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Some recent advances and applications in Distinct Element modelling of masonry structures

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Abstract. In this paper, advanced numerical models are used to study the progressive damage of a historic building, namely the Palazzo of Podestà and the Civic Tower of Accumoli (central Italy). The dynamic behaviour of the structure is analyzed following important seismic events such as those that occurred in 2016-2017. Discontinuous and continuous approaches are used. In the formers, the masonry response is represented both with Discrete Element Method (DEM) and the Non-Smooth Contact Dynamic (NSCD) method; in the latter the masonry nonlinearity is replicated using the Concrete Damage Plasticity (CDP) model. The numerical results showed a good correspondence of all the approaches with the real damage suffered by the structure after the seismic sequence.

Introduction

In 2016, a series of catastrophic seismic shocks caused victims and considerable damage to the heritage structures in the Central Italy regions [1,2]. These earthquakes heavily stroked the Norcia, Visso, Arquata del Tronto, Amatrice and Accumoli villages [3,4].

Figure 1. The geographical location of Accumoli village.

The case study of this paper is located in the Accumoli village, in the Lazio region (central Italy). The historic center of Accumoli, before this disaster (Fig. 1), was the tangible testimony of a troubled history.

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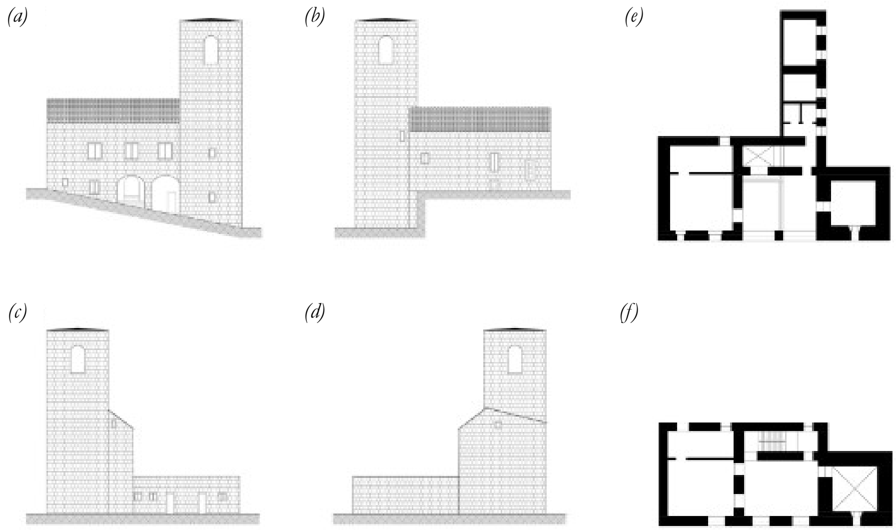

Figure 2. North (a), South (b), East f (c) and West façade (d), Ground (e) and first floor (f).

Accumoli dates to 1211, the territory was initially much larger than the current ones including several municipalities. At the heart of this small village there is the case study of this paper, i.e. the Civic Tower of Accumoli and the adjacent Podestà palace. The Tower dates to the twelfth century, it is unique in its kind in the entire Tronto's valley. It is in via Tommasi, featuring a square plan measuring 6.15x6.15 m^2 with walls of 1.20 m thickness at the base and 1.00 m at the top. In elevation, the maximum height exceeds 20 m (Fig. 2). The bearing structure consists of multi-leaf walls [5,6], the perimeter curtains are in cut stones and the inner core is in irregular stones. The structure ends with a pitched roof in reinforced concrete.

Next to the tower, there is the Palace of Podestà. It dates to the thirteenth century, and it is the oldest structure in the Accumoli village. The palace has a rectangular plan of 8.6x16 m^2 dimensions and a maximum height of 10 m. It consists of ground and noble floors. In the latter, there are architrave windows, instead on the ground floor there are two arched openings, typical of medieval public buildings. The bearing structure is made of square and smooth sandstone ashlars. (Fig. 2). On the north side of the palace, there is a little annex of one floor. It has a rectangular plant of 10x3.8 m.

After the 2016 earthquakes, the complex exhibited visible cracks, especially on the tower as visible in Figure 3.

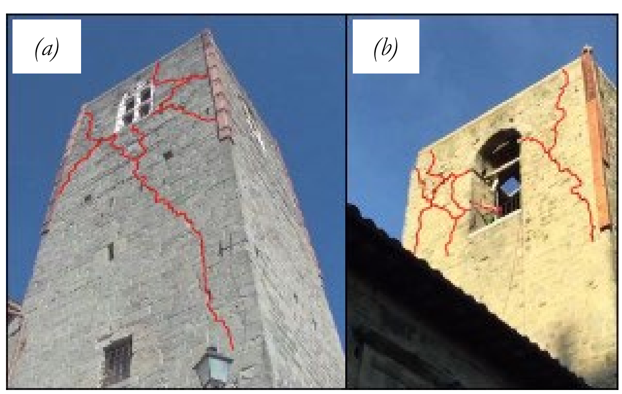

Figure 3. Real damage of the North façade (a) and West façade (b).

Discontinuous and continuous approaches

Numerical models were created to have a complete picture of the progressive damage that the structure undergoes when subjected to a seismic sequence. A comparison was made between the discontinuous and the continuous approach [7–9].

In the discontinuous approach, the dynamic response of the structure is studied with the Non-Smooth Contact Dynamic (NSCD) method [10–12] implemented in LMGC90© open-source code and with the Distinct Element Method (DEM) [13–15] implemented in 3DEC© code. A 3D numerical model is created, and the masonry is discretized in different individual rigid blocks, reproducing the real behaviour of the structure, and analysing the progressive damage under a seismic action [16–18]. The size of the blocks has been approximated to obtain a fair compromise between a good degree of detail and a not too expensive computational burden (Fig. 4) [12]. Furthermore, it was decided to model the tower also considering its internal filling (Figure 4.b-c-d) as can be seen in Figure 4c, made with larger blocks than the two external leaves in order to limit the computational burden.

The blocks in the NSCD method are subjected to Signorini's law (i.e., impenetrability condition) and to the dry-friction Coulomb's law. The contacts have than a non-smooth nature.

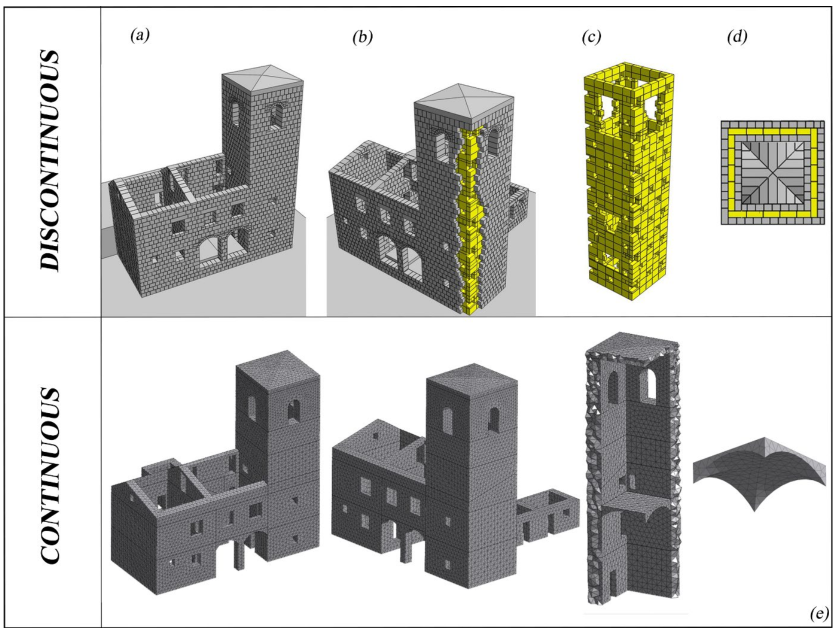

Figure 4. Discontinuous (a-d) and continuous model (e).

DEM models use smooth functions to represent interactions between blocks. A Mohr-Coulomb constitutive model is used.

Differently, in the continuous approach, the masonry is approximated to a fictitious and homogeneous isotropic medium [19]. To reproduce the nonlinear behaviour of the masonry, the Concrete Damage Plasticity (CDP) model [20,21] is used. Such a model is one of the most used to analyse the masonry behaviour under horizontal loads [8]. Indeed, it can simultaneously provide the compression and tension damages and consider the recovery of stiffness due to cracks closure.

Numerical results

The structural behaviour of the structure was first studied under gravitational loads, then the records of the three most important seismic events that occurred in Central Italy in 2016 were applied in the three main directions to obtain a first comparison between the numerical and the real damages.

The three events taken into consideration are summarized in Table 1. The events were applied in sequence considering 10 seconds of the peak amplitude of each and two seconds of rest between one event and another, the total time histories apply were of 34 seconds.

*Table 1. Characteristic of the three main shocks of the Central Italy seismic sequence of 2016 recorded in Amatrice (AMT) and Accumoli (ACC) station, where * indicates that the site classification is not based on a direct $V_{s,30}$ measurements.*

Seismic event		M_L	Depth [km]	Station	Class EC8	R [km]	R [km]	R [km]	Channel NS PGA [cm/s²]	Channel EW PGA [cm/s²]	Channel UD PGA [cm/s²]
1st	24/08/2016	6	8.1	AMT	B*	1.38	4.62	8.5	368.39	-850.8	391.37
2nd	26/10/2016	5.9	7.5	AMT	B*	25.93	26.09	33.3	-58.55	90.74	-49.11
3rd	30/10/2016	6.1	9.2	ACC	B*	35.33	35.32	47.10	-122.44	75.95	-44.07

Figure 5 shows an excellent correspondence of results between DEM and NSCD. The part of the structure that is most affected by the seismic sequence is the belfry; in fact, following the first two events the formation of crack patterns on it is visible. Following the earthquake of 30th October 2016, it is possible to notice the propagation of crack patterns between the palace and the tower. Furthermore, the palace after the last shock is damaged near the openings on the ground floor. The tower instead highlights the formation of vertical crack patterns on all the façades. On the other hand, the FE model also shows the vulnerability of the bell-cell. After the first event, horizontal cracks at its base are visible; instead, at the end of the sequence, a crack appeared also in the upper corner of the single arched windows. In contrast to the discrete approaches, the continuous showed important cracks in the connection between the tower and the palace just after the first events (Fig. 5).

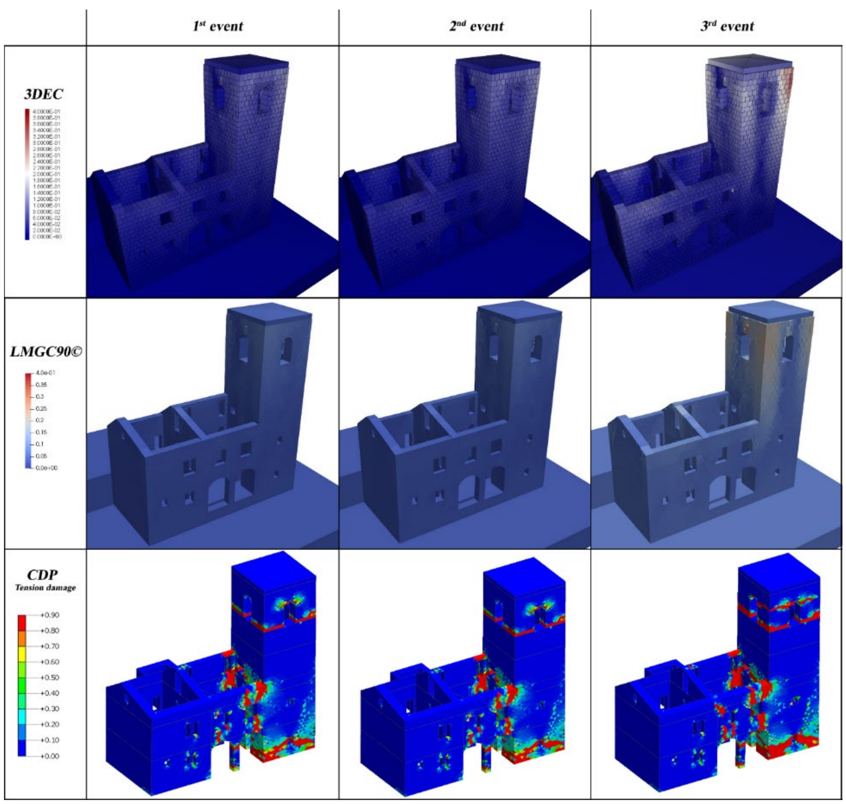

Figure 5. Comparison between results of 3DEC©, LMGC90©, and FEM.

Finally, it is important to stress the fact that all the approaches were able to identify the bell-cell as the most vulnerable element, as incidentally demonstrated by the 2016 seismic sequence. However, the cracks' pattern is more accurate with the discontinuous approaches instead than with continuous one. It is certainly linked to a loss of the resistant properties of the mortar, but also to a masonry's texture with irregularities, at least in the filling. With these boundary conditions, the masonry exhibits crumbling instead of a monolithic behaviour, the first one impossible to catch with continuous approaches.

Conclusions

The Palazzo of Podestà and the Civic Tower were studied through continuous and discontinuous approaches. The latter allows to represent the discontinuities of the masonry, capturing the dynamic behaviour of the structure following the seismic sequence of Central Italy in 2016. It is possible to note a good correspondence between the models with the NSCD and DEM methods and the real damage. In particular, the global and local behaviour of the structure is obtained. Furthermore, good results are obtained with the continuous approach, which, however, unlike the discontinuous approach, cannot faithfully reproduce the cracks because the texture of the masonry has a high influence on the structural response.

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