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Assessing the seismic vulnerability of a historical building

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ABSTRACT

The work deals with the structural analysis of an historic masonry building, *Palazzo del Capitano* in Mantua, subject to significant static instabilities due to an overturning of the longitudinal façades, probably related to ground settlements.

The exact geometry of the structure is acquired by means of the laser scanning technique and thanks to previous investigations, the main mechanical properties of the materials are reasonably well defined.

Based on these information a three-dimensional finite element model of the entire structure is implemented, taking into consideration all the geometrical (contact between not connected panels and large displacement effects) and material (elasto plastic damage behavior of the masonry) nonlinearities, in order to investigate the seismic behavior of the structure by means of nonlinear dynamic analysis.

The outcome of the analysis points out that the longitudinal façade, overlooking *Piazza Sordello*, is poorly constrained both to the floors and to the transverse bracing elements, therefore not able to counteract its deformation when a seismic event occurs.

Finally suggestions to reduce the seismic vulnerability of the building are critically assessed by the implemented finite element model.

1. Introduction

The conservation and the restoration of ancient buildings belonging to the culture heritage, preserving their main architectural features, are becoming a very sensitive problem in Italy as in other Countries. In fact, many historically interesting structures in most of the Italian cities are currently used with different functions, such as residential areas, offices, and museum centers; and hence they require a sufficient level of safety against to both the vertical and horizontal loads. In particular, the seismic vulnerability of such structures is a point of extremely high concern since these buildings usually posses a very low seismic resistance.

Italy is one of the countries with the highest seismic risk in the Mediterranean area. This is primarily due to the high frequency and intensity with which earthquakes occur. These seismic phenomena are a consequence of the geographical position of the country in the area where the African plate and the Eurasian one converge.

The seismic risk of a structure is a measure of the expected future damage caused by the earthquake which is expected to occur in the site of construction. It depends on three factors: hazard, the intensity of the expected seismic action; vulnerability, a measure of the inadequacy of the structure to resist to seismic actions; and exposure, which is related to the architectural value of the building and to the possible consequences of any structural damage in terms of loss of human lives.

In this paper we investigate the structural response of *Palazzo del Capitano* in Mantua, in relation to both static and seismic conditions. This building is located in the northern part of Italy in the *Lombardia* region, classified by the Italian code as an area of low seismic hazard, but where on May 29th, 2012, a 5.2 Richter scale earthquake occurred. This building, whose construction dates back to the thirteenth century, is part of the *Palazzo Ducale* complex and represents, for its position and for the majesty of its size, one of the most spectacular creations of the Italian architectural landscape, see Fig. 1. The building has had significant static problems related to the inclination of the longitudinal façades, probably due to ground settlements, for many centuries. The first documents describing these problems date back to the early years of the eighteenth century. This deformation scenario appears to be accentuated especially at the level of the second floor, where the great hall, called *Salone dell'Armeria*, takes up the whole storey. Between the end of the eighteenth century and the early years of the twentieth one provisions were taken to contain these out of plane displacements, such as the inclusion in the *Salone dell'Armeria* of some tie-rods and bracing walls.

The seismic behavior of old masonry structures is particularly difficult to be investigated, see e.g. [1]. It depends on many factors such as material properties, to be characterized by direct inspection, see e.g. [2]; geometry of the structure, to be defined by proper surveys; stiffness of the floors (diaphragm effect) and connection

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between orthogonal walls and structural and nonstructural elements. In particular the key point is the material behavior modeling. In fact experience shows that masonry mechanical behavior is dominated by the nonlinear phase, characterized by cracks opening, dissipative and brittle behavior with a softening branch. The modeling of these materials still represents a challenge in the scientific community. Many efforts were made in the last years to improve the modeling techniques for masonry structures, see e.g. [3–6]. Elasto-plastic analysis may be used to simulate masonry nonlinear behavior, however they fail to simulate crack formation and the brittle behavior when the material enters the softening regime. Limit analysis methods have been frequently applied in order to investigate the collapse mechanism of masonry structures subjected to given load distributions, see e.g. [7–10]; however, these approaches fail to consider the actual dynamic nature of the load condition under seismic excitation, which represents the major concern for this type of buildings. Smeared crack approaches or damage models may be used to simulate the local loss of strength masonry material suffers when it enters the nonlinear behavior, see e.g. [11–13]. However, the numerical analysis itself is still a very difficult task especially when dealing with large and complex structures. As an alternative to modeling masonry as a homogenized continuum, discrete element approaches may be applied to model the structure as an assembly of blocks with suitable interface laws, see e.g. [14,15].

In the present paper the importance of considering the exact nonlinear and three dimensional behavior of the masonry structure is shown, in order to put in evidence all the structural deficiencies of the palace when an earthquake occurs. To this purpose the exact geometry of the structure is reconstructed by means of a laser scanning technique, while information regarding the mechanical properties on masonry material are derived by previous investigations and literature search. Based on these information a three dimensional finite element model, endowed with an elastic plastic damage constitutive law, is adopted to determine the seismic vulnerability of the building by means of nonlinear dynamic analyses.

After a careful diagnosis and evaluation of the safety of the structure in its current state, suggestions for retrofitting the building, without altering its original conception and historical value, and reduce its seismic vulnerability are critically assessed by the above implemented finite element model.

2. History of the building

Some parts of the historical background of *Palazzo del Capitano* are still unknown, especially those referring to the ancient period, until the eighteenth century and the Austrian domination.

The Palace construction can be placed at the same living time of the first Lords of Mantua, possibly between the last years of the thirteenth century and the first decade of the fourteenth century. It was originally used as the residence of the Lords until the second half of the fifteenth century, when St. Giorgio's Castle was built.

During the *bonacolsiano* period the building was lower with one single floor, narrower without the front arcade, and shorter because the northern part originally coincided with an alley (located where the entrance to the palace currently is) that separated it from the adjacent *Magna Domus*.

Subsequently, probably around 1328, the Gonzaga family came into possession of the original nucleus, expanded it with the creation of the new front of *Piazza Sordello* and with the extension beyond the alley that separated the *Magna Domus* and finally raised an upper floor, consisting of the great hall called *Salone dell'Armeria*.

The new façade of *Palazzo del Capitano*, overlooking *Piazza Sordello*, was built following the model of the adjacent *Magna Domus*. It was proposed indeed a partition of the front: at the ground floor a marble arcade, at the first floor a series of single lancet windows and at the second floor double lancet ones with round arches, built always along the lines of those of the adjacent building.

The rear front of *Piazza Pallone* conformed differently from the front one. The ground floor had no arcade and on the whole façade it is difficult to reconstruct the original openings, owing to the limited evidence and the numerous reconstructions.

As far as the configuration of the façades is concerned, it is reported that in the second decade of the fifteenth century, Gian Francesco Gonzaga closed the double lancet windows with round arches on the second floor and opened others with pointed arches.

With regard to the original configuration of the interior spaces of the building, it is believed that the environment preserving more traces of the past is the original gallery on the first floor, *Corridoio del Passerino*. It was originally subdivided into various rooms by means of wooden partitions, then removed between 1902 and 1906, to reduce the load on the underlying arcade. The *Salone dell'Armeria* was conceived as a great open space initially used as a representation room and then as a weapon depot. It held its original features until interventions were made in the twentieth century.

The beginning of the eighteenth century sanctioned the end of almost four hundred years of Gonzaga domain. Between 1708 and 1866 there was a period of transition characterized by foreign domination starting from the Austrian Government then passing to the French one. Throughout the course of the eighteenth century various restoration works were made to the roof and to the timber beams in the *Salone dell'Armeria*, as shown in various official surveys and reports from the Austrian Government. In particular, the first documents stating the presence of inclination of the longitudinal façades and of some tie-rods in the great hall date back to the first half of the eighteenth century.

In 1866 Mantua entered the Reign of Italy, which in 1946 became the Italian Republic. This was – more specifically between 1898 and 1937 – the period of greatest activity around *Palazzo Ducale*. While works of recovery of the Renaissance appearance of the front façade of the *Palazzo del Capitano* began and were completed, the fears for the stability of the structure of the palace were becoming stronger and stronger. In 1906, to reduce the inclination of both longitudinal walls (the one over *Piazza Sordello* leaning toward the interior of the hall and the one over *Piazza Pallone* leaning toward the outside) the decision of building in the *Salone dell'Armeria* a bracing system consisting of tie-rods and three masonry partitions walls was reached. In particular two walls overlapping with the transverse walls of the rooms below were

Fig. 1. Picture of *Palazzo del Capitano* in its current state taken from *Piazza Sordello*.