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Non-Smooth Dynamic Analysis of Local Seismic Damage Mechanisms of the San Felice Fortress in Northern Italy

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Abstract

The May 2012 seismic swarm, with epicenter in the Modena plane, in Northern Italy, had severe consequences on the historical buildings of the area. In particular, the fortified structures suffered specific, recurring damage and collapse mechanisms. The present paper deals with the case of the San Felice sul Panaro Fortress, which saw the collapse of 4 out of 5 towers and many other global and local effects. The work starts with an in-depth knowledge path, as a fundamental premise for a conscious intervention. The combination among historical analysis of the building, seismic history of the site, materials and pathological survey, structural identification, on-site inspections and tests, allowed to interpret the crack pattern and to identify the damage mechanisms activated by the earthquake, successively examined with specific structural analyses. In particular, the present paper concentrates on the numerical modelling of the identified local mechanisms, adopting a type of analysis first developed at the University of Parma for applied mechanics, based on the use of non-smooth dynamics software, through a Differential Variational Inequalities (DVI) formulation specifically developed for the 3D discrete elements method. It allows to follow large displacements and the opening and closure of cracks in dynamic field. Once the modelling instrument was calibrated, thanks to the comparison with the real damages previously inspected, it was also applied to foresee the behavior of the same mechanisms with different actions and with different types of strengthening.

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Keywords: seismic damage; local mechanisms; non-smooth dynamics; DVI formulation; strengthening, restoration;

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To the merely technical assessments, some considerations were added on the different levels of respect of the restoration principles guaranteed by the different interventions considered.

1. Introduction

Traditional masonry buildings react to seismic actions with the activation of recurrent damage mechanisms strictly related to the building typology. In Italy, the first systematic filing of these mechanisms was carried out after the 1976 Friuli earthquake, specifically for churches [1]. Later, also other building typologies were inspected (palaces, towers) and the catalogues of seismic damages found a place also in the most recent technical codes for the seismic protection of enlisted buildings [2]. Only recently, after the 2012 Emilia earthquake, a similar analysis was conducted also for the fortified buildings, first in [3] for brick masonry castles of the Emilia area, then in [4] widening the study area to six Italian regions hit by other significant seismic events. This allowed to identify the most recurrent damage mechanisms for the different fortified building typologies, both for prevention and for analysis purposes.

In particular, the case of the San Felice sul Panaro fortress is here analyzed, with the aim to identify the mechanisms of damage activated by the 2012 earthquake and to model them in order to design adequate consolidation interventions. In particular, the main mechanisms are identified from damage survey and explained also considering the historical analysis. For their modelling the linear and nonlinear kinematics analyses provided by the NTC guidelines [5] were excluded as they do not consider the effect of the vertical component of the earthquake. Moreover, there are problems to properly consider the dynamic filter effect exerted by the underlying structure. For this reason, it was decided to model the mechanisms in dynamic range with an innovative approach using discrete elements in accordance with a "non-smooth" approach [6]. First, the results of these kinematic models were validated by comparing their behaviour with the damage detected. Then, after the introduction of the reinforcements, the analyses were repeated to check the effectiveness of the proposed strengthening.

2. The case study: the fortress of San Felice sul Panaro

2.1. The historical evolution of the fortified complex

The Fortress is located along the walls of the ancient Castellum Sancti Felicis and, to date, is centrally located within the City of San Felice sul Panaro, near Modena, Italy (Fig. 1). The fort was built in 1340 by the will of Obizzo III d'Este. Initially the complex, quadrangular, was formed by the mere walls, from pre-existing keep, and a gate tower on the opposite side [7].

In the fifteenth century, Niccolo III d'Este promoted an adjustment intervention of defensive structures in order to make them effective also against the fire arms recently introduced in the combat modes: the corner towers and machicolation were added to the pre-existing structures, but it is not clear how structurally efficient these connections were. Towards the end of the century some inner buildings were also raised [8].

During the sixteenth and seventeenth centuries the fortified system saw a progressive worsening of its conditions, due to the loss of strategic importance of the place. In the eighteenth century the roofs (which had been first introduced on the towers in the fifteenth century) were restored, and a blockhouse was added. Since 1860 the fortress became property of the municipality that started restoration works [9].

During the twentieth century, the fortress sees major changes. In the '20s a reinforced concrete water tank was built inside the main tower (also called keep): a deep crack formed at its first use, so the tank was immediately emptied and never used again. Between the 60s and 70s reinforced concrete ring beams were inserted on all the towers roofs except the keep: during the last earthquake these ring beams contributed to the collapse of the top of the minor towers. In 1985 (Fig. 2), a total restoration was planned: the main work involved the removal of the tank inside the tower, the consolidation of the main tower walls by inserting hidden tie rods and restoring the original floor levels [10].

Generally, the fortress is realized with multiple layers walls in solid clay bricks and aerial lime mortar. The floors have a vaulted structure (mainly in the lower levels) and are made in wood in the upper levels, but some have been substituted by reinforced concrete structures in the XX century.

Fig. 1. An aerial view of the Estense Fortress in San Felice sul Panaro before the earthquake.

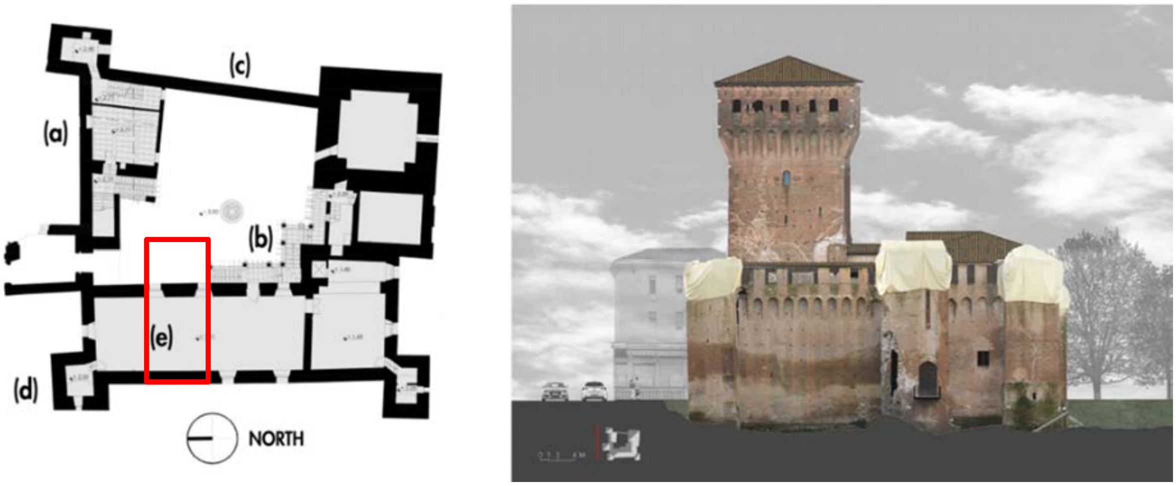

Fig. 2. Plan of the ground floor. The red rectangle identifies the zone that was modelled. Right: the fortress after the earthquake.

2.2. The effects of the 2012 earthquake

Currently the fortress shows serious damage caused by severe shocks (5.8 and 5.9 Richter magnitude) occurred in the days of 20 and 29 May 2012 respectively. The effects of the earthquake have been magnified by the vertical component of the acceleration, typical of "near-fault" cases. In addition, by comparing the on-site registered response spectra [11] with those provided by the standard codes for the site, we note that the earthquake of 2012 is comparable with the expected earthquakes for high return periods, well in excess of 475 years adopted by the Italian technical code (Fig. 3). Indeed, it is the first time that the Fortress of San Felice suffers an earthquake of such intensity.

In the keep, in addition to shear cracks in the lower part and in the battlements, the seismic swarm has generated the slippage of the upper part with respect to the lower part, connected to the lower buildings; as a consequence, the internal horizontal elements detached and in some cases collapsed. Even the towers show shear cracks on several sides due to lack of effective connections with the curtain wall or for the thrust of the internal vaults. The top part is collapsed as a result of stress concentrations generated by the presence of the reinforced concrete ring beam.

In particular, in the north entrance tower, the expulsion of a corner of masonry was generated by the presence of a reinforced concrete floor. On the north side, out-of-plane failure mechanisms affect the battlements and machicolation (Fig. 2). Finally, in the west part the crack pattern is horizontal, extending longitudinally along the side, and is repeated at different heights. A more extensive description of the damages can be found in [3].

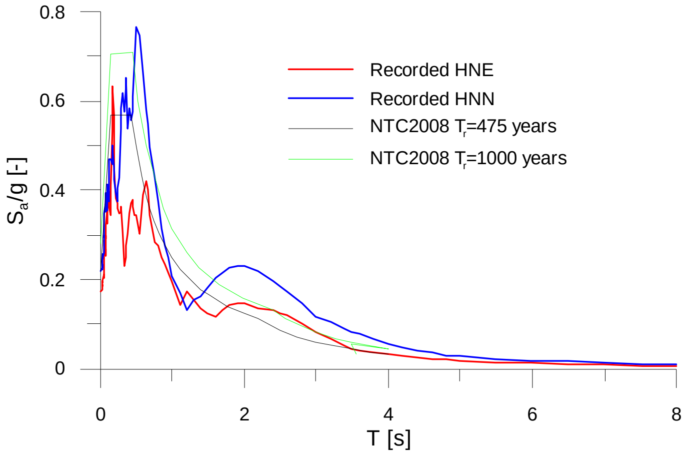

Fig. 3 Response spectra obtained from recorded data.

3. Knowledge path for the identification of the damage mechanisms

The analysis focused on the major collapse mechanisms identified (see Fig. 2): (a) walls curtain battlements; (b) columns of the external stairs; (c) east wall; (d) battlements of the towers; (e) building on the west side. As an example, we report here the analysis of the latter, which is the most complex.

Starting from the laser scanner survey, it was possible to spot the structural elements that, following the earthquake, have suffered significant residual displacements with respect to their original configuration. Once the out of plumb, the crack pattern and the weaknesses have been quantitatively measured, the collapse mechanisms were identified and classified according to the schedule of the instability mechanisms proposed in [3]. Cracks and out-of-plumbs allowed to identify the different masonry blocks that displayed a rocking mechanism during the earthquake (Fig. 4). Endoscopies permitted to observe the stratigraphy of walls and floors and thus to compute the loads to be considered in the analysis.

The identified mechanism is quite complex since it presents multiple degrees of freedom. For its modelling the linear and nonlinear kinematics analyses described by the NTC Guidelines [5] were discarded as they do not consider the effect of the vertical component of the acceleration. Moreover, they are more suited for mechanisms that present a single-degree-of-freedom and show some complications to properly consider the dynamic filter effect exerted by the structure. For these reasons, a dynamic time-history analysis has been here preferred. In particular, the mechanism was modelled using ChronoEngine, an object oriented C++ library that can be freely used to develop simulation software [12]. The library, that was conceived for dynamic analyses in the field of applied mechanics, if properly calibrated has been proved to be a useful tool also in the field of seismic engineering [13].

For the building on the west side, a portion of length 2 m was considered (Fig. 4). The different masonry parts identified in Fig.4 were modelled as rigid blocks. Also the vault at the first floor was represented with rigid blocks. The reinforced concrete slab at the second floor was modelled as a rigid slab hinged at the ends, where rotational springs were added to simulate the slab deformability. The wooden truss was modelled as a rigid body whose ends lay into masonry holes. Friction between wood and masonry or masonry and masonry was taken into account by means of a Coulomb friction coefficient equal to 0.65 and 0.75 respectively [13]. The dynamic interaction between blocks was considered by means of a coefficient of restitution equal to 0.8 [13]. The coefficient of restitution is the parameter that expresses the dissipation of energy during the inelastic impact between one or more bodies.

It can be defined as the ratio between the energy of a body before and after the collision. The higher is the coefficient and the lower is the energy dissipated and thus the lower the related damping.

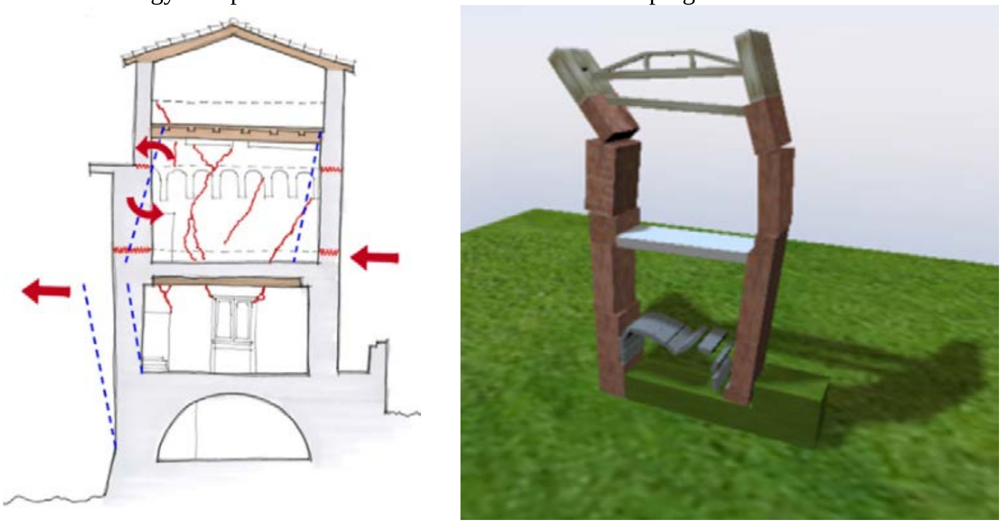

Fig. 4 The analysed out-of-plane damage mechanism.

The whole model lays on a rigid base ground, thus ignoring soil-structure interaction. The seismic input was applied at the base ground by means of the three components of the recorded accelerograms (Fig. 5). For the accelerograms, the second main shock of 29th May 2012 (M_L =6, M_I = 5.8) was considered since a station named San Felice sul Panaro (which is very close to the fortress and at an epicentre distance of 4.7 km) has recorded the event [11].

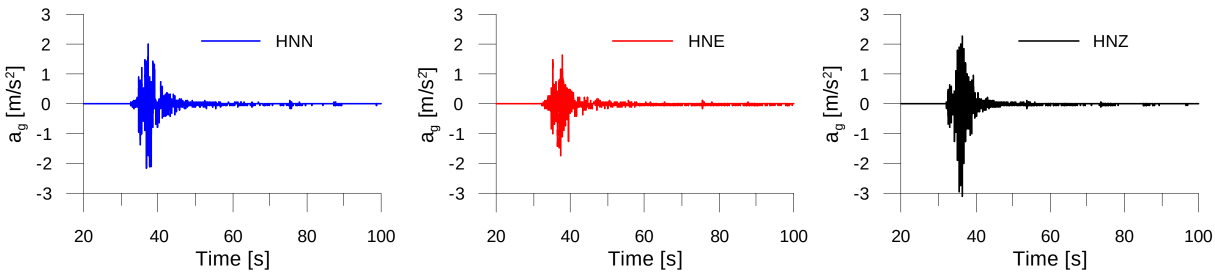

Fig. 5 The recorded accelerations at San Felice sul Panaro seismic station.

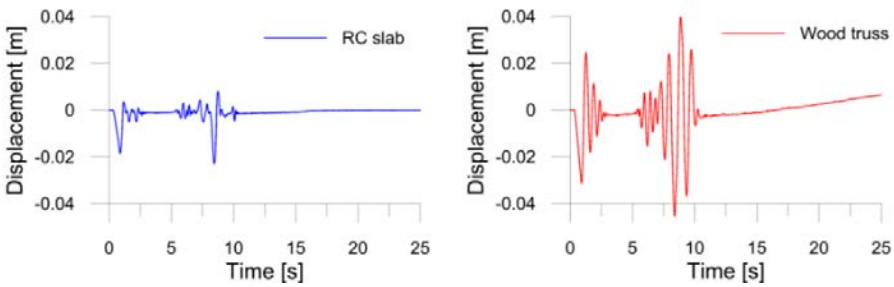

Fig. 6 The time history of the horizontal displacements.

To integrate the equations of motion, the Differential Variational Inequalities method (DVI) has been used [14,15]. Fig. 4 shows the mechanism in the displaced state for a seismic input that leads the analysed mechanism to collapse. On the contrary, in agreement with the experimental evidence, with the real input shown in Fig. 5, the modelled structure survived from the earthquake. Fig. 6 shows the computed time history of the horizontal displacements of the centres of gravity of the floors (r.c. floor and timber truss), in the NE direction. These graphs show that the upper part is the most vulnerable, since it undergoes larger displacement (up to 40 mm), that could lead, in more severe cases, to the slippage of the truss from the wall.

4. Considerations on the possible strengthening interventions

The dynamic analysis, in accordance with the crack pattern, has pointed out the critical aspects of the inspected vertical out of plane bending mechanism: the possible slipping out of the roof king post trusses from the walls and the stress concentrations caused by the wall thickness variation (evidenced in Fig. 4). The mechanism has been activated by the earthquake, but has not reached the collapse conditions: an intervention on these criticalities is therefore urgent to hinder further evolutions of the damage. The first issue can be easily faced inserting an effective connection between the trusses extremities and the walls: a traditional steel connection to an external anchorage looks like the best option, also considering the restoration principles.

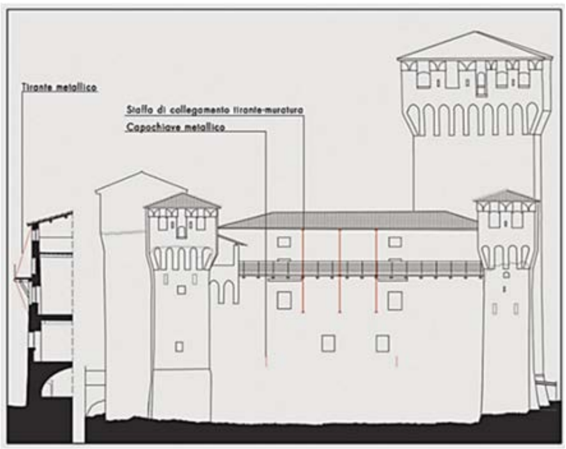

Fig. 7 Scheme of the proposed intervention, highlighted in red [16].

The second issue is more complex, both from a technical and from an aesthetical point of view. One possible solution could be the thickening of the upper part of the wall to reduce the abrupt stiffness change, but this would cause on one side the increase of the weight and as a consequence of the seismic action on the top of the wall, on the other side an asymmetrical change in the inner volumes with effects on the geometric perception of the room and its architectural elements (windows, trusses, decorative elements). Therefore, a different solution was attempted: the insertion on the external side of the wall of a vertical steel element which could take up the vertical tensile stresses induced by the inspected mechanism. This solution can appear to be more invasive from an aesthetic point of view, but it can be observed that it respects all the main principles of restoration: it is reversible, it respects authenticity, it has a structural impact which is limited to the identified mechanism, without changing the static behaviour of this building portion also with respect to the other areas. Moreover, it must be underlined that this wall had been rebuilt, with a clearly identifiable brick masonry pattern, in the mid XX century, with the insertion of a modern walkway in steel and timber. The new strengthening intervention would thus be inserted in this already modified structures, connecting to the walkway structure and to the new wall, with very limited influence on the original parts (Fig. 7).

The first analyses on the distinct elements model, taking into consideration also these strengthening proposals, show an improvement in the seismic behaviour of this part of the structure, with respect to the previously identified damage mechanism.

5. Conclusions

The present work deals with the seismic assessment and upgrading of the Italian fortress of San Felice sul Panaro, hit by an earthquake in 2012. The work focuses on the local damage mechanisms that were activated by the earthquake. Initially, they have been defined by means of a multidisciplinary approach that started from the history of the castle and exploited modern survey technologies like laser scanner and endoscopies. Some mechanisms are quite complex therefore to study their seismic behaviour, a time history analysis using a discrete element approach was adopted. In particular, for the first time, the library Chronoengine, developed in the field of applied mechanics, was used for a real civil structure. The library is based on the differential variational inequalities approach (DVI), which permits to save computational time and to model a huge number of rigid blocks undergoing large displacements. The numerical simulations permitted to replicate the observed evidences. Then, adding the seismic interventions, it was possible to check their efficiency. These very first results are promising however, to foresee the future behaviour, more analyses will be performed with natural accelerograms compatible with the spectra of the Italian technical code. Furthermore, comparisons with more standard linear and nonlinear kinematic analyses will be carried out.

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