Redesign of Strengthening Interventions on Historical Buildings. The Case Study of an Earthquake-Damaged Bell Tower

Redesign of strengthening interventions on historical buildings. The case study of an earthquake-damaged bell tower.

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Abstract. In the case of degraded building material and developing cracks, steel tie-rods allow for a fast, relatively simple, and very effective strengthening intervention, especially for high rise masonry structures such as medieval bell towers. However, their design has a high impact on the external aesthetic of the structure; thus, they are generally not considered as an acceptable definitive solution. Here, several designs are proposed for the replacement of such a pre-existing reinforcement system with less invasive options. These candidates are then compared considering multiple factors such as the conservation of the architectural design, the uncertainties in terms of geometric and mechanical properties, the nonlinear behaviour of the damaged masonry walls, and the required level of structural safety. The placement of these alternative strengthening interventions along the tower height is also optimised according to the specific crack pattern – reflected in a subdivision of the calibrated Finite Element Model in of macroelements – and the most probable collapse mechanism. Their viability is finally assessed and ranked.

Keywords: Strengthening interventions, Masonry Bell tower, Seismic retrofit, Cultural heritage structures.

1 Introduction

Throughout the years, extreme hazards, such as earthquakes, highlighted the high seismic vulnerability of bell towers. On the one hand, this sheds light on the importance of dynamic monitoring as a tool for preventing earthquakes and of maintenance [1]; on the other hand, its vulnerability could require a proper design of strengthening interventions. Due to their distinguishing structural morphology, bell towers are exposed to several risks. Indeed, high states of tension could occur at the base of the structure, and also the motion of the bells themselves highly affect their vulnerability. This is even worsened by the vibrations occurring within the whole structure, both in case of extreme events, such as earthquakes, and recurrent actions, such as wind.

Moreover, geometric characteristics play a key role in the definition of their vulnerability. Specifically, bell towers are characterised by slenderness, which heavily affects the static scheme. Many slender bell towers can indeed be considered as one-dimensional structures, and, therefore, they present a cantilever behavior. The possible presence of adjacent lower structures, capable of providing a horizontal constraint, can profoundly modify the behavior of the structure, limiting its effective slenderness, and simultaneously constituting localised stiffening and points of possible concentration of efforts. Eventually, some architectural elements, such as bell cells and spiers, characterized by large openings, can represent a weakness, because they may cause a shear failure of the structure due to sliding. [2, 3].

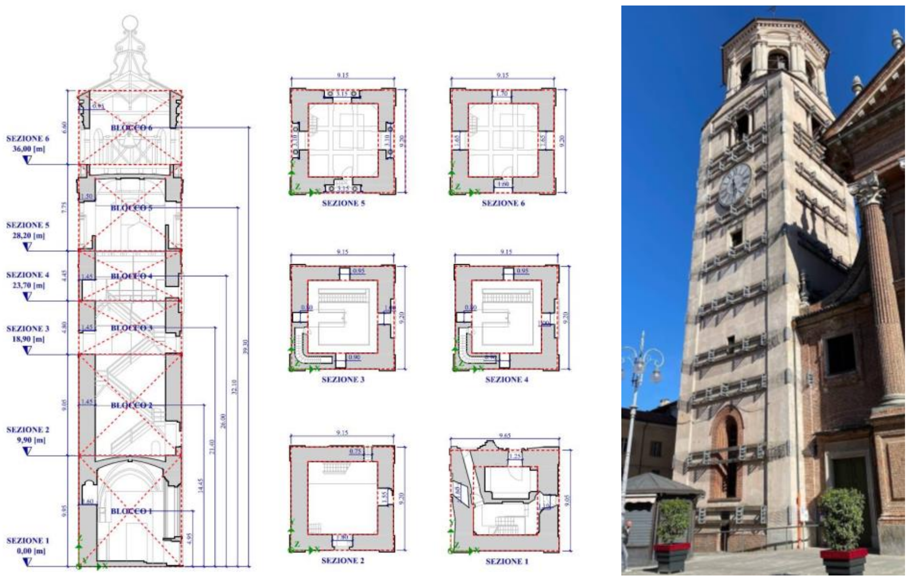
In the light of these considerations, the need to ensure their safety and safeguard has inspired several and even more sophisticated refurbishment techniques and adaptation interventions. However, often consolidation techniques and strengthening interventions conflict with the criterions of minimum intervention and safeguard of the historical architectural asset, which is mainly based on the concepts of reversibility, non-invasiveness, durability, verifiability, and maintainability. This mainly leads to the critical issue of designing an intervention that ensures the safety of the structure itself and at the same time completely fulfils the minimum intervention criterion. Some examples already exist in the scientific literature on the application of non-invasive techniques for the restoration of masonry tower, such as: (i) the application of FRP tapes in the case of Santa Lucia's church, located in Ancona [4–6], the Monza cathedral bell-tower [7], or the Lossetti Tower in Beura-Cardezza [8]; (ii) the injections of consolidating mortar in the case of the façade of the church of S. Pietro Celestino in Isernia, the cracked areas of the bell tower of the church of S. Maria del Parco in Boiano, and in the dome of the church of S. Francesco in Agnone [9].

The present research work aims to study the effectiveness of some candidate interventions on bell towers, considering the interesting case study of the bell tower of the San Giovenale cathedral, located in Fossano (CN), where a temporary, very invasive reinforcement system is currently installed. The case study is presented in Section 2, recalling the history of the structure itself and the various interventions which have been performed throughout the years. Consequently, the study on the effectiveness of interventions, and in particular the application of fibres and grout injections, has been carried out in Section 3, by means of a Finite Element Model (FEM), with as main result the dynamic properties of the structure and the pushover curves in the several cases. The results are then discussed in Section 4, assessing and ranking the viability of the interventions in the various cases. Finally, conclusions are drawn in Section 5.

2 The case study of Fossano Bell Tower

The case study of the present work is represented by the bell tower of the San Giovenale cathedral, located in Fossano (CN). The church was built in 1771 by the architect Quarini, while the bell tower was designed later and presents a different architecture. The bell tower (see Fig. 1a) has a squared plan up to 35 meters from the base with a medium thickness of the walls of 1.5 meters. The belfry has on octagonal plan with a medium thickness of the walls of 0.5 meters and rises up to 46 meters, corresponding to the top of the wooden roof. The structure has three typologies of slab: the first one, placed at 9.9 meters, is made of masonry, the second one, placed at 28.2 meters, is made of wood, and the third one, placed at 35 meters, has a mixed masonry-wood stratigraphy (see Fig. 1a). The criticality of this case study resides in the quite poor condition of its building materials.

The structure is a well-known case study, subject of several research works over the years [10, 11]. It presents a crack pattern that shows a widespread presence of vertical cracks, clearly visible in the masonry parts. However, these cracks are hidden on the exterior of the walls, since they are completely concealed by the plaster, detached in some points. The resulting crack pattern is mainly due to the earthquake which occurred in 1887, followed by a consolidation intervention, which resulted to be particularly effective. This intervention consisted in filling the internal staircase up to the belfry by using masonry with good consistence. Furthermore, the bell tower was enhanced by steel rings with a diameter of 60 mm, placed on its internal masonry walls, with the aim of contrasting the widening of the present cracks and thus improving the overall behaviour, especially considering possible future horizontal actions (such as earthquakes). This intervention also helped the increasing vibrations due to the vehicular traffic. The most recent intervention goes back to 2012, following a future development of vertical cracks on the facings of the bell tower, with a temporary intervention composed by rings with 11 steel ties, placed both on the external and on the internal part of the structure (see Fig. 1b).



(a) (b)

Fig. 1. Bell tower of S. Giovenale Cathedral: (a) schematization of the bell tower and (b) representation of the temporary intervention.

3 Study on the effectiveness of the strengthening interventions

3.1 Description of the interventions

According to the above-mentioned criteria of reversibility, noninvasiveness, durability, verifiability, and maintainability, three possible interventions were hypothesized for the Fossano bell tower: (i) application of Fiber Reinforced Polymers (FRP) tapes, (ii) injections of consolidating mortar, and (iii) a combination of these two interventions.

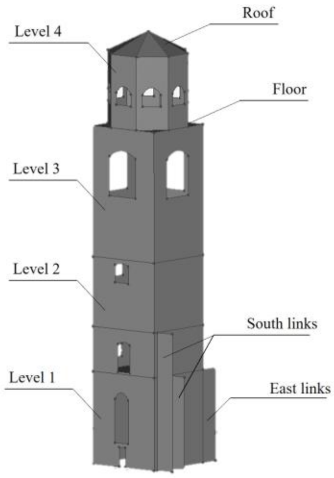
FRP tapes. The use of FRP tapes has been widely exploited as a strengthening solution for masonry buildings. Indeed, the polymeric matrix reinforced with continuous fibres allows to transfer their high mechanical properties to masonry, unable to endure significant tensile stresses [6]. Among the well-known properties of FRPs, they are lightweight, with high resistance to chemical agents and corrosion, high fatigue resistance, reliability and durability over time, low thickness, adaptability to surfaces of different shapes, and easy applicability to complex structural shapes, low invasiveness, and reversibility. Moreover, they proved to be effective in the case of earthquake-damaged structures, such as the present case study.

Injections of consolidating mortar. The consolidation of the masonry by injection is probably the most used technique in strengthening interventions, due to the high percentages of internal voids. This type of technique is called "passive", since it does not require the execution of operations that alter the balance or the external appearance of the structure. However, it requires the existence of voids that allow the binding mixtures to enter the masonry, which have the purpose of improving the mechanical performance of the wall, eliminating cracks and cavities, thus strengthening the bonds between the components of the masonry itself. It was especially used in buildings of considerable artistic and architectural value, where it was desired to keep the structure as faithful as possible to its original appearance [9]. Moreover, this consolidation is supposed to be effective since the structure mainly presents vertical cracks. However, injections may take several months to reach complete consolidation.

Combination of the two interventions. The two interventions described above could be complementary, especially when a preliminary restoration of the compactness and the hardness of the masonry is needed prior to the application of other techniques. Therefore, their combination is possible due to the non-mutually exclusive nature of the individual interventions: if on the one hand the grout injections require a consolidation time to be effective, on the other hand, the application of the FRP tapes immediately produce a beneficial effect on the strength and confinement of the masonry. This combination may enable to obtain high-performance of the material also in the case of highly damaged masonry.

Modelling of the interventions. The effectiveness of the chosen strengthening interventions was assessed by means of a FEM. In particular, the bell tower of Fossano was modelled considering both the masonry structure and the FRP tapes as regular curved shell elements [12, 13].

As a main hypothesis, the compressive behaviour of the masonry was modelled by using the Drucker-Prager constitutive law, while the tensile one was based on a multidirectional fixed crack model. A Poisson's ratio of 0.3 was assigned to all the macro elements of the bell tower, while the values of the Young's modulus and of the density are reported in Fig. 2.



Element	ρ [kN/m³]	E [MPa]
Level 1	20	$2.69\cdot10^3$
Level 2	20	$1.32\cdot10^3$
Level 3	20	$1.25\cdot10^3$
Level 4	20	$2.47\cdot10^3$
East link	20	$5.00\cdot10^2$
South link	20	$5.00\cdot10^2$
Floor	22	$1.80\cdot10^6$
Roof	26	$1.00\cdot10^4$

Fig. 2. FE model of the Fossano bell tower with macro elements and corresponding mechanical properties.

Having defined the geometry and the materials, the two interventions were modelled, first separately and then combined. For what concerns the FRP tapes, the first ones were positioned at the level of the floors and the roof for the construction of the perimeter curbs. Then further perimeter bands were placed just above and just below the openings to provide a horizontal confinement to the walls to contrast any phenomena of instability or overturning towards the outside. Subsequently, vertical bands were placed along the entire height of the walls with the dual purpose of reinforcing the walls both against out-of-plane and in-plane bending phenomena. Finally, for additional shear reinforcement of the masonry, it has been decided to place bands arranged as braces [14].

Secondarily, the consolidation intervention by grout injections was modelled by modifying the mechanical properties of the masonry of the bell tower. This was possible because the masonry at the base level of the bell tower has been proven to have an increased value of Young's modulus and average compressive strength with respect to the central and final section, which show significantly lower mechanical properties as well as a considerably more aggravated crack pattern.

Therefore, it was decided to operate the injections only in the central and top part of the bell tower (except for the belfry), to obtain a structure as homogeneous as possible regarding the mechanical characteristics. Concurrently with the increase of the stiffness modulus, the increase in density due to the injection of the consolidating mortar was also calculated. This enabled to analyse the behavior of the bell tower even during the intermediate phase of the intervention, i.e., that of injected mortar but not yet consolidated.

3.2 Seismic assessment of the strengthened structure

In order to evaluate the effectiveness of the proposed consolidation interventions, it was decided to perform first a modal analysis, and, consequently, a non-linear static analysis. In this way, it was possible to obtain a comparison before and after the interventions.

Modal analysis. As a first step, a modal analysis was performed on the structure. A comparison of the main modal quantities, i.e. natural frequencies and mode shapes, for the first three vibrational modes is reported in Table 1 and in Fig. 3.

Table 1. First three fundamental frequencies [Hz] of the tower.

Nr. of mode	Type	Present condition	With FRP fibers only (gain)	With grout injections only (gain)	With FRP tapes and grout injections (gain)
1	Flexional X	1.128	1.124 (-0.35%)	1.317 (+16.80%)	1.317 (+16.82%)
2	Flexional Y	1.161	1.162 (+0.07%)	1.357 (+16.84%)	1.357 (+16.90%)
3	Torsional	3.254	3.257 (+0.10%)	3.934 (+20.92%)	3.937 (+21.01%)

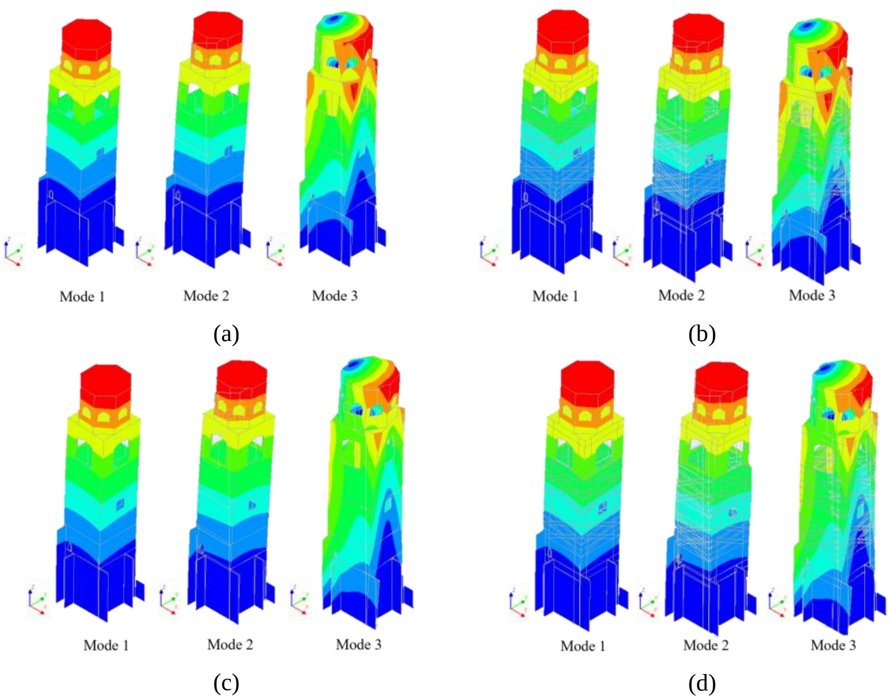


Fig. 3. Vibration modes: (a) present condition, (b) FRP tapes (c) grout injections, and (d) FRP tapes + grout injections.

As observable from Fig. 3, there is no remarkable change in the mode shapes at low frequencies since the overall dynamic behavior of the structure still remains the same. However, it is interesting to observe the change in frequencies reported in Table 1. In particular, in the case of an intervention of FRP tapes, the natural frequencies associated to the first three modes of vibrations of the structure do not improve. Indeed, the application of FRP tapes does not significantly affect the mass and the stiffness of the bell tower, but only the resulting stresses. On the other hand, a grout injection has a greater influence on the eigenfrequencies of the structure, because it is modelled as a variation on the mass of the structure and on the stiffness of the masonry material.

Pushover analysis. Subsequently, a non-linear static (pushover) analysis was performed. Just as a brief recall, a pushover analysis is an iterative procedure to identify in each calculation step the multiplier of the horizontal forces which determines an increase in the displacement of the control point, updating the model from time to time with the addition of the plastic hinges in the points of the structure that they plasticise. Since the critical eigenvalue is unknown, two different pushover analyses were performed, one for each mode: one considering the first mode applied in the x-direction (positive and negative) and one considering the second mode applied in the y-direction (positive and negative). Results of the pushover analysis in Fig. 4.

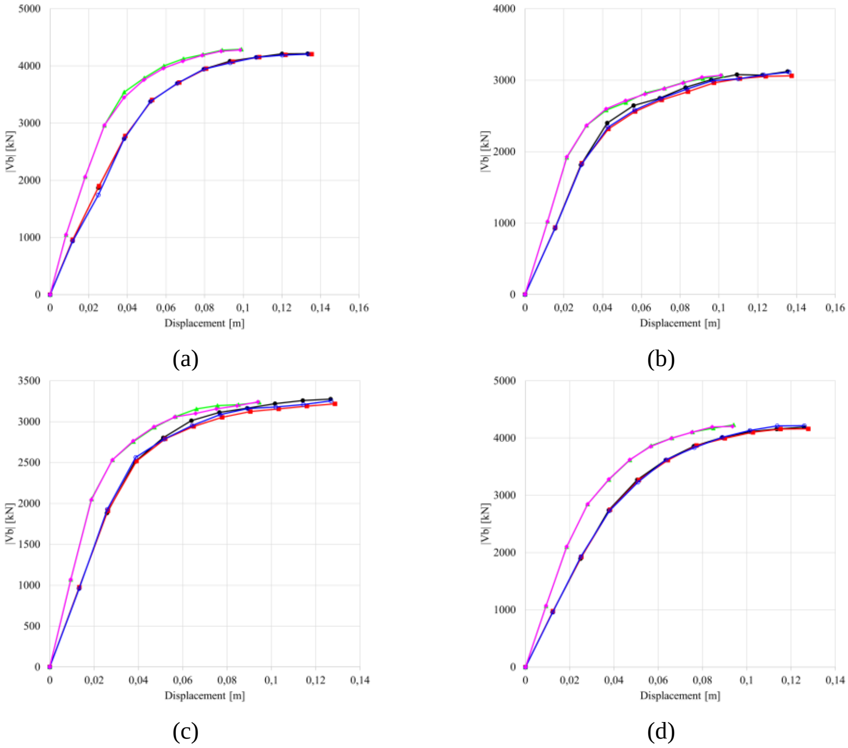


Fig. 4. Pushover curves in (a) x-direction, (b) -x-direction, (c) y-direction, and (d) -y-direction in the case of: Present condition, Grout injection (not consolidated), Grout injection (consolidated), FRP tapes, and FRP tapes + Grout injections.

In general, it is observable that the type of intervention which leads to an increase of resistance of the structure in terms of shear force at the base (V_b) is represented by the grout injections. Moreover, the percentage increase in resistance is almost equal in the four considered directions, highlighting how the interventions positively affect the asymmetric behavior of the bell tower. Indeed, the difference between +x/-x and +y/-y are due to the contacts with the neighbouring church. However, it is interesting to observe how the grout injections lead to a worsening of the resistance immediately after its application, i.e., not consolidated mortar. Indeed, as long as the injections are not consolidated yet, the intervention does not produce any beneficial effect on the structure, rather the displacement of the control node increases compared to the present condition case. This sheds light on the fact that the intermediate phases of the interventions often present the greatest criticalities [15], and, therefore, the structure should be appropriately supervised during the application of the grout injections.

4 Discussion of the results

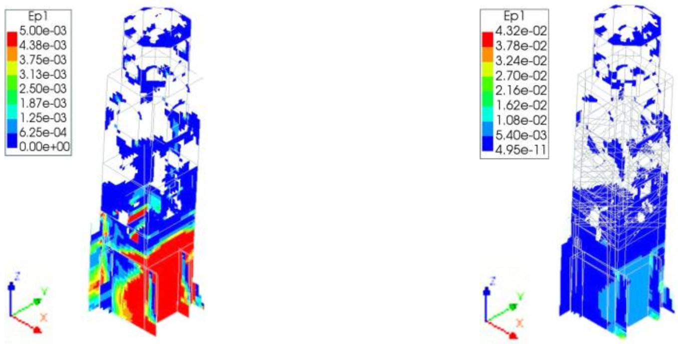
The capacity curves of the structure allowed to rank the candidate interventions in terms of ductility factor μ and dissipated energy W. On the one hand, the ductility factor describes the deformation which can undergo the material up to failure and it is expressed as the ratio between the ultimate displacement and the displacement at the elastic limit point. On the other hand, the dissipated energy is calculated as the underlying area of the capacity curve up to that limit.

Table 2. Ductility factor μ [-] and dissipated energy W [J].

Direction	Present condition		With FRP tapes		With grout injections (Not consolidated)		With grout injections (Consolidated)		With FRP tapes and grout injections	
	μ [-]	W [J]	μ [-]	W [J]	μ [-]	W [J]	μ [-]	W [J]	μ [-]	W [J]
+Y	3.18	0.184	3.33	0.183	3.34	0.181	4.02	0,126	4.03	0,124
-Y	2.53	0.221	2.51	0.222	2.55	0.220	2.72	0.152	2.83	0,151
+X	2.56	0.246	2.53	0.245	2.61	0.245	2.82	0,172	2.84	0,170
-X	3.15	0,190	2.53	0.245	3.33	0.186	3.52	0,128	3.56	0,128

From Table 2, one can observe that μ increases with the proposed interventions, and, in particular, it reaches its highest value in the case of grout injections. As expected, a similar result is valid in the case of W, which decreases almost 40% in the case of the strengthened structure with FRP tapes and grout injections in the positive x-direction. However, also observing the pushover curves, the best trade-off between ductility, dissipated energy and resistance in terms of V_b is observed in the case of FRP tapes combined with gout injections, as expected. In this case, the values of μ result to be higher and the dissipated energy lower than in the previous cases, with an increase of V_b in all the four considered directions.

Prediction of crack pattern. Exploiting the results obtained from the pushover analysis, it was also possible to predict the possible crack pattern, and to prove the effectiveness of the selected interventions. In particular, total strains can identify the critical areas of a structure. Consequently, the plastic strain can be used to identify the areas in which the crack formation could take place [15, 16]. In the case of the bell tower, the results for crack propagation have been reported in the x-direction in the present condition and in the case of intervention with FRP tapes combined with grout injections, as reported by Fig. 5.



(a) (b)

Fig. 5. Crack propagation in the positive x direction: (a) present condition and (b) intervention with FRP tapes and grout injections.

From Fig. 5 it is observable that the cracks mostly concentrate on the base of the bell tower in both cases. However, the cracks are less likely to spread when the structure is strengthened. Moreover, in the case of Fig. 5a, the plastic strain results to have lower values than in the case of Fig. 5b, i.e., cracks start to form for higher values of displacements when the structure is strengthened, leading to a global improvement of its structural behavior. Therefore, the crack pattern confirmed that the intervention with FRP combined with grout injections is effective.

5 Conclusions

The present work aimed to evaluate the effectiveness of different consolidation interventions for the masonry bell tower of the Church of S. Giovenale located in Fossano (CN). The assessment of these candidate interventions was carried out by means of FE analysis. This allowed to identify the combined use of FRP tapes and mortar injection as the most suitable kind of intervention. This result was assessed on the basis of a linear dynamic analysis and a non-linear static analysis. The latter also allowed to point out the most likely potential crack pattern for the structure. Moreover, the aesthetic impact of the proposed solutions on the tower is clearly lower with respect to the present temporary intervention.

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