Semi-automated creation of accurate FEM meshes of heritage masonry walls from point cloud data

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Abstract. The structural analysis of buildings requires accurate spatial models. Additionally, pathologies such as settlement-induced damages are paramount in the assessment of heritage assets. This spatial information is used as a basis for Finite Element Method (FEM) meshes to evaluate the stability of the structure. Traditional data acquisition approaches rely on manual measurements which are labor intensive and error prone. Therefore, major simplifications are made to document structures efficiently. The goal of this research is to provide faster and more accurate procedures to capture the spatial information required by a FEM.
This paper presents a semi-automated approach to create accurate models of complex heritage buildings for the purpose of structural analysis. By employing non-destructive techniques such as terrestrial laser scanning and photogrammetry, a complex mesh of the structure is created. Also, a methodology is proposed to capture crack information. A stepwise approach is elaborated to illustrate how the spatial information is adapted towards a FEM mesh. The results show a significant difference between the geometry our model and a traditional wire-frame model. Not only does accurate modelling result in deviating loads, it also affects the behavior of the object. Through the proposed approach, experts can develop highly accurate FEM meshes to assess the stability of the structure up to as-built conditions.

Keywords: spatial modelling, structural analysis, point clouds, finite element method.

1 Introduction

The documentation and consolidation of heritage structures is paramount to the preservation of humanities history. Over the years, the methods and instruments for the non-destructive data acquisition have drastically changed due to the advancements in the fields of robotics and sensors [1]. These innovative technologies do not only capture data faster, they also allow for a more thorough documentation of the asset. Instead of interpolating the sparse geometric data available, advanced statistics are used to directly fit realistic models on the point cloud [2], [3]. As a result, the asset is digitally reconstructed with a degree of detailing and metric accuracy that was previously unavailable. The structural analysis of heritage structures is a widely researched topic. Commonly,

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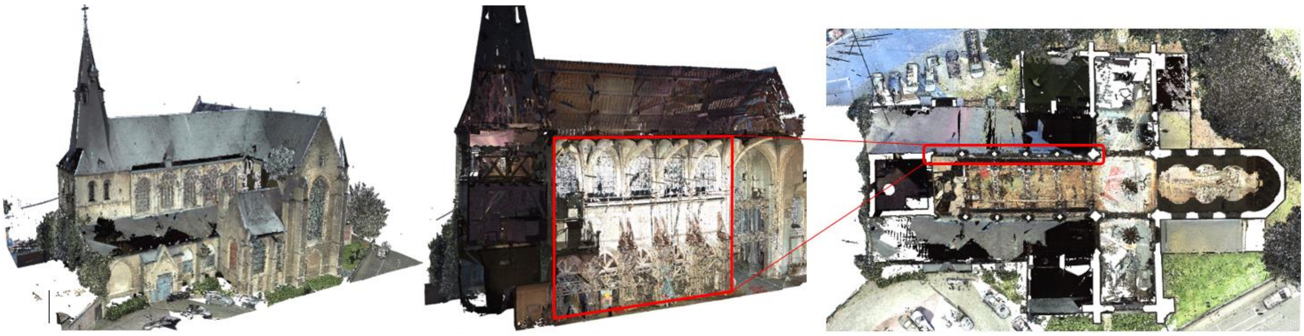

Figure 1. Overview point cloud data Sint-Jacobs Church, Leuven, Belgium: Colorized point cloud (left), Elevation view with northern nave wall in red (mid) and plan view northern nave wall in red (right).

Finite Element Methods (FEM) are used together with a FEM mesh representation of the geometry of the structure [5]. Typically, these meshes are constructed from simplistic 2D or 3D models [6]. While this is efficient, the abstractions in the geometry lowers the accuracy of the analysis [4]. Another prominent factor in the assessment of heritage structures is the impact of pathologies such as cracks. The integration of this information requires the precise location of the cracks in the model and a realistic representation of the geometry. However, traditional methods lack the accuracy and spatial density to efficiently reconstruct realistic meshes of both the hull of the asset as well as the crack information [7]. The automated creation of the geometry of FEM meshes from point cloud data is still ongoing research. Due to the sheer size of the point cloud information, automated approaches are computationally challenging. Also, the scanned objects are often partially occluded, the data is unevenly distributed due to the range to the sensor and there is noise present in the data set [8].

The emphasis of this work is on the creation of realistic and accurate FEM meshes based on dense point cloud data. More specifically, we look to semi-automatically generate a complex FEM mesh of heritage masonry wall. Additionally, crack information is extracted and incorporated into the model.

2 Background

The Saint Jacob's church is a three-nave church located in the city of Leuven, Belgium (Fig. 1). This Gothic style church was constructed during numerous construction phases. The oldest parts of the church, the Romanesque bell tower and the foundations, date back to 1220. Over the centuries, critical settlement-induced damages were reported due to the inferior underground and the posterior load additions that were not accounted for by the early foundations. A number of consolidation measures were performed up to 2005, including a steel shoring system to support the nave and massive concrete pillars to relieve the columns [9]. Several measurement campaigns were performed in the church. For instance, from 1994-2005, the relative displacements were observed at the base of the columns supporting the walls which revealed settlement-induced deformations of up to 9.3mm over 11 years. Recently, a detailed data acquisition was performed including terrestrial laser scanning and photogrammetry (Fig. 1). The resulting point clouds and imagery is used in this research as a basis for the FEM mesh and the crack detection.

3 Related Work

Several researchers have proposed approaches to semi-automatically generate Finite Element Method (FEM) meshes based on point cloud data. Some researchers focus on the automated extraction of building details such as trusses and beams while others put the emphasis on creating a FEM mesh of walls, roofs or the entire structure. For instance, Armesto et al. exploits photogrammetry to extract trusses for the evaluation of historic timber roof structures [10]. Koehl et al. developed an automated approach to model heritage roof structures for diagnosis and documentation purposes [11]. Castellazzi et al. proposed stacked 2D raster images to automatically create a FEM of an entire structure [12]. The majority of approaches are limited to the creation of abstract models of the asset. For instance, Lubowiecka et al. proposed the use of accurate surface representations but make significant abstractions to create the final FEM mesh [6]. Barazzetti et al. fit complex primitives onto point cloud data to create a detailed model of an entire structure. By controlling the manual modelling process, they also integrate information concerning the consecutive construction stages of the asset [13], [14]. Their approach favors consistent geometry opposed to metric accuracy. In our research, we preserve the metric accuracy by using the watertight mesh as a direct basis for the FEM mesh. Some researchers compute the FEM mesh directly on the point cloud. For instance, Hinks et al. transforms the initial point cloud to a voxel octree and uses this representation as a basis for the FEM mesh [15]. In our work, we first compute a Poisson mesh through the data to deal with outliers, noise and occlusions. Crack modelling has also been considered to create a realistic FEM. Cardani G. et al. proposed the use of BIM for the documentation of crack patterns in existing buildings and a procedure to translate the information to a FEM [16]. Similar to our approach, Arias et al., employs photogrammetry for the detection and mapping of cracks in a structure [17]. Based on the imagery, they first create a wire-frame model of a bridge and then compute a Delaunay mesh for the data representation. We extend their approach by mapping the texture information on the complex mesh and integrating crack information from point cloud data and imagery directly into the complex volumetric mesh.

4 Methodology

In this paper, a framework is presented to accurately construct FEM meshes and integrate crack information. More specifically, volumetric tetrahedrons are fit onto a watertight volumetric mesh based on point cloud data. The workflow is composed of two parallel methods. The former converts the point cloud to a complex FEM mesh through a series of semi-automated procedures. The latter extracts crack information and enhances the FEM mesh to incorporate the crack geometry. Both workflows are discussed in detail in the following paragraphs.

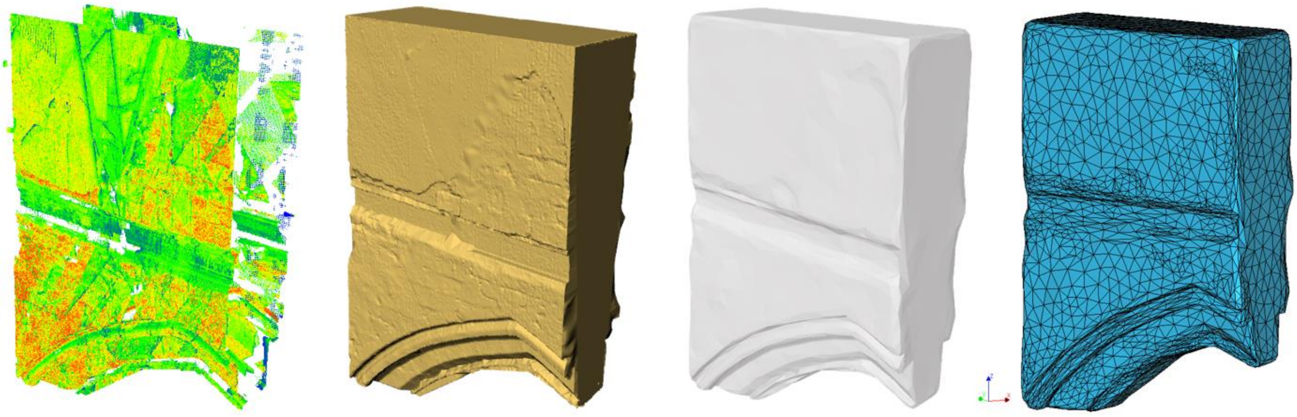

Figure 2. Overview methodology FEM mesh creation: Point cloud colorized by intensity (a), Watertight triangular mesh (b), Volumetric simplified mesh (c) and final FEM mesh (d).

4.1 FEM Mesh

The creation of the FEM mesh is considered a reverse engineering problem that can be solved with reconstruction techniques. As input, our algorithm takes any point cloud data (Fig.2 a). First, a Poisson surface is computed to determine the best fit mesh [18]. A course to fine meshing approach is employed. The course meshing computes a rough shape representation to acquire the initial shape. The fine meshing refines the initial geometry to better approximate the point cloud. Once the mesh is created, the holes are interpolated and the geometry is made watertight (Fig.2 b). Given the surface representation, the mesh can be filled and transformed into a volumetric representation of the geometry (Fig. 2 c). The final FEM mesh is created by fitting generic entities to the volumetric mesh. More specifically, tetrahedrons are considered for the discretization of the geometry as is common in structural analysis (Fig.2 d). For structural analysis, it is imperative that the connections between elements are consistent in order to transfer forces correctly. Therefore, the mesh is treated as a single entity. In the case hinges are defined between elements, the individual mesh elements are altered. While the reverse engineering process is automated, the geometry is manually checked and enhanced as the reconstruction algorithm struggles with severely occluded and complex areas. The result is a FEM mesh that accurately relates to the real geometry of the asset.

4.2 Crack Extraction

Crack detection proves troublesome in point clouds due to the sparsity of the laser scan data. Typically, cracks are merely visible as lines on a wall without sufficient depth or width to be detected with laser scanning (Fig.3 a). Therefore, the use of photogrammetry is proposed for the extraction of the crack information. Given the external orientation of each image, the high quality texture of the imagery is projected back onto the reconstructed mesh (Fig.3 b). Once the model is textured, it is exported to a CAD environment that provides an intuitive modelling platform. The user manually determines the crack locations and marks the edges of the cracks on the surface of the model (Fig.3 b). Once the position at the surface is known, an automated algorithm takes the input geometry and incorporates the information in the watertight mesh (Fig.3 c). First, the crack

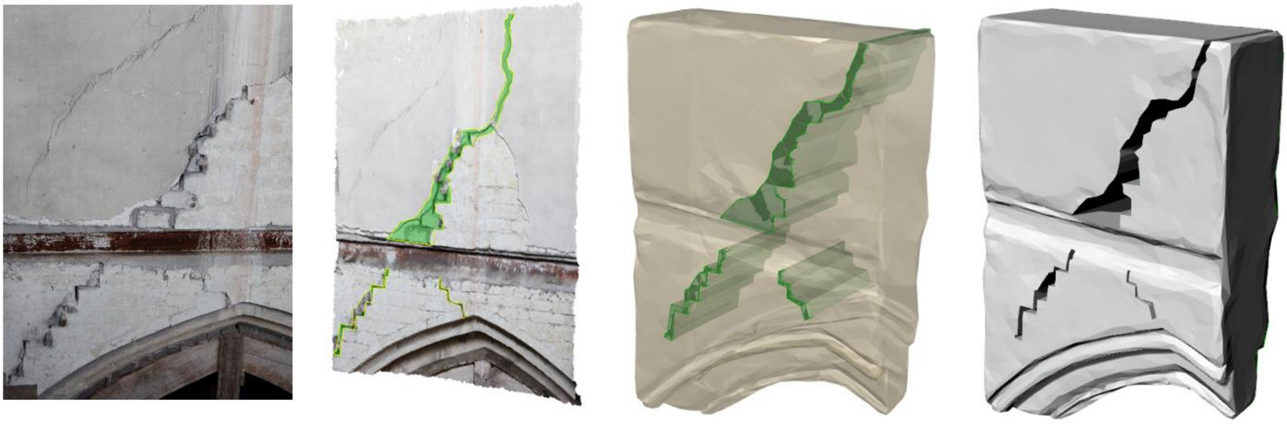

Figure 3. Overview Crack detection and modelling: Crack imagery (a), Textured Mesh with manually modelled crack geometry in green (b), Collision in green between Crack geometry and Volumetric Mesh (c) and the Crack representation in the final model (d).

edges are joined to form a closed polygon. Next, the best fit vertical plane on the mesh is computed near the crack. The created surface is extruded orthogonal to the plane to pierce the mesh. The resulting solid is used to create a void in the mesh. The mesh is made watertight again by merging the boundary of the void with the initial mesh geometry. The result is a set of holes in the mesh that cannot transfer forces in a FEM (Fig.3 d).

5 Experiments

The FEM reconstruction and crack modelling were tested on the northern nave wall in the Sint-Jacobs church (Fig.4 left). The wall has visible settlement-induced cracks at the surface (Fig.4 mid). Also, large portions of the wall are occluded by the shoring system that supports the wall (Fig.4 right). During the data acquisition, over 100 Million points were captured on the wall surface along with more than 700 pictures. The imagery was registered to the scans in the Software CapturingReality [19]. The watertight mesh was computed using the 3DReshaper software [20] and the volumetric mesh was converted to a FEM mesh without loss of accuracy in the Software Diana [21]. The metric comparison between both models was made using Cloud Compare [22]. The final FEM mesh of the nave of the initial wire-frame model and the complex model are shown in Fig. 5. The simplistic model was based on sparse total station measurements.

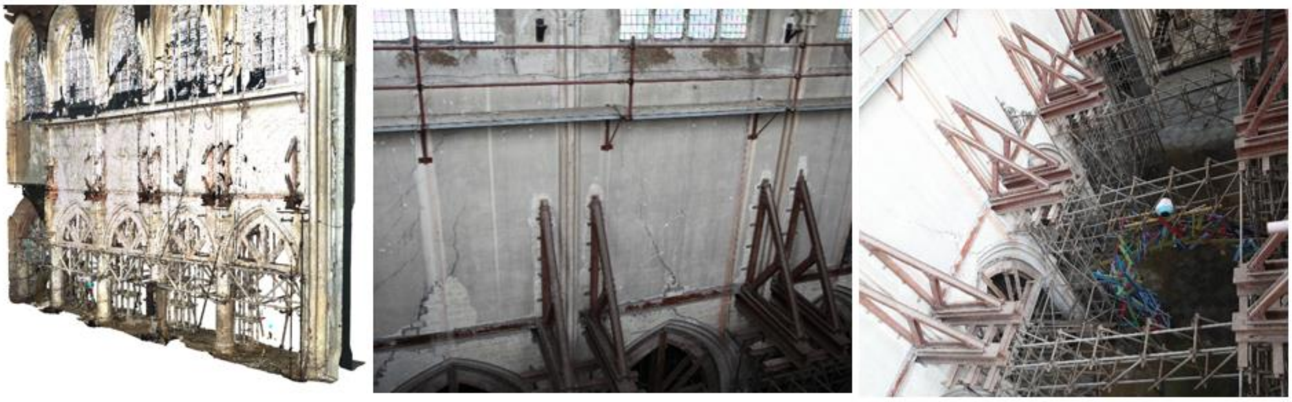

Figure 4. Overview northern naïve wall point cloud (left), settlement-induced cracks in the imagery (mid) and the occlusions caused by the shoring system in the church (right).

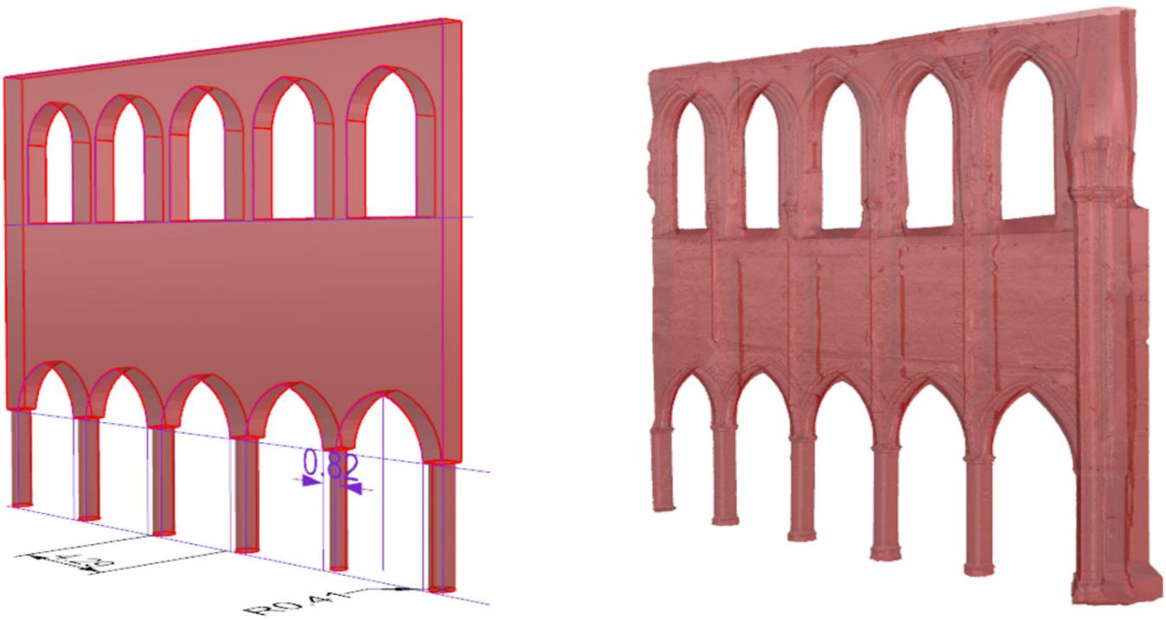

Figure 5. Overview of the traditional wire-frame FEM mesh (left) and the automatically reconstructed FEM Mesh from point cloud data (right).

Table 1. Deviations between both meshes and ground truth.

Statistics	Wire-frame Model	Complex Model
95% interval	0.266m	0.009m
% Data within 0.05m	42.3%	98%
% Data in within 0.015m	13.1%	89.5%
Volume	222.6m³	277.1m³

Fig 6 and Table 1 depict the deviations of both models with respect to the initial point cloud which serves as ground truth. Overall, it is observed that there are major differences between both models. The wire-frame model deviates up to tens of decimeters compared to the initial point cloud. In contrast, nearly 90% of the complex model lies within 0.015m of the initial data save for some interpolation errors. The main deviations in the wire-frame model are due to modelling abstractions such as window and pillar placement at fixed distances, wall verticality and uniform wall thickness. These deviations result in a volume difference of approximately 55m³ or 20% of the total volume. Given an averaged mass of circa 2000kg/m³ for masonry, the difference in self-weight is approximately 110 tons. Another crucial difference between both models is the detailing of the objects. For instance, the complexity of the connections between the walls and the columns is a key factor in how the forces are transferred through the structure (Fig.7 a). As these details are not included in the simplistic model, the assessment of the wall using the wire-frame model is suboptimal. Prior experiments prove that the loading difference and the modelling abstractions have a significant impact on the structural assessment of the asset [3]. Given the averaged ground sampling distance and the mesh accuracy, the cracks were detected with a global accuracy of 0.006m (Fig.7 b). However, in order to properly model the solids, the cracks were modelled slightly larger than the surface geometry.

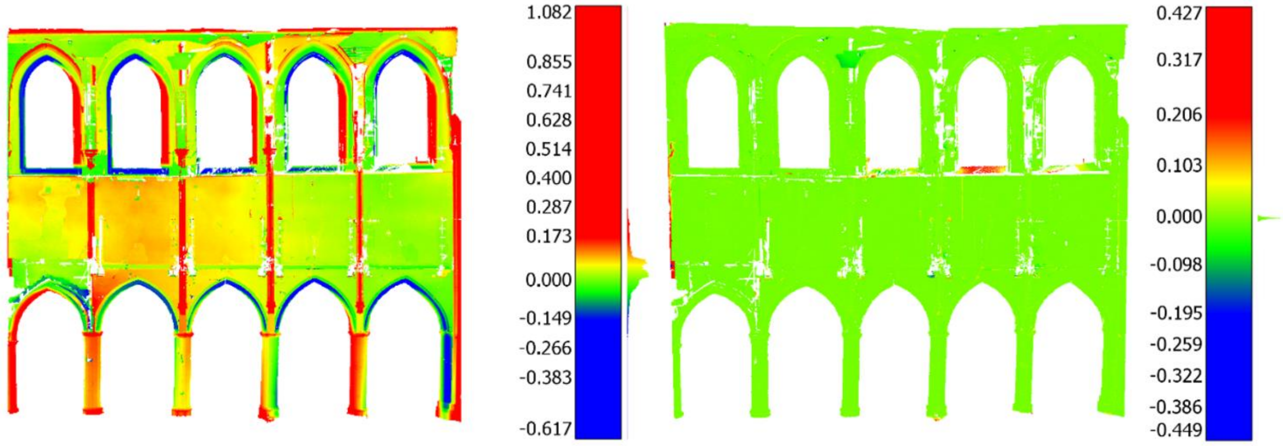

Figure 6. Signed distance [m] between the point cloud and the traditional wire-frame FEM Mesh (left) and FEM complex mesh (right).

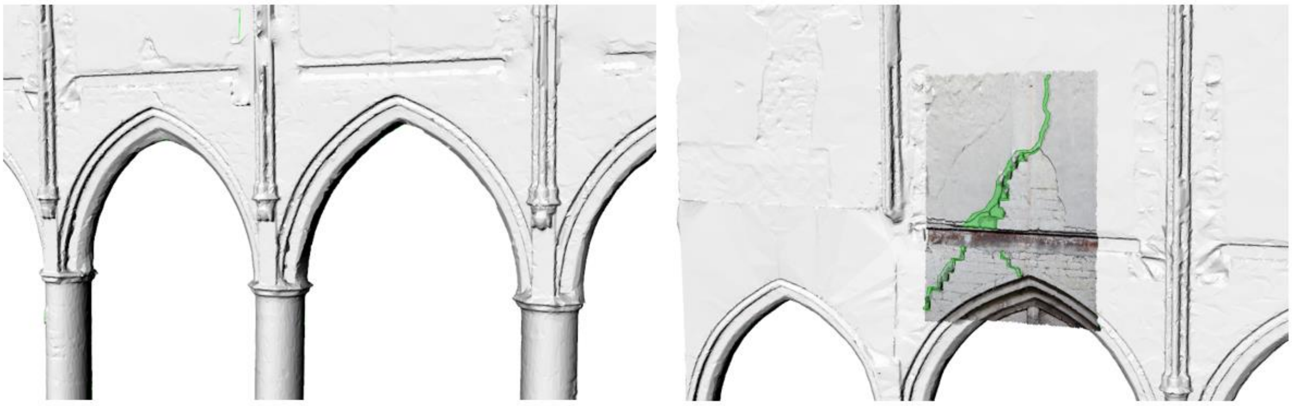

Figure 7. Complexity of arches FEM mesh near the connection of the walls and the columns (Left) and modelled cracks in FEM (right)

Overall, all relevant cracks were incorporated in the FEM mesh. Additionally, partially occluded cracks are also modelled based on the user input. Overall, it is stated that given the accurate geometry, the structural analysis will yield significantly more realistic results compared to traditional wire-frame models.

6 Conclusions

In this paper, a method is presented to create an accurate and realistic FEM mesh of a heritage masonry wall. More specifically, the geometry of the wall is semi-automatically extracted from point cloud data. Additionally, crack information is incorporated in the model using photogrammetry. The result is a complex mesh that better approximates the real geometry of the asset than a traditional model. The experiments prove that our method is capable of reliably reconstructing accurate geometry even in a cluttered and occluded environment. The complex model is compared to the initial wire-frame model in terms of accuracy and detailing. It is shown that the complex model estimated the volume 10% more accurate than the traditional model and included detailing such as non-planar walls, inclinations and wall detailing. These aspects are expected to have a major impact on the structural assessment of the model. The presented workflow allows heritage experts to better digitize their assets and create FEM meshes that more accurately reflect the geometry of the object and facilitate the integration of crack information in the model.

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