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AN ASSESSMENT OF THE STRUCTURAL BEHAVIOUR OF THE GARISENDA TOWER IN BOLOGNA THROUGH FINITE ELEMENT MODELLING AND STRUCTURAL HEALTH MONITORING

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Abstract

The Garisenda Tower, built in the XI century in Bologna (Italy) is a tilted Tower of 48 m high, with a square cross section, that represent the cultural symbol of the city. From the date of its construction, the tower was subjected to various accidents (such as fires, lightings and earthquakes) and interventions of consolidation. Nevertheless its structural configuration and the natural decay of the materials during the years, makes the tower inherently vulnerable to static and seismic actions, thus requiring a constant evolution of its structural health. The purpose of the study is to evaluate the current structural health of the Garisenda tower, through the development of a number of Finite Element models, in order to account for the influence of the geometrical configuration (actual inclination, cross section variability), peculiar construction techniques ("a sacco" masonry) and potential material degradation. To this aim, it has been of fundamental importance to integrate information related to both the actual geometrical configuration from data provided through static and dynamic monitoring and masonry texture, quality and material mechanical properties. In particular, to evaluate the effects caused by an eventual reduction in the material properties at the base, composed by selenitic stones, on the structural behavior, Three Dimensional Finite Element models with brick elements have been developed. The results of the FE analyses indicate that a material degradation at the base of the Tower could lead to local increase of stress levels close to material strength. Moreover, the analyses results also allow to better interpret some trends of behavior as resulted from the monitoring data.

Keywords: Masonry tower, Structural Health Monitoring, Three Dimensional Finite Element Methods

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1 INTRODUCTION

The correct management of the historical buildings is a matter of crucial importance that passes through a deep knowledge of their present state and its eventual evolutions during the centuries. The availability of only partial information regarding the original project and the construction techniques, together with strong limitations in the number and extent of in-situ tests for materials characterizations (related to preservation issues), make the assessment of the actual safety level of a monumental building of extreme difficulty [1]. For this reason, data acquired from a structural health monitoring system become of fundamental importance since their proper interpretation may help in increasing the knowledge and better understanding the structural behavior of the monument. The aim of the present study is the analysis of the current structural health of the Garisenda tower. The Garisenda tower is a masonry tilt tower built in the XI century in Bologna (Italy). Although several studies and strengthening interventions have been carried out in the last decades, a continuous attention should be payed on the evaluation of the structural health and on the consequences of the natural decay of material properties in terms of safety and stability [2]. In the present work, the assessment of the current structural behavior of the Garisenda tower is conducted through different Finite Element (FE) models able to take into account the actual geometrical state and variation of inclination as detected from the monitoring system as well potential material degradation at the base. First, the available knowledges related to the tower geometrical configuration and material properties are illustrated and correlated/integrated with the information obtained from the static and dynamic monitoring. Then, the results of structural analysis carried out by mean of FE models with different levels of complexity and accuracy are presented. In particular, to evaluate the effects caused by a material degradation at the base on the structural behavior, Three Dimensional Elements models were performed.

2 GARISENDA TOWER

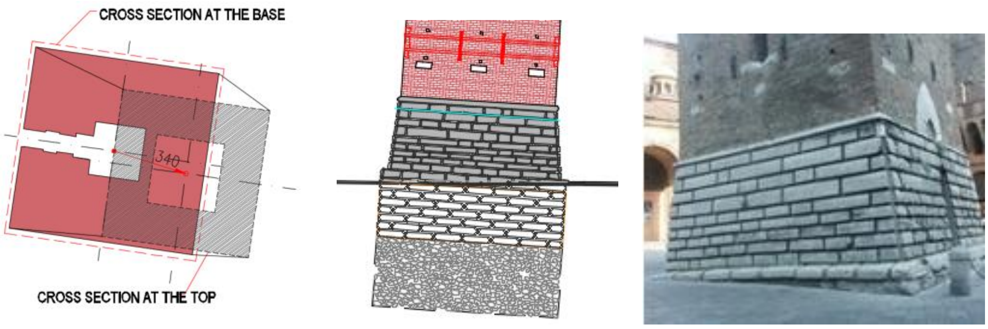
The Garisenda tower, built in the heart of the city of Bologna in the 11th century, together with its nearby Asinelli tower, is known as one of the "The Two Towers", that are the main cultural symbol of the city (Fig.1a)[3]. It has a height of 48 m and with an overhang of 3.4 m towards South-East. It is one of the most leaning Tower in Italy.

a) b)

Figure 1-a) The Two Towers of Bologna (Asinelli and Garisenda towers). b) The Garisenda tower

2.1 Geometrical configuration and material proprieties

The cross section of the tower, approximately square, is composed by two external skins and an internal infill. Its thickness decreases with the height as shown in Figure 2a. Starting from the foundation, the first few meters of the tower are composed by an external and internal perimeter of selenitic stones (thickness of around 50-60 cm). In 1889, another external selenitic layer was added to cover the heterogeneous and unsightly portion of the wall in the first 3.5 m (Figure 2b) [4].The properties of the material, summarized in Table 1, have been characterized through in situ tests (both destructive and non-destructive) [5].



(a) (b) (c)

Figure 2-a) Tower cross section at two different heights (b) Foundation (c) External selenitic stones

Material	Specific Weight γ	υ	Elastic Modulus E_m	Compressive strength f_m	Shear strength $f_{v,m}$
	[KN/m^3]		[MPa]	[MPa]	[MPa]
Masonry bricks	18	0.2	3000	4	0.5
Selenitic stone	24	0.2	5000	7	0.7
infill	17	0.2	2500	4	0.5

Table 1: Material properties

2.2 The Static Structural Health Monitoring (SHM) results

A static SHM system was installed on the Garisenda tower at the beginning of 2011. This system allows monitoring: movements of the main cracks, deformations of critical portions of masonry, inclination, strains along the steel ties (installed on the height of the tower to provide a lateral confinement to the masonry) and environmental parameter (such as temperature, wind speed). Additional details on the monitoring system are available in previous work developed by some of the authors [6], [7]. The results obtained from the analyses of the data recorded by the SHM system highlighted a slight evolutionary trend especially in relation to the inclination. Six inclinometers are installed in the East and South fronts at different levels (13.20 m, 30.65m and 43.3m). The data recorded show an increase in the Tower inclination toward East of around 1.3 mm/year and also a slight inclination northwards.

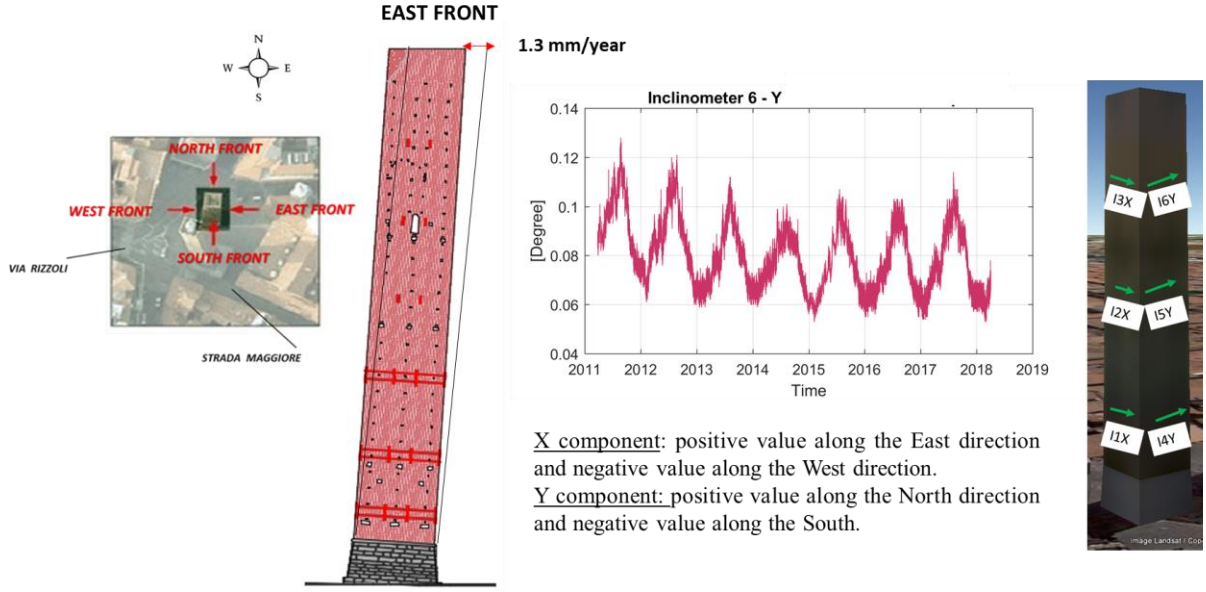


Figure 3-(a) Inclination detected toward East from the X-component of the inclinometers. (b)Inclination detected towards North Y-component of the inclinometers

2.3 Actual state of degradation

Over the last year, some surveys and visual inspections revealed that small portions of the selenitic layer are degrading and becoming chalk, with a significant reduction of the mechanical characteristics of the original stone. This phenomenon is observed at the base in the corner under slope, both on the outside and in the inner side (Figure 4a). Externally the selenitic blocks, that cover the first meters of the tower, have suffered relative displacements mainly concentrated on the East front (Figure 4b). The internal selenitic stones, on the other hand, show the presence of a deterioration process underway due to chemical processes linked to humidity. This phenomenon is particularly pronounced in the South-East corner (Figure 4c).

(a) (b) (c)

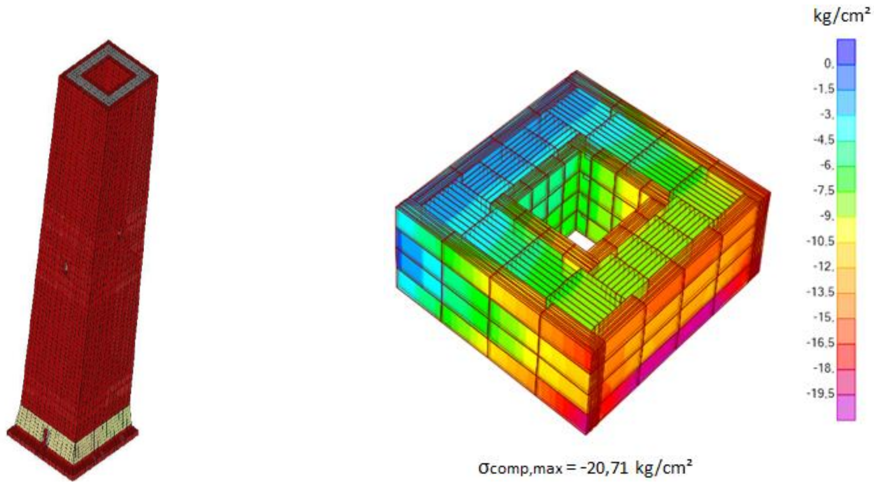
Figure 4-(a) Corner mainly affected by the degradation phenomenon. (b) Displacements of the selenitic blocks of the East front (c) Degradation of the internal selenite basement

3 NUMERICAL ANALYSES

Structural analyses have been carried out on 3D FE models of the tower in order to assess (i) the effect of static loads and wind accounting for the tower inclination and thermal variations, (ii) the dynamic properties through comparisons with data from SHM, (iii) behavior under earthquake loadings, (iv) the influence of the material degradation at the basement on the structural behavior, (v) possible cause of specific trend detected through the SHM [2]. In this section, for sake of conciseness, the attention is focused only on the study of the variation of the stress levels due to the material degradation at the base of the tower by means of a Three-Dimensional Finite Element Model (Figure 5a). In detail, the following models/limit cases have been considered:

1) UNDmodel: model with materials having full strengths and elastic moduli according to values provided in Table1,
2) DEGmodel_1: model with a portion of the external and internal selenitic stones having reduced values of elastic moduli (Figure 6a);
3) DEGmodel_2: model with a portion of the entire wall (including the internal infill) with reduced elastic moduli,
4) DEGmodel_3: model with the entire East side with the external selenitic stones having reduced values of elastic moduli.

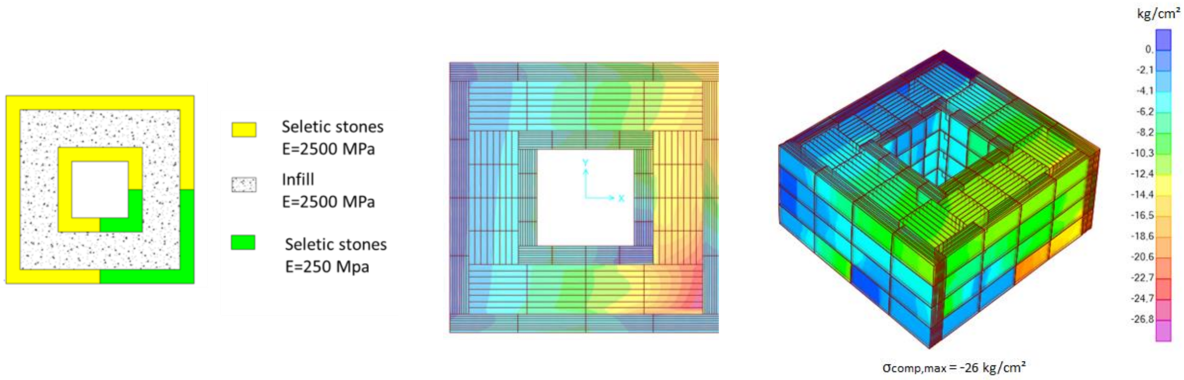
First, the stress levels as obtained from UNDmodel are reported in figure 5b. It can be noted that the maximum compressive stresses accumulates on the external selenitic blocks concentrated on the South-East corner (around 2 MPa), while the internal infill achieves compressive stresses of the order of 1 MPa.



(a) (b)

Figure 5-(a) Three-Dimensional Finite Element Model of the Garisenda Tower. (b)Stress levels at the base of the tower considering the material not degraded.

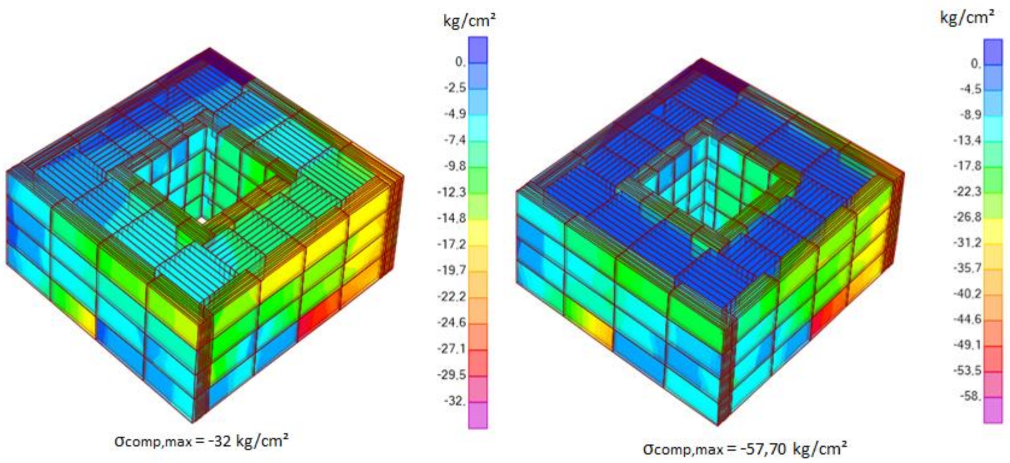
In model DEGmodel_1, the degradation detected in the external and internal perimeter constituted by blocks of selenite has been simulated progressively decreasing the elastic modulus of the material in the South-East corner, evidenced in green in Figure 6a (in particular several analyses have been carried out reducing the elastic moduli from 2500 to 250 MPa). The analyses have been conducted considering only the self-weight. The results obtained in terms of contour maps, considering an elastic modulus of the corner equal to 250 MPa, are presented in figure 6b. It can be noticed that the maximum value of the compressive stress in selenitic blocks remains of the same order of magnitude whilst increase in the infill (reaching values of the order of 2.6 MPa).



(a) (b)

Figure 6-(a) Identification of the areas interested by the reduction of the Elastic modulus. (b) Contour maps, considering an elastic modulus of the corner equal to 250 MPa

DEGmodel_2 includes the effect of a possible deterioration in the infill material through 2 reductions in the elastic moduli: (i) from 3000 MPa (initial value) to 1500 MPa, (ii) from 3000 MPa (initial value) to 300 MPa. Figure 7 displays the contour maps of the stresses levels in the selenitic stones and infill for the two cases. It can be noticed that the degradation of the infill causes a redistribution of the tension moving the maximum stresses in the selenitic stones close to the deteriorate corner (peaks of the order of 3.2 MPa and 5.7 MPa).



(a) (b)

Figure 7-(a) Contour maps of the stress level at the base section obtained reducing the infill Elastic modulus by: (a) 50% and (b) 90%

DEGmodel_3 investigates the possible cause of the inclination detected by the inclinometers in the North direction of the tower. In this model, the properties of the selenic stone for all the external portion of the East side were reduced to 250 MPa. This phenomenon could be related to the results obtained by recent investigations that detect a small cavity on the Eastern front towards the edge opposite to the one actually under slope, causing a weakening of the section. From this latter case, it can be inferred that if all the side under slope as well as the internal infill would become completely deteriorated, there would be peaks of tension in the infill of the order of 3.5 MPa and close to material strength. Analysing the displacements in the Y-direction of this model (corresponding to North direction of the tower), it has been possible noticed that the presence of a degradation in all the side under slope actually provokes a displacement, although of the order of tenths of millimetres, in North direction.

4 CONCLUSIONS

The main conclusion of the present work can be summarized as follows:

- The structural health of the Garisenda tower has been investigated with a particular attention to the effects of the potential material degradation detected at the base of the tower. First, the present state of the tower has been studied through survey and non-destructive tests correlated to the data obtained by a static and dynamic monitoring system.
- The effects caused by a reduction in the material properties at the base, composed by selenitic stones, on the structural behavior, has been investigated by means of Three Dimensional Finite Element models with brick elements.
- Considering the degradation only in the selenitic stone and with a concentration in the South-East front, the results obtained reveal that the maximum compression value in the selenite blocks remains substantially unchanged but creates a sort of arc effect that leads to the loading of the first blocks alongside the deteriorated ones.
- A deterioration of the infill material would cause tensions that could reach the limit of the material strength with a considerable reduction of the safety levels of the building.
- In addition, it has been confirmed that the tower is undergoing a slight displacement northwards due to a deterioration of the coating portion on the North-East front.

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