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A kinematic limit analysis approach for seismic retrofitting of masonry towers through steel tie-rods

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A B S T R A C T

The paper provides an insight into the seismic strengthening of masonry towers by means of horizontal and vertical steel tie-rods. The approach is based on the kinematic theorem of limit analysis with pre-assigned failure mechanisms. Among all the possible ones, five of them commonly observed during post-earthquake surveys are selected: (#1) vertical splitting; (#2) base rocking; (#3) Heyman's diagonal rocking; (#4) combination of splitting and diagonal rocking; (#5) base sliding.

The aim is to put at disposal a procedure that can be used in any case of technical interest. To provide general output applicable in different contexts, towers are supposed isolated and idealized with a constant hollow square cross-section, without openings and any type of irregularity. Different mechanisms can be activated as a consequence of geometric features (base, height and thickness of the walls) and masonry mechanical properties, here assumed obeying a Mohr-Coulomb failure criterion.

Thanks to the simplicity of the approach, comprehensive sensitivity analyses with different heights, base widths and wall thicknesses varying in the range of technical interest, as well as large scale Monte Carlo (MC) simulations with several geometries and three different sets of mechanical properties are carried out.

The possible introduction of horizontal and vertical steel tie-rods is investigated in the same way, simply considering the contribution of the reinforcement in the internal dissipation in limit analysis computations. The results of the analyses show that, depending on the geometry of the tower and the mechanical properties of masonry, different mechanisms can be activated and therefore the choice of the reinforcement must be done on the basis of the expected failure mode. In addition, it is possible to predict the change in the active failure mechanism due to the introduction of reinforcement, as well as to evaluate the increase in the load carrying capacity.

1. Introduction

The seismic vulnerability reduction of cultural built heritage in general and of masonry towers in particular has been considered an important issue in the last decades. Masonry towers usually exhibit a high seismic vulnerability, clearly demonstrated by the extensive damages and catastrophic collapses observed in past earthquakes [1–11]. Such poor behavior under horizontal loads is easily understandable, remembering that they were conceived exclusively to withstand gravity loads. Considering that Italian and international standards have imposed the evaluation of their structural performance even in the presence of horizontal loads [12–15], the determination of their load carrying capacity is becoming critical. The clear aim is to push forward the research in the field of analytical and numerical modelling, in order to establish methods that are reliable, predictive of the masonry towers actual behavior in the case of an earthquake and relatively simple to use for common practitioners. The final target is to obtain - at regional scale - a quantitative insight (in the form of vulnerability indices) into the vulnerability level of towers and propose strengthening interventions that are really able to increase the lateral load carrying capacity.

Italian Guidelines for the Built Heritage [14] suggest the utilization of a simplified manual approach based on the concept that a masonry tower can be assimilated to a cantilever beam made by a no tension material and that failure occurs, in the majority of the cases, due to the formation of a flexural hinge in correspondence with the base. Whilst such an assumption can be theoretically consistent with the actual behavior of a generic tower, it is not very frequently observed in practice, because it has been seen that failure may be more probable for the formation of different failure mechanisms, like vertical splitting, combined shear and flexural failures near the base, Heyman's diagonal cracking [16,17], splitting combined with diagonal yield lines at the base and so on.

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Several methods of analysis, showing different levels of accuracy and complexity, have been proposed in the recent past for the analysis of historical masonry structures and towers in particular, the most diffused being Finite Elements (FEs) with masonry treated as a homogeneous (sometimes orthotropic) material with softening in tension and compression [18–23], beam/equivalent frame/macro-elements approaches [24–29], rigid body and spring models (RBSM) [30,31], homogenization in the non-linear range [32,33] and limit analyses (LA) combined or not with FEs [34–36], No Tension Material Modelling NTM [37–39] and so on. To categorize all of them into fully separated groups is certainly not possible. On the contrary, there is a quite wide overlapping; as a matter of fact, some of them may be sometimes regarded as specializations of a general method (discretization with rigid infinitely resistant elements or macro-blocks) interacting with interfaces that exhibit different mechanical properties (e.g. in NTM modelling contact interfaces between blocks are assumed, RBSM mildly couples shear and axial damaging springs, LA is usually coupled with triangular rigid elements and modified Mohr-Coulomb interfaces, and so on). Another common root is the discretization of the domain into either FEs or Distinct Elements (DEs) [40–42]; again, this latter technique could be also regarded as a special FE procedure where the kinematic description of the elements is given only by rigid body motions. The framework is therefore complex and multifaceted and the reduction of the existing approaches into single categories would be over-simplistic. As a matter of fact, taking into consideration the development of numerical methods for structural analyses, it is widely felt that the most accurate approach to deal with masonry requires advanced FEs [43–46], able to properly account for the complexity of the problem through the adequate level of accuracy needed. However, in engineering practice, the utilization of sophisticated methods is not so common and the tendency is to use simplified procedures, at the same time maintaining an acceptable level of agreement with the expected real behavior. Such considerations apply in particular to towers, where the approximation to a cantilever beam is also suggested by the Italian Guidelines for the Built Heritage [14]. In this framework, if the tower is isolated and geometrically regular, collapse is due to the formation of a flexural hinge at the base. Unfortunately, several recent works in the field of towers and chimneys [4,8–10,31], reporting damages and presenting advanced incremental and LA computations, show that both the behavior is much more complex and different mechanisms can be activated with higher probability. The identification of the active mechanism is paramount for an effective strengthening, in the light of a seismic vulnerability reduction. Classically, strengthening of towers is obtained in practice by introducing either horizontal or vertical steel tie-rods [47,48], sometimes with a given value of pre-tension of the rods, but their efficacy considerably depends on the real crack pattern responsible for the collapse. Another strategy is to use injection or deep repointing [49], but this could be costly and change the vibration period. In some recent studies, different authors have investigated the applicability of new composite or smart materials for the retrofitting of existing masonry constructions [50–53], including the possibility of introducing FRP sheets or rods for the seismic upgrading of bell towers [50,51] with a lower invasiveness. The technology is different, because failure can occur due to delamination and debonding of the strips, but the concept in terms of vulnerability reduction estimation is the same.

As a matter of fact, a strengthening system can be introduced for two reasons: (1) to repair a tower after an earthquake that has caused the appearance of a well-defined crack pattern (corresponding to a full or partial activation of a mechanism); (2) to reduce the seismic vulnerability of undamaged structures and hence prevent possible future damages in the event of earthquakes. In the first case, a restoration of the masonry properties to the undamaged state is needed before the application of the reinforcement and therefore, at least theoretically, the approach to use towards a strengthening intervention is the same.

The present paper provides an insight into the effectiveness of strengthening through horizontal and vertical steel rods. To properly deal with such an issue first requires the knowledge of the actual mechanism activating in the unreinforced case.

In order to simplify the procedure and provide general results applicable to real practice with an acceptable level of approximation, towers are assumed isolated and idealized considering a constant hollow square cross-section, the absence of both openings (e.g. doors, belfry, etc.) and any type of irregularity (e.g. internal vaults, changes of wall thickness, stairs, etc.).

Among all the possible mechanisms, five (those commonly observed during post-earthquake surveys) are considered. They are: (#1) vertical splitting into two parts; (#2) base rocking; (#3) Heyman's failure with diagonal crack and overturning [16]; (#4) combination of splitting and diagonal overturning; (#5) base sliding. In the framework of the upper bound theorem of limit analysis, the active mechanism is that associated with the minimum multiplier.

The activation of a particular mechanism turns out to be a consequence of both the tower geometry (base, height and thickness of the walls) and the mechanical properties adopted for masonry. In the present investigation a Mohr-Coulomb failure criterion with tension cutoff is assumed.

Being the possibilities reduced to only five options, sensitivity analyses and large scale Monte Carlo (MC) simulations can be performed, changing the tower height, the base length and the walls thickness. In MC simulations, the probability distribution functions adopted are uniform (even if this topic would be extremely interesting to investigate, we have indeed at disposal insufficient statistical information regarding the actual distributions of the different geometric parameters).

The introduction of horizontal and vertical strengthening is dealt with in the same way, adding the contribution of the steel rods to the internal dissipation.

Sensitivity analyses are conducted changing the height of the towers in a wide range of technical interest, assuming different values for the base width and the ratio between the base width and the wall thickness. MC simulations are carried out again on realistic cases on large samples (500,000). Three different sets of material properties are finally analyzed.

The results of the analyses show that different mechanisms can be activated, depending on the geometry of the tower and the mechanical properties of masonry, and therefore the choice of the reinforcement is not immaterial. In addition, it is possible to qualitatively estimate the change in the active failure mechanism due to the introduction of the reinforcement, as well as to quantitatively evaluate the increase of the load carrying capacity.

2. Failure modes of masonry towers subjected to lateral loads

Masonry towers may exhibit different failure modes, as a consequence of their peculiar features, such as geometry, vertical precompression level, masonry quality and structural irregularities. By means of a detailed post-earthquake analysis of the occurrence probability of different collapse modes, it is possible to establish a kinematic limit analysis approach, where the load carrying capacity of an idealized tower (with constant cross-section and free from any kind of irregularity) is evaluated applying the kinematic theorem of limit analysis on a reduced number of pre-assigned failure mechanisms, which are selected among all the possibilities according to the observed probability of occurrence. In the framework of the upper bound theorem, the normalized collapse acceleration is equal to the failure multiplier. Such an approach appears particularly interesting for the following reasons: (1) it is fast and straightforward (hence it can be used in common design without specific skills); (2) it reflects the real behavior of a tower subjected to horizontal loads; (3) it allows performing both comprehensive sensitivity analyses and large scale Monte Carlo (MC) simulations, at a fraction of the time needed in standard FE computations.