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THE SEISMIC VULNERABILITY OF TOWERS' BRICK MASONRY SPIRES: LEARNING FROM HISTORY

Daniele Ferretti [1] and Eva Coïsson[2]

[1] DICATeA, Università degli Studi di Parma,
Parco Area delle Scienze 181/A, 43124 Parma, Italy
e-mail: daniele.ferretti@unipr.it

[2] DICATeA, Università degli Studi di Parma,
Parco Area delle Scienze 181/A, 43124 Parma, Italy
eva.coisson@unipr.it

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Abstract. *The May 2012 Emilia earthquake has once again underlined the high vulnerability of the spires that often complete masonry towers and belfries. These daring structures, which are typical of the Lombard architecture, but later spread throughout Italy, can have the shape of a circular or polygonal cone and are usually made of clay brick masonry, sometimes topped by a stone decorative element. Indeed, this building feature was once even more widespread, as many cases were found of towers whose spire was damaged by an earthquake and that was then restored or rebuilt with a different – more stable – shape. Starting from the observation of numerous real cases, both in recent and historical earthquakes, some considerations are made on the type of collapse and on the shape and position of the damaged area. The recurrent types of seismic damage, consisting in the overturning or shear sliding of the top of the cone, are then analyzed with finite element models. One interesting observation that was made during the on site inspections refers to a very particular strengthening solution found in the bell tower of the Parma Cathedral, adopted as a paradigmatic example: a large timber log was hung to the top of the spire, anchoring the angel-shaped weather vane. Its weight contributes to the stability of the top part of the spire increasing both the shear strength and the overturning stability. Also this technical solution has been modelled in order to verify its contribution to the stability of the structure and to propose a possible up-to-date version for the reconstruction or strengthening of the recently damaged spires.*

1 INTRODUCTION

The landscape of many cities and towns, particularly in Italy, is dotted with hundreds of bell-towers, many of which are covered with a characteristic conical or pyramidal element: the spire. These daring masonry elements, usually made with specifically designed solid clay bricks arranged radially, had a vast diffusion in the Romanesque era, particularly in the Po plane with the spread of the Lombard architecture, but masonry spires continued to be built also in the succeeding centuries, up to the late XIX century, and in other areas.

Considering the very low tensile strength of the masonry, the spires end up thrusting on the supporting structures, as vertical cracks develop dividing the cone or pyramid in separate, inclined radial elements. Therefore, often strengthening elements have been inserted – since the beginning or added during centuries – particularly focused on the possible opening of the separate "slices". Some examples are the Ghirlandina tower, in Modena, which presents three levels of radial iron tie rods, and the bell tower of the Caorle Cathedral, which has iron rings in the lower part (fig. 1).

The recent earthquake of May 2012 in the Emilia area highlighted the extreme vulnerability of these elements to the horizontal actions but, opposite to what could be a first thought, the vulnerability does not concern the further increase of the vertical cracks and the separation of the slices, but the loss of the top part of the spire, either for overturning or for shear collapse. Nearly all the masonry spires in the epicentral area showed this type of collapse, sometimes limited to the top stone decorative element, sometimes including a part of the brick masonry cone (fig. 2). There were reports of similar damages in other areas, with different earthquakes, like Friuli and Calabria, with different distances from the epicenter (fig. 2).

Figure 1: Traditional strengthening techniques for masonry spires: radial tie rods in the Ghirlandina tower in Modena (left), iron rings in the Caorle Cathedral (right).

Figure 2: Some examples of seismic collapses of spires in different areas and at different levels. From top left, clockwise: Madonna dell'Alica di Pietrapennata (Calabria), Campobasso (Molise), Cordenons (Friuli - photo by Gigi Cozzarin), Sant'Agostino (Emilia), with the detail of the collapsed top element.

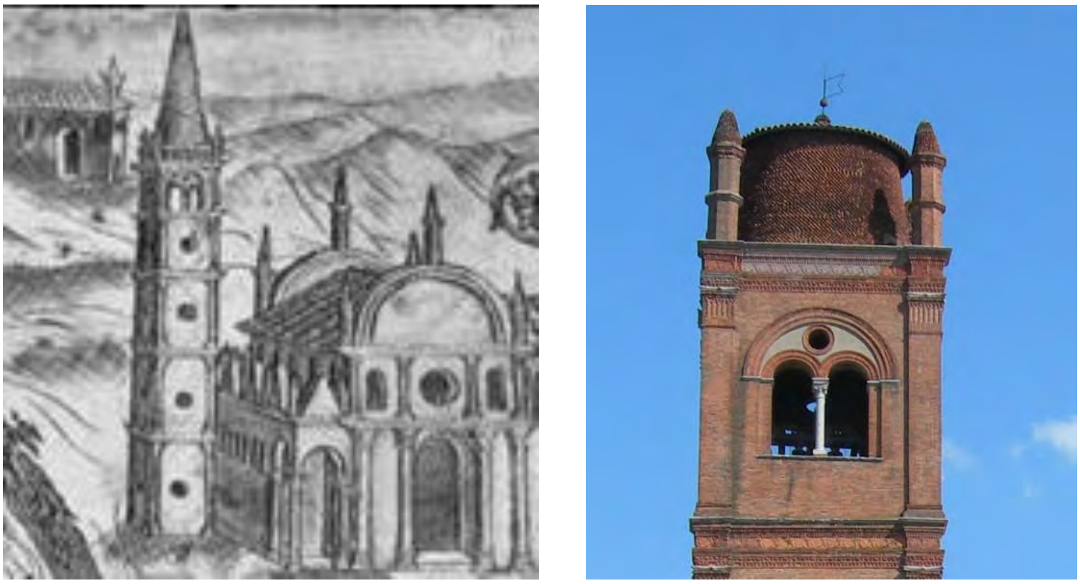


Figure 3: Other spires damaged by earthquakes during history: San Giorgio fuori le mura in Ferrara (on the left a drawing of its original shape) lost its spire in the 1570 earthquake and was then covered by a circular roof.

2 THE SEISMIC BEHAVIOUR: SCHEMES AND MODELS

The damage mechanism of the top of the spires is not at all a new discovery, although specific studies are very limited.

The Italian technical law for the protection of cultural heritage from the seismic risk [1] indicates, among the 28 possible damage mechanisms to the macro-elements of churches and bell-towers, the possible rotation or shear damage to protruding elements. In particular, the drawing n. 26, which illustrates the bell-towers' spires expected mechanism (fig. 4a), shows an inclined crack, relatable either to an overturning mechanism or to a diagonal shear damage. The indicated stabilizing elements are the good quality of masonry, the limited dimensions, and the presence of anchor bolts or other connections, while the vulnerability is increased in particularly slender elements. These indications have the merit of focusing the attention of practitioners to this often neglected element, but the experimental evidence of some Italian earthquakes, shown only in part in figure 2, highlights one major difference in the damage mechanism: the tilt angle of the collapse plane is always horizontal or semi-horizontal rather than inclined, as indicated in Fig. 4a. Moreover, in many cases, only the top stone element collapsed, detaching from the brick masonry.

Some scientific studies have also been carried out on stone masonry spires, reporting both analytical and experimental modeling [2,3]. The uplift, rocking and collapse of stone spires is investigated, considering varying diagonal crack height below a solid tip (fig. 4b,c). Of course the results can vary with the geometry of the real element (fig. 4d), but in most cases, the horizontal crack is not related to the most probable collapse mechanism. This difference from the real cases shown in figure 2 can also be related to the different building techniques: the clay bricks have usually a smaller height to width ratio, compared to the stone blocks, thus can hinder the diagonal propagation of cracks along the joints in favor of a horizontal shear failure.

The existing studies seem to indicate collapse mechanisms which are not completely adherent with the real collapse cases previously analyzed, at least for brick masonry spires: the experimental evidence indeed shows horizontal cracks which are compatible with shear failure (as clearly happened in the Cordenons case shown in figure 2) or with an overturning with horizontal failure plane. To inspect further these possible mechanisms, compatibly with the experimental evidence, some numerical analyses on models of a brick masonry Italian spire have been carried out.

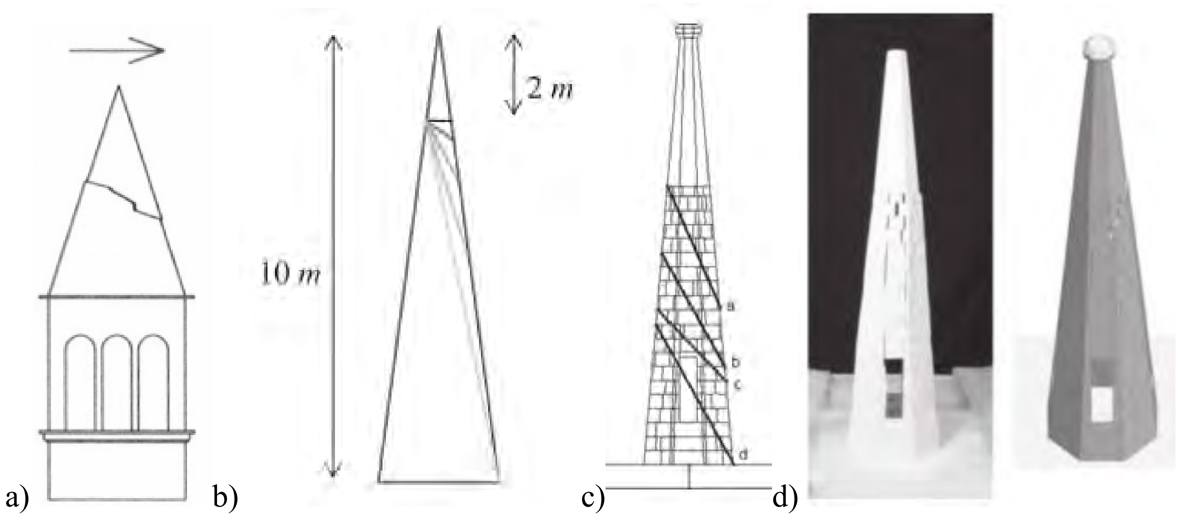


Figure 4: The damage mechanism indicated in the Italian law for the protection of cultural heritage from the seismic risk (a [1]) and the mechanisms analyzed by De Jong and others (b [2], c [3], d [3]).

3 NUMERICAL MODELING OF AN EMILIAN SPIRE

3.1 The case study

To inspect the selected aspects of the seismic response of brick masonry spires, the bell-tower of the Parma Cathedral was chosen as a case study. The bell tower was built between 1284 and 1294, close to the south corner of the cathedral’s façade, with an approximately square cross-section up to 58 m and topped by a 15 m high conical spire. The square part is made of a 1.62 m thick three leaf masonry, with a regular brick masonry cladding and a less organized infill. To increase the waterproofing, the spire was covered in 1596 by lead sheets over a wooden structure, which caught fire in October 2009 when hit by a lightning. Despite the damages, this event allowed to unveil the structure of the spire, which had been hidden for centuries. The spire is made with petal shaped clay bricks made on purpose and externally glazed, organized radially as shown in figure 5, connected by a good quality lime mortar. A stone element with the shape of a cone topped by a sphere constitutes the point of the spire and sustains a golden angel-shaped weather vane.

This case study was chosen not only because of the amount of information and researches which were gathered consequently to the lightening and following restoration, but mainly because of the presence of a very particular element: the weather vane is indeed stabilized by the presence of a long timber log, connected by an iron chain and hanging inside the spire. Although this element had been clearly inserted with the aim to keep the angel vertical even in case of strong winds, its weight can also play a role in the seismic behavior of the top of the spire, increasing the shear strength and the stabilizing bending moment against the possible overturning in this area characterized by low vertical stresses. Indeed, since its construction, this bell-tower has been subjected to many earthquakes, five of which hit Parma with an estimated intensity of 7 or more on the Mercalli scale (very strong to destructive) and there were no reports of damages to the top of the spire [5].

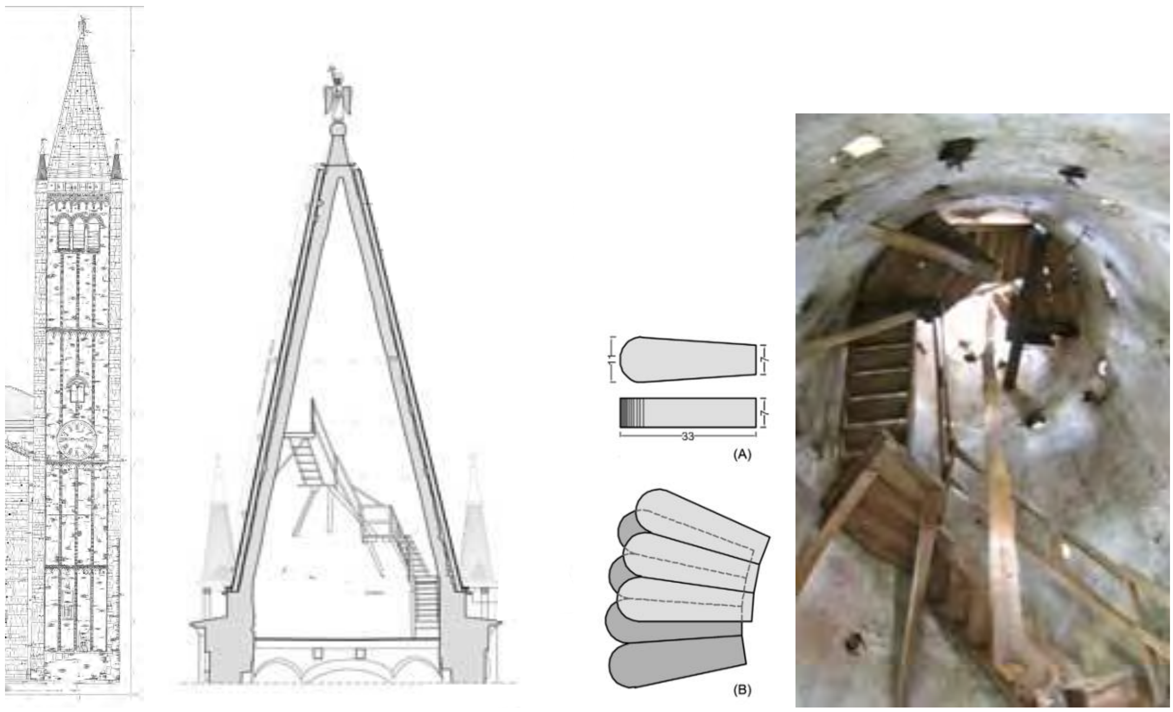


Figure 5: The Parma Cathedral’s bell tower. From left to right: front view, vertical section of the spire, geometry and texture of the bricks ([4]), timber log inside the spire (during the restoration works).

In order to identify the seismic behavior of the chosen case study, four different 3D numerical models were analyzed by means of implicit direct integration of motion equations:

1) A global linear-elastic model of the whole bell-tower, in order to assess the filter effect and thus the seismic actions expected at the base of the spire.
2) A non-linear model of the spire to localize the damaged zone.
3) A linear elastic model with discrete crack in the previously identified damaged zone in order to model the failure mechanism of the spire.
4) A linear elastic model with discrete crack at the interface between masonry spire and stone top element, in order to compare the results with and without the timber log.

3.2 Seismic input

The seismic input applied at the base of the tower was the second main shock of the Emilia earthquake (M_W=6, M_L=5.8), measured at the Mirandola station (code MRN) at 07:00:03 GMT of May 29, 2012 [6]. The depth of the hypocenter was 10.2 km and the epicentral distance was 4.1 km. This earthquake was chosen because it has the features of the expected earthquakes in the Po plane, characterized by an alluvial soil (classified C or D according to EC8), by active faults between 5 and 10 km deep and by a densely built environment which makes very probable the occurrence of near fault effects.

The filter effect produced by the bell-tower was reproduced by means of a 3D finite element linear elastic model with 10 nodes quadratic tetrahedron elements (C3D10), using the program Abaqus 6.12 [7]. As previously described, the main shaft is composed of a three leaf masonry. As no specific mechanical parameters were available, the adopted values were taken from the tests made on the ruins of the Civic Tower of Pavia, which had similar building characteristics [8,9]: E=1500 MPa, ν=0.15 γ= 18 kN/m^3. The soil-structure interaction was not taken into consideration even if it has been proven that it might have a significant effect [10]. The damping is considered as a viscous damping **C**, depending on the mass **M** and stiffness **K** by means of the Rayleigh formulation $\mathbf{C} = a\mathbf{M} + b\mathbf{K}$, where a is the mass proportional damping constant and b is the stiffness proportional damping constant. The values of these two parameters were taken from literature, in similar cases of experimental measures of damping derived from the environment vibration tests [11]: a = 0.2 and b = 0.0006.

First, a modal analysis was carried out and allowed to calculate the values of the natural frequencies: f_1=0.469 s^{-1}, f_2=0.474 s^{-1}, f_3=2.365 s^{-1}, f_4=2.374 s^{-1}, f_5=2.577 s^{-1}. The last frequency corresponds to the torsional mode.

An implicit dynamic analysis was then developed, integrating the motion equations, adopting as a seismic input at the tower's base the Mirandola earthquake previously described. The output at the base of the spire was then recorded, in the form of the three components of both acceleration and displacements (fig. 6).

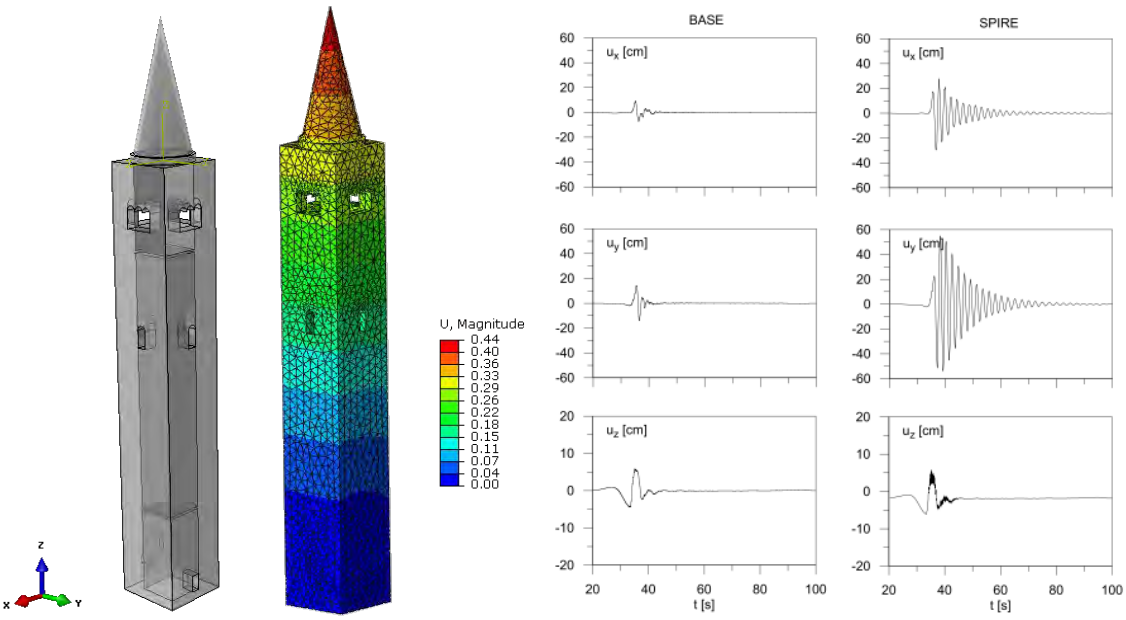


Figure 6: Global model (left, with displacements) to identify the filter effect (right: comparison between input at the base of the tower and output at the base of the spire in terms of displacements).

3.3 Damage mechanism identification

Considering the discrepancies between the existing models and the real collapse mechanisms observed, a specific analysis was dedicated to the identification of the position and inclination of the damage plane. With this aim, a 3D finite element model of the spire was made in Abaqus with tetraedron elements C3D10 and "concrete damage plasticity" material model [7]. The parameters were referred to literature, for a good quality masonry made of solid clay bricks and lime mortar, considering that these slender and daring elements were usually built with particular care. The adopted values were: f_c= 8.0 MPa, f_{ct}=0.4, MPa, G_F=10 N/m, E=4000 MPa, Ψ=30°, ε=0.1, f_{b0}/f_{c0}=1.16, K=0.667.

Moreover, a cyclic damage of the cohesive tensile constitutive law was introduced to hinder the closure of the cracks after their first onset.

After a first static analysis, applying only the dead load of the structure, an implicit dynamic analysis was then adopted, applying as an input the accelerograms obtained as output from the previous global analysis.

The results show a widespread damage at the base of the spire and a more concentrated damaged area at about two thirds of the full height, as shown in figure 7.

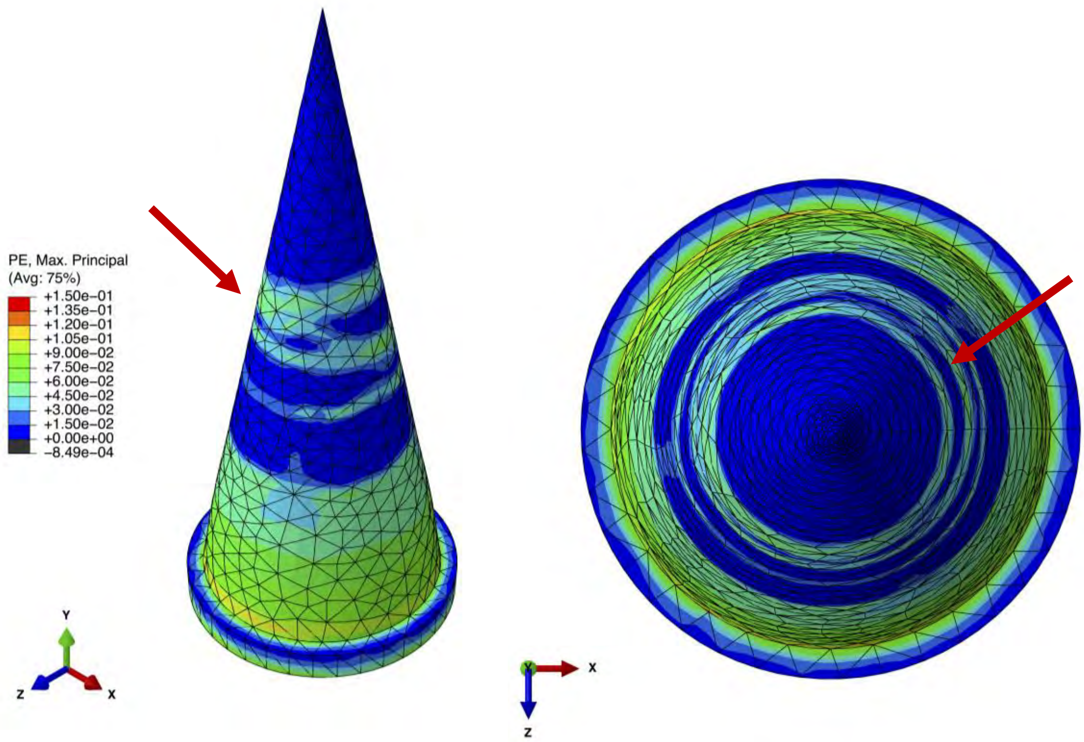


Figure 7: 3 D finite element model of the spire with damage plasticity material model: the shape and position of the damaged areas are clearly identified.

3.4 Seismic behavior modeling

The experimental evidences have highlighted that the possible expected mechanisms are shear or overturning collapses, characterized by large displacements in localized cracks. The damage plasticity model previously adopted, which describes the cracks by means of strains on a continuous material, is not suitable to represent these types of failure. Therefore a new model was adopted, inserting a discrete crack at the position highlighted by the previous analysis, about 4 m from the top of the spire. The material composing the spire was considered linear elastic, as the non-linearity was concentrated in the crack, modeled with contact elements.

In order to focus on the failure mode, considering that cracks will develop since the first motion phases, both the cohesion and the tensile strength were neglected, while the friction coefficient was adopted equal to 0.4.

The results show clearly a translation of the top of the spire caused by a shear failure. When the center of pressure then moves close to the border, thus decreasing the contact surface, first rocking and then overturning take place and at last the top falls down (fig. 8a).

The analysis was then repeated without the vertical component of the seismic action, thus simulating the effects of an earthquake to a larger distance from the epicenter, with respect to the examined Mirandola earthquake but equal pga. In this case, the continuous presence of the vertical loads increases the friction forces and, although the mechanism is similar to the previous case, the sliding is smaller (fig. 8b), the top of the spire does not fall and no rocking or overturning phenomena occur.

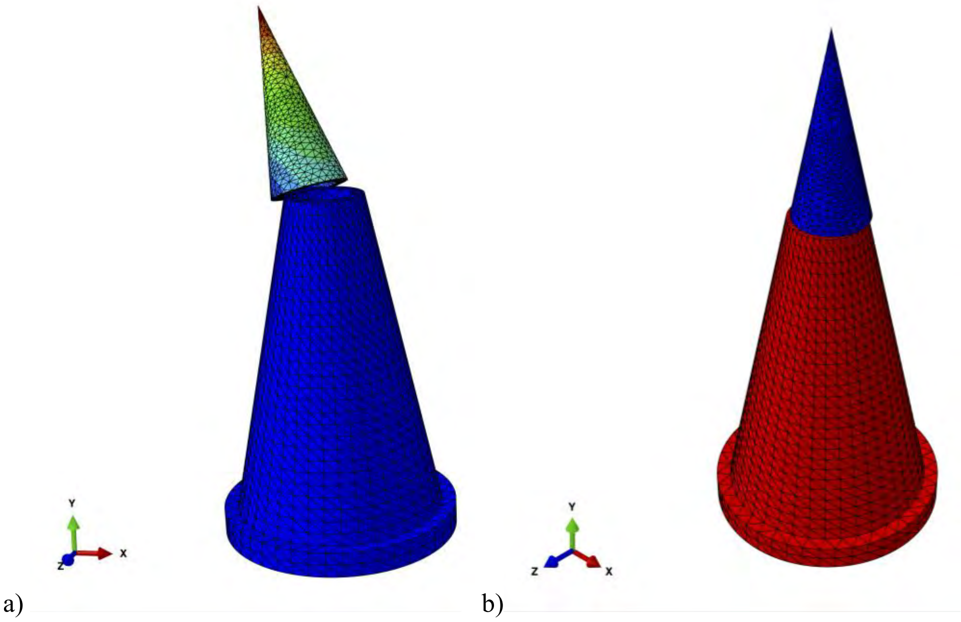


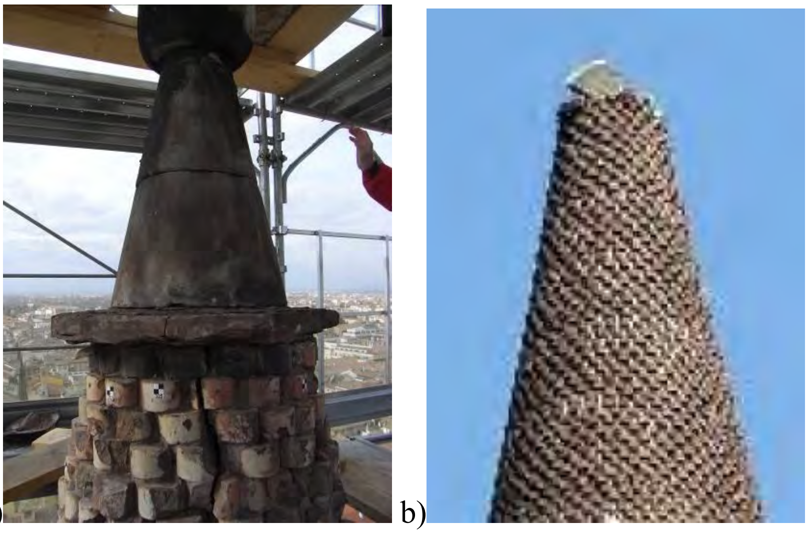
Figure 8: Comparison between discrete crack models with (a) and without (b) vertical accelerations: in both cases the top of the spire shows shear damage, but only when vertical accelerations are considered the collapse occurs.

3.5 The effects of the timber log

As previously described, the analyzed Parma bell-tower presents a peculiar characteristic: a timber log suspended with an iron chain to the top of the spire. The log behaves like a pendulum and thanks to the chain it does not transfer any appreciable horizontal action or bending moment to its support. The log also transfers its weight on the spire, thus increasing its shear strength. Moreover, in the described case of near fault effects with high vertical accelerations, the effects of the log are even more valuable as when the negative acceleration tends to decompress the masonry, the vertical action of the log on the spire is higher than the bare gravitational load.

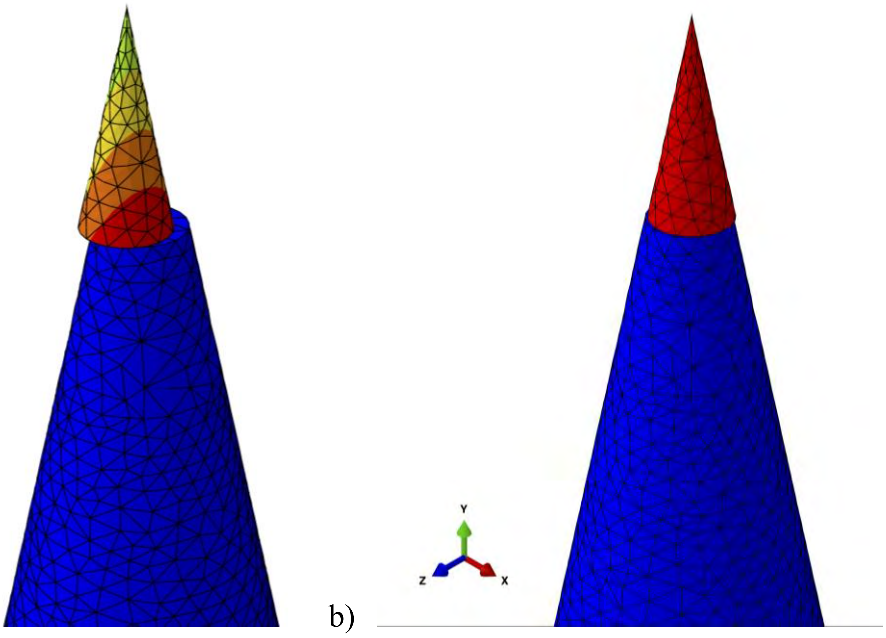
On the block identified in the previous section (4 m high) the effects of the timber log are expected to be negligible, since its weight is very small compared to the block's weight. Nevertheless, its effect can be much more interesting if we consider the possible collapse of the stone element at the top of the examined spire (fig. 9a), whose weight is comparable to the log's one. This type of collapse has also been observed in several cases in the Emilia earthquake (fig. 9b). Thus, the previous model has been modified, moving the contact elements from the area within the spire to the interface between the brick masonry spire and the stone top. The results of this analysis is reported in fig. 10a, showing the sliding of the top stone element. The analysis was then repeated introducing the presence of the log. In both cases the collapse is reached, given the high intensity of the considered earthquake, but the results reported in fig. 10b for the same time step show the stabilizing effects of the timber log, which delays the shear failure. More analyses will be made to define the exact increase of the safety index (in terms of pga ratio) which is given by the presence of the log.

These first results however suggest the possible introduction of an up-to-date version of this historical (unforeseen) stabilizing element for the reconstruction or strengthening of the recently damaged spires.



a) b)

Figure 9: The stone element at the top of the analyzed spire of the Parma Cathedral's bell-tower (a) and the collapse of a similar element on the bell-tower of San Benedetto Po (Mantova) after the Emilia earthquake (b).



a) b)

Figure 10: The deformed shape of the spire without the timber log (a) and with the log (b), at the same time step.

4 CONCLUSIONS

The recent seismic event in the Emilia region has underlined the high vulnerability to earthquakes of the typical brick masonry spires on top of the bell-towers. The damage mechanism is generally connected to a horizontal or semi-horizontal failure plane. The existing methods for the analysis of masonry spires usually consider inclined failure planes which are not compatible with the real observation.

Numerical dynamic analyses were then carried out starting from a specific well documented case study (the bell-tower of the Parma Cathedral) in order to understand the mechanisms induced by earthquakes.

- The observed damage mechanism was a shear sliding failure at about 2/3 of the height of the spire, in agreement with a large number of recorded case studies.
- This effect is increased in case of high vertical accelerations (near fault effects) which reduce the vertical stresses in the masonry and consequently its shear strength.
- The timber log hanging from the top of the analyzed spire was proven to have favorable effects against the possible collapse of the stone element topping the spire, which is another widespread mechanism documented in the recent Emilia earthquake.

The analyses, which focus on the advanced phases of failure, were carried out neglecting the cohesion and tensile strength of the masonry. More information on the initial phases of the failure mechanism can be obtained considering appropriate values of these material properties for masonry before cracking.

Furthermore, more general conclusions would require to repeat the analyses with an appropriate number of accelerograms with different characteristics and to take into consideration the soil-structure interactions.

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