NUMERICAL EVALUATION OF CRACKING AND CRUSHING IN ANCIENT MASONRY TOWERS

A. Carpinteri, S. Invernizzi and G. Lacidogna
Department of Structural and Geotechnical Engineering, Politecnico di Torino, 10129 Torino, Italy

ABSTRACT

In the present paper a comparative numerical study of two XIII century masonry towers preserved in Alba (Italy) is described. The buildings have been recently analyzed and monitored because of an emerging damage pattern, also due to some seismic events during the last few years. Nondestructive evaluation techniques have been adopted to assess the present situation of the towers without perturbations. Such investigations revealed the presence of concentrated damage zones as well as the deviation of one of the towers from verticality. Both towers have been analyzed through a preliminary linear elastic analysis, and a good agreement has been found with in situ measurements of the stress level by means of flat jack tests. This model validation allowed proceeding with the nonlinear analysis in order to evaluate cracking and crushing in the masonry. In the case of “Torre Sineo”, an increasing tilt mechanism has been simulated. Cracking and crushing of the masonry have been both taken into account, as well as the influence of geometrical nonlinearity. The opening of sub-vertical radial cracks anticipate compression crushing, while the evolution of the top displacement shows an almost linear evolution with respect to the tilt of the basement. The numerical simulations have also predicted the damage in correspondence to the main openings. On the other hand, the main vertical crack detected in “Torre Astesiano” has been taken into account by vanishing the elastic modulus in the corresponding narrow band. In this case the analysis reveals that, although the static stress field is not influenced in a sensible way, damage is responsible for high strain localization in the cracked area and for a change of the dynamic properties of the tower. In both cases, the numerical analysis has given a valuable picture of possible damage evolutions, providing useful hints for the prosecution of structural monitoring.

1 INTRODUCTION

The damage assessment of historical masonry buildings is often a complex task. It is crucial to distinguish between stable damage patterns and damage evolution leading to a catastrophic structural collapse [1]. Some damage patterns can be subsequently activated by unpredictable events like earthquakes, or by improper functional extensions and restorations. In addition, the limited ductility of the masonry, combined with the large scale of the tower, provides a rather brittle structural behavior [2].

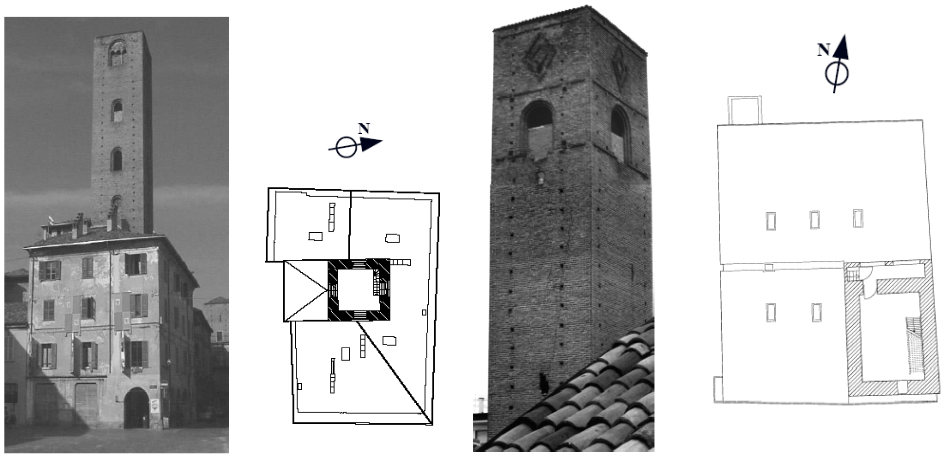
In the following, a survey of several numerical simulations is presented, that have been carried out on two medieval towers (Alba, Italy). The analyses range from linear static to nonlinear simulation of masonry cracking and crushing. The evaluation of eigenfrequencies and modal shapes, preliminary to further dynamic analyses, has been also accounted for. Many of the aspects faced in this study are rather typical and are present in analogous tower structures, broadly present in the Italian territory [3] [4].

1.1 Description of the two towers

These masonry buildings from the 13th century are the tallest and mightiest medieval towers preserved in Alba. Torre Sineo (Figure 1a) is square, 39 m high, and leans to a side by about 1%. Wall thickness ranges from 0.8 to 2 m. The bearing walls are *a sacco*, i.e., consist of brick faces enclosing a mixture of rubble and bricks bonded with lime and mortar. Over a height of 15 m, the tower is incorporated in a later building.

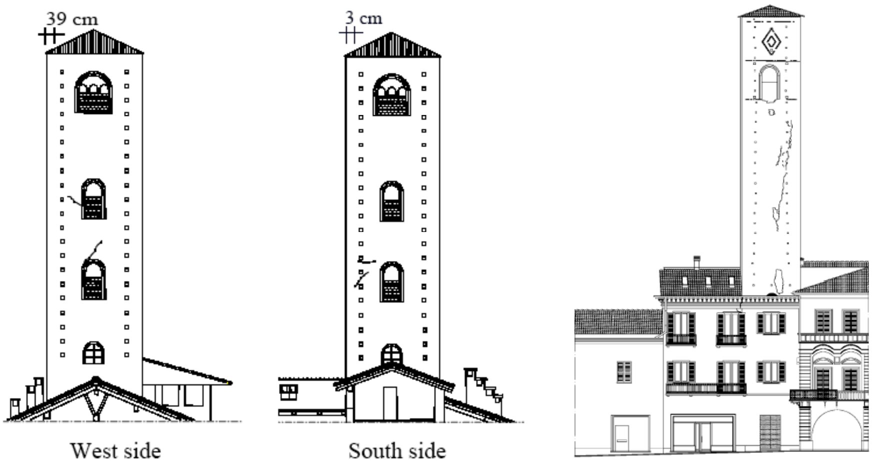
Torre Astesiano (Figure 1b) has a similar structure, but has a rectangular base. The filling material is more organized, with brick courses arranged in an almost regular fashion, which, however, are not connected with the outer wall faces. In this case too, the total thickness of the masonry ranges from 2 m at the bottom to 0.8 m at the top. Total height is about 36 m and the tower does not lean on any side. It is also incorporated in a later building, approximately 15 m high, built when the tower had been completed.

The geometry of the towers and the buildings they are embedded in was fully acquired and organized within a CAD system. The positions of the openings and the variations in the thickness of the tower walls was carefully recorded, together with the positions of the main cracks observed in the two structures. From the architectural standpoint, Torre Sineo is characterized by Roman arch windows on all sides, at each floor. The loggia has elegant double arch windows.



(a) (b)

Figure 1: Elevation view and plan of the towers with the surrounding buildings: Torre Sineo. (a), and Torre Astesiano (b).



(a) (b) (c)

Figure 2: Elevations and crack patterns of the towers: Torre Sineo (a) (b), Torre Astesiano (c).

The deviation from verticality of the Sineo Tower was evaluated with an optical instrument (Sokkia SEF 4110R). One side of the tower leans to the north. Maximum eccentricity, of 39 cm to the north and 3 cm to the west, was measured at the top. Measurements performed at different heights suggest that the tower experienced a rigid body tilting, i.e. no sensible deviation from straightness was recorded. A cracking network can be observed on both the internal and the external views of Torre Sineo. The most significant cracks are located inside the tower, mainly between the sixth and the eighth floor. On the outer surfaces, minor cracks are observed, mostly near the windows, and in particular between the sixth and the seventh floor. The cracking pattern and the slant of the tower are schematically summarized in Figure 2a-b.

On the other hand, Torre Astesiano has large windows only in the upper part. The intermediate floors, in fact, are illuminated by narrow slits. Architectural ornamentations at the loggia level are defined by three brick cornices in relief and two concentric rhombi, on all four sides. The cracking configuration is not characterized by cracks distributed over the entire surface of the masonry, but rather by a long vertical crack in the upper part of the southern facade (Figure 2c).

2 NUMERICAL ASSESSMENT OF CRACKING AND CRUSHING

2.1 Numerical model

Complete three-dimensional FEM models of the towers have been built using twenty-node isoparametric solid brick elements, in order to perform the analysis with the commercial code DIANA. At least five nodes are present in the thickness of the tower walls. The models take into account the presence of openings and the variation of the wall thickness at different levels. On the other hand, the presence of wood floors has been disregarded. Both structures are mainly subjected to their dead load. As far as Torre Sineo is concerned, also the effect of an increasing tilt of the foundation has been considered, combined to the load provided by the wind action exerted to the upper region of the tower. The main mechanical parameters of the models have been directly obtained from the single and double flat-jack tests, described more in details in a previous work [5]. Additional parameters, like the fracture energy of masonry, have been assumed on the basis of destructive experimental tests carried out on similar structures. A crack model based on total strain has been adopted to represent the nonlinear behavior of the masonry [6]. More detailed models can be adopted in case of laboratory specimens [7], but they become extremely demanding from the computational point of view when real-scale structures are considered. Both tensile Mode I cracking with linear softening and compressive crushing are taken into account. Since a fixed crack model was chosen, the shear retention behavior is explicitly evaluated by the code upon the provided factor β = 0.01. The mechanical parameters used in the analysis are summarized as follows: Young's Modulus E equal to 5000 MPa; Poisson ratio ν equal to 0.2; density equal to 1600 kg/m^3, tensile strength f_t equal to 0.3 MPa; fracture energy G_F equal to 50 J/m^2 and compression strength f_c equal to 2 MPa.

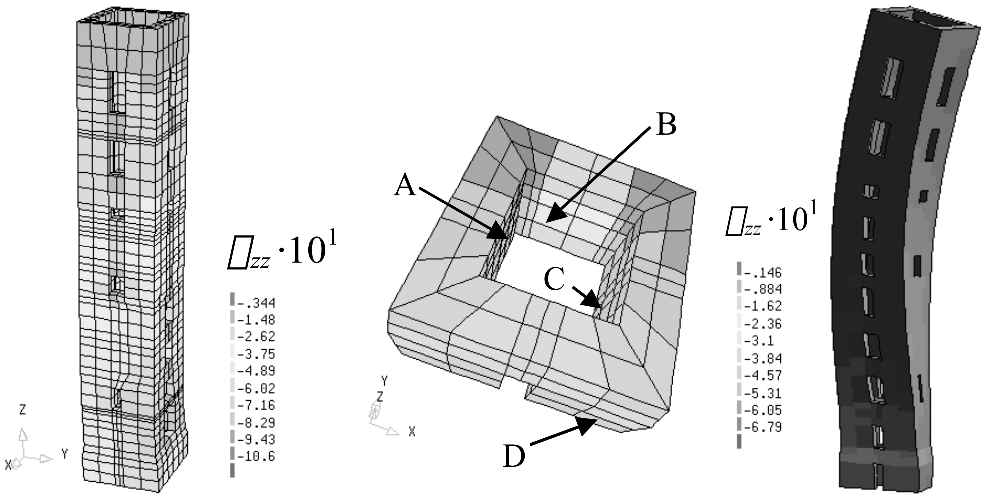
1.2 Elastic analysis

A first elastic analysis was performed taking into account the presence of the dead load. In the Sineo Tower case, the effect of tilt has been considered in an indirect way, imposing inclined ground acceleration. This allows solving the linear problem in the framework of small deformation and small displacement hypotheses. The vertical stress in the whole Torre Sineo structure is depicted in Figure 3a. In Figure 3b, on the other hand, only the foundation floor wall is shown. Vertical stresses are predicted that are in good agreement with experimental flat-jack results. Point

B, that is located beneath a large opening in the upper floor, is lightly loaded with a stress of about 0.3 MPa (vs. measured 0.297 MPa). On the other side, point C is much more loaded, with a stress greater than 0.7 MPa (vs. measured 1.059 MPa). Point D, placed on the external wall opposite to the tilt of the tower, presents a vertical stress of about 0.5 MPa (vs. a measured one of 0.502 MPa). The very high stress measured at point A, equal to 2.4 MPa, is not predicted by the numerical analysis, but it is likely to be ascribed to a local heterogeneity of the masonry wall and to the corresponding stress concentration. Analogous agreement is obtained in the case of Torre Astesiano.

The analysis reveals that the structures are basically in elastic conditions, since the level of stresses is everywhere smaller than the intrinsic strength. Such consideration is still valid when the effect of the wind load is taken into account. The linear investigation was extended to a modal analysis, in order to give a first estimate of the dynamic response of the structure. The first natural frequency of Torre Sineo is computed to be equal to 0.123 Hz, which corresponds to a period of 7.38 s. The first two modal deformations are basically connected to bending in the two orthogonal directions. The first torsional shape is linked to the fourth natural frequency, and is shown in Figure 3c. A more detailed dynamic study of the structure is currently under development, in order to give a structural interpretation of the damage growth due to some recent seismic events.

The good agreement between measured and numerically calculated stresses provides the necessary validation of the FEM models; therefore, the analysis was extended in order to predict Torre Sineo damage evolution, and to evaluate the effect of the localized damage pattern in Torre Astesiano.



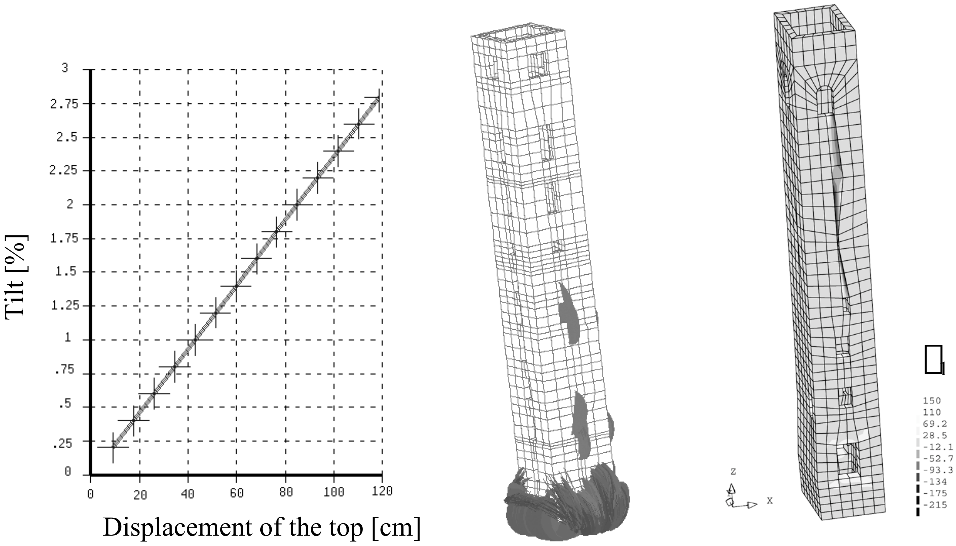
(a) (b) (c)

Figure 3: Mesh of the Torre Sineo model and contour plot of the vertical stress field [MPa] (a); details of the ground floor wall where the vertical stress field [MPa] has been calculated and measured in situ. (b); First torsional modal shape related to the fourth natural frequency (c).

1.3 Nonlinear analysis

Aim of the nonlinear analysis is to provide an assessment of the structural stability in the case of an increase in the tilt of the tower. The analysis has been carried out taking into account both mechanical and geometrical nonlinearity. Mechanical nonlinearity concerns the nonlinear stress-strain constitutive equations due to smeared crack arise once the tensile strength is overcome. On the other hand, geometrical nonlinearity means that the geometry is updated after each load step. This is necessary to have a correct estimate of the stresses induced both by the tilt and the bending of the tower itself.

First of all, the dead load and the wind load were applied to the structure. At the end of this first loading step, no damage has arisen in the structure. After that, the tilt is increased. The diagram in Figure 4a shows the evolution of the calculated displacement at the top of the tower with respected to the tilt. A tilt of 1% refer to a displacement of the tower top equal to 42 cm, slightly greater than the actual amount, due to the fact that the analysis considers also the wind action (with a mean speed of 25m/s, corresponding to a renewal time of 50 years). As the tilt is increased, the first cracks enucleate in the model. The region that is most sensitive to cracking is placed in the lower part of the tower. In the foundation floor wall principal tensile stresses arise along the circumferential direction [5], and their magnitude is higher close to the apertures in the tower. When the tensile strength is reached, the cracks start to open.



(a) (b) (c)

Figure 4: Evolution of the Torre Sineo top displacement with respect to the tilt (a); Crack pattern relative to the 3% tilt of the foundation (b); strain localization close to the damaged area in the Torre Astesiano (c).

In Figure 4b, discs represent the plane of cracks at gauss points in the cracked elements. It is worth noting that such cracks will develop in the sub-vertical radial direction. The presence of the internal cavity plays its unfavorable effect. In fact the first and wider cracks develop because of the stress intensification close to the re-entrant corners of the tower.

It is worth noting that, although the displacement of Torre Sineo top evolves almost linearly with the tilt, the damage increases in the structure. After the foundation region, the parts close to the openings in the upper segment of the tower start to crack. This can be noticed from Figure 4b, which refers to a tilt of about 3%. Moreover, this evidence is in good agreement with results from termography, which indicate the area close to the openings to be particularly sensitive to damage [5]. When the tilt is greater than 3%, also crushing of elements, due to the achievement of the ultimate compressive strength, comes into play. It can be concluded that the value of tilt equal to

3%, and the corresponding horizontal displacement of the tower top equal to 125 cm, should be considered as the ultimate conditions for the Torre Sineo.

On the other hand, Torre Astesiano does not present a considerable tilting mechanism, but shows a very localized damage pattern. Therefore, in this case the damage has been directly introduced in the model by vanishing the masonry stiffness in the corresponding narrow band. Comparison between the damaged and undamaged condition revealed that, although the vertical stress field is not basically influenced by sensible redistributions, the dynamic characteristics of the Torre Astesiano change. In addition, the torsional stiffness of the tower decreases dramatically. Further analyses are necessary to evaluate the real carrying capacity of Torre Astesiano with respect to horizontal loads.

3 CONCLUSIONS

Appropriate nonlinear numerical simulations have been proposed as a general procedure to assess the stability of an historical masonry tower, to be combined with NDE techniques. The approach has been followed in the study of two medieval towers respectively called Torre Sineo and Torre Astesiano in Alba (Italy). The main damage mechanisms in both structures have been clearly individuated, discriminating between stable and evolving patterns. The evolving scenarios have been studied, in order to provide a stability assessment and to describe the progressive decrement of the safety factor. The results from the numerical analysis, combined with monitoring of the structure [8], give valuable hints in order to assess not only how, but also when, structural restoration should take place. In addition, nonlinear input parameter values are specified, based also on the experimental validation, which are usually hard to decide, and thus could help in similar analyses.

4 ACKNOLEDGEMENTS

The present research was carried out with the financial support of the Italian Ministry of University and Scientific Research (MIUR) and of the European Union (EU).

5 REFERENCES

[1] Binda L, Gatti G, Poggi C, Sacchi Landriani G. The collapse of the Civic Tower of Pavia: a survey of the materials and structure. *Masonry International* 1992;6(1):11-20.

[2] Carpinteri A, Marega C, Savadori A. Ductile-brittle transition by varying structural size. *Engineering Fracture Mechanics* 1985;21: 263-271.

[3] Modena C, Valluzzi MR, Tongini Folli R, Binda L. Design choices and intervention techniques for repairing and strengthening of the Monza cathedral bell-tower. *Construction and Building Materials* 2002;16: 385-395.

[4] Giannini,R., Pagnoni, T., Pinto, P.E., Vanzi, I., 1996. Risk analysis of a medieval tower before and after strengthening. *Structural Safety* 18(2/3): 81-100.

[5] A. Carpinteri, S. Invernizzi, G. Lacidogna, Nonlinear simulation and damage assessment of an historical masonry tower, *Fracture Mechanics of Concrete Structures*, (eds. V.C. Li, C.K.Y. Leung, K.J. William, S.L. Billington), American Concrete institute, USA, Vol. 2, pp. 709-716, 2004.

[6] Rots JG, Nauta P, Kusters GMA, Blaauwendraad J. Smeared crack approach and fracture localization in concrete. *Heron* 1985;30(1):1-48.

[7] Rots JG. (Ed.). *Structural masonry - An experimental/numerical basis for practical design rules*. CUR report 171 (in Dutch), Gouda: CUR; 1994. (English version) Rotterdam: Balkema; 1997.

[8] Carpinteri A, Lacidogna G. Monitoring a masonry building of the 18th century by the acoustic emission technique. In*: Proc. of the 7th International Conference on Structural Studies, Repairs and Manteinance of Historical Buildings*, Bologna; 2001, p. 327-337.