



Seismic vulnerability assessment of a monumental masonry building



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ABSTRACT

The seismic assessment of monumental buildings requires the consideration of safety and conservation objectives, both for the building and its cultural heritage assets. In order to face these issues, the paper presents the results of a diagnostic analysis carried out on a specific monumental masonry building: the Civic Museum of the small city of Sansepolcro in Tuscany. The building is one of the most important and renowned civic structures, built by a mediaeval Commune to house the town government, this building is also characterized by the presence of one of the masterpieces of late 15th-Century Renaissance art: “the Resurrection”, a large fresco painted by Piero della Francesca. Within this context, three modelling strategies of different complexity are proposed: equivalent frame model, rigid macro-block model and finite element model. In the first part, a full three-dimensional non-linear static analysis and a more simple approach directly based on the limit analysis theorems are used in order to understand the macro-scale structural behavior. Afterwards, the results of the finite element method analyses performed on a detailed 3D model of the wall panel containing the fresco are used in order to investigate the causes of the crack pattern on this important artistic asset.

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1. Introduction

The analysis of interpretative models that can effectively define the “structural safety” of historic constructions belonging to cultural heritage is currently a topic of great attention. Whilst for new masonry constructions it is possible to achieve important information toward the correct interpretation of their structural behavior, and then have adequate tools to properly evaluate their response to severe earthquakes, when an analysis involves historic masonry structures such tasks becomes complex, mainly for two different reasons: (i) difficulties in understanding and modelling the seismic response of historic constructions, because these were designed using an empirical approach; (ii) problems in acquiring data on material mechanical properties and structural details (e.g. connections between walls, etc.), due to their dispersion and the need of avoiding expensive and destructive tests [1]. To complicate the problem, the conservation of heritage structures should last over time against degrading agents and natural decay, without losing their integrity and authenticity. This means that the need to guarantee an “acceptable level” of structural safety for building’s occupants should be always related to a principle of “minimum

intervention” to the building. Within this context, a common denominator among the best-known international guideline documents [2–4], on the assessment of cultural heritage assets, is a qualitative method. Qualitative methods are based on the analysis of historical construction stages (which can occur in different periods in history) and antique original documents, the precise survey of architectural details and the interpretation of the seismic behavior of the building, based on the damage (due to previous events, if any) or on similar structures.

Furthermore, it should be considered that any risk assessment analysis for a masonry structure should involve both architectural parts (arches, partition walls, facades, openings, etc.) and artistic assets (statues, pinnacles, frescoes, paintings, libraries). The analysis of effects of an earthquake on the artistic assets that are present in an historic construction is new and is becoming more important to the heritage bodies, mainly because extensive damage could be caused to these assets by earthquakes of small magnitudes. For their conservation and protection, the analysis of the damage mechanisms is crucial and, to evaluate their vulnerability, the development of appropriate numerical modelling methods is essential [5–9].

This is the background of this investigation dealing with an important historic construction, the Civic Museum of Sansepolcro, that besides being one of the most renowned civic structures built

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by an Italian commune during the Mediaeval times to house the city government, it is also characterized by the presence of one of the masterpieces of late 15th-Century Renaissance art: “the Resurrection”, a large fresco painted by Piero della Francesca.

Following the procedure introduced by Lagomarsino and Cattari [1] for the analysis of the seismic vulnerability of architectural and artistic assets, the evaluation process used to perform this task, takes into account several contributions from different research areas and involves two key stages which are iterative and continually informed each other: phase 1 (or knowledge stage) and phase 2 (or analysis stage). In such a context, it is important to emphasize how the two subsequent levels of analysis should not be intended as a one-way process, but the results of the structural analysis has to come from the reiterative check of the outcomes of the knowledge level.

Thus, since the main concern of the first stage is the achievement of an extensive knowledge of the fabric for structural analysis, in the first part of the paper, an overview of the construction stages of the Museum and in particular of the wall containing the fresco during the centuries is presented. Afterwards the geometric and damage survey, carried out to provide all the data necessary to complete the following numerical modelling stage, is described. The on-site investigation, aimed at qualitatively defining the structural composition of relevant parts of the building, is also illustrated.

Next, to study the structural behavior of the building and of its greatest artistic asset, the Piero Della Francesca’s fresco, in the second stage a performance based multi-scale approach is followed [1,10,11]. In such a context, according to the NTC [12] and IMIT [13] instructions, a global analysis of the Museum is made by using the equivalent frame approach. In particular, a full three-dimensional (3D) pushover analysis is performed to predict the macro-scale behavior of the building. Afterwards, since a comprehensive assessment would also require to analyze possible local collapse mechanisms (mainly out-of-plane ones), a macro-element approach based on the limit analysis theorems is used complementarily to the global analysis. After completing the analysis phase at macro-scale level, it has been considered crucial to have, at a more detailed level, a more precise assessment of the seismic vulnerability of the wall containing the fresco. To this end, the results of a Finite Element (FE) analyses carried out on a detailed three-dimensional model of the wall are used to provide an interpretation of the observed cracking pattern.

2. As-built information

To study the actual structural state of both the building and the wall panel supporting the Piero Della Francesca’s fresco “the Resurrection” a standard diagnostic procedure (historical background, surveying and nondestructive testing) was conducted [14–17].

2.1. Historical background

The Piero Della Francesca’s fresco known as “the Resurrection” is located in the Civic Museum of Sansepolcro (Italy), one of the most interesting architectural complex built by a mediaeval Commune to house the town government (Fig. 1). Historically known as “Palazzo della Residenza”, since the representatives of local power held their meetings there, this building is the result of a series of complex architectural modifications related both to the transformation of the urban site and to the change in use of the building itself. Constructed in various stages, the entire complex is, in fact, a stratified structure that consists of three main structural units (A, C, D) joined together by two 15th-century masonry buildings (E).

The first section of the structure (A) appears to date back to the second half of the 13th century and incorporates an older tower (B), which contained a prison in use until the 19th century. A stonework stair connects the floors of the unit, while on its east side, a great barrel vault (G), perhaps recalling the original gate of the old town, connects the first floor of the building (the so-called “piano nobile”) with the Government building (H), headquarters of the Government Auditor.

Once it had become the seat of the Florentine Commissary along with its offices, in the middle of 15th century, the palace was included in an urban redevelopment programme. As far back as 1444, work first began with the construction of two monumental rooms (Piero’s and Matteo di Giovanni’s rooms, C) that stood above a pre-existing underground level (a storage basement). Hence, exploiting its structural potential, new buildings (E, F), aimed at a more regular and uniform layout, were added to the structure, which took on the features of a typical 15th-century Tuscan palace. During this period, entrusted with the job of completing the extension and modernization work of the palace’s interior, Piero Della Francesca painted the prestigious “the Resurrection” (ca. 1460) on the essential bare wall between Piero’s and Matteo di Giovanni’s rooms (Fig. 2). Despite the numerous subsequent changes made over the centuries, the 15th century layout is still legible while visiting the present-day rooms of the Museum. The last modification of the structure dates 18th century, when a new building (D) was added, giving the structure the current L-shaped layout with an inner cloister. Converted to the Civic Museum in 1975, the complex owes much of its current appearance to work carried out between 1991 and 1997, during which the courtyard was covered with a glass structure and the original entrance, which opened onto the square, was substituted by a large glass door that maintains a continuity between the internal and the external and renders the different historical phases tangibly visible.

2.2. Surveying

Even if Sansepolcro did not experience any devastating earthquakes in the past, an evaluation of the of historical seismic activity in such area [18] shows how the Civic Museum was exposed to an earthquake of degree 9 in the Mercalli-Cancani-Sieberg (MCS) scale in the past and to seismic events stronger than magnitude 7 (MCS scale) at least three times since the Piero Della Francesca’s fresco was painted (Fig. 3).

In such a context, using past earthquakes as full scale tests, the actual damage location shown by the construction is an important indication of the seismic response of the construction, and it highlights the parts of the masonry structure with higher seismic vulnerability.

The crack pattern of the construction is quite complex: since no or little coupling effect can be operated by the horizontal (flexible) floors, vertical structures (walls) tend, in fact, to behave independently. Damage seems to localize maximally in correspondence of the longitudinal façades, north and south (Fig. 4), being massive structures presenting significant heights and lack of transversal walls as bracing elements. It is possible to note that on the southern façade there is a relevant out-of-plumb (of about 60 mm, based on a general estimate), as a consequence of an out-of-plane rocking displacements of the perimeter walls (with a limited detachment of the façade from the masonry structure). Under such conditions, the internal wall panel supporting the Piero Della Francesca’s fresco, being the only shear resistant wall able to restrain the overturning motion of the southern façade, manifests a severe cracking pattern, characterized by a combined failure mode with vertical and diagonal cracks (Fig. 5).

Conversely, the western and eastern façades appears to be in a decent state of conservation, since almost the totality of

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