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A MESH GENERATION METHOD FOR HISTORICAL MONUMENTAL BUILDINGS: AN INNOVATIVE APPROACH

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Abstract. *The numerical modeling of historical monumental buildings is a challenging task for contemporary civil engineers. One of the main reasons for this is that the use of traditional simplified structural schemes is inadequate due to the complex geometry of such historical structures. Therefore, it is necessary to resort to a fully 3D modeling technique that is performed using Computer Aided Design (CAD). In general, CAD-based modeling is an expensive and complex process and it is often performed manually by the user, which inevitably leads to the introduction of geometric simplifications or interpretations. In this study, an innovative mesh generation approach for the structural analysis of historical monumental buildings is presented. The method consists in a peculiar breakdown of the geometry starting from laser scanner or photogrammetric surveys. Moreover, this new approach involves a structural discretization that guarantees the generation of 3D finite element meshes as well as their mechanical characterization. The most relevant feature of the proposed method is the possibility to directly exploit 3D and detailed point clouds surveyed on historical buildings for structural purposes. As a result, a large reduction in the required time in comparison to CAD-based modeling procedures is achieved. A geometrical and structural validation of the method is carried out on a masonry tower application. The findings show good reliability and effectiveness of the mesh generation approach.*

1 INTRODUCTION

Nowadays, when dealing with structural analyses of historical buildings the Finite Element Method (FEM) is very often used in order to manage the huge complexity of the problem. However, the numerical modeling of historical monumental buildings is still facing significant difficulties linked to the description of nonlinear non-homogeneous material such as masonry, of complex geometry and boundary conditions [1, 2, 3]. Indeed, the use of traditional simplified structural schemes is frequently inadequate. Consequently, the recourse to a fully 3D modeling using the Computer Aided Design (CAD) is commonly unavoidable. Generally, CAD based modeling is a laborious operation which inevitably leads to the adoption of geometric simplifications (*Defeaturing*) or interpretations to speed up the process.

In order to reduce the time required by the creation of the geometrical model of these structures, a crucial support can be supplied by automatic advanced survey techniques such as Terrestrial Laser Scanner (TLS) or photogrammetry, which can rapidly generate 3D detailed point clouds. In particular, in the field of architectural heritage several TLS and photogrammetric applications have been performed: from simple documentation to monitoring the condition of historical buildings, and also in order to support restoration works or structural checks [4, 5]. Moreover, aiming at designing the urgent rehabilitation interventions of damaged structures after seismic events the automated survey techniques (e.g. TLS or photogrammetry) are the only tools which can lead to a rapid and detailed 3D geometric acquisition of buildings.

Nevertheless, aiming at the rapid generation of FE meshes the high geometrical accuracy of the TLS and photogrammetric surveys become a drawback. Indeed, several studies try to transform 3D point clouds in FE models, but in most cases the output is too simple or considerably simplified. For instance, in [6] a 3D point cloud is used to generate models of the cross sections of historical walls for structural analysis application, while in [7] an example of FE analysis of a historic theater is performed using laser scanning data limited to the inner surfaces of the building. Other interesting contributions are proposed in [8, 9], where an attempt to precisely capture the geometry of the building through the automatic reconstruction of its boundary is presented. Moreover, in [10] a method to automatically transform point cloud data into solid models for computational modeling is developed. 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.

When dealing with complex historical buildings, one of the most frequent problems is represented by the impossibility to generate “closed surfaces” from the point cloud of the surveyed object. Therefore, it is not possible to directly transform the outer surfaces into a solid geometry and consequently into a FE mesh as done for various objects (see for instance [11, 12]).

Aiming at solving this lack of numerical tools, a new procedure for the rapid transformation of a 3D point cloud into a FE model has been presented by the authors in [13]. The procedure, called *CLOUD2FEM*, starts from an automated survey of historical monumental buildings and semi-automatically generates a FE model. In this study, in order to deepen the potentialities of the method some further findings are presented thought an application to the case study of the main tower of the San Felice sul Panaro (Italy) fortress.

2 AN INNOVATIVE MESH GENERATION APPROACH

The new mesh generation approach aims at offering a simple and effective tool for practitioners to be able to build FE models of complex monumental buildings with a minimal time investment. Indeed, the method principal innovation is the simple transformation of complex point clouds (originating from TLS or photogrammetric surveys) into FE models.

In order to achieve this goal, we propose to break down the geometry of the structure through the application of a systematic procedure that recursively performs the subdivision of the 3D domain into bi-dimensional sub-domains. This operation can be carried out by slicing the structure perpendicularly to an opportune direction (typically the vertical direction). The slicing step is chosen according to the complexity of the building along the slicing direction. A boundary polygon that encloses the points of each slice can be computed using a concave hull algorithm. Consequently, it is possible to obtain a filled region for each slice of the building that describes the entire structure.

In order to speed up the meshing operation and to guarantee the automatic mesh generation, each slice is idealized as a digital image composed of picture elements (pixels) with a certain resolution. Since the digitalization is performed on each slice with a fixed space region, they are stackable. The slices stacking sequence generates the volume elements (voxels). The full reconstruction of the original 3D geometry is obtained by stacking all of the slices: this produces a 3D matrix composed by voxels. The resulting dataset is simple and easy to use with the finite element technique: each voxel is automatically transformed into an eight-node hexahedral finite element. For practical usage this operation could be performed selectively: for instance only on filled parts (certain voxel values). Therefore, the structure is completely discretized as an unique continuum generated by the assembly of eight-node hexahedral elements. The resulting FE model is characterized by elements of the same dimensions. This aspect introduces an automatic defeaturing of the model that the user can set according to the structural complexity.

Once the mesh is built, its material assignment can be generally conducted by selecting single or groups of elements. In addition to this, the mechanical characterization of the FE model can be conducted in a further simpler way. Indeed, once the digitalization of each slice has been concluded, the material characterization of the FE mesh can be simply conducted on each slice by the user through a material ID assignment before the stacking operation (i.e. through the pixel code in a bi-dimensional environment).

Upon these features the resulting discretized geometry is already containing all the information to use with the FE model including the mechanical properties associated with the material features. The new mesh generation approach guarantees by means of a simple procedure the construction of a discretized geometry and then an automatic creation of a fine FE solid model. This rational organization is certainly the key novelty introduced by the method. Furthermore, since we are dealing directly with the definition of the FE nodal coordinates and with the connectivity matrix the proposed method is generally customized to work with any commercial FE software.

3 APPLICATION TO THE MASTIO TOWER

In order to deepen the potentialities of the proposed mesh generation method, the application to the main tower (Mastio) of the San Felice sul Panaro Fortress is presented and discussed, see Figure1. Such a monumental building is located near the city of Modena, in the town of San Felice sul Panaro (Italy). In 2012, it has been hit by the Emilia earthquake with two magnitude peaks on May 20^{th} ($M_W = 5.86$) and on May 29^{th} ($M_W = 5.66$), and it is object of several studies that aim to preserve its integrity [14, 15, 16].

3.1 Mesh generation and optimization

A morphological survey for the San Felice sul Panaro Fortress was planned by request of the Municipality in order to generate a functional representation of the state of the building after

Figure 1: The main tower of the San Felice sul Panaro fortress.

the earthquake. In particular, a fine laser scanner point cloud of the whole building (including inner rooms) has been surveyed. In order to apply our mesh generation method, this point cloud has been exploited.

An accurate description of the point cloud manipulation phases as well as the FE mesh generation of the Mastio tower is reported in [13]. The first points cloud slicing has been performed using a vertical slicing step of $0.200\ m$ with the resolution of the digitalization of each slice equal to $0.115\ m$. This assumption produced a fine FE model which counts 661,105 elements and 745,668 nodes (i.e. 2,237,004 dofs). Such a model, which accurately reproduces the geometrical features of the structure as shown in [13], is evidently usable for linear static and dynamic analyses. However, it ends to be very time consuming when used with nonlinear analyses. Here, we present some comparisons using a optimized (coarse) model characterized by a vertical slicing step equal to $0.250\ m$ with the resolution of each slice also equal to $0.250\ m$, which is, more or less, the greater dimension of a brick. Therefore, the consequent mesh is only composed by cubic eight-node hexahedral finite elements (each one $0.250 \times 0.250 \times 0.250\ m$). The resulting stacking sequence is composed of 121 horizontal slices, where each one is represented by a grid of 52×50 pixels. In Figure 2, the stacking sequence of three illustrative slices is sketched. The final mesh is then characterized by a

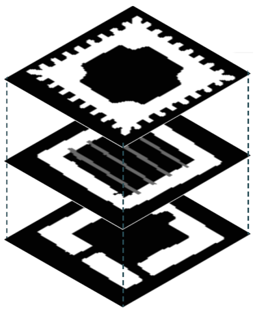
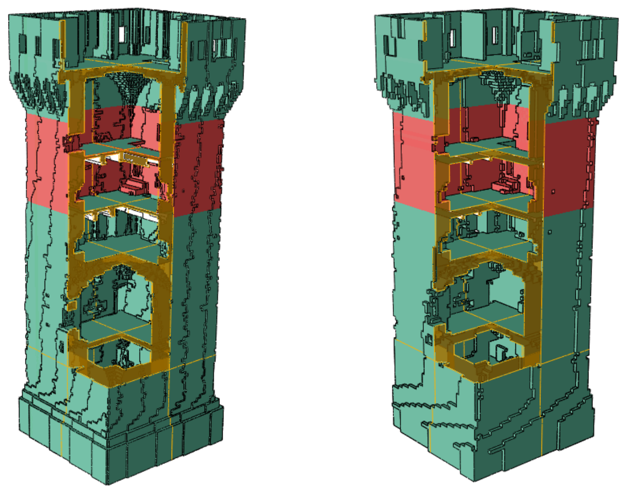


Figure 2: Example of stacking sequence.

considerable reduction of the number of degrees of freedom (443,076). More precisely, it counts 147,692 nodes and 118,554 elements. By comparing the two meshes in Figure 3 (the finer mesh in Figure 3(a) and the coarse mesh in Figure 3(b)) as well as in Table 1 it appears that the two models are equivalent from the structural point of view. Figure 4 illustrates the detail of the vault of the 6th level, which is in particular a groined vault (Figure 4(a)). As can be noted, when the surface is irregular (curved) (e.g. for vaults) the resulting FE mesh is a jagged representation of the original geometry (Figure 4(b)). Despite this fact, it is always possible to



(a) Finer mesh

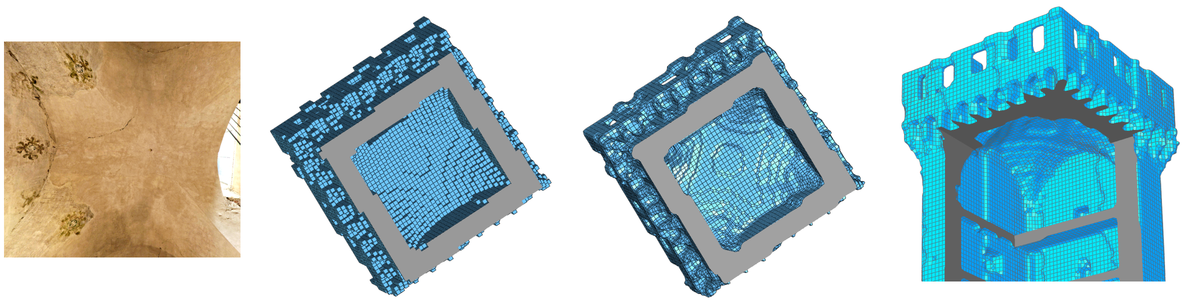
(b) Coarse mesh

Figure 3: Meshes. Each color is correspond to a material index: green portions indicate masonry, red portions point at reinforced masonry and white regions refer to timber elements.

Model	Mass $[ton]$	Max dimensions $\{L \times B \times H\}[m]$	h_g $[m]$
Finer	3,032.11	9.90 $\times$ 9.80 $\times$ 30.60	14.07
Optimized	3,081.99	10.00 $\times$ 10.00$\times$ 30.50	13.89

Table 1: Mass, overall dimensions and center of mass height.

improve the mesh accuracy using a smoothing method to reduce the faceting, see Figure 4(c) and Figure 4(d). These methods decrease high curvatures variations (jag) and have to be chosen in order to not produce shrinkage, see for instance [17]. Despite the geometrical improvement, the mesh enhancements are limited by the performance of the parametric finite elements [18]. Nevertheless, if we aim to assess the global behavior of a historical structure, the geometrical accuracy of the raw mesh can be considered satisfactory even if vaults are present. Furthermore, the recovered fields can be improved by standard recovery procedure [19].



(a) Groined vault

(b) Raw mesh

(c) Smoothed mesh

(d) Smoothed mesh (detail)

Figure 4: Detail of the groined vault of the 6th level.

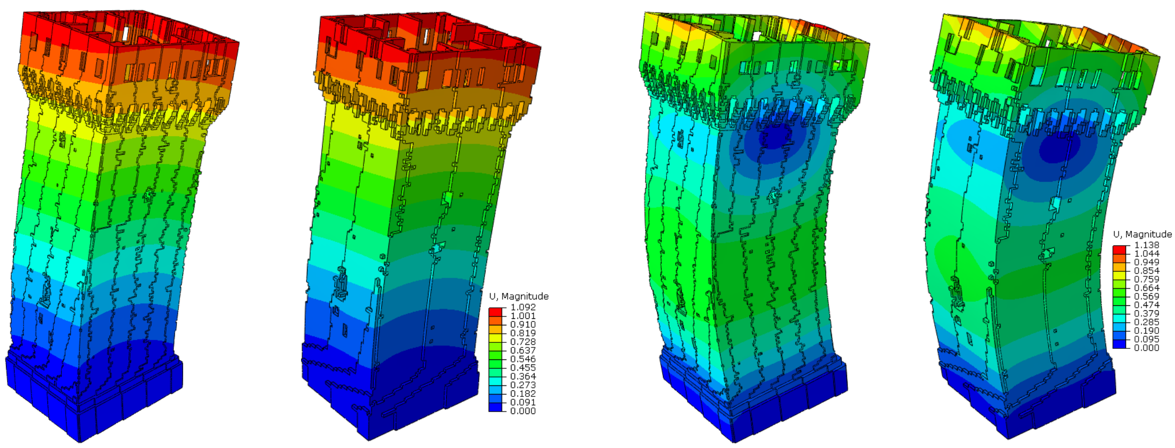
3.2 Structural Analyses

The semi-automatically generated FE models are tested within structural analyses. In order to assess the accuracy of the coarse model, a linear natural frequency analysis (eigenvalue analysis) is carried out and a comparison with the finer model is performed. For simplicity, clamped boundary conditions have been considered for nodes located at the ground level. Table 2 collects the obtained results in terms of computed frequencies and computed errors. It appears that the computed error is always less than 5.5% for the first six modes. Figure 5 illustrates the

Mode no.	Finer Fr. (Hz)	Coarse Fr. (Hz)	Error (%)	Mode descr.
1	1.9131	1.8635	2.592%	1^{st} bending mode (E-W)
2	1.9276	1.8705	2.962%	1^{st} bending mode (N-S)
3	4.5437	4.4004	3.154%	torsional mode
4	7.0804	6.6999	5.374%	2^{nd} bending mode (E-W)
5	7.1654	6.7792	5.390%	2^{nd} bending mode (N-S)
6	8.1623	7.8249	4.133%	axial mode

Table 2: Natural frequencies analysis: frequencies of the main mode shapes of the Mastio tower of the San Felice sul Panaro Fortress. Comparison between *CLOUD2FEM* based finer and coarse model.

Mode shape no.2 and no.5 of the finer model (Figure 5(a) and Figure 5(c), respectively) and of the coarse model (Figure 5(b) and Figure 5(d), respectively): colors are associated to the magnitude of the computed amplitude (normalized). Mode shapes are in very good agreement.



(a) Mode no. 2. Finer mesh freq. =1.9276 Hz

(b) Mode no. 2. Coarse mesh freq. =1.8705 Hz

(c) Mode no. 5. Finer mesh freq. =7.1654 Hz

(d) Mode no. 5. Coarse mesh freq. =6.7792 Hz

Figure 5: Mode no. 2 and mode no.5. Displacements magntiude.

Consequently, the coarse model is structurally equivalent to the finer one. In this way, it can be utilized to carry out advanced numerical analyses, such as nonlinear analyses, with a reasonable computational cost.

4 CONCLUSIONS

The mesh generation approach introduces a simplified description of the geometry and leads to a FE model able to precisely catch the geometry features and the corresponding mass properties. The mechanical properties are defined by a punctual characterization, which leads to a very accurate description of the structure since each voxel can be automatically associated with a particular property definition. The most relevant feature of the proposed method is the possibility to directly exploit detailed 3D point clouds surveyed on historical buildings for structural purposes. As a result, a large reduction in required time in comparison to CAD-based modeling procedures is achieved.

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