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Discontinuous vs continuous approaches for the nonlinear dynamics of an historic masonry tower

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Abstract

The present paper investigates, from an advanced numerical point of view, the progressive damage of the Amatrice (Rieti, Italy) civic clock tower, after a long sequence of strong earthquakes that struck Central Italy in 2016. Two advanced numerical models are here used to provide an insight into the modalities of progressive damage and the behaviour of the structure under strong dynamic excitations, namely a Discrete Element Method (DEM), the Non-Smooth Contact Dynamics (NSCD) method, and a FE Concrete Damage Plasticity (CDP) model. In both cases, a full 3D detailed discretization is adopted. From the numerical results, the role played by both the actual geometries and the insufficient resistance of the constituent materials are envisaged, showing a good match with actual crack patterns observed after the seismic sequence.

Keywords: masonry towers; concrete damage plasticity model; non-smooth contact dynamics method; non-linear dynamics.

1 Introduction

The seismic events, which hit Central Italy on 24th August 2016, 26th and 30th October 2016 and 18th January 2017, caused casualties and significant damage mostly to buildings and architectural heritage of the Italian regions of Marche, Lazio, Abruzzo and Umbria [1–3]. An icon of damage and destruction of a long sequence of strong earthquakes of 2016-2017 is the Amatrice civic clock tower which will be investigated in this paper.

Symbol of the city of Amatrice (Rieti, Italy), the Civic Tower (Fig. 1) rises in Cacciatori del Tevere square, underlining the crossroads of two main streets of the city centre, Via Roma and Corso Umberto I.

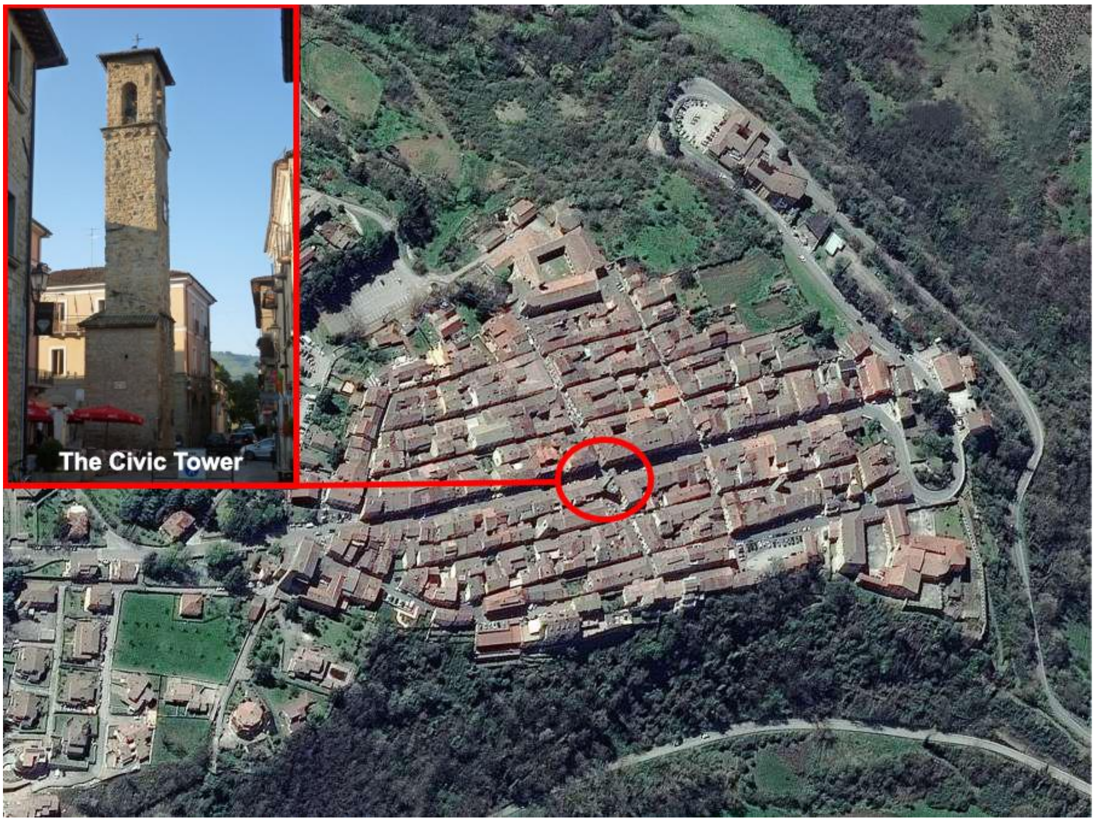

Figure 1: Geographical localization of the Civic Tower.

There are few historical data about the Civic Tower, its origins are placed back to medieval times, as early as 1293 it was mentioned in ancient documents. The clock tower was originally connected to the Church of Santa Lucia, demolished in 1684 by the feudal "lord" Alessandro Maria Orsini: on this occasion, the base of the tower was reinforced and a small annex was added on two sides.

The last and probably the only consolidation intervention was carried out on the tower in 1979, when, following the earthquake of the Alta Valnerina (Central Italy), significant damage was noticed to the tower. In 1985 the original bell of 1494 was replaced because it had undergone a crack during the restoration phases: a lighter one has been inserted in the tower to avoid high oscillations as in the past.

The civic tower of Amatrice has a rectangular plan of 4.00 m x 5.30 m and a height of about 25 m. At the base, there is a small overhang leaning only two walls, to east elevation with a depth of 1.5 m, and to north elevation with a depth of 0.60 m. This annex houses the staircase leading to the entrance of upper floors. In its vertical development there are three distinct areas marked by the reduction of the wall thickness.

Three advanced numerical models are here utilised to have an insight into the modalities of progressive damage and to provide a picture of the actual behaviour of the structure, considering and not considering past retrofitting interventions [4,5].

2 Methods

In this section, the principal peculiarities of Discrete Element (DE), Non-Smooth Contact Dynamics (NSCD) and FE Concrete Damage Plasticity (CDP) models and the main modelling assumptions are highlighted.

For the NSCD and DEM two advanced numerical models are built to adequately represent the behaviour of the investigated real structures [6–8]. A full 3D detailed discretization is used to provide insight into the modalities of progressive damage and the behaviour of structures under strong dynamic excitations, analysing the influence of the brick fragments of really small element size (Figure 2).

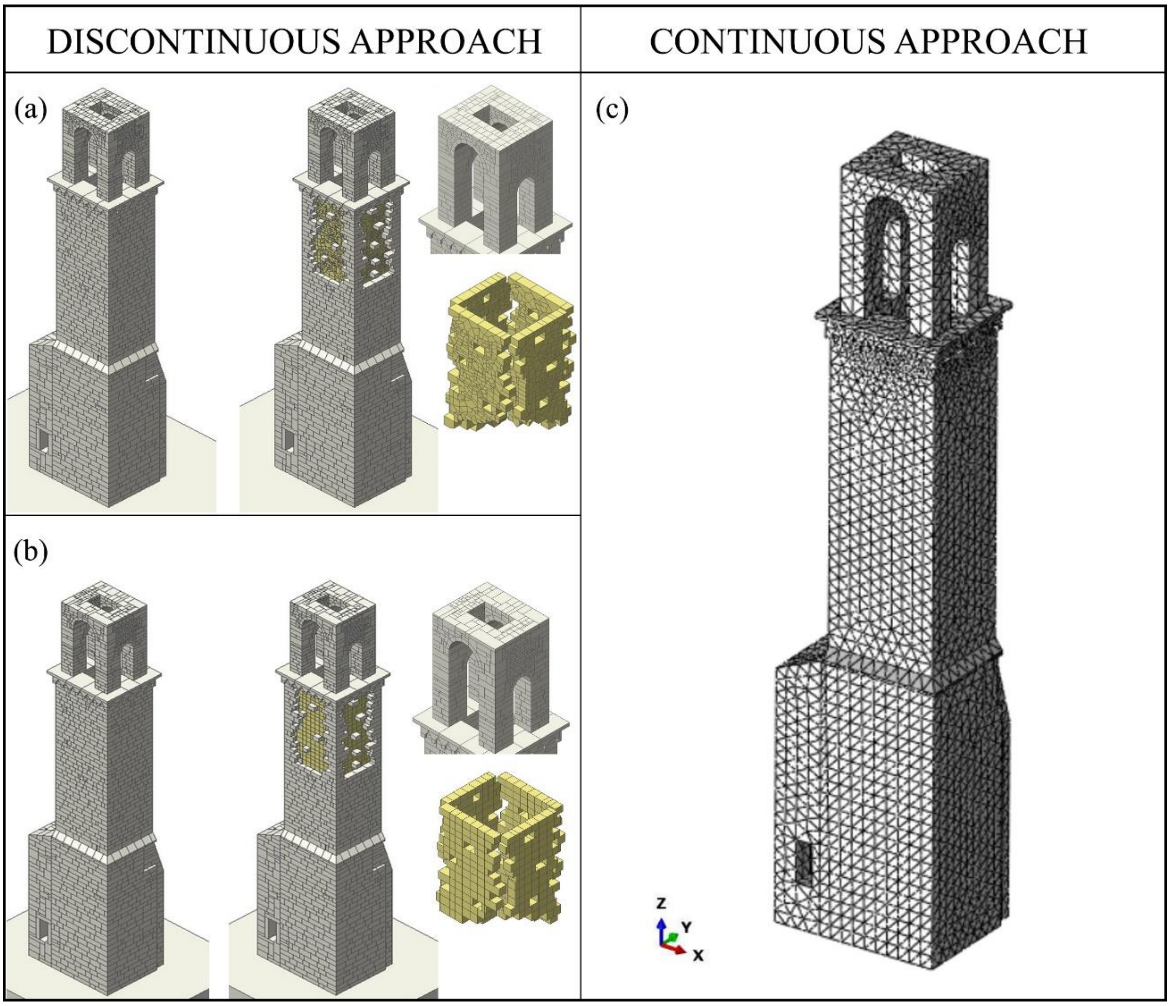

Figure 2: Model 1 (a), Model 2 (b) and FE model (c).

Masonry units were represented as an assemblage of distinct rigid blocks which may take any arbitrary geometry. In particular. it was decided to use an accurate mapping of the masonry where the size of the blocks is directly taken up by the reliefs of the facades, considering the rounded shape of the stone (Model 1), while the internal wall texture has been hypothesised.

An attempt was then made to establish the degree of influence, in the local and global response, by acting with a regularization of the stone with a more prismatic geometry, i.e. flat surface (Model 2) avoid further computational burdens.

In the NSCD method [9,10], the rigid blocks of the structure are undergoing shock laws and Coulomb friction. The tower exhibited a complex dynamic behaviour, 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 usually occurs right before or during the collapse with velocity discontinuities.

In DEM [11,12] models, smooth functions are used to describe the interactions between blocks with velocity continuities and the non-linear behaviour of the mortar assigned to the interfaces corresponds to a Mohr–Coulomb constitutive model, which involve the cohesion, the friction angle, and the tensile strength as parameters. The stiffness of the interfaces is represented by two springs in the normal and shear direction, linking the contact stresses with the relative blocks' displacements.

The 3D FE model (Figure 2) of the tower is also created and non-linear dynamic analyses are conducted using computer code Abaqus©, assuming for masonry a CDP material model [13]. Although a CDP approach is conceived for isotropic brittle materials like concrete, it has been widely shown that its basic constitutive law can be also adapted to masonry. CDP model allows to analyse materials with different strengths in tension and compression, assuming distinct damage parameters.

3 Results

The dynamic behaviour of the civic clock tower of Amatrice was firstly investigated under the actions of gravity loads on the whole system. Afterward, real seismic records in the three main directions were applied.

The effect of the four main shocks (Table 1) occurred in the seismic events of Central Italy of 2016 are considered.

Seismic event		M_L	Depth [km]	Station	Class EC8	R [km]	R [km]	R [km]	Channel NS PGA [cm/s^2]	Channel EW PGA [cm/s^2]	Channel UD PGA [cm/s^2]
1st	**24/08/2016**	6	8.1	AMT	B*	1.38	4.62	8.5	368.39	-850.8	391.37
2nd	**24/08/2016**	5.4	8	AMT	B*	-	-	20.9	-93.28	105.58	63.77
3rd	**26/10/2016**	5.9	7.5	AMT	B*	25.93	26.09	33.3	-58.55	90.74	-49.11
4th	**30/10/2016**	6.1	9.2	AMT	B*	10.12	11.49	11.49	393.63	521.62	317.82

Table 1: Characteristic of the four main shocks of the Central Italy seismic sequence of 2016 recorded in Amatrice (AMT) station, where * indicates that the site classification is not based on a direct Vs,30 measurement.

The final time histories were obtained as an assemblage of the 10 peak amplitude seconds of each event, distanced by 2 seconds of rest, for a total of 46 seconds of duration.

The principal purpose of these analyses is the comparison of the numerical damages with the real ones. This is achieved by comparing the crack patterns of the civic clock tower of Amatrice in Figure 3 with those on the numerical models of all codes.

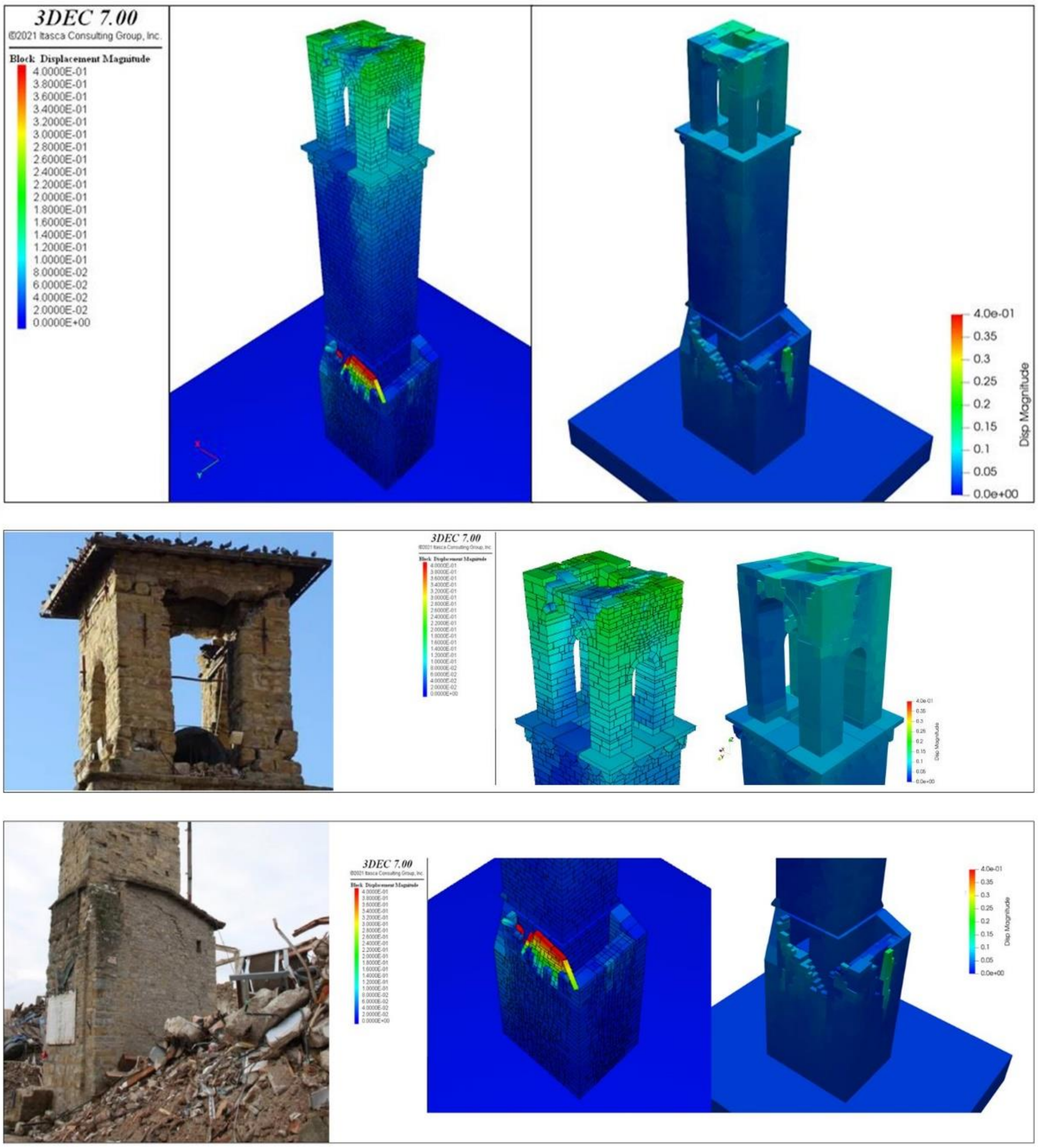

Figure 3: Model 2: comparison between 3DEC©, LMGC90© code and reality after first event.

The Model 2 highlights, after the first event, a severe damage on the upper part of the annex walls, for both NSCD and DEM, with evidence of a well-defined crack pattern (Figure 3). This damage becomes even more pronounced in the specular model without steel chains in the bell cell. After the second event and the third event an overall deterioration of the structure is noticeable. After the fourth a clear collapse is addressed.

In the Model 1, after the first two events, the annex damage is limited compared to Model 2, due to an irregular shape of blocks that permits a better interlocking. The presence of the steel chains (Figure 4) allow to exclude a trigger of collapse in the bell cell for Model 1 as well, only leaving the possibility of a partial crumbling of the smaller blocks in the upper part. With the fourth event (higher magnitude), the collapse of the bell cell is always reached.

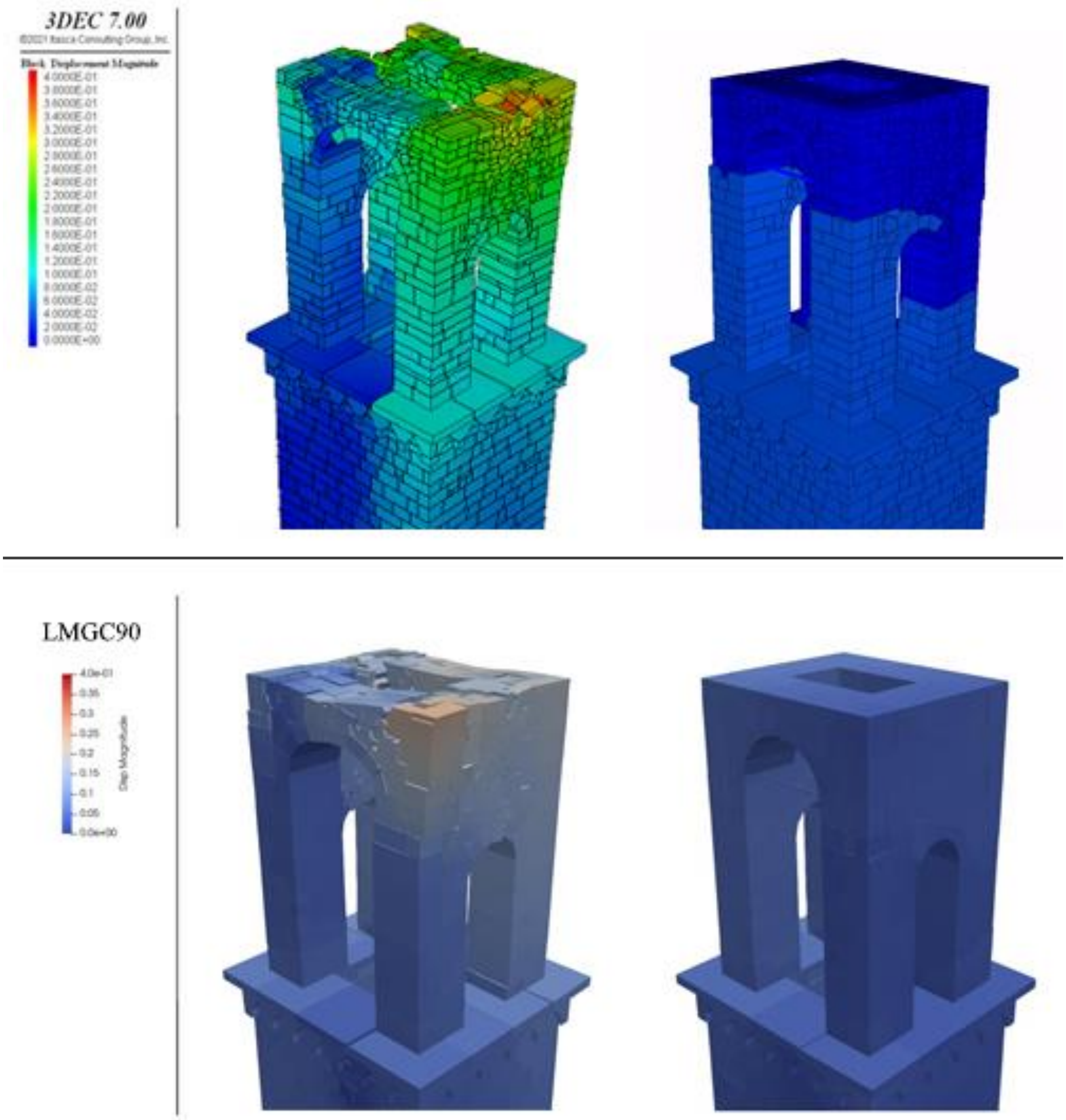

Figure 4: Model 1 without steel-bars (on the left) and with the presence of steel bars (on the right), particular of the belfry.

In Figure 5 the damages obtained with FE CDP model are reported, for the same time steps as in Figure 3. Similar results are noticeable: heavy damage at the bell cell and annex. Otherwise, there is a substantial damage along the tower that is only just visible in NSCD/DE models and which, now, does not seem to be associated with the real damage following the seismic shocks ended on 18th January 2018.

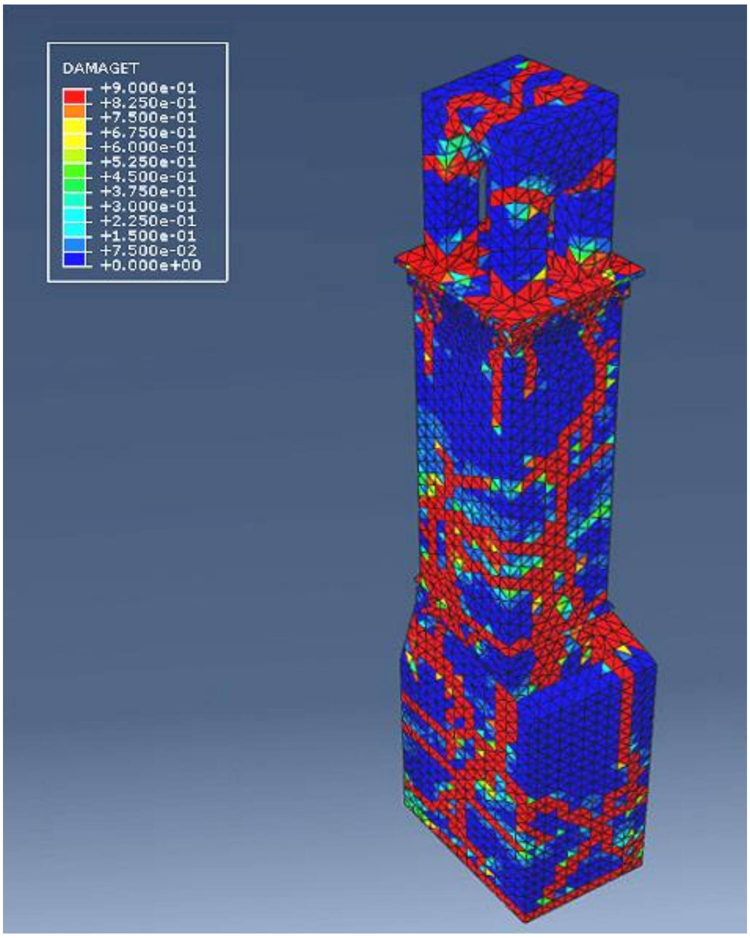

Figure 5: Expected damage obtain with FE CDP model implemented in Abaqus©.

Further analyses on the influence of the mechanical parameters will be necessary.

4 Conclusions and Contributions

The numerical assessment of the civic clock tower of Amatrice (Rieti, Italy) is investigated by means of both discontinuous and continuous approaches.

The numerical results underline that the modelling of the masonry and of past retrofitting interventions influences the numerical results, and the comparison with the existing structural damages caused by the seismic sequence that took place in Central Italy in 2016. In particular, the two different levels of detail for the discretization of the masonry, in the discontinuous approaches, provide deeper insight into the dynamical behaviour of the structure, also exploring the possibilities of the approach to represent the discontinuities of masonry material.

It is possible to assess a good correspondence between the analysis carried out and the real events, with both LMGC90 and 3DEC models capable of capturing the global and particularly the local crumbling that also actually took place.

Furthermore, a great result was achieved through the steel-bars modelling. The output of the analysis shows peculiar differences in the behaviour of the belfry depending on the presence or absence of the reinforcement.

Further analyses must instead be conducted with the FE model where material resistances can highly influence the structural response, making a sensitivity analysis necessary.

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