Seismic vulnerability of old Italian fortifications

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ABSTRACT

The damages recorded in the recent seismic events have highlighted that also very robust structures, such as old castles, are vulnerable with respect to not too high seismic actions. However, the damages have allowed not only of understanding the structural behavior of these ancient old fortifications, but also the influence of many factors affecting the specific response.

In this paper an overview of the most recent developments in the seismic assessment of Italian medieval castles is presented. The study discusses on the identification of the most vulnerable elements and on their analytical evaluation. Then, an application to an ancient castle chosen as case study is shown.

1 INTRODUCTION

Italy is one of the countries with the highest seismic activity worldwide. Only in the new millennium 20 earthquakes with Richter scale above 5.0 ("INGV Istituto Nazionale di Geofisica e Vulcanologia," 2017) have struck the country. To this it must be added that Italy has a huge architectural heritage, also demonstrated by the highest number of sites recognized by the UNESCO Organization. Infact, accordingly to the updated list Italy has nowadays 53 sites protected within the WORLD HERITAGE LIST. (UNESCO, 2017). It is evident, therefore, that the combination of these aspects defines a high seismic risk of these heritages that must be reduced and prevented.

However, in recent years many researches in the field of seismic performance of historical buildings have classified different typical damages typologies starting from their actual seismic performance (Binda & Saisi, 2005), (Cattari et al., 2014), (Coïsson, Ferrari, Ferretti, & Rozzi, 2016). These studies have encouraged the knowledge evolution and improvements in risk management of cultural heritage, consisting of ancient buildings, churches, convents, historic palaces, castles and fortresses (recently Laterza et al., 2017a, Laterza et al. 2017b, among the others).

Castle and fortresses, as it has been observed in the recent case in the Emilia earthquake in 2012, are also extremely vulnerable also for moderate seismic actions. As for fortifications, (Cattari et al., 2014) proposed an abacus of potential collapse mechanisms (figure 1), starting from the damages shown by a large number of fortifications after the seismic event of Emilia (Italy) in 2012. Evidently, although this study may be considered complete, in the same publication it is clarified that the list of the considered damage mechanisms is limited to the Emilia's fortifications typology.

(Coïsson, Ferretti, & Lenticchia, 2016) with the aim to propose a set of potential collapse mechanisms relevant to castles after earthquakes, considered damages suffered by 750 Italian with different typologies since Friuli earthquake in 1976 to Emilia earthquake in 2012. At the end, a GIS database was proposed summarizing many information (such as, among the others, typology, localization, material and damages suffered), that may be considered valid for a large part of the Italian territory. By the means of this data collecting, for example, it has been possible pointed out some differences between damages suffered by the Emilia and Irpinia castles after their respectively earthquakes.

In according to the ("Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale," 2007), no seismic vulnerability valuation is suggested as specific methodology of calculation for castles as, on the contrary, it is indicated for other specific ancient structures such as towers and churches. However, seismic assessment of castles may be performed by individuating the reference typologies defined in the guideline.

Several studies of seismic vulnerability in medieval castles along the Italian territory have been developed using finite element modeling approach, predicting the global response of the structures and the most vulnerable elements taking into account the influence of external factors such as differential settlements in the soil, any intervention applied during the years and other environmental factors (Casolo & Sanjust, 2009) (Betti, Orlando, & Vignoli, 2011).

In southern of Italy, especially in Basilicata, most of its fortifications, influenced by Federico by the Aragonese style, show variations in the design of its towers and, in general, in the defense system developed at that time. Frequently it is possible to found, as notable features, circular towers and the use of slopes at the base (Cairns & Cairns, 1999).

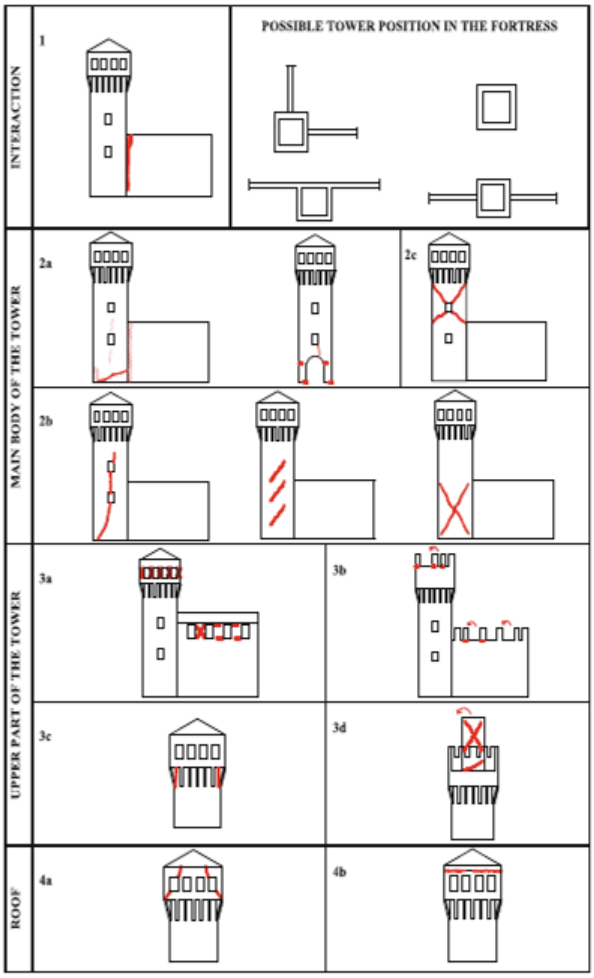


Figure 1. Damage mechanisms proposed by (Cattari et al., 2014) for the Emilia fortress.

This paper is focused on the seismic performance of old fortifications, with particular attention to the ones placed in the south of Italy. In particular, a case study is herein investigated: the Tramontano Castle, located in Matera (Italy). In this work are discussed the results obtained implementing a finite element model of the towers of the castle. The numerical investigations are conducted with the goal of investigating the distribution of tensile stresses within the elements for individuating potential collapse mechanism. Then, the obtained results are compared with the one proposed in literature for the same elements investigated.

2 DESCRIPTION OF THE TRAMONTANO CASTLE.

2.1 *Short history of the investigated building*

The Tramontano castle (Figure 2) is located in Matera- Italy. It appears like the complement of a system of fortification existing in Matera by order of the count Tramontano in the year 1497 and that was never concluded due to the murder of the same by the community in the year 1512, this fortress would serve the control of the only transit route of regional importance that at that time interested the Matera's territory (Di Pede & Longo, 1994). Over time, the castle become jail until the firsts years of the 17th century. After the 1980’s earthquake, the structure was aim of structural interventions (Raffaele Giuria et al., 2010), and actually it is in process of electric interventions. Due to the localization of the building, this structure is inside of the Matera’s historic center, which has been included in the World Heritage List of UNESCO in 1993 (http://www.sassiweb.it/).

Figure 2. Tramontano castle in Matera-Italy

The castle contains characteristics of defense against old armaments, such as moat and a main tower, and at the same time a system resistant to modern weapons at the time, based on gunpowder, which would be resisted by means of walls with large Thicknesses and towers of low height (Di

Pede & Longo, 1994), The castle has 3 towers and a system of perimeter walls that connect the towers and the extension of other walls in the corners that show the unfinished work. The towers are not slender, they have walls of great thickness, a conic-cylindrical form, that starts from a greater diameter in the base until a point where it remains constant until the end of the tower. Like most of the strengths of Aragon style, it possess merlons of great thickness and a system of battlements in the top of the towers.

With respect to the position of the towers, two of them are corners and there is a central one, the last one, being the most outstanding, it has a height of 23 meters, a diameter at the base of 21 meters, and a diameter of constant section of 18 meters, its walls have an average thickness of 5 meters, with the exception of the highest level, which has a larger vault system and reduces the thickness of the walls, this tower has 4 internal levels, solved with a vault system.

On other hand, the corner towers have a height of 14 meters, slightly more than its adjacent walls, internally they have two levels, also with system of domes, towers have a diameter of 16 external meters at the base and 13 meters in the constant section, The walls have an average thickness of 4 meters (figure 3).

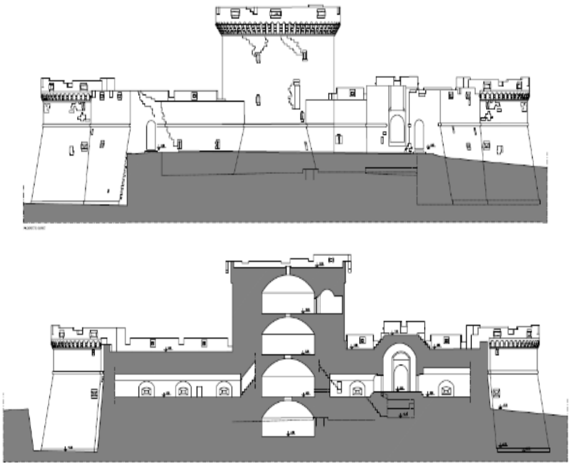


Figure 3. Floor levels and sections of Tramontano castle

2.2 *Current state of structure*

The Tramontano castle presents an excellent state of conservation, although it have not finished its original design, it conserves the totality of its decorative elements.

Historically the south tower, raised bridge, vaults and some parts of the external structure has presented diversified cracks, with injuries that have reached up to 3 cm, which significantly reduces the bearing capacity of the walls.

The origin of these cracks has been due to geomechanical alterations of the lands due to a reduction of the hydraulic regime presumably determined to the long periods of drought of the years. Likewise, the earthquakes of 1980 in Irpina and the earthquake that was felt in the year 1990 in Matera aggravated the situation of the cracks of the structure (Raffaele Giuria et al., 2010).

Other signs of deterioration are evident in the pluvial drainage areas of the structure, where erosion of the structure material is evident (figure 4). Another identified deterioration factor has an animal origin, where bird feces are observed along the castle, while on the south tower, there is a superficial crack with vertical direction (figure 5).

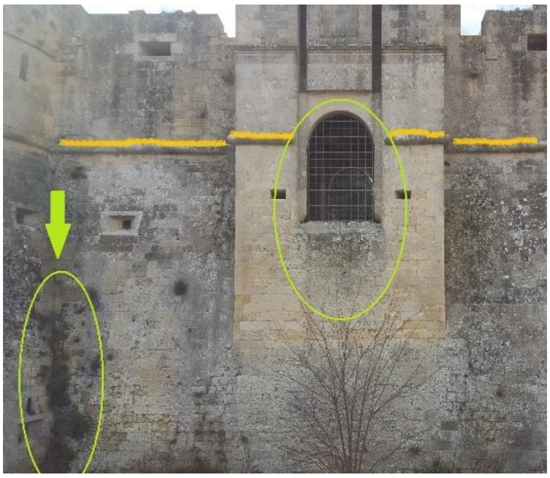


Figure 4. Erosion on the walls due to pluvial drainage

Figure 5. Superficial crack on the south tower.

2.3 *Mechanical characterization*

The body of the structure, like most of the constructions of the time, has been built with a masonry system, made with two leaves of calcarenite rock blocks as well as the internal system of vaults (Di Pede & Longo, 1994).

In order to characterize the masonry of the Tramontano Castle, since no material test is available, in this study the reference values suggested by Italian Design Code Instructions ("Circolare 2 febbraio 2009, n. 617 Istruzioni per l'applicazione delle «Nuove norme tecniche per le costruzioni»," 2009) have been used. In the present case, two types of masonry have been identified: "*Muratura a blocchi lapidei squadrati*" referring to the external leaves of the walls, and "*Muratura in pietrame disordinata*" for the filling material between the leaves. The values suggested by the Italian Design Code Instructions are summarized in Table 1.

Table 1. Mechanical properties of material of Tramontano castle

Type of masonry	Properties				
	F m	τ_0	E	G	W
	N/cm2	KN/m2	N/mm2	N/mm2	KN/m3
Muratura conci di pietra tenera-calcarenite	100	20	690	230	22
	180	32	1050	350	
Muratura in pietrame disordinata	140	28	900	300	19
	240	42	1260	420	

Moreover, due to the absence of experimental tests, the knowledge level (LC) has been assumed equal to LC1 (limited knowledge level), in accordance with the (*Norme tecniche per le costruzioni*, 2008). With respect to the given values of the masonry strength, the minimum values of the intervals reported in table C.8A.2.1 of the NTC-08 (*Norme tecniche per le costruzioni*, 2008) has been adopted. Then, the assumed values have been divided by a confidence factor. In this case, following the indications reported into ("Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale," 2007), the confidence factor has been defined as the sum of four partial factors as follows: FC1 relative to the geometric survey, FC2 related to the specific identification of the history and construct of the structure, FC3 relative to the knowledge of the properties of the materials and FC4 in Reference to knowledge of the soil and foundations. Definitively, in this case the confidence factor is equal to FC = 1+ (0.00 + 0.12 + 0.12 + 0.06) = 1.3.

2.4 *Seismic action*

In this study the seismic action has been defined by referring to a reference period V_r equal to 50 years, and by assuming a Category C for the ground category. In Table 2 and Figure 6 are reported the parameters for defining the seismic action and the Elastic response spectrum of the horizontal action by referring to the Life Safety Ultimate Limit State.

Table 1. Period of return and values of ag, F0 and T*c, Soil characteristics and Tb, Tc y Td Values of the case of study

Limit state	SLV
Probability of overcoming *Pvr* (%)	10 %
Return Period (years)	475
Max. horizontal acceleration at the site *ag* (m/s2)	0,139
Amplification factor *F0*	2,503
Start period of the constant velocity of the acceleration spectrum *T*c* (s)	0,345
Ground category	C
Ss	1,68
Cc	1,49
St	1,2
S	2,02
agS (m/s2)	0,28
Tb (s)	0,17
Tc (s)	0,51
Td (s)	1,65

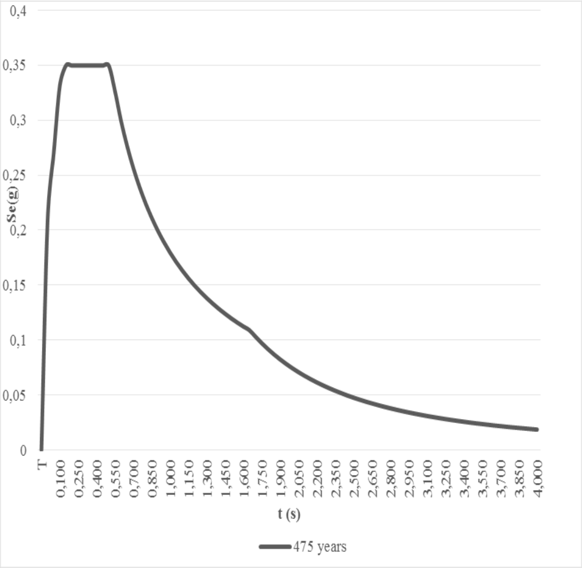


Figure 6. Seismic elastic spectrum of the study area for a period of return of 475 years.

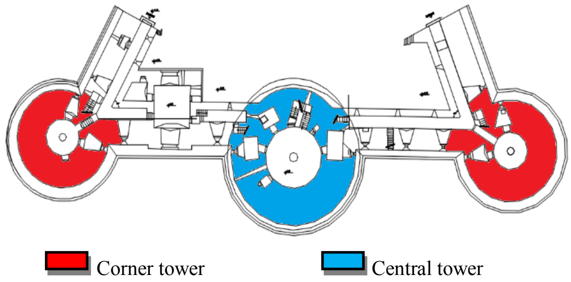


Figure 7. Division into macro elements of the structure.

NUMERICAL RESULTS

2.5 *Numerical model*

A finite element model has been developed by using SAP 2000 V16 software program for performing elastic analyses under vertical and seismic loads. Due to the thickness of the walls and the variation of properties, external leaves have been modelled as *elastic thick shells elements,* while the filling material has been modeled through *elastic solid elements*.

In this study are shown the numerical results obtained with the FEM models of the castle towers (the corner and the central tower, figure 7) by also studying the influence of the contiguous walls for the central tower. Moreover, for the central tower two different models have been implemented as follows: in the first one no connections has been assumed and therefore only the central tower has been models. In the second model, on the contrary, also the adjacent walls fully connected with the tower have been taken into account.

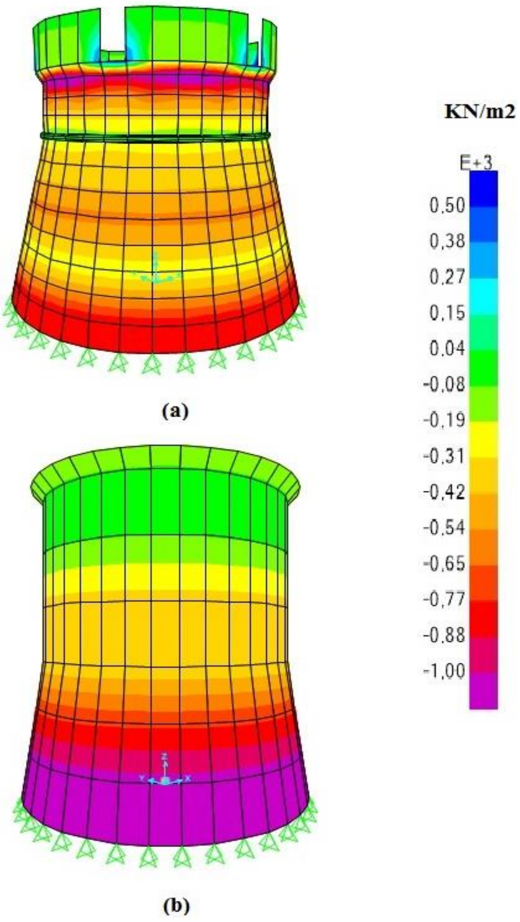
2.6 Static Analysis for vertical loads

The static analysis of the Tramontano castle has been developed with the aim of investigating the distribution of internal stresses under vertical loads, and by comparing the predicted tensile stresses with the cracks patterns that one can observed in the current state.

For the corner tower, tensile stresses under vertical loads may be measured only at the top of the towers, i.e. in the merlons and battlements of its upper zone. On the other hand, the whole outer contour wall works under compression, the maximum compressive stresses are present at the top of the constant circular section area, just below the battlements (Figure 8a). In the central tower (Figure 8b), the compressive stresses are accentuated mainly in the base and are evenly distributed throughout the whole section.

The measured fundamental frequency of the corner tower has been 4.93 Hz and the highest displacement of 2.70 cm (figure 9a).

However, in the central tower modeled without perimeter walls, the maximum displacements occur in the highest zone as expected, and they reach 1.6 cm. The frequency of the tower is 1.80 Hz, and it has a vibration period of 0.5 seconds. The absence of external walls allows a free movement and proportional to the height of each element, (figure 9b).



(a)

(b)

Figure 8. Distribution of normal stresses due to vertical loads in the (a) corner tower, (b) central tower. Modal Analysis

On the other hand, the central tower modeled with perimeter walls (figure 9c), which simulates a good connection tower-walls, allows to observe that in the vibrate mode, the period of the structure is 0.40 seconds, Frequency of 2.56 Hz. and the highest displacement of 1.80 cm

If the results of the modal analysis are compared (same way of vibrating), it is observed that the period of the structure is reduced, as a result of the stiffness provided by the perimeter walls, likewise, the frequency increases in a 43%, going from 1.8Hz to 2.59Hz.

Regarding the deformations, with the connection of the adjacent walls the tower suffers greater deformations in its upper part but they are reduced in the connected zone, this is because at the moment of the modeling the lateral displacements of the walls have been restricted (assuming that the corner towers reduce the displacement of the walls), that is to say, the displacement that undergoes the tower in its inferior zone, is product of the elastic deformation of the walls. In the same way, the energy is concentrated in the zone of greater displacement that is the upper zone of the tower.

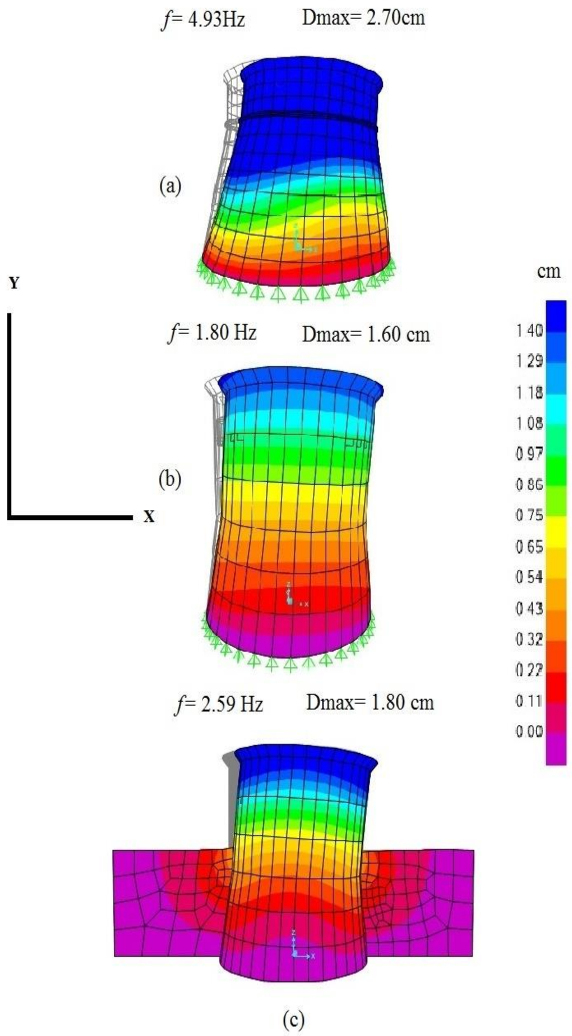


Figure 9. Distribution of displacements of the first vibration mode of. (a) corner tower (b) central tower without adjacent walls, (c) central tower with adjacent walls.

2.7 *Seismic action effects*

The towers of the Tramontano castle have been modeled by applying vertical loads plus seismic loads, using the design spectrum for a return period of 475 years, as defined in (*Norme tecniche per le costruzioni*, 2008) for SLV of the structure.

The corner tower presents the highest stresses at the base, especially in the Y face with values upper than 130 kN/m^2, while in the X face of the tower, the tensile stresses are low (figure 10a).

On other hand, the isolated central tower presents stresses on its faces towards the X axis, the maximum stresses are concentrated at the base, which exceed 500 kN/m^2, due to their geometry the stresses are symmetrically equal on the opposite side of the tower (figure 10b).

However, the connection with the structure with the central tower generates that the tensile stresses increase in the tower-wall contact area, especially in the high zones of the perimeter wall. However, normal stresses in the base of the tower decreases considerably, going from values exceeding 500 kN/m^2 to average values of 300 kN/m^2 (figure 10c).

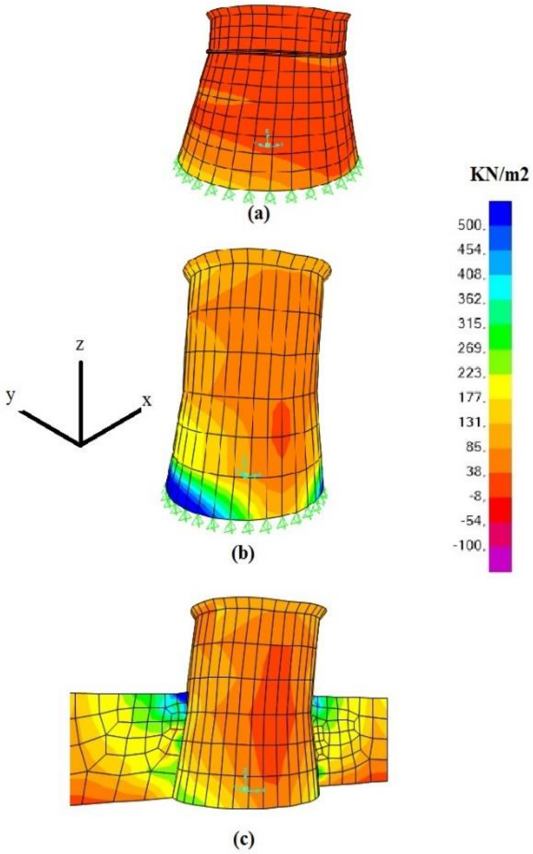


Figure 10. Distribution of tensile stresses due to vertical loads plus seismic load in the (a) corner tower. (b) central tower without adjacent walls (c) central tower with adjacent walls

The shear stresses of the structure also present substantive changes among towers by modeling the quake plus vertical loads. The corner tower presents the greatest shear strength in the base and the center body of the tower (figure 11a).

The isolated tower presents the greatest shear stresses at the base of the tower and gradually decreases with increasing height, the maximum values exceed 300 kN/m^2 (figure 11b). On the contrary, the tower connected to the perimeter walls presents shear stresses much lower than the isolated tower, having average values at the base of 130kN / m, just as happens with the tensioning forces, these are transmitted to the Parallel walls, especially in the lower area. The highest shear strength in the tower occur in the high zone of contact with the walls, approaching 300 kN/m^2 (figure 11c).

The good connection with perimeter walls guarantees a reduction in the tensile and shear stresses in the tower, however, it also allows to identify the most vulnerable areas of the structure in the interaction, as is the case of the area of contact between both, in the highest level as at the base.

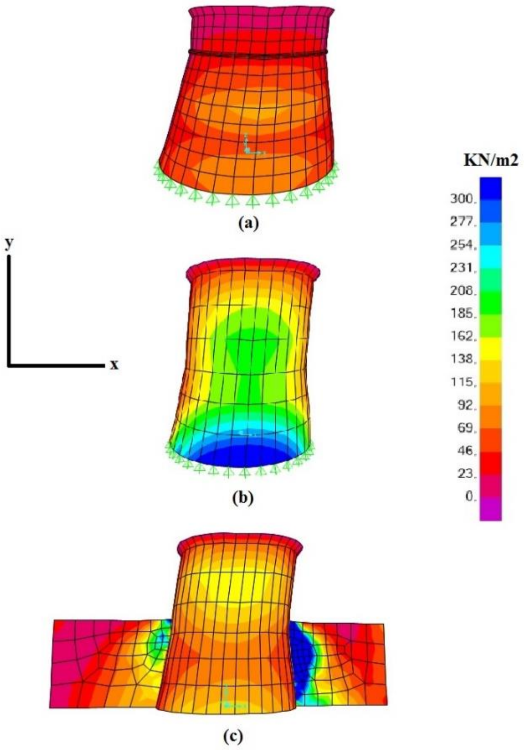


Figure 11. Distribution of shear stresses due to vertical loads plus seismic load in the a) corner tower. (b) central tower without adjacent walls (c) central tower with adjacent walls

3 DISCUSSION OF RESULTS AND POTENTIAL DAMAGE MECHANISMS

The obtained results from the implementation of FEM models allow us to identify the distribution of normal and shear stresses in the towers, considering for the central one the connection with the rest of the fortification. It is evident, that the geometry and the constructions details play a fundamental role in influencing the structural behavior of this type of fortifications, and on the distribution of internal stresses due to vertical and lateral loads.

Similarly, the results obtained confirm that for the towers, if the elements behave as monolithic macroelements, the failure may occur at the base of the elements, either for overturning or for sliding (it depends on the aspect ratios of the considered element). On the other hand, if the damage mechanism is triggered by tensile stresses, the failure in the base of the tower is presented on the orthogonal face to the seismic direction (figure 12a), whereas if the damage mechanism is activated by shear stress, the damage occurs on the parallel surface to the earthquake direction. (Figure 12b).

For the wall- tower well connected modeled, the adjacent walls, inhibit the flexural failure at the tower base along the direction where the walls are present. For this particular case, the damage occurs mainly in the Tower-wall interaction, where it would be reflected with vertical cracks or the collapse of the top of the wall.

The potential damage mechanisms identified for the castle studied are comparable with damage mechanisms proposed by (Cattari et al., 2014) as can be seen in figure 1, especially for the mechanisms related to the wall-tower interaction, as well as damages in the base of the monolithic macroelement and cracks along tower.

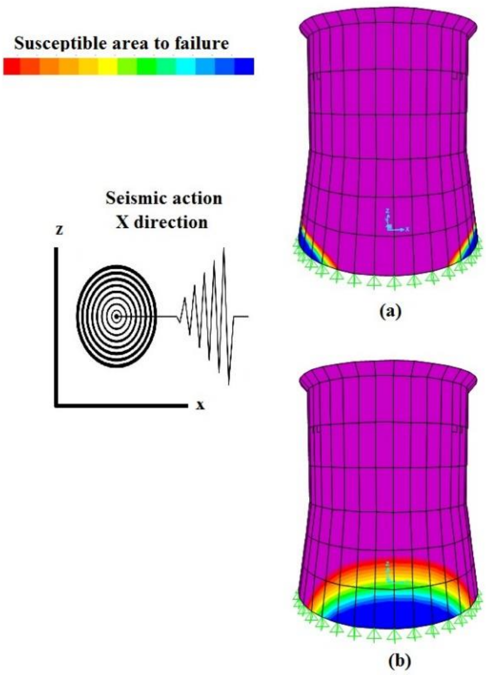


Figure 12. Susceptible area of potential damage of the tower to the seismic action in X direction by (a) Tensile stress. (b) shear stress.

Other mechanisms that could potentially be present in the Tramontano castle are present in the church response mechanism abacuses described in ("Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale," 2007) due to irregularities in the height of the structure, such as the plane- Altimetric or the mechanisms of the campaniles and domes

4 CONCLUSIONS

Elastic analyses with a finite element model have been carried out and presented in this paper. The study has been focused on the tramontane Castle of Matera (Italy). The numerical simulations of the towers under vertical and lateral loads have permitted of identifying the distribution of the internal stresses of the towers under two scenarios by considering also for the central tower: no connection with the adjacent walls, and on the contrary considering a good connection with the walls. These scenarios has been developed with the aim to provide potential damage mechanisms for this structure typology, as well as to do a comparison with damage mechanisms proposed for the castle typologies. The obtained numerical results confirm that the adjacent walls modify, if well connected, the concentration of normal stresses, and therefore the response mechanism along the direction where they are present.

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