Seismic damage of Bell Towers: analysis and safeguards aspects

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Abstract. This paper deals with the damage occurred on bell towers during seismic events, with a special attention to the recent Italian earthquakes.

There are two possibilities of their reconstruction: *where it was* and "apparently" *how it was*, or the construction of a new bell tower in the same place.

Some strengthening, rehabilitation and first aid interventions carried out on the towers after severe damages due to recent earthquake are critically analysed.

Starting with an introduction of the seismic computational verification procedure according to the Italian Code for the bell towers, in the second part of the paper innovative retrofitting techniques made by composite materials are considered.

At the end, two cases of study are analysed: Ghirlandina Tower and San Barnaba Bell Tower, both in Modena.

Introduction

Historical slender masonry towers like bell towers, for their structure, are particularly vulnerable under seismic excitation.

After severe damages, the *reconstruction* process takes place in two different ways: a) reconstruction of the bell tower "apparently" equal to the damaged one: this solution is based on retrofitting strategies without visual impact, or on the improvement of the quality of existing masonry and b) reconstruction of the bell tower by new aesthetic and structural characteristics.

Examples of application of these kinds of reconstruction are respectively the Majano bell tower (UD) and the Gemona tower (UD) collapsed after the Friuli's earthquake (1976) [1,2].

For the bell tower of Gemona (UD), the reconstruction process was made by reinforced concrete with external stones set inside: from the visual point of view the solution is apparently equal to the previous tower but, in the reality, the new one is structurally different.

For the bell tower of Majano (UD), the second solution has been used: a tower with new construction technology (reinforced concrete) and morphology has been rebuilt.Cultural positions against first solution define this one as "false" reconstruction; rivals of second solution say that this kind of reconstruction is the cause of the "cancellation of historical memory". Nevertheless the best way is to rebuild the collapsed structure due to earthquake not *how it was* and *where it was* but aesthetically close to the old one and, at the same time, ensuring an adequate capacity to satisfy the seismic demand of the specific site.

Morphologies and technologies frequent in Italy

Towers have been built using different technologies and morphologies; in such cases due to long construction process, in the same structure different construction types and materials can be found.

In order to simplify the analysis, these kinds of structures here are considered as a single Macro Element that can be: a) isolated bell tower, b) bell tower with lateral connections to other buildings, c) bell tower seated on a church.

The presence of adjacent structures is able to produce some restraint to the tower, modifies the natural frequencies of the structure and then the seismic demand generally increases.

The main typologies of masonry used in tower construction field are: solid masonry, two-leaf masonry and multi-leaf masonry (generally in the bottom part of the tower in order to achieve higher values of thickness).

In Emilia the bell towers were usually made by bricks, while in Friuli and Abruzzo by local stones.

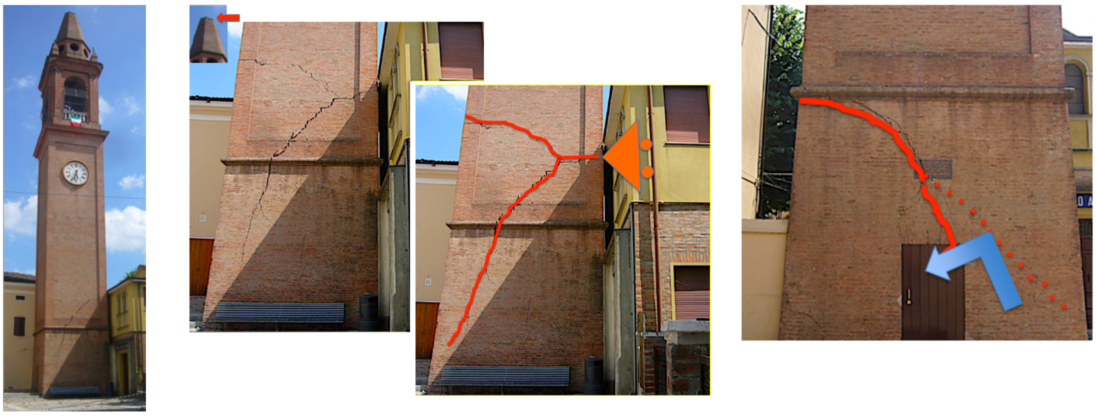
Pre-determined potential seismic failure mechanisms

Many authors e.g. Doglioni et al. (1994) [1] dealt with the definition of pre-determined failure mechanism of towers evidencing some possible critical aspects related to adjacent buildings and to the presence of a bell cell on top. To each mechanism, a specific crack pattern is associated.

Seismic mechanism: Y shaped cracks and diagonal cracks

In some cases we observed the Y shaped crack associated to bell towers connected to other buildings. During the earthquake, the structure shakes in two opposite directions with a consequently formation of two inclined cracks orthogonal to the two tensile directions. The stiffer point of contact between the tower and the building behaves like a hinge and the tower rotates around this point with horizontal axis.

The tower bell of Cavezzo Church (MO) (Fig.1), after Emilia's earthquake occurred on May 29th 2012, has reported both Y shaped (Fig.1.B) and diagonal cracks (Fig.1.C) on the facade orthogonal to the one in contact with the adjacent building, inclined cracks deviated due to the presence of openings [2].



(A) (B) (C)

Figure 1: Tower bell of Cavezzo Church (MO) after earthquake on May 29th 2012

X shaped cracks and dislocation phenomenum due to roto-traslation

The X shaped cracks are typical for isolated tower in which the main failure mechanism is translation of the upper part of the tower with a consequently rotation of itself. In several cases after the formation of the first diagonal crack, the upper part starts rapid sliding so there is no time for the formation of the second inverse diagonal crack and a dislocation in the upper part of the macro crack takes place [1,2].

The isolated tower of Reno Centese, Cento (FE), made by brick masonry, during earthquake in 2012, was under "cosmetic" restoration: an inclined severe crack occurred with successive sliding, and also two dislocations appeared in two directions [2], the tower was prone to collapse.

First aid

One classification based on the structural function of the "first aid" intervention used on the bell towers (Fig.2) after recent earthquake in Italy can be done: A) spur, B) belting, C) cage.

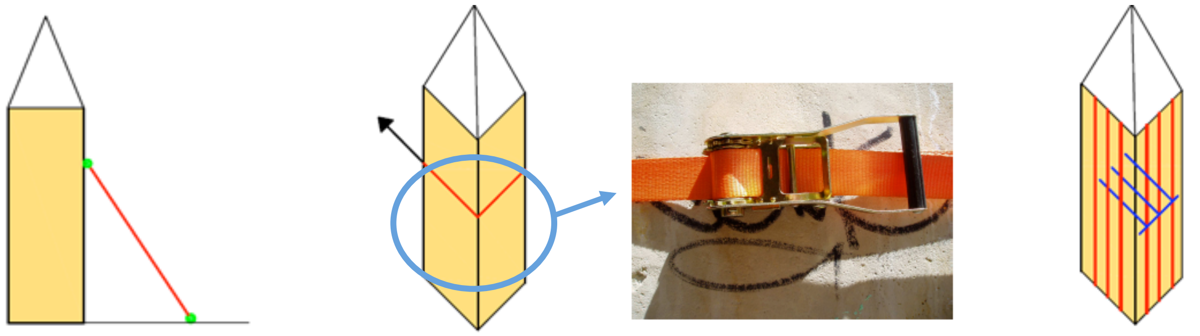

A) Spur B) Belting C) Cage

Figure 2: Schemes of first aid interventions and provisional guard

The *belting* is a tension system closed in on itself made by belts put in tension with specific devices; with this intervention the tower, under dynamic event, maintains a good connection between adjacent walls. Innovative belts are made by polyester strips (PES).
This solution is quick, not expensive and represents one of the innovative interventions after earthquake.
The disadvantage is related to the viscous elongation of synthetic belts that needs periodic control.

Another possibility is represented by the *cage* system made by timber and steel or only steel. In comparison to the latter intervention, in this case a strong dynamic interaction between old and new structure takes place. The disadvantage of this intervention is the difficulty to replace the cage with the final strengthening intervention due to its bigger dimensions.

One example of innovative first aid is represented by the bell tower of Reno Centese (Fig.3) after the Emilia’s earthquake in 2012.

Figure 3: Tower bell of Reno Centese

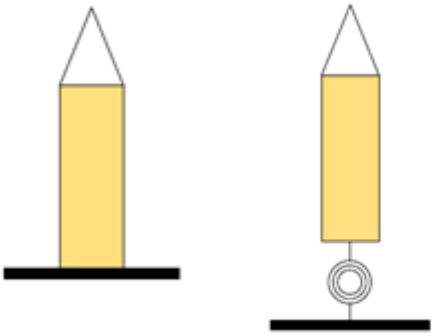


Figure 4: Fixed restraint or rotational spring

The starting point was the use of fibre-reinforced projected cement mortar in order to close cracks and, in addition, to confine the masonry below.
Finally horizontal and vertical strips, made by double layer of glass and carbon fibres, were applied.

Seismic verification and strengthening techniques

In order to perform the computational seismic verification of a tower, according to Italian Codes, it is necessary to take into account soil-structure interaction.

The analysis generally is carried out in both fixed and elastic constraint (rotational spring) at ground level (Fig.4).
In the case of elastic constraint, several studies have been made in order to evaluate the rotational stiffness of the spring (condensed soil stiffness), in particular Gazetas (1991) [7] and Viggiani (1999) [8] proposed respectively for spring stiffness:

$$K_\alpha = \frac{3{,}6 \cdot G \cdot B^3}{(1-\nu)} \quad [\text{kNm}] \quad (1) \qquad\qquad K_\alpha = \frac{E \cdot B^3}{I_\alpha(1-\nu^2)} \quad [\text{kNm}] \quad (2)$$

where: G = shear modulus, E= Young modulus, B = side of the squared foundation, ν = Poisson coefficient, I_α= dimensionless coefficient of influence [8].
Under the basis of minimum and maximum values of E (or G), two values of K_α are obtained and represent the *lower and upper bound of the stiffness,* these values are then multiplied by f_D coefficient that takes into account the depth of the foundation [7].

The first possibility is to compute a dynamic modal analysis to determine seismic forces from the spectrum of the site using the beam theory verification: observing the state of the effective damage after seismic event, the procedure gives unreliable results. Using Macro-element approach, considering masonry infinitely rigid, strong in compression and not in tension, is possible to use limit analysis for partial/total mechanisms that gives reliable results. Different collapse mechanisms are taken into account (also with inclined crack) [5], in order to determine the smallest load multiplier that implies the collapse, allowing a comparison between the capacity and seismic demand. For an in depth inspection, *push-over* analysis can be used: the verification of the bell tower is computed by an incremental horizontal load step until the collapse occurs [3]. This procedure is difficult for non-linear mechanical procedure and also is sensible to the different static "equivalent" load path.
In many cases, the seismic computational verification of this kind of historical structures, made according to the code, result "not satisfied"; improving the ductility of the structure with opportune devices, lower seismic forces (increasing the behaviour reduction factor) can be considered.

The first innovative application in Italy of fibre-reinforced material (**FRP**) as seismic safeguard of ancient towers, was the Torrazzo Gonzaga (2001); A. Di Tommaso, A. D'Ambrisi and P. Foraboschi proposed [4] the lining of composite materials inside the drum in order to contrast collapse mechanisms during seismic event [6]. Also a confinement of the stem was made by using steel bars with high elastic limit.

An evolution of composite materials for historical masonry structures is represented by **FRCM** (Fiber Reinforced Cementitious Matrix), a cementitious matrix modified by polymer and reinforced with carbon fibre. A relevant application is at Noto Cathedral, ruined for collapsing columns.

Bell tower of San Barnaba and Ghirlandina tower in Modena

The b*ell tower of San Barnaba (MO*) is seated on the church. The dynamic analysis, in this case, should introduce many uncertainties, so the limit analysis with collapse mechanisms has been used.
The two main mechanisms are (Fig. 5): A) mechanism 1: rotation towards the outside of the upper part of the bell tower around a hinge placed on the bottom side of standing out trunk, B) mechanism 2: frame mechanism of the bell cell. To give obstacles to the activation of this mechanisms, L stainless steel profiles in the internal corners, and belting composite strips in CFRP (Carbon Fibre Reinforced Polymers) have been applied.

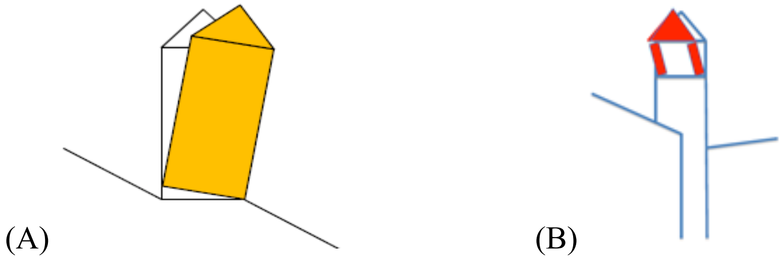
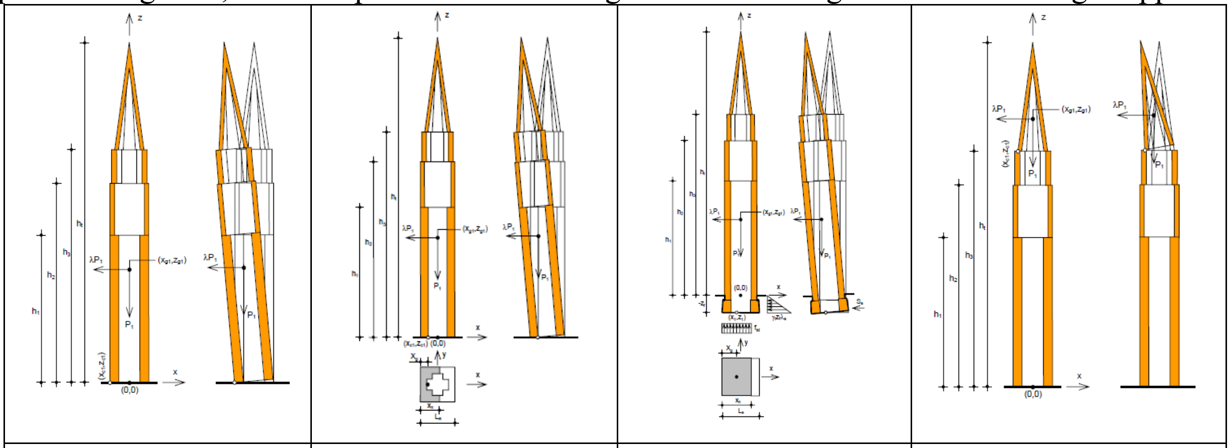

(A) (B)

Figure 5: Collapse mechanisms considered (San Barnaba MO)

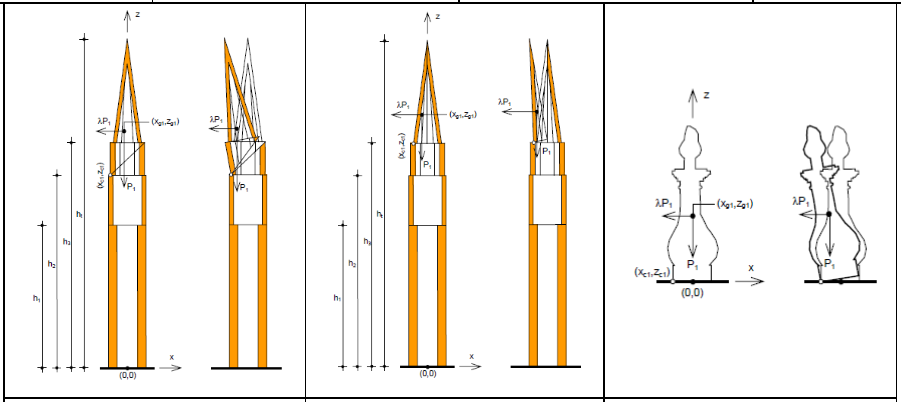
In 2009 A. Di Tommaso was commissioned for a seismic verification of the *Ghirlandina Tower*, in particular: 1) modal dynamic analysis, 2) analysis with collapse mechanisms.

For the *modal analysis*, a FEM model has been used made by beam element and restraint to the soil by rotational spring (condensed soil-structure interaction).

Consequently studies confirmed the reliability of the model [5]. Some conclusions: a) shear verification is satisfied for all sections of the tower, b) the sections above 60 m from the base are not satisfied for axial force and bending moment.Local and global collapse mechanisms are reported in figure 6; the most probable one is the global overturning. Now local belting is applied.



Mechanism 1A	Mechanism 1B	Mechanism 1C	Mechanism 2



Mechanism 3	Mechanism 4	Mechanism 5

Figure 6: Main collapse mechanisms considered for Ghirlandina Tower

Conclusions

The bell towers are structures with strong symbolic image that must be conserved. The conventional procedure of verification gives no safe condition following the codes for new structures. The goal should be to apply techniques for increasing the ductility of these structures.

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