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3D FE PUSHOVER AND NON-LINEAR DYNAMIC ANALYSES OF A MASONRY CHIMNEY BEFORE AND AFTER SHORTENING

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Abstract. *A masonry chimney 50 meters high, severely damaged by the May 2012 Emilia-Romagna (Italy) seismic sequence is numerically analyzed by means of non linear static and dynamic FE techniques. The state of damage on the upper part of the structure led to take the decision to shorten the chimney for security reasons, with a reduction of the height up to 37 meters. A modal pushover analysis (MPA) where force distributions based on the principal vibration modes is used to analyze the structure, finding for the 50 meters case crack patterns consistent with the observed ones. In addition, it is shown how, before and after shortening, the behavior factor to be used in modal response spectrum analyses, estimated directly from the MPA results, is slightly higher than unity, indicating a very low dissipative capacity. To validate static approach results, non-linear dynamic analyses are carried out using natural accelerograms and for the masonry material a damage-plasticity model. The residual deformations obtained and the crack patterns found exhibit convincing similarities with the real behaviour and address how the shortening may be beneficial to improve stability.*

1 INTRODUCTION

In recent years, mainly with the aim of improving the dynamic behavior of the heritage buildings, the seismic analyses of masonry structures have become an important issue in civil engineering. Among the others, slender structures such as chimneys or towers require particular attention in the evaluation of the seismic behavior. Nowadays, the difficulties concerning such structures are mainly related to the complexity, from a computational point of view, in reproducing the nonlinear masonry response in the dynamic field. The strong influence of the higher modes of vibration often increases the problem. One of the first studies on the possible failure mechanisms of masonry chimneys under earthquake excitation is reported in [1], whereas in [2] Riva and co-workers used a simplified model composed by elastic beam elements connected through nonlinear joints, to study the seismic vulnerability of a 97.2 m high masonry tower in the historical centre of Bologna, Italy. More recently, the increased computing power allowed for more advanced analyses using two- or three-dimensional finite elements, some studies dealing with this topic are [3]-[4]. An interesting state-of-the-art review of seismic assessment and strengthening techniques of masonry chimneys is reported in [5].

The present paper deals with the seismic damage assessment of an unreinforced masonry chimney built at the beginning of the 20th century in the service of a sugar factory in Ferrara, Italy. A survey campaign performed after the 2012 earthquake sequence in Northern Italy (Emilia earthquake), evidenced diagonal cracks in the outer surface of the stack at an altitude of approximately 45 m. The damages mainly were composed of large open cracks, grossly inclined at 45°, but also a deterioration of the mortar along the cross section circumference or even partially missing was detected. Due to the position of the masonry chimney, close to the university buildings, the structure has required a subsequent shortening of the upper part. In the current form the chimney is 37.6 m high. The structures after and pre shortening are depicted in Figure 1. In order to explain the causes of the widespread damages and to analyze the different seismic behaviors pre and after the shortening activities, a series of numerical analyses of the chimney previous and in the current form are presented in the paper. In particular, both Modal Pushover Analyses (MPA) and nonlinear Response History Analyses (RHA) using three-dimensional nonlinear finite elements are utilized.

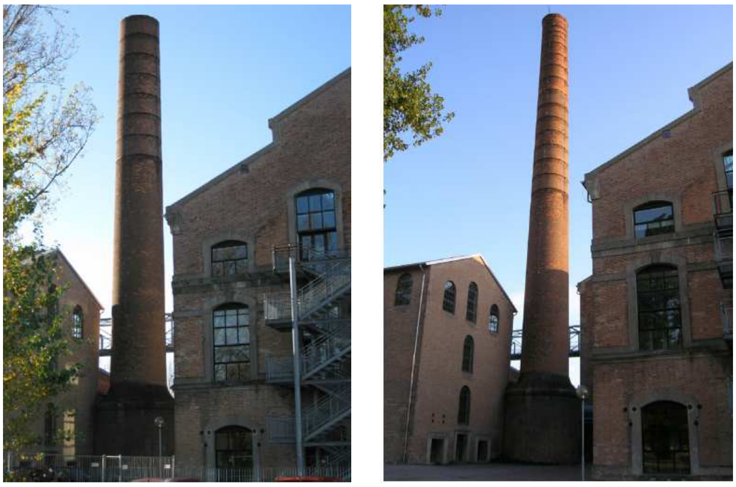

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Figure 1. The chimney (a) after and (b) before shortening.

2 NUMERICAL MODELS

The FE analyses presented in the paper are performed using a tridimensional model composed by 8-node solid (brick) elements. The mesh was generated assuming 75 subdivisions along vertical axis while 16 subdivisions were adopted in in the planes of the cross sections. The resultant model is composed by 1200 finite elements and 2432 nodes.

The original 50m-high chimney was discretized using 100 and 16 equal subdivisions along the vertical axis and in the planes of the cross sections, respectively, resulting in 1600 solid elements and 3232 nodes (for a detailed description the reader is referred to [6]-[7]). All the simulations previously presented are performed by means of two different software packages. In particular, pushover analyses are developed using DIANA [9][8], while response history analyses are performed with ABAQUS [10]. The nonlinear behavior of masonry is involved into both simulations. Concerning the DIANA software, the material nonlinearities are reproduced by means of a traditional total strain crack model, belonging to the family of the smeared crack constitutive laws. In particular, the effects due to cracking are taken into account by using a linear softening for the stress-strain relationship in tension and a shear retention factor $\beta = 0.05$. The model parameters are summarized in Table 1.

Young's modulus	Poisson's ratio	Strengths Compressive	Tensile	Ultimate tensile strain	Shear retention factor
E	ν	f_c	f_t	ε_t	β
MPa		MPa	MPa	‰	
1500	0.15	3.5	0.1	0.5	0.05

Table 1. Material properties used in the pushover analyses.

The material properties, such as the compressive strength, are estimated from laboratory test results [6]-[7], whereas, in the absence of a specific experimental characterization, the value of Young's modulus was chosen in agreement with the indications reported by the Italian Building Code [8], for existing masonry structures. The constitutive model used for the numerical simulations in ABAQUS, the so called Concrete Damage Plasticity (CDP) model, is based on the assumption of a scalar isotropic damage with distinct damage parameters in tension and compression and is particularly suitable for applications in which the material is subjected to loading-unloading conditions such as dynamic analyses. Masonry is assumed to obey a Drucker-Prager strength criterion with non-associated flow rule. A value equal to 10° is adopted for the dilatation angle. Software ABAQUS allows for smoothing the strength domain by means of an eccentricity parameter, which in the q-p plane represents the distance between the points of intersection with the p-axis of the cone and the hyperbola. A value of 0.1 is adopted in the simulations.

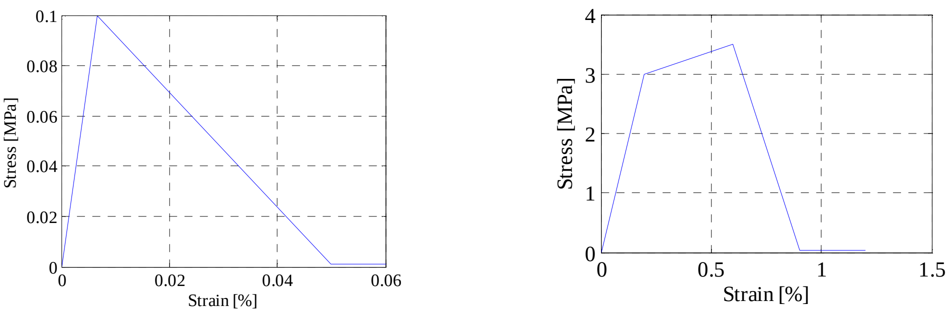

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Figure 2. Representation of the masonry constitutive behavior in (a) tension and (b) compression.

During the analyses performed the ratio between the ultimate compressive strength in a biaxial stress state and that in uniaxial conditions must be also considered. Such ratio is reasonably set equal to 1.16. The final stress-strain relationships in tension and in compression adopted for the dynamic analyses are depicted in Figure 2. The damage variables in tension (index "t") and compression (index "c") are defined by means of the following standard relations:

$$f_t = E_0(1 - d_t)(\varepsilon_t - \varepsilon_t^{pl}) \tag{1}$$
$$f_c = E_0(1 - d_c)(\varepsilon_c - \varepsilon_c^{pl}) \tag{2}$$

where f_t, f_c = uniaxial stresses; E_0 = initial elastic modulus; ε_t, ε_c = uniaxial total strains; ε_t^{pl}, ε_c^{pl} = equivalent plastic strains; and, finally, d_t, d_c = damage parameters. Geometric nonlinearities is accounted for in all analyses. The masonry mass density assumed in the simulations is w = 1800 kg/m^3 ([6]-[7]).

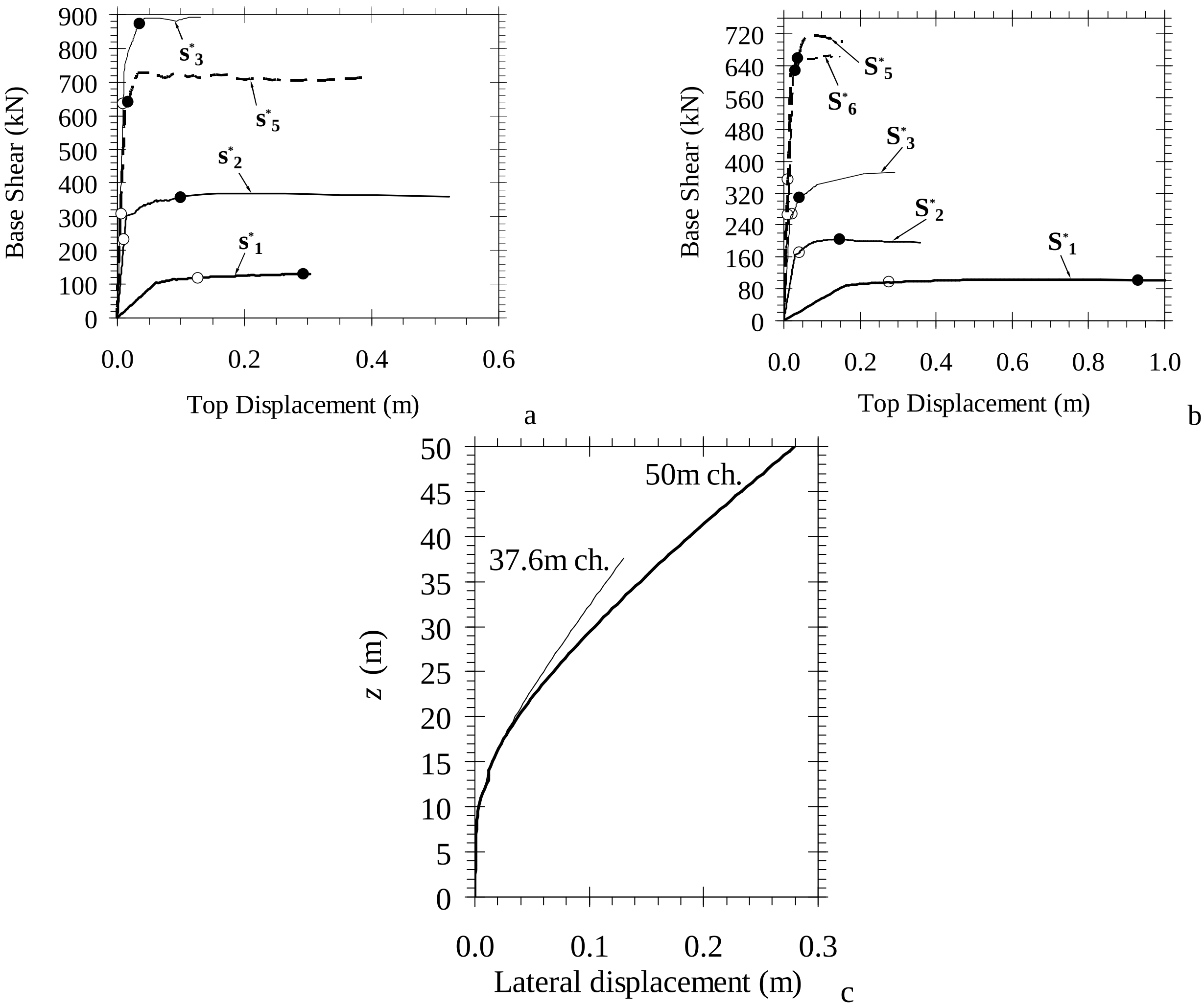
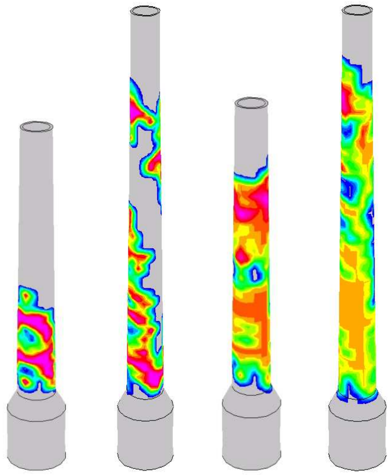


Figure 3. Pushover curves for (a) the shortened, and (b) the original chimney and (c) final profiles of the lateral displacement obtained from the analyses. Open and solid circle data points in Figure 3a,b locate the target displacements obtained assuming a ground motion multiplier equal to 1 and 3, respectively.

3 MODAL PUSHOVER ANALYSIS (MPA)

The Modal Pushover Analysis (MPA) was introduced in [11] for multi-storey framed structures to improve the pushover methods based on force distributions proportional to one single mode of vibration. The basic idea of MPA is to combine the results of N pushover analyses, the n-th of which is based on the invariant force distribution proportional to $\mathbf{s}^*_n = \mathbf{M}\boldsymbol{\phi}_n$, with $\mathbf{M}$ and $\boldsymbol{\phi}_n$ being the global mass matrix and n-th elastic mode shape, respectively.
In this section a series of analyses using the MPA procedure are discussed. All modes with effective mass larger than 5.5% of the total mass are used for the MPA of the shortened chimney. The amount of activated mass for the modes considered is approximately 71%. The lateral loads are reproduced by body forces applied to the FE mesh. The corresponding plots of the total base shear versus the horizontal displacement of one of the nodes located at z = 37.6m are reported in Figure 3a.
In order to estimate the possible damage evolution of the chimney undergoing seismic excitations of increasing intensity, two different ground motion multipliers (GM_{ER}) were used in evaluating the inelastic response spectrum, i.e., GM_{ER} = 1 (open circle data points of Figure 3), and GM_{ER} = 3 (solid circle data points). It can be noted by inspection that, for GM_{ER} = 1, only the target point for mode m1 turns out to be located on the “plastic” branch of the corresponding pushover curve, whereas no damage is to be expected for the other modes. In the present paper also the results obtained by the original 50m high chimney ([6]-[7]) are reported in order to compare its seismic response to that of the shortened chimney. For these simulations, all modes with effective mass larger than 4.5% of the total mass were used for the MPA. In analogy to the case of the shortened chimney, the amount of activated mass for the selected modes is approximately 71%. The corresponding pushover curves referred to the horizontal displacement of one of the nodes located at z = 50m are reported in Figure 3b. The target points for modes M1, M2 and M3 and ground motion multiplier GM_{ER} = 1 are located beyond the elastic branch of the corresponding pushover curves, indicating that these modes may contribute to the damage pattern of the chimney. The lateral displacement profiles obtained for the chimneys, 37.6 m and 50 m tall structures, from the MPA for GM_{ER} = 1 are reported in Figure 3c. These displacements were computed by combining the four target displacements using the Square-Root-of-Sum-of-Squares (SRSS) rule. The maximum lateral displacement attained at the top resulted to be approximately 0.13m for the shortened structure, while for the 50 m tall chimney was reached the value of 0.28 m. It can be remarked that, for the 50 m tall chimney, the total base shear obtained from the combination of the five modal contributions is 554 kN, approximately corresponding to 9.5% of the self weight, while for the shortened structure the total base shear estimated (combining the four modal contributions with the SRSS rule) is 754 kN, approximately corresponding to 14% of the self weight. The damage patterns corresponding to GM_{ER} = 1 are reported in Figure 4a and Figure 4b for the shortened and the original chimney, respectively. Because of the high masonry thickness, the base of the chimneys turns out to be never affected by damages. In the shortened chimney the cracks are triggered only by the fundamental mode (m1) at elevations lying in the range 8–21 m. Conversely, the higher-mode effects play a crucial role for the original chimney. This feature reflects on the final damage map obtained from the combination of the “modal” maps (comb. in Figure 4b). The combination of the modal damage maps for GM_{ER} = 3 are reported in Figure 4c and Figure 4d for the shortened and the original chimney, respectively. In this case, with the exception of the top 5 meters, the stack of the 37.6m-high chimney turns out to be damaged, because of the contributions of modes m2, m3 and m5. More and more evident are the higher-mode effects for the original chimney, where cracks form up to z = 46 m.



m1 comb comb. comb.

GM_{ER} = 1 GM_{ER} = 3

a b c d

Figure 4. MPA damage patterns for the shortened chimney, with target displacements corresponding to ER ground motion multiplier equal to (a-b) 1, and (c-d) 3.

4 NONLINEAR RESPONSE HISTORY ANALYSIS (RHA)

In this section, a series of nonlinear dynamic analyses (RHA) are compared in order to have an insight into the behavior of the structures under different input accelerograms. To perform the numerical analyses, real registrations available in internet databases, are used. Four ground motions are considered, namely Christchurch (CH), Irpinia (IR), Niigata (NI), and Emilia Romagna (ER). It is worth mentioning that ER is the accelerogram registered in Mirandola –i.e. very near the epicenter- during the first shock (20th May 2012). Both horizontal and vertical components of acceleration are considered in the simulations, after proper scaling, to obtain compatibility with horizontal and vertical elastic response spectra. The horizontal component of the ground motion used during the analyses is the east-west one. The horizontal displacements obtained by the dynamic analyses of one node located at the top of the chimney are depicted in Figure 5, both for the 37.6 m and 50 m tall chimney.

As expected, the residual displacement found for the 50 m tall chimney is generally higher. To evaluate the diffusion of damages over the chimney and to compare the seismic behavior of the structures in the previous and in the current form, a series of damage patches depicted at different time steps are shown in Figure 6 for the 50 m (NI ground motion) and in Figure 7 for the 37.6 m tall structure (ER ground motion), respectively.

The damage patches at the end of simulations confirm that damages over the 50 m tall structure is much more concentrated on the upper part, where diagonal cracks were in-situ observed.

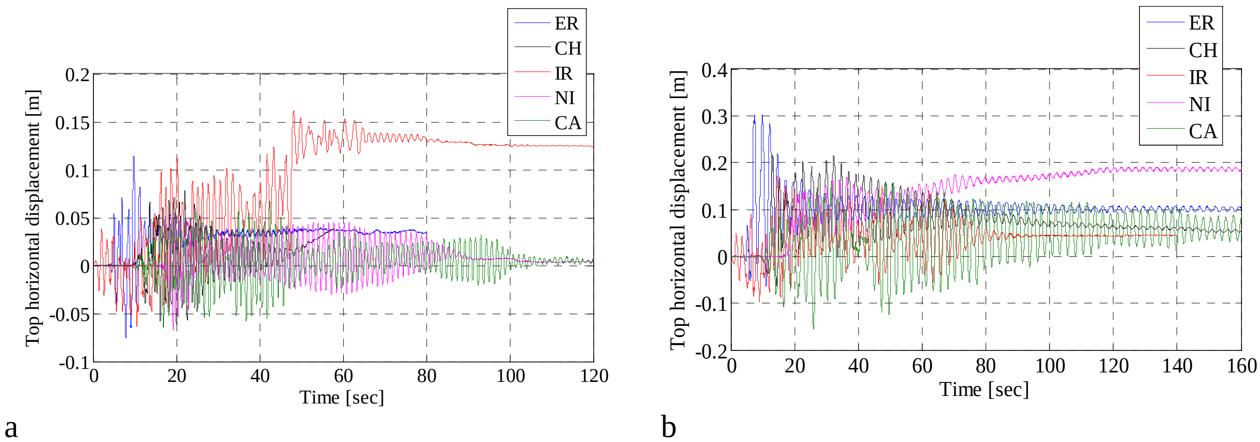


Figure 5. Top displacement time histories for (a) the shortened and (b) the original chimney (CA indicates a further accelerogram registered during the 2012 seismic sequence in Casaglia, a town not far from the cimney).

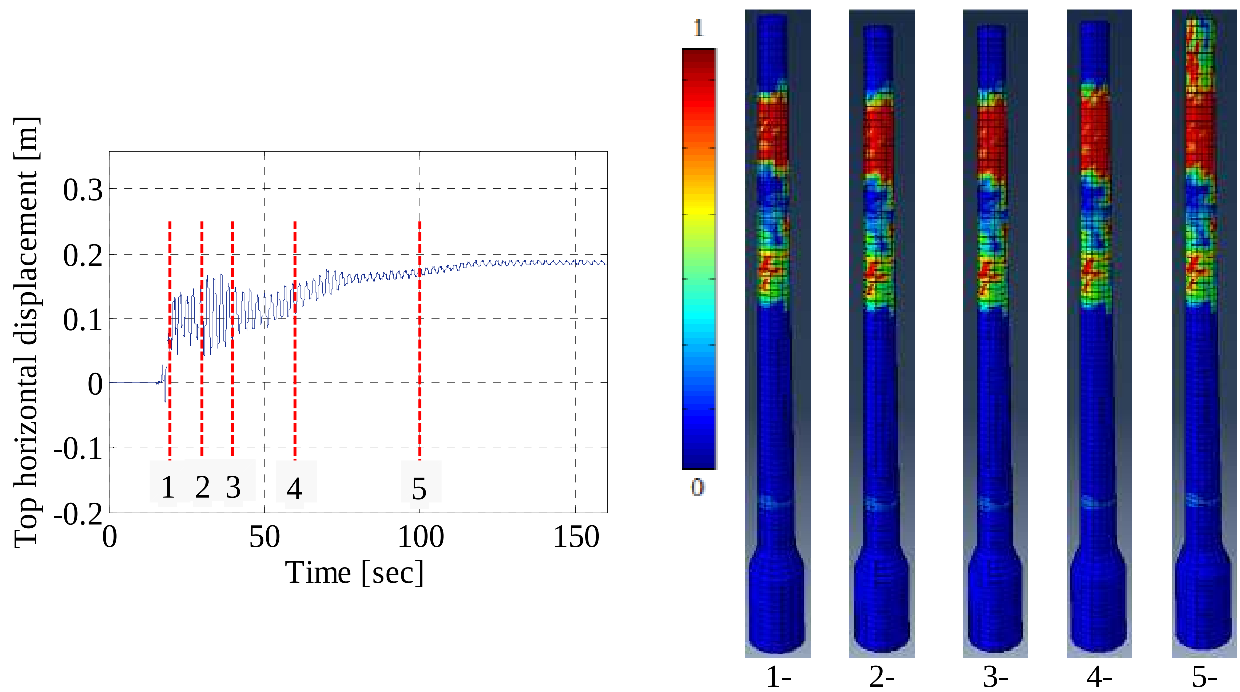


Figure 6.Damage map in tension at different time steps - NI ground motion.

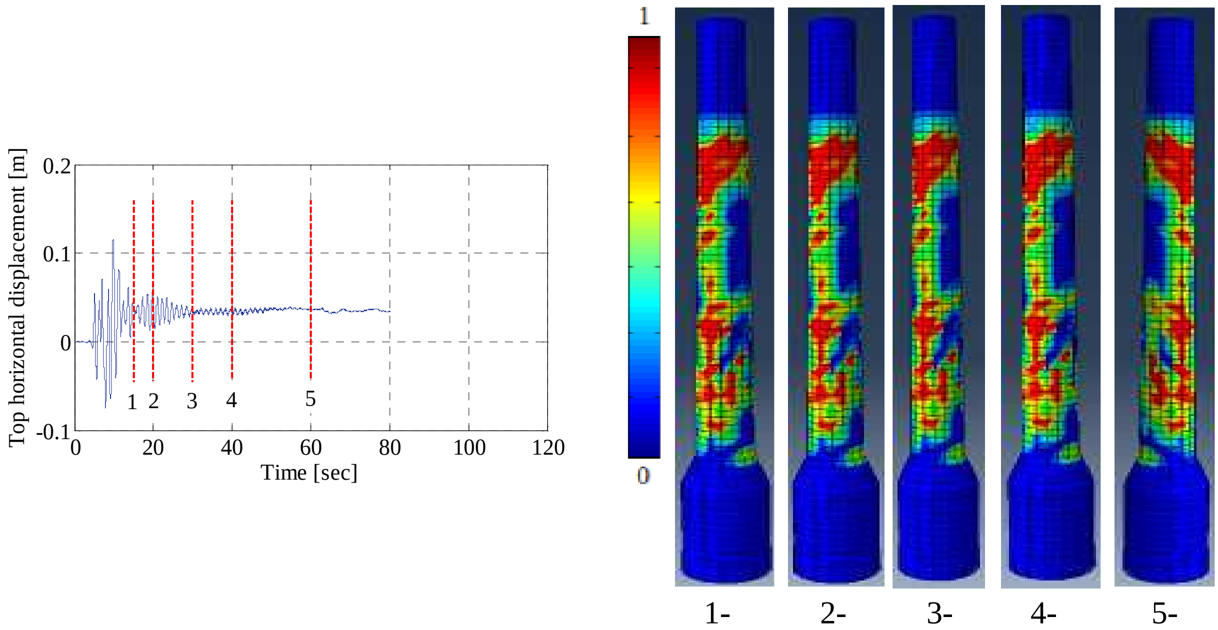


Figure 7.Damage map in tension at different time steps - ER ground motion.

In all the other simulations, depending on the type of accelerogram used, the damage tends to widespread along the entire height of the structure, but mostly affecting the last 10 meters. In the case of the 37.6 m tall chimney, the results seem to suggest again that the more susceptible part to seismic damage coincides with the medium/upper zone of the structure, but a clear trend is visible, with damage in tension spreading over a larger zone from the top to the bottom. The comparison between the horizontal top displacement of the original and of the shortened chimney, confirmed also by the two series of damage patches, suggested that the general seismic behavior of the chimney seems to slightly improve after shortening, even if the conclusion on this issue is contrasted.

5 CONCLUSIONS

In the present paper, the results obtained by a series of nonlinear analyses on a masonry chimney before and after shortening are discussed. The masonry chimney, object of the present study, evidenced severe damages after the Emilia's earthquake occurred on May 29, 2012. At the end of the survey campaign, conducted with the aim of detecting possible damages occurred after the main shock such as cracks or mortar deterioration, it was decided to shorten the structure at the height of 37.6 m, to permit a rapid re-opening of the area. The simulations performed concerned two geometric models, the original 50 m tall chimney and the 37.6 m one. Modal Pushover Analyses (MPA) and Response History Analyses (RHA) were performed using the same tridimensional finite element model, involving both the geometries. The results obtained by the 50 m tall structure shown that the chimney was particularly prone to higher mode effects, as expected by authors and confirmed by the damage maps obtained with the MPA and RHA analyses. In general a good agreement was found between MPA and RHA results. Comparing the results obtained by the MPA and RHA analyses, it was found that the new shortened structure, whose seismic behavior is the objective of the analyses presented, exhibits a slightly different seismic behavior. In general, it can be underlined that the shortening of the original structure produces a global small improvement of the seismic behavior of the chimney. This is proved by the results obtained with the MPA analyses, which showed a lateral displacement equal to 0.13 m, instead of 0.28 m reached with the previous geometry. Damage maps obtained by means of the RHA analyses indicate that also the upper part of structure suffered of severe damages while MPA results suggested that damages mostly affect the lower part of the stack. The differences detected in the two type of simulations performed are probably connected to the vertical component of the ground motion that was not possible to consider into the MPA analyses.

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