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On the generation of numerical models from point clouds for the analysis of damaged Cultural Heritage

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Abstract. Nowadays, a growing necessity for preservation and documentation of the Cultural Heritage is related to the precise 3D surveys as the input for multidisciplinary analysis. An efficient tool that meets the aforementioned requirement is the HBIM approach, linked to numerical models for structural analysis. In this context, the innovative CLOUD2FEM procedure, which semi-automatically generates numerical models from point clouds, has been applied to the surveyed point clouds – obtained by laser scanning – in a complex case study of a damaged building: the San Felice sul Panaro Fortress (Italy), hit by a severe earthquake in 2012. The numerical model generated is employed in the framework of advanced seismic nonlinear analysis. The promising results show the effectiveness of the method.

Keywords: *Cultural Heritage, point cloud, geometric modelling, HBIM, structural analysis, FEM*

1. Introduction

The field of documentation and conservation of Cultural Heritage, in particular of architectural interest, is experiencing a strong innovation in these years [1], linked primarily to the digitisation of information. This topic can be found above all in the phase of data acquisition and integrated data management.
With regard to the first, thanks to the rapid development of new techniques and technologies, first of all terrestrial laser scanning (TLS) and new methods of close-range photogrammetry (CRP), the geometry of objects can be described in a complete and very detailed way through high density point clouds. On the other hand, this new type of data, which was normally not available until twenty years ago, sets the basis for creating new approaches to the management of data and objects, not only in terms of documentation but also envisaging an integrated knowledge management, bringing great flexibility of use and new application possibilities.
An obvious example is given by the possibility of being able to derive from point clouds the necessary data for the management of the asset and its study in structural terms. In the first area, interest is growing in applying a Building Information Modelling (BIM) approach to existing assets, which is described here as Historical Building Information Modelling (HBIM). HBIM can be described as a multidisciplinary system composed by parametric library parts mapped onto the point cloud, in order to allow the modelling of complex or also irregular shapes that characterise historic buildings [2]. While BIM approach can be considered consolidated, there are still open issues and limitation in HBIM [3]. Nevertheless, various case studies are devoted to identifying best practises for the use of BIM tools in

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ancient context [4]. Furthermore, recent methodologies support the creation of more detailed structural analyses based on objective high-precision data, thereby increasing the reliability of the results [5].
The connection between Geomatics, the modern scientific discipline that deals with surveying with the most recent digital methodologies, and the sciences that deal with structural verification and control, has become tighter. These modern developments can stimulate new collaborative and interdisciplinary contributions towards a better knowledge and management of the assets, especially when dealing with ancient buildings which deserve and require special attention.
This paper presents some considerations derived from such a scientific collaboration, specifically devoted to compute a complete 3D model useful for a Finite Element Method (FEM) analysis.

1.1. Case of study and historical information

The case of study, here presented and discussed, is based on *San Felice sul Panaro Fortress* (Latitude: 44.8388; Longitude: 11.1412), the symbol of the homonymous city (Figure 1) in the province of Modena (Italy), that was hit by a severe earthquake in 2012. The historic fortress is particularly interesting for the intrinsic complexity of the building and this peculiarity has influenced all the phases of the survey and the following data processing. The final goal is to obtain a complete model with high precision and geometric detail.



Figure 1. Geographic location of the case study, from left to right: Emilia-Romagna region overview (satellite imagery), San Felice sul Panaro Fortress overview (aerial imagery AGEA, 2011).

On 20 May 2012 San Felice sul Panaro was hit by the Emilia earthquake with a magnitude peak of Mw=5.86 and an epicentre located between *Finale Emilia* and *San Felice sul Panaro* municipalities. Nine days later another magnitude peak of Mw=5.66 followed. Further minor peaks were recorded in the following days. [6]
The roofs of the different towers have suffered a considerable damage that has led, in some cases, to the collapse of the roof itself. Furthermore, the external perimeter walls have suffered a serious decay and, in some cases, partial collapses. Also, the interior rooms have been damaged by numerous collapses, involving their walls and their vaults. As a first measure of response to the earthquake, the Municipality of San Felice sul Panaro installed large plastic tarpaulins to prevent infiltration of rainwater into the towers with collapsed roof and all the cracks have been filled with mortar. In the following months, steps were taken to ensure safety by means of interventions aimed at preventing further deterioration [7]. Debris, rubble and the any unsafe elements have been subsequently removed as shown in Figure 2 in order to avoid further damages.



Figure 2. Perspective view of the North side, from left to right: before the earthquake, after the first event, condition at the epoch of survey.

2. Geomatic techniques

2.1. Data collection and data processing

A survey of the building was planned through the use of geomatic techniques, mainly TLS, CRP and total station for the alignment network. The Fortress had suffered numerous and serious damages and at the epoch of the survey it was in a state of heavy degradation. The survey, performed by Abacus srl, was aimed at obtaining a detailed representation of the condition of the building and its output is a dense point cloud. All the metric information have been gathered, georeferenced and linked in a relation within a database towards a BIM system, from which it will be possible to derive subsequent further results as necessary. In this context a BIM approach is a convenient and efficient tool for the storage of multidisciplinary data, which can be used as a support for restoration procedure or as collection of the actual condition. The geomatic survey resulted in 163 different point clouds from different scanning positions, composed by over 40 million points (Figure 3).

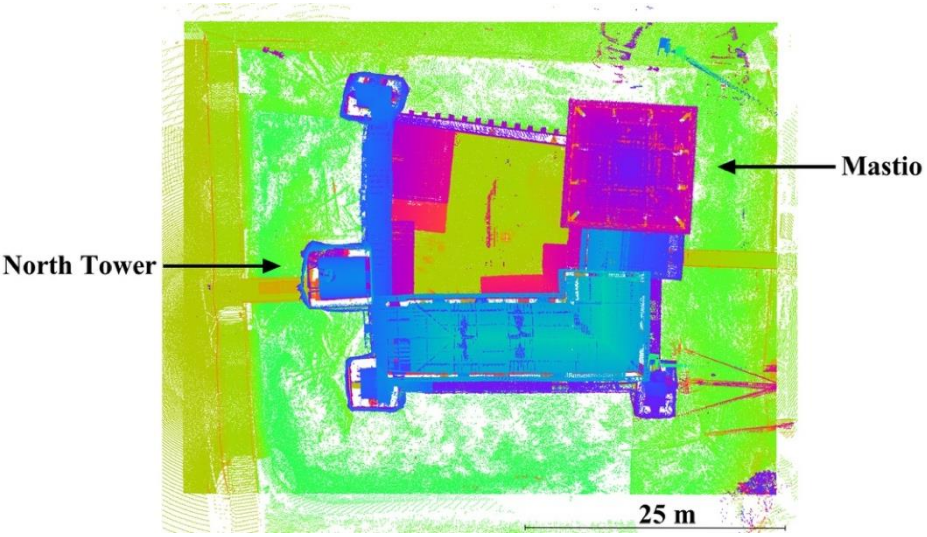

Figure 3. Initial raw point cloud of the entire Fortress, gradient colour based on elevation, highlighting the principal elements object of this work.

In order to obtain a complete and coherent geomatic model, targets (as visible in Figure 4) were placed on both the interior and exterior of the whole building, acquiring data for each room and each façade.
The point cloud is initially reduced to 3.2 million with a regular spatial sampling of 5 centimetres in order to obtain a model that could be processed without losing any relevant detail for further analysis. Moreover, any elements outside the surveyed perimeter of the Fortress was manually removed from the point cloud in a brief cleaning phase. The final dataset is then composed by only 1.9 million points.

2.2. Innovative approach on critical issues

The CLOUD2FEM [8] procedure has been applied to transform the point cloud dataset into a model suitable for FEM analysis. This allows to transform through a semi-automatic workflow any three-dimensionally surveyed historical monumental buildings into a sequence of two-dimensional slices of containing all the relevant geometrical data in a pixel grid format. Finally, the aligned pixel grids are stacked into a voxel model. Therefore, the output of the geomatic techniques becomes the input of the structural analysis.
The mentioned procedure is now stressed analysing the whole Fortress, discretized through a sequence of slices perpendicular to the Z-axis (horizontal). Critical aspects and peculiarities emerge from this analysis and offer suggestion for further investigations, regarding both the geometric and structural perspective, as the Mastio, the tallest and most stressed tower, composed by six floors [8] and the North Tower, involved by a partial collapse of the perimeter walls. Furthermore, an extension and adaption of

the CLOUD2FEM procedure has been applied to the detailed analysis of the different floors and their vaults at a higher resolution [9].
The TLS survey difficulties derived from the presence of debris, discontinuities, furniture, stairs and railings. The point cloud was also predictably affected by these problems, due to foreign elements not belonging to walls, floors and structural elements in general terms. In a traditional geometric approach, the creation of a complete and watertight model is time-consuming. Nevertheless, the structural analysis needs a filled model and the proposed method guarantees its creation despite the critical issues.
An explanatory example is given by the analysis of the Giulio II Hall, in the Mastio tower. This room is characterized by a great amount of debris as a consequence of the earthquake. Its vault is also compromised by a complex crack pattern as show in the picture captured inside the room (Figure 4). It is possible to observe the details captured from the cross-section of the point cloud, where the real geometry of the floor is not directly visible and therefore measurable. This happens not only in Giulio II Hall, but also in several other spaces due to different causes: presence of furniture or stairs (Figure 5).



Figure 4. Picture from the interior of the Giulio II Hall in the Mastio.

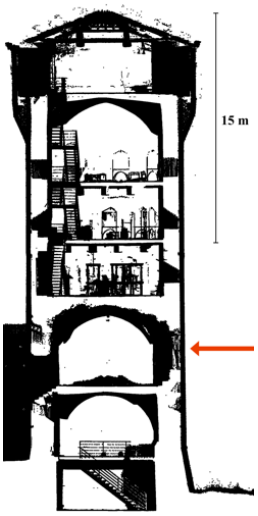

Figure 5. Cross-section of the Mastio, with Giulio II Hall highlighted.

Concerning the North Tower, it has been possible to measure the rotation of the perimeter walls along the whole elevation of the tower. In particular, the study is then focused on the vault at the second level, deformed due to the rotation of the walls. It has been possible to measure the displacements between the theoretical geometric model of the original vault, starting from the real model obtained from the surveyed point cloud.
By comparison of the two models it is clear the displacement between the surveyed vault and its geometrical model. Furthermore, on both models isolines have been overlapped at a constant step. In particular, on the peak of the surveyed model an irregular trend can be clearly observed (Figure 6).
Following the results of this analysis, the distance between subsequent slices in correspondence of each transition between floors was decreased in order to increase the resolution of the final model, down to 0.1 meter (Figure 7). This new proposed approach allows a more accurate geometrical analysis for the vaults and also the structural analysis will benefit from the improved accuracy [10].

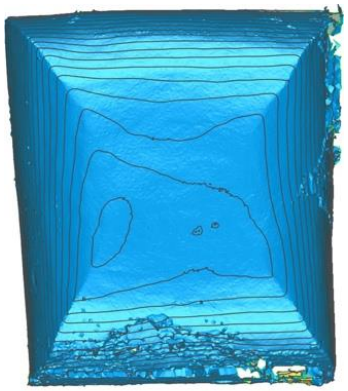

Figure 6. Mesh of the vault with isolines.

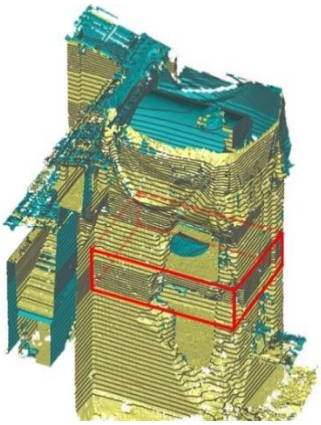

Figure 7. Polygonal model of the North Tower. Studied vault highlighted in red.

3. FE modelling and analysis

3.1. Generation of the FE model

Following the CLOUD2FEM procedure [8], the pixelized two-dimensional slices, which contain all the significant geometrical data, are stacked to generate a voxel model. Figure 8 shows an example of stacking of the slices. Successively, the voxels are automatically transformed into solid hexahedral FEs. Consequently, the output of the CLOUD2FEM procedure is a FE solid model ready to be used in the framework of numerical analysis.

In the case at hand, the FE model generated refers to the damaged condition of the structure, see Figure 8. Therefore, this model could be used to investigate the current condition of a damaged building, which can be beneficial for the knowledge of its actual structural behaviour and, consequently, for the design of repairing and strengthening interventions. To this aim, the updating of the FE model by means of ambient vibration measurements could improve the reliability of the model. A vibration-based FE model updating procedure for historical masonry structures which have suffered severe damage due to seismic events has been recently developed in [11].

However, numerical models are often employed to understand the causes of the occurred damage [12]. Thereby, the undamaged configuration of the structure (before the earthquake) appears to be in the engineers' interest.

The rational discretization of the model generated through the CLOUD2FEM procedure also allows to simply process the slices to obtain the model of the undamaged structure, see Figure 9. Indeed, by manually processing the 3D voxel model slice by slice, the collapsed portions of the structure can be added in the voxel grid. Additionally, by following the same process, the material properties can be defined along the whole model domain (Figure 9). This operation, although manual and, in general, time consuming, allows to obtain a very accurate description of the materials distribution in the structure (e.g. different kinds, textures and degradation states of masonry, etc). In Figure 9, the materials of the undamaged model have been characterized in according to the material definition collected in [13].

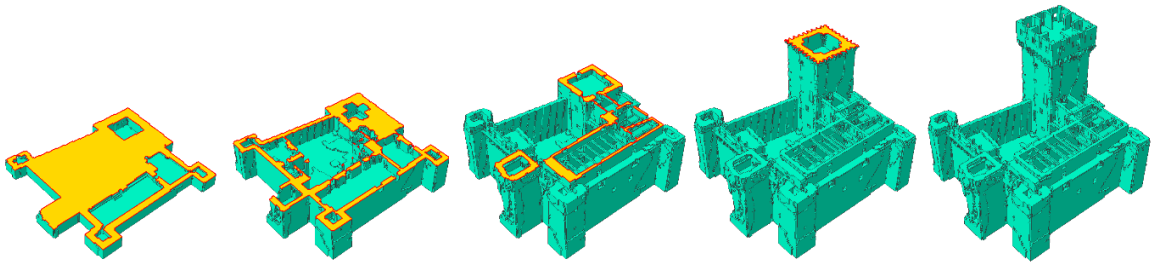

Figure 8. Example of stacking of the slices to generate a 3D solid model.

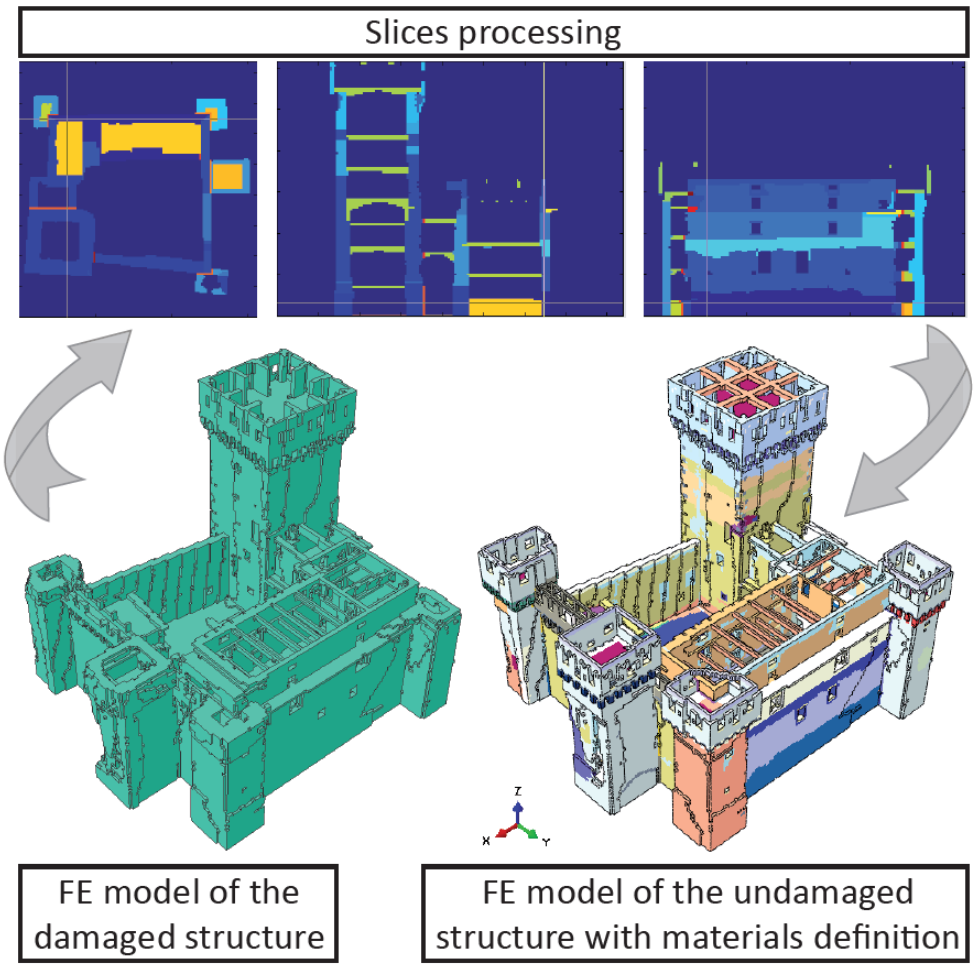

Figure 9. FE models generated from the point cloud: example of slices processing to obtain the model of the undamaged structure, as well as the material definition.

3.2. FE nonlinear analysis

To show the effectiveness of the approach, a nonlinear dynamic analysis has been carried out employing the undamaged model of Figure 9. The actual accelerogram, recorded on May 29th, 2012 close to the fortress, has been applied at the base of the structure. Particularly, a plastic-damage constitutive law has been adopted for masonry, following the setting of the mechanical parameters given in [14]. Additionally, a Rayleigh damping model has been used, as adopted in [15].

Figure 10 shows the accelerogram applied at the base of the structure (top) and the nonlinear dynamic analysis results (bottom), in terms of tensile damage contour plots at subsequent instants. The obtained cracking pattern, predicted by the numerical model (Figure 10), is in good agreement with the damages experienced by the actual structure: among all consider for instance the severe damage computed for the surrounding towers, localized at the upper part (Figure 10), and the experienced damage that ended with the collapse of the towers upper part (Figure 2).

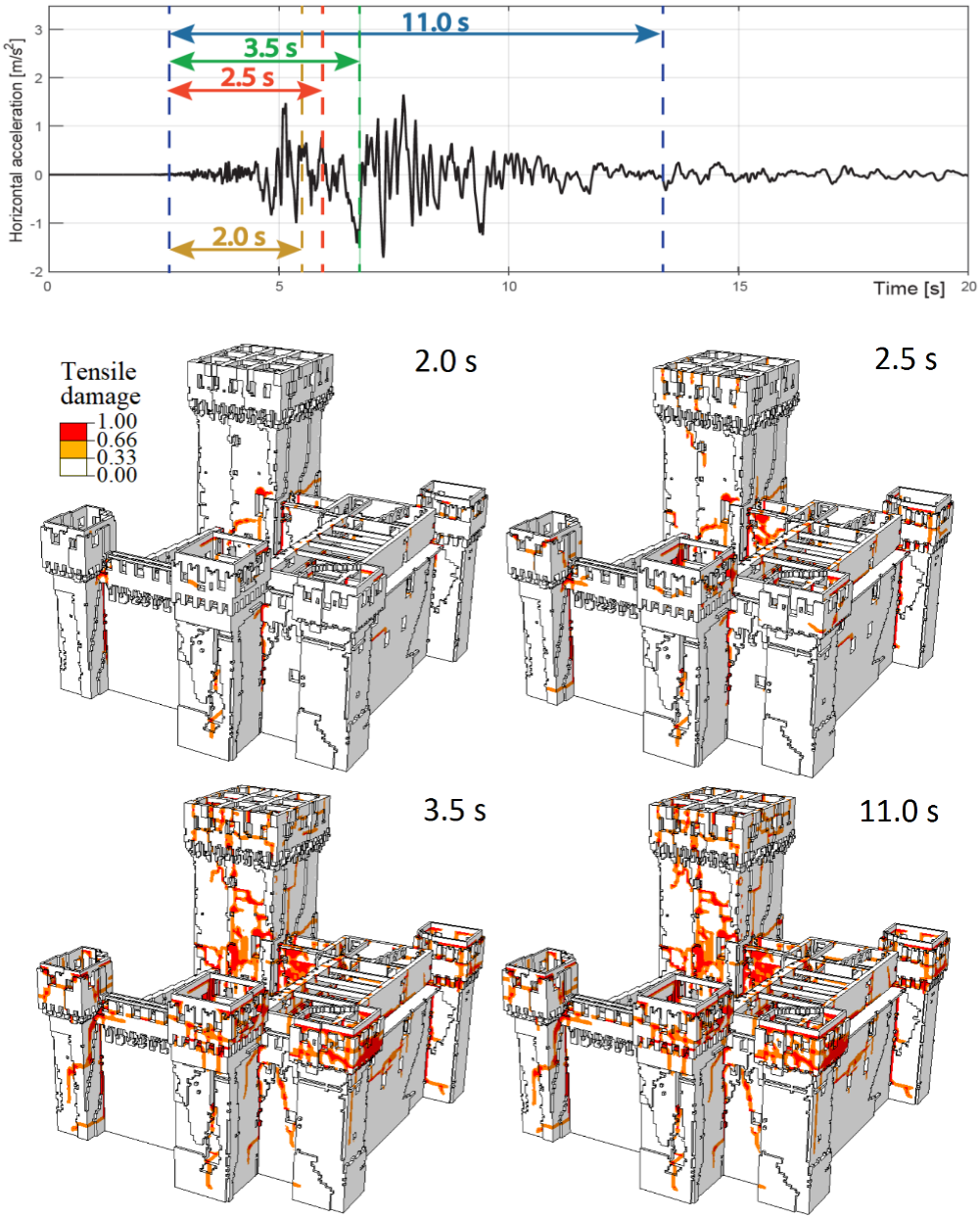

Figure 10. Nonlinear dynamic analysis: accelerogram applied at the base of the structure (top) and tensile damage contour plots at subsequent instants (bottom).

4. Conclusions

The innovative CLOUD2FEM procedure has been applied to a whole historical building damaged from an earthquake in the 2012: the San Felice sul Panaro Fortress. Several surveyed point clouds are an efficient support for multidisciplinary studies aimed to the conservation of the Cultural Heritage, towards a HBIM approach. The precise 3D model was completely analysed. Moreover, the model has been exploited in detail to investigate all the peculiar elements of the building from different perspectives: geomatic and structural. Complex elements, such as vaults or damaged structures, have been further investigated in a comprehensive geometric analysis. Finally, the 3D numerical model semi-automatically generated has been employed in the framework of advanced seismic nonlinear analysis. The promising results showed the effectiveness of the method.

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