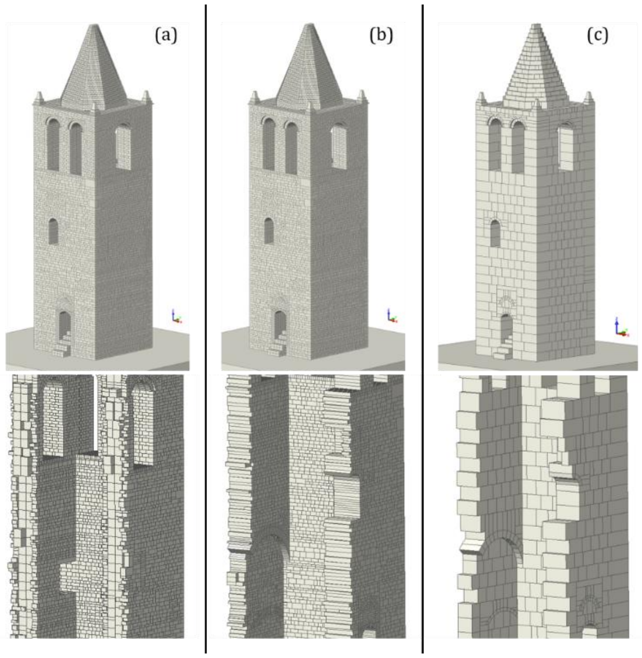

Figure 8. 3D discrete element models of the Rotella (AP) civic clock tower: (a) multi-leaf masonry, single-leaf masonry (b) and single-leaf masonry with bigger blocks (c).

5 NUMERICAL RESULTS

The main results of the nonlinear dynamic analyses are reported in Figure 9. For this purpose, it has been applied to the main shock of the seismic sequence of 2016 in the Centre of Italy. The dynamic action used in the nonlinear analyses is recorded near Rotella (AP) in Ascoli Piceno (ASP) station in Italian Accelerometric Archive (ITACA)) for the main events of 24th August 2016, 26th October and 30th October.

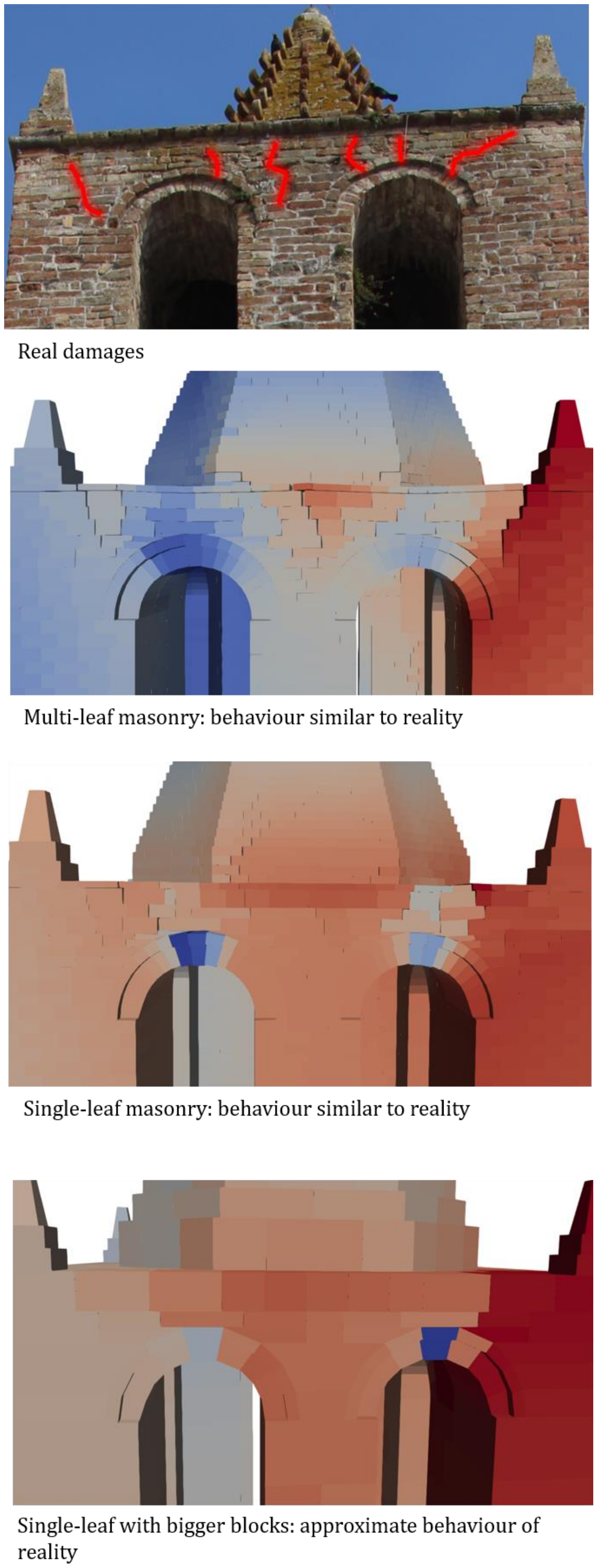

Figure 9. Failure mechanism of the Rotella (AP) civic clock tower.

Harmonic oscillations applied to the basement of the tower is considered first, and a systematic parametric study is done, aimed at correlating the global vulnerability to the amplitude and frequency of the excitation. Also, from the numerical results, both the role played by the actual geometry and the insufficient resistance of the constituent materials are envisaged, showing a good match with actual crack patterns observed after the seismic sequence. Finally, the numerical analyses provide a valuable picture of the actual behaviour of the tower, thus giving useful hints for future effective strengthening interventions.

6 CONCLUSIONS

The results obtained for the Rotella civic clock tower stroked by the Central Italy seismic sequence are here briefly reported and summarized, underline the high vulnerability of these types of structures, and especially of the bell cell.

The availability of experimental estimations of modal properties becomes relevant for structural and seismic assessment processes. Considering the increasing interest towards the opportunities provided by the dynamic monitoring as a tool for non-invasive techniques, this study would like to be a contribution to the development of rational and sustainable procedures for non-destructive investigation according to the current codes for heritage structures. In particular, the main results are used as input data for subsequent numerical analyses of the civic tower.

A discontinuous approach and the NSCD method, implemented in the LMGC90© is used in order to assess numerically the real damage. The NSCD method 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. 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.

The numerical investigation pointed out that no collapse mechanism passes the safety check. This outcome suggests that the reconstruction of the collapsed parts on the top of the towers if pursued, should be complemented by specific strengthening devices.

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