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An innovative numerical modeling strategy for the structural analysis of historical monumental buildings

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ABSTRACT

In this paper, an innovative numerical modeling strategy for the structural analysis of historical monumental buildings is presented. The strategy is based on a procedure that enables the semi-automatic transformation of a three-dimensional points cloud surveyed through terrestrial laser scanner or closed range photogrammetry into a three-dimensional finite element mesh, as well as its mechanical characterization. Therefore, an increase of the level of automation in the mesh generation process is attained and a large reduction in the required time in comparison with traditional modeling procedures is achieved. In order to validate the new strategy, an application to the case study of the San Felice sul Panaro (Italy) fortress is carried out. The reliability of the proposed model is assessed through a comparison between the results of structural analyses and the crack pattern experienced by the structure during the Emilia earthquake (2012). Moreover, the vulnerability assessment of the main tower of the fortress is performed through simplified pushover analyses conducted on the generated mesh.

1. Introduction

The conservation of historical buildings often exploits structural analyses as a way to better understand the authentic structural and constructive features and to estimate the safety conditions of the building. Typically, structural analyses are a fundamental tool to catch the weaknesses of the structure under vertical or seismic loads, which is necessary to understand the cost and magnitude of the safety interventions required [1–4].

Historical structures are characterized by an enormous complexity in terms of geometry, materials properties, loads and boundary conditions, hence, in most cases, the Finite Element Method (FEM) has been used in order to model these features. From the first significant contributions [5–7], related to famous examples of architectural heritage, the FE analysis of historical buildings has been considerably developed. An interesting review of classical and advanced approaches for the structural analysis of masonry historical constructions can be found in [8]. A contribution to the issue of FE modeling and analysis of architectural heritage through the discussion of an illustrative case study of an Italian medieval castle has been presented in [9], where a three-dimensional numerical model of the castle has been used to identify the main sources of damage and assess the effectiveness of the restoration works. Another significant contribution is the structural and seismic assessment of the 19th-century Petruzzelli theater in Bari (Italy), presented in [10]. The numerical model of Brunelleschi's Dome of Santa Maria del Fiore, with an *ad hoc* nonlinear procedure to replicate the mechanical behavior of masonry, has been reported in [11]: the obtained results allowed to assess and discuss both the Dome's internal stress and cracking pattern. In [12], a multidisciplinary approach, with a balanced fusion of historical analysis, precision surveys, experimental inspections and numerical modeling, enabled to spot the damage mechanisms of the French Panthéon. In [13], the seismic assessment of an old masonry tower has been addressed by developing three FE models with different levels of complexity while, in [14,15], the seismic risk assessment of a masonry chimney has been evaluated by using advanced analysis techniques. Moreover, the FEM modeling of the towers of a temple in Cambodia has been presented in [16], whereas a comparative numerical study on a 12th-century masonry tower has been described in [17]. To assess the safety of the tower under seismic loads, the authors employed different numerical analyses such as nonlinear static, limit, and nonlinear full dynamic analyses. Finally, in [18], the results of a wide numerical campaign conducted on the clock tower in Finale Emilia (Italy), collapsed during the main shock of the devastating Emilia earthquake seismic sequence (2012), are collected.

From the above literature overview, it appears that the interest for the numerical modeling of historical buildings increased in

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the last years and that the FEM can be considered as an effective tool to investigate the structural behavior of this kind of buildings. Notwithstanding this, the numerical modeling of historical monumental buildings is still a challenging task for contemporary civil engineers. One of the main reasons for this is that, due to the complex geometry of such historic structures, the use of traditional simplified structural schemes is inadequate. Thereby, it is unavoidable to resort to a fully three-dimensional modeling that often is performed using the Computer Aided Design (CAD), as is the case in most of the cited studies. In general, CAD based modeling is an expensive and complex process, often manually carried out by the user, which inevitably leads to the introduction of geometric simplifications (*Defeaturing*) or interpretations.

In order to reduce the time that the user has to spend to reproduce the complex geometry of these structures, a precious support can be supplied by automatic advanced survey techniques such as Terrestrial Laser Scanner (TLS) [19] and terrestrial photogrammetry [20], which can generate three-dimensional detailed points clouds in a rapid way. Although the TLS is still today an expensive survey technique in comparison with closed range photogrammetry systems [21], its usage is showing a high growth coupled with a continuous technological development. In particular, in the field of architectural heritage several TLS and photogrammetric applications have been performed: from simple documentation [22] to monitoring the condition of historical buildings, and also in order to support restoration works or structural checks [23,24]. An example is reported in [25], where a detailed geometric survey of a Portuguese Castle is conducted by means of the laser scanning technique, allowing for a precise characterization of dimensions and disposition of the masonry blocks used for the FE discretization. Another example is shown in [26], where the significant deformation of a Spanish Church has been surveyed by means of TLS: the three-dimensional structural model has been created in a CAD environment using the results of the laser scanner survey. Thereby, the current deformation of the church has been directly considered in the structural analyses.

Several studies try to transform three-dimensional points clouds in FE models, but in most cases the output is simple or dramatically simplified. For instance, in [27] a three-dimensional points cloud is used to generate models of the cross sections of historical walls for structural analysis application, while in [28] an example of FE analysis of a historic theater is performed using laser scanning data limited to the inner surfaces of the building. Massive structures, such as masonry bridges can also be investigated by summing the laser scanner survey information to those obtained by ground penetrating radar and as a result generate a fine picture of the external and internal features [29]. Here, the cloud simplification lies on the sampling of some points that are useful to reconstruct the geometry by means of regular shapes. Other interesting contributions are proposed in [30,31], where an attempt to precisely capture the geometry of the building through the automatic reconstruction of its boundary is presented. Moreover, in [32] a point-based voxelization method to automatically transform point cloud data into solid models for computational modeling is developed. The method constructs a Triangular Irregular Network (TIN) mesh by means of a voxel grid bounding the cloud region. The resulting model captures the three-dimensionality of the survey, but does not capture the whole structure, since it is designed for the façade only.

One of the most frequent problems when dealing with complex historical buildings is the impossibility to generate "closed surfaces" from the point cloud of the surveyed object. Thereby, it is not possible to directly transform the TIN mesh surfaces into solid geometry and consequently into a FE mesh, as done, for instance, for agricultural objects in [33] and for Michelangelo's David in [34]. In order to solve this lack of numerical tools, recently in [35,36] the authors developed a procedure that allows the simple and rapid transformation of a three-dimensional point cloud into a FE model. The procedure, called *CLOUD2FEM*, starts from TLS or photogrammetric surveys of historical monumental buildings and semi-automatically generates FE models.

On the basis of this procedure to generate FE meshes, an innovative numerical modeling strategy for the structural analysis of historical monumental buildings is presented in this paper. The strategy is mainly composed of: (i) a structural breakdown that allows a fine semi-automatic creation of the geometrical domain starting from a TLS or photogrammetric survey; (ii) a structural discretization capable of always guaranteeing the generation of the FE mesh by means of three-dimensional hexahedral elements; and (iii) an easy and effective treatment of the mechanical characterization of the FE mesh and of the connections between adjacent macro-elements. The main innovative feature of the proposed numerical modeling strategy of historical buildings consists mainly in the possibility to intensely exploit TLS and photogrammetric surveys of historical buildings for structural purposes, with a large reduction in required time in comparison with CAD-based modeling procedures and with an increase of the level of automation in the mesh generation process.In addition, this novel approach resolves the auto-meshing failure issues which often characterize historical structures complex geometries. Moreover, a detailed materials characterization of the generated models is achievable, as well as the possibility to iteratively sub-structure the numerical model. Finally, the simplified management of adjacent macro-elements connections is useful to assess their structural interaction.

In order to show the potential and the reliability of the proposed strategy, the application to the case study of the San Felice sul Panaro (Italy) fortress is presented. This application aims at validating the numerical strategy from the structural point of view according to the requirements of the Italian guidelines on cultural heritage [37] (§2.5). Several linear and nonlinear static analyses under vertical and horizontal loads have been performed. Much attention has been paid to the modeling of the connections between fortress adjacent macro-elements. A comparison between structural analyses results and the crack pattern experienced by the structure during the Emilia earthquake (2012) has been carried out. Moreover, the vulnerability assessment of the main tower of the fortress is performed through simplified pushover analyses conducted on the generated mesh.

The paper is organized as follows. Section 2 presents the new numerical modeling strategy for structural analysis of historical monumental buildings. Section 3 presents the case study features. Section 4 summarizes the results of the structural analyses, validating the FE model through a comparison between the numerical results and the crack pattern affecting the structure due to the Emilia earthquake and showing the vulnerability assessment of the main tower of the fortress. Some concluding remarks end the paper (Section 5).

2. Numerical modeling strategy

The goal of the proposed strategy is to offer a simple and effective tool for scientists and practitioners to be able to build FE models of complex large-scale structures, such as monumental buildings, with a minimal time investment. To achieve this goal the strategy innovations are twofold: (i) simple and effective reduction of complex laser scanner and photogrammetric point clouds to FE models and (ii) simple and easy manipulation of the FE models into any commercial or custom FE code.