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Apparent and resistant section parametric modelling of timber structures in HBIM

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Abstract

Historic timber structures are frequently composed by irregular section beams. Moreover, due to abiotic and biotic agent action, wood, as a biodegradable material, is especially vulnerable to decay, which can led to destruction of external and even internal layers of the element. Due to this, a beam's resistant cross-section, which is the healthy section part that supports the structure, and the beam external apparent cross-section may not coincide, which can lead to improper structural assessments regarding the load-capacity of that element. HBIM technology is currently being used for the representation and analysis of historic timber constructions' structural health. In this work, a methodology is proposed and applied that, based on the combination of LIDAR data with non-destructive tests, allows to obtain a single 3D HBIM model of degraded irregular wooden structures. This HBIM model contains both the apparent parametric model, that represents the structure external geometry and collects all necessary data for construction's conservation analysis, and also a parametric resistant model, that represents the beam's undamaged section, allowing to carry out a more accurate structural analysis. In this work, the methodology was first applied to an irregular and decayed beam at laboratory conditions for framework calibration, and then applied to a case study for validation. The case study was the Guimarães chamber roof (Portugal) which structure is made up of several truss systems composed by irregular beams, several of which with signs of past decay activity.

Key works: timber structures, laser scanning, resistance drill, HBIM, structural analysis.

1 Introduction

Historic timber constructions may present complex configurations with irregular cross section elements. Often, timber was used for roof structures due to its light height and possibility to create large open spaces, but it can also be found in other uses, many of which are still in service and are part of mankind historic and cultural heritage. As a result of both construction methods and decay, this type of structures may show significant variation in the cross-section geometry along the same element Lourenço et al. (2013; 2018). For this reason, in the cultural heritage field is common the use of photogrammetric (Arias et al., 2007; Armesto et al. 2009) and LIDAR based technics in order to obtain the geometry of the elements that compose the structure. As one of the most broadly used tools, the laser scanner allows to survey highly complex structure geometries in a short period of time, obtaining cloud points which contains the elements external geometry. Several works as Balleti et al. [2013], Cabaleiro et al. [2016] [2017], have already applied this technology to model timber constructions.

Timber structures are susceptible to different type of actions, like xylophagous insects and fungi attack when exposed to specific environmental conditions, causing decay to the element material both in a superficial and also internal way, resulting in reduction of the resistant cross-section area. In that perspective, it is reasonable to differentiate between the external apparent cross-section, which includes the decayed and sound part, and the resistant cross-section corresponding to the healthy section part able to sustain loading. For this reason, not only is important to survey the apparent element geometry with non-destructive tests, but also to obtain the beams resistant geometry. In order to determine the elements' extent of decay and conservation state, non-destructive tests (NDT) and semi-destructive tests (SDT) are carried out in situ without influencing the elements integrity. Some of these tests are: visual inspection (Riggio et al. [2017]), moisture content measurements, (Frontini et al. [2017], Osuna-Sequera et al [2019], Arriaga et al [2021]), stress wave (Lechner et al. [2014]), pin penetration test (Lourenço et al. [2007], Branco et al. [2017]) and drilling resistance tests. The latter is a method that consists in inserting a needle drill into the timber to analyze the state of the material. The energy needed for the needle to proceed at a same speed is recorded in a graph, from this graph the element's superficial decay depth, internal degradation, and other imperfections as cracks or knots can be detected (Kasal et al. [2011]). In works like Branco et al. [2017], and Cabaleiro et al. [2018], the results of this test were used to define the resistant cross-section of the beams composing different timber structures.

Moreover, as it can be seen in the work of Quattrini et al. (2017) and Perria et al. (2017) in the cultural heritage field the creation of a 3D model can be a valuable tool for supporting the assessment and analysis process. With timber structures in particular, and especially with complex ones formed by a high number of structural elements, the 3D model can be used to visualize the building in a simpler way, being able to see hidden elements that would be difficult to see otherwise Perria et al. [2017]. Furthermore, with the implementation of BIM technologies in the cultural heritage field, every modeled element may be linked to a database (presented through a table or spreadsheet), where its parameters and characteristics are shown (Pocobelli et al [2018]). This means that the historical construction model, in addition to contain the elements' geometry, can be used to hold other type of relevant information for the historic building analysis and conservation, Cheng et al. [2021], Mol et al. [2020]. This HBIM model can be modified at any time, uploading data regarding past and future intervention results and the structure's state evolution as seen in Mol et al. (2020), being, in this way, a valuable information source for later works.

As already mentioned, historic timber structures can be made up of very complex and irregular elements, thus modelling this type of structures with a high level of detail in a 3D software may be very time-consuming. Currently some works as Pöchtrager et al. [2017] and Yang et al. [2017] have made progress in the timber structure field by increasing the level of automation. However, in these works the timber structure is modeled using uniform beams with constant rectangular section along their length. In order to make a more realistic 3D representation of the beam outer shape for timber structures composed of highly irregular beams, a methodology that allows to create a model more adjusted to the real element shape is needed. In this way, some works have accelerated the modeling process of historic timber structures obtaining 3D models that can represent the elements' geometry with high precision. For instance, in Bassier et al. [2016] a parametric model of a roof timber structure is created from point cloud meshes using ScanTo3D built-in, and is exported to BIM software. Also, in Prati et al. [2019] and Massafra et al. [2020] generative algorithms are created in Grasshopper® that allowed to model wooden trusses and to create simplified BIM models used to introduce relevant information.

Numerical analysis by finite element models (FEM), is a technic that can be carried out in the cultural heritage field in order to assess the structural performance or the risk of collapse of historic structures (Bertolini-Cestari et al. [2016], Bassier et al. [2016]). Throughout time old timber structures may have undergone different kind of modifications, produced either by degradation, external actions effect or by interventions (Bertolini-Cestari et al. [2016]). As a consequence, the current structure is different from the one originally constructed, being the structural analysis a useful tool to verify if the construction's structural integrity has been compromised. In addition, the structural analysis could be performed to assess the structure's response to extreme unexpected events (Longarini et al., 2020) or even to assess the effectiveness of future interventions (Li et al., 2021). Recently, in works as Bassier et al. [2016], Massafra et al. [2020], there has been progress implementing the structural analysis in HBIM timber structures models.

Although the significant advances made to the modeling of timber structures using BIM, the consideration of decay and irregular cross-sections of existing structures still needs attention. One of the most significant problems that decayed timber structures present is that the apparent external shape of wooden beams does not coincide with their resistant section. This is why the apparent 3D model may not be adequate for resistance calculation or analysis, since it cannot accurately reflect the real structural performance of the construction. Therefore, a 3D model representation of the resistant beam, in addition to the apparent one, would be desirable in order to make a more realistic and complete HBIM structure model. Furthermore, it would be preferable to use parametric models which requires less storage space, combined with a methodology that involves short processing times.

The objective of this work is to propose and validate a methodology that, based on LIDAR and non-destructive test data, such as the resistance drill tests, allows to create a single HBIM model of irregular timber structures formed by parametric models comprising both apparent and resistant cross-sections. The apparent parametric model represents the structure's external geometry and it is used also to collect all the necessary data for the structure's conservation state analysis. On the other hand, the parametric analytical resistant model represents the structure's non-decayed material geometry and it is used to carry out the structural safety analysis. This methodology will be applied both in a laboratory case for calibration and also in a real case study for validation.

2 Methodology

For the creation of the apparent and resistant 3D models of the decayed timber beams, the parametric beam model that is proposed will be first explained and then how to apply it within a global framework to perform the complete modelling of the structure in HBIM.

2.1 Parametric beam modelling

The methodology used to represent this type of irregular beams is based on the creation of a parametric beam model that may be valid for any beam with these characteristics. This model is starts from the creation of two irregular octagonal parametric sections, each one located at one end of the beam section to be represented (figure 1a-b). The octagonal section was chosen as it was found to be an optimized section to represent irregular section beams in wood (Nocetti et al, 2021). Between these two parametric sections (Figure 1.a) a progressive extrusion is carried out creating one beam segment (Figure 1.b). This process is repeated with the intermediate sections of the beam along its length (Figure 1.c). The model will increase in accuracy with the increase of considered intermediate sections. The appropriate number of sections to use will depend on the degree of irregularity of the beam and the need for higher accuracy. It is recommended that each beam should always have a minimum of three sections (one at each end and one in the centre) and also additional sections in each area where there is a significant change in section geometry, as to represent all possible critical sections. The values of each octagonal parametric section may be obtained by accurate optical measurements, such as from laser scan cloud of points, for the apparent section and from non-destructive tests, such as drilling resistance tests, for the resistant section. In this framework, the values for the parametric octagonal section are obtained, in the case of apparent geometry, by approaching the point cloud section to an irregular octagon and thus obtaining the corresponding values (Figure 2.a). In the case of resistant geometry, the octagon parameters values (Figure 2.b) will be obtained from the point cloud and from the resistance drill graphs (Figure 2.c) [Cabaleiro et al. 2018]. As a general rule, for each resistant section to be measured, four tests are made (two horizontal and two vertical) from which the length of the resistant material is obtained.

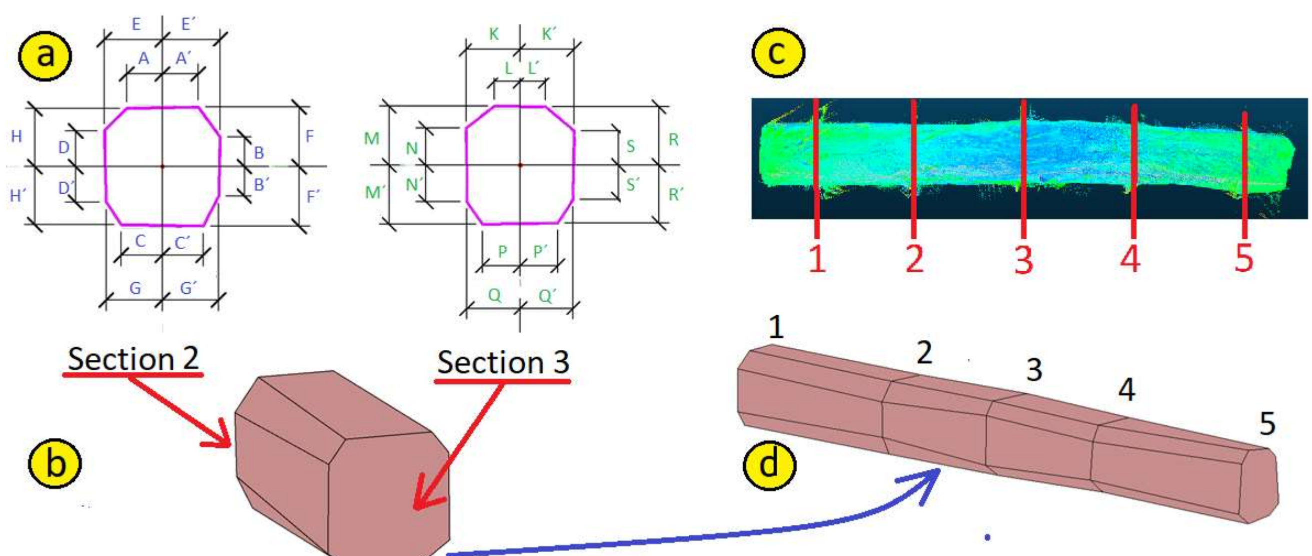

Figure 1. Source of information for the parametric models: a) beam sections created using a parametric irregular octagonal section; b) progressive extrusion between two beam sections (section 2- section4; d) cloud of points of the measured beam sections; c) beam modelled from several parametric sections (section 1-2-3-4-5).

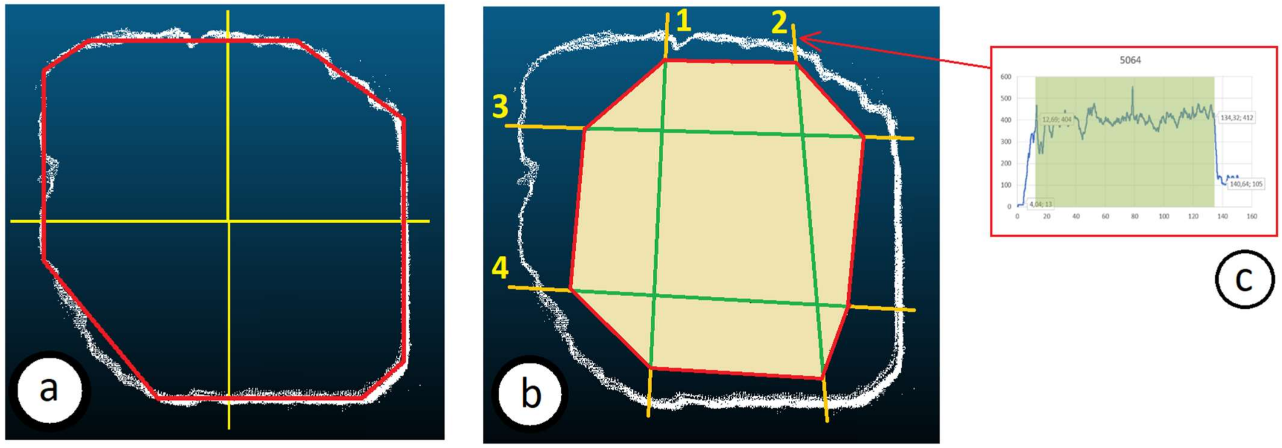

Figure 2. Representation of the cross-sections a) apparent section octagon geometry from the point cloud section. b) resistant section octagon geometry from the point cloud and the resistance drill graphs; c) drilling resistance graph.

2.2 General methodology for the HBIM model

In order to represent the apparent and resistant 3D models of a decayed irregular timber beam in HBIM, (figure 3), a general framework is proposed in this work. With this process, a complete HBIM model is proposed that will allow to carry out the structural simulation and safety analysis of a timber structure.

1) Field data collection - this phase consists in the onsite acquisition of the geometry and structural health information of the timber elements. Geometry is obtained by visual inspection and laser scanner, whereas the condition state of the elements and other relevant data is obtained by combining visual inspection with non-destructive tests such as drilling resistance, moisture content measurement and pin penetration. In order to carry out a proper structure's beams modelling and resistant analysis, it is recommended to test the extreme sections of the beam (near the supports) and a mid-spam section using drilling resistance tests as to obtain information on the depth of decay. Also sections where there is a sudden change in geometry or visually present a high degree of decay should be tested.

2) Beam apparent geometry 3D modelling - in this phase the orthogonal projection of every beam point cloud in the sections tested by drilling resistance is obtained. From the section's projection, all needed geometry dimensions are taken as to include in the octagonal cross-section parameters (as explained in section 2.1). Then the progressive extrusion is made between each section, thus obtaining the corresponding 3D model for each beam.

3) Structure's apparent HBIM model - all 3D modelled beams are inserted into the structure general HBIM model. Furthermore, all the information obtained during the first phase, such as photographic records and visual inspection data (including damage and defect location), is linked to each beam apparent model and consequently to the structure model in general.

4) Beam resistant (analytical) 3D modelling - from the drilling resistance test data, the needed values (depth of decay) are extracted to be introduced in the octagonal parametric section of the beam model, considering only the non-decayed section. Next, the progressive extrusion between of each section is carried out, thus obtaining the resistant 3D model of the beam, a model that in this case will have a structural analytical component. This resistant model is embedded within the apparent model. This model has represent the beam's mechanical properties for non-decayed wood, while the apparent model does not have the resistant mechanical properties assigned to it. For combination of the models, the longitudinal axis of the beam that passes through the centroid of the sections and the coordinates of the beginning and end points of the beam are used as a reference. In the case of beams that do not present any type of decay, the resistant model coincides with the apparent model.

5) Structure's complete HBIM model – by combining both models, a HBIM model which contains the structure apparent and resistant geometry is obtained. This model allows to access data obtained and collected in the apparent model (visual inspection results, humidity and other surface test results) to analyze the beams' structural health. On the other hand, the resistant model can be used to perform a safety analysis by exporting the geometry to a structural calculation software.

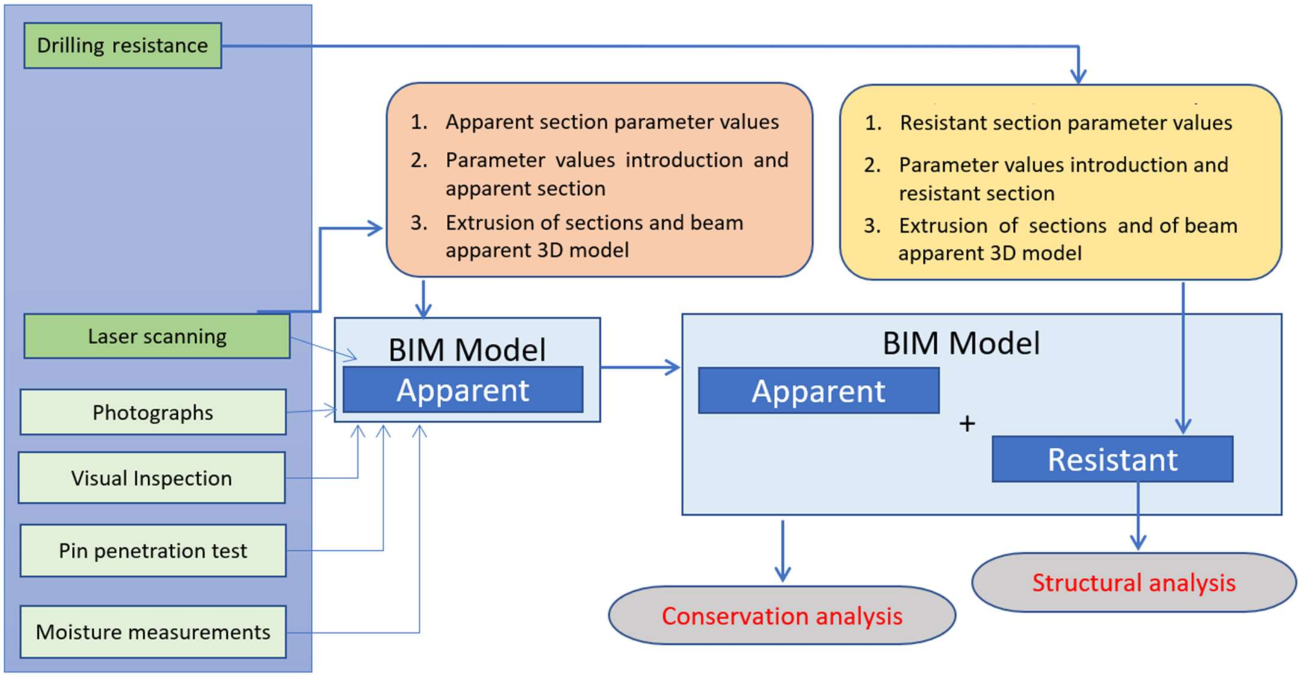

Figure 3. Detailed diagram of the HBIM model creation for an existing timber structure composed by irregular decayed beams.

3 Laboratory case study

In order to calibrate the proposed methodology, a beam was tested on laboratory controlled conditions. This case consists of a chestnut beam (Castanea sativa Mill) with an irregular and variable cross-section along its length (Figure 4.a). With regard to its dimensions, it is approximately 1.2 m long and has an average cross-section area of approximately 160 cm^2. The element presents significant signs of decay caused by xylophagous insects attack and fungi presence on its surface, along with humidity action. The element was tested four times by section using drilling resistance (2 horizontal and 2 vertical measurements) in five different sections along its length (Figure 4.c). Subsequently the beam was scanned, obtaining a 2.8 E6 points cloud (Figure 4.b).

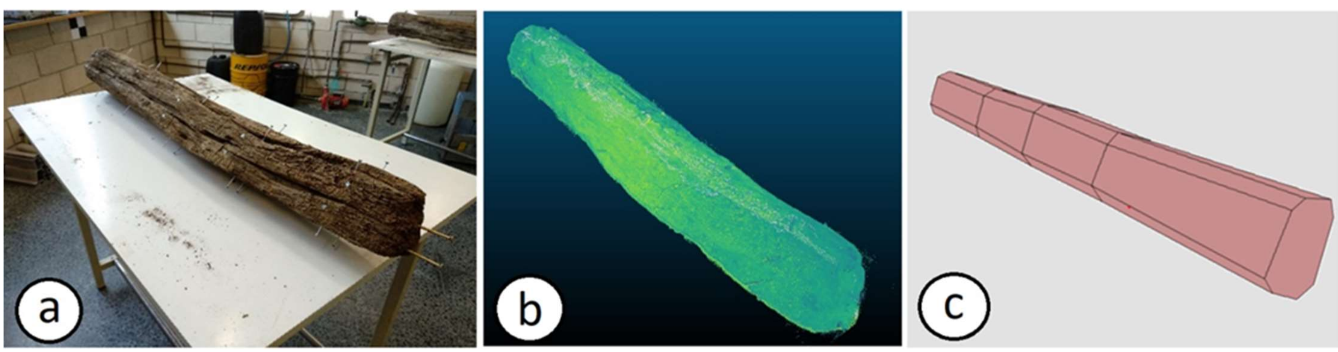

Figure 4. a) tested laboratory beam; b) point cloud obtained from the beam; c) apparent parametric model of the beam.

In this way it was possible to obtain the resistant sections from the resistance drill test data and the apparent sections from the laser scanner point cloud. So as to create the apparent parametric beam model, the apparent section parameter values were extracted from the point cloud in the areas where resistance drill tests were carried out. Next, the apparent beam geometry was modelled performing a progressive extrusion between sections (figure 2). Once created the beam apparent geometry (figure 5.b), the process is repeated to create the resistant model (figure 5.a). This model, unlike the apparent one, possesses an analytical component for the structural analysis and it is embedded in the apparent model of the beam (figure 5.c). In this way it is obtained a complete beam HBIM model.

The measurement equipment used was Faro Focus 3D laser scanner, that allows to measure in a range of 0.6 to 120 m with an error of ± 2 mm and a Resistograph® 3450 to perform the resistance drill tests. This tool has a 3 mm drill bit with feed rate of 30 cm / min and 1500 rpm. The software used were CloudCompare 2.10 for point clouds processing, Revit 2019 for HBIM modeling and ANSYS 2019 for numerical structural analysis

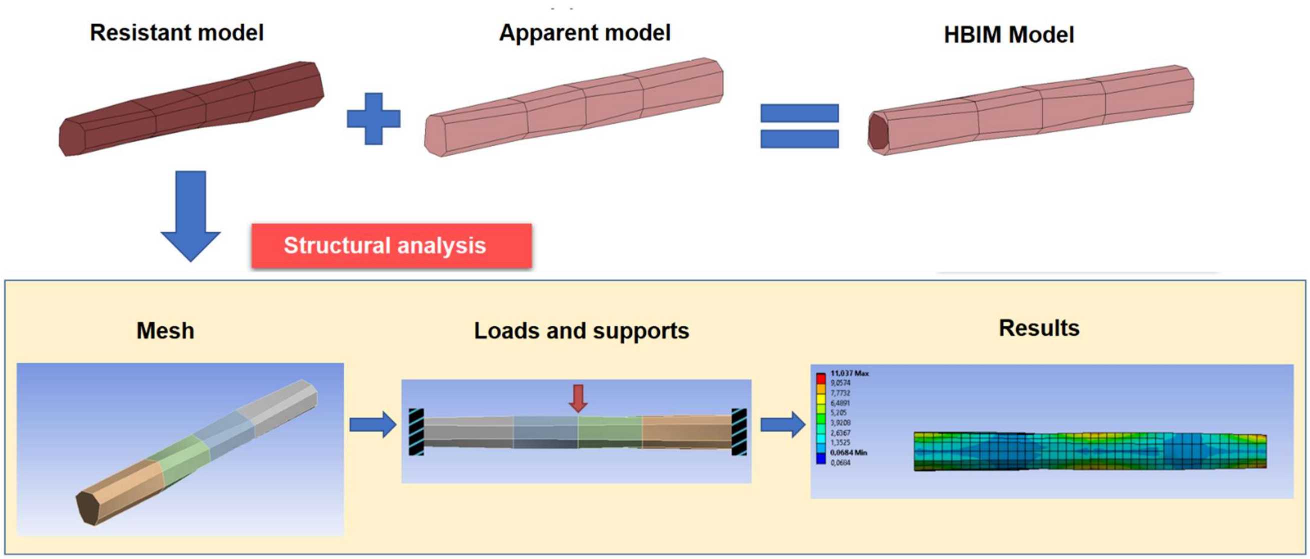

Figure 5. a) beam resistant model. b) beam apparent model. c) beam complete model (resistant + apparent). d) structural beam analysis starting from the analytical model

On one hand, the resistant model allows to perform a detailed beam resistant analysis (see figure 5d), while on the other hand, the apparent model allows to represent the beam more accurately, without the need to use complex renderings. To verify the apparent model capacity to represent the real shape of the beam, a model rendered from the point cloud of the laboratory beam (Figure 6a) was compared, with the apparent parametric model made (Figure 6.b). For that aim, the two beams volume were compared, obtaining a difference of less than 3%, while the memory resources occupied by the rendered beam model were 4 MB while for the parametric beam they were 115 kB.

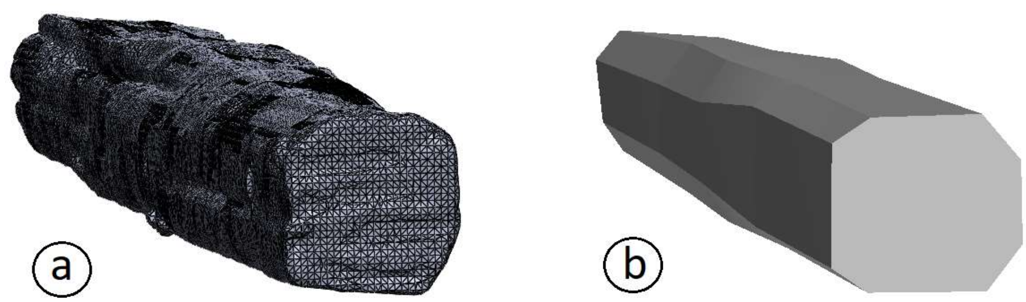

Figure 6. laboratory beam: a) rendered model, b) parametric model

4 Field case study

The methodology proposed and initially used in the laboratory beam was then applied in a field case study. The selected structure was the Guimarães chamber´s roof in Portugal (Figure 7), a complex roof structure with multiple irregular beams with signs of past decay activity. The old Municipal Chamber is located between the Largo de Oliveira Square and the São Tiago Square, in the heart of the Guimarães historic center, being one of the most recognizable historical buildings in the city. Regarding the architectonical characteristics, the building with an almost rectangular plant has a hipped roof with a ground and first floor. The ground floor has no interior area and connects the two squares through a series of arches. The first floor consists of two large rooms, one of them stands out for having a curved polychromatic wood ceiling. The surface of the roof that supports this painted vault is 41 m^2. On the other hand the main façade is formed by four broken arches in the lower part and a porch supported by a cornice with five shutters and iron balconies on the main floor. The structural system used is composed of granite masonry load-bearing walls. The current building is the result of various constructions and renovations throughout the Middle Age. Its original function was to house the council men and court meetings in the first floor, while the open ground floor was reserved to house the market or part of it. Currently, it is used as a museum and exhibitions are housed there.

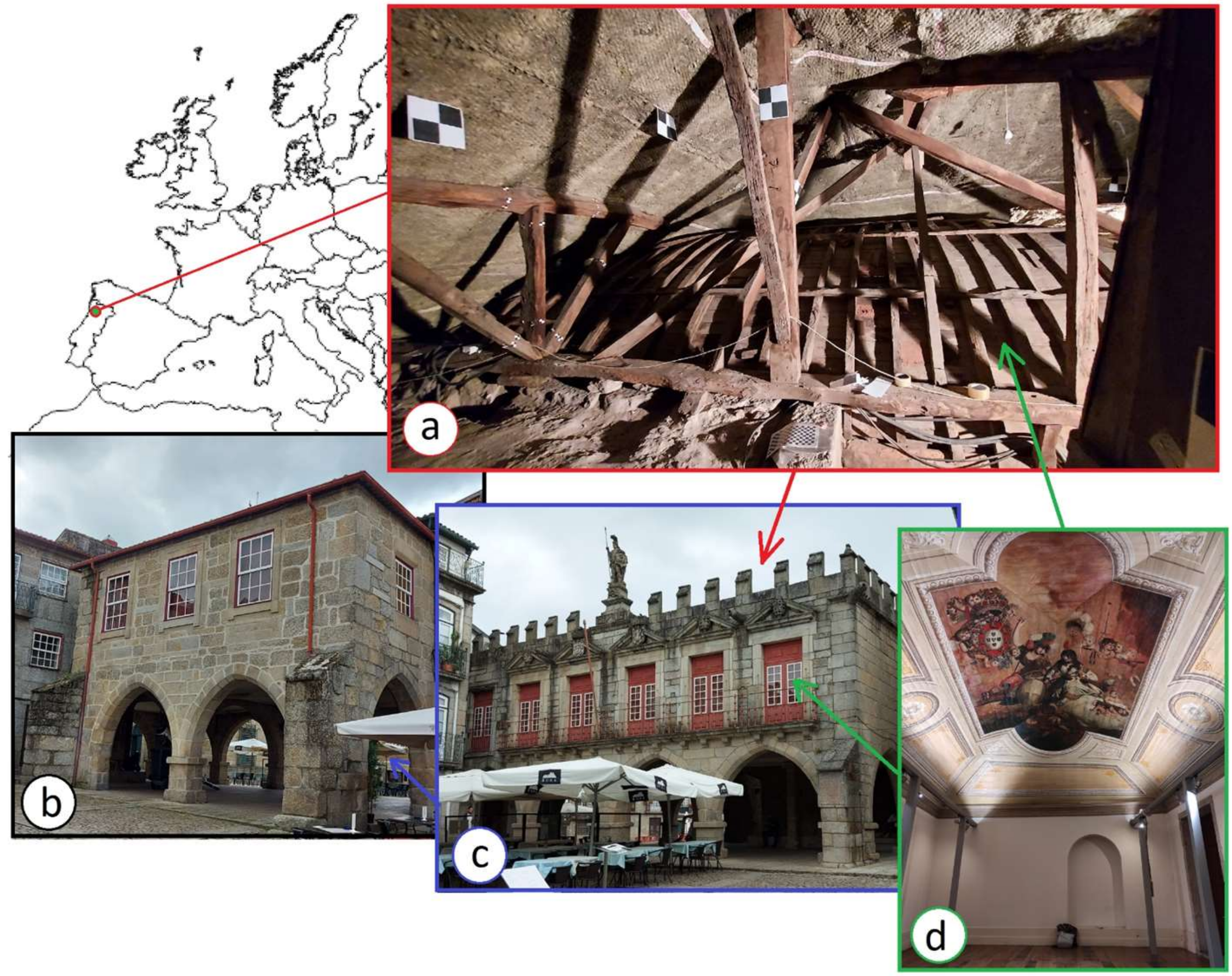

Figure 7. Guimarães chamber building in Portugal. a) Roof of the room with curved polychromatic wood ceiling; b) North view of the building; c) South view of the building; d) Room with curved polychromatic wood ceiling.

The roof of the building is composed of a set of timber trusses and beams that supports a system of rafters and the tiles weight. Visual inspection revealed that a significant part of the structure had been recently remodelled, so many of the beams and trusses were in good condition and presented a constant regular section along their length. For that reason, this work will mainly focus on the study of two of trusses, which in addition to present a highly irregular geometry, also showed significant decay signs (figures 8.a and 8.b). Each of the two trusses is made up of 4 beams, where the beam with the largest section was in contact with the roof. In order to carry out the trusses' structural health and resistance capacity analysis, their resistant and apparent geometry were modelled. In addition to this, the entire roof apparent geometry was also modelled and included in the HBIM model.

In the data acquisition, 10 scans were performed distributed in the roof according to figure 9a. From each scan an average of 1.7×10^8 points were obtained, which were registered in a single reference system (Figure 9.b). This registered system was used to isolate the A and B trusses' geometry in separate point clouds, occupying 10 and 27 million points, respectively. On the other hand, drilling resistance tests were made on both trusses, carrying out 34 test on truss A and 32 test on truss B. Furthermore, a visual inspection was made and detailed photos were taken of the whole roof to identify its general condition

With these data, the complete HBIM model of the entire timber roof was created. This model included, besides A and B trusses apparent and resistant model, the apparent geometry of all structural elements that compose the roof, comprising more than 91 modelled elements (Figure 10).

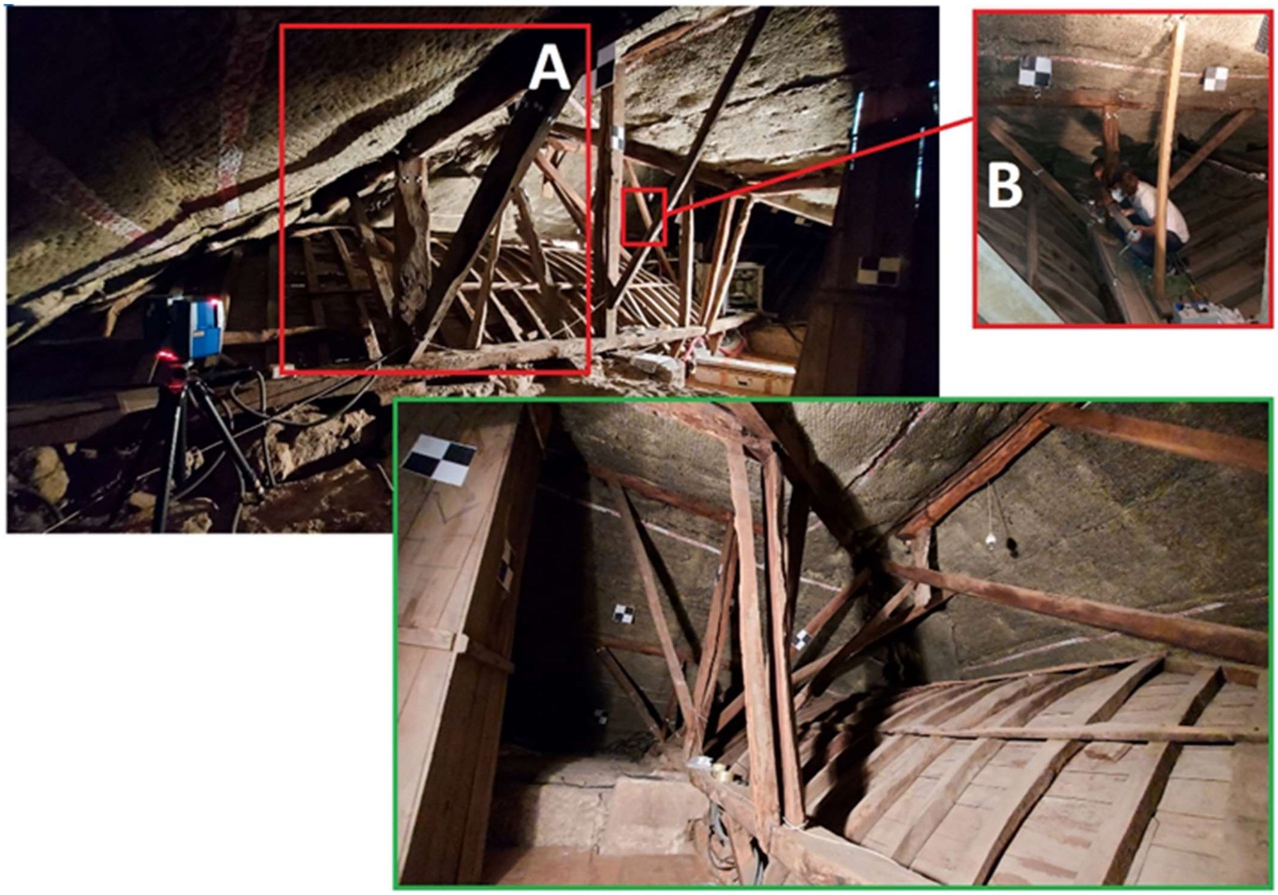

Figure 8. Guimarães chamber roof detail, with indication of the analyzed trusses (A and B).

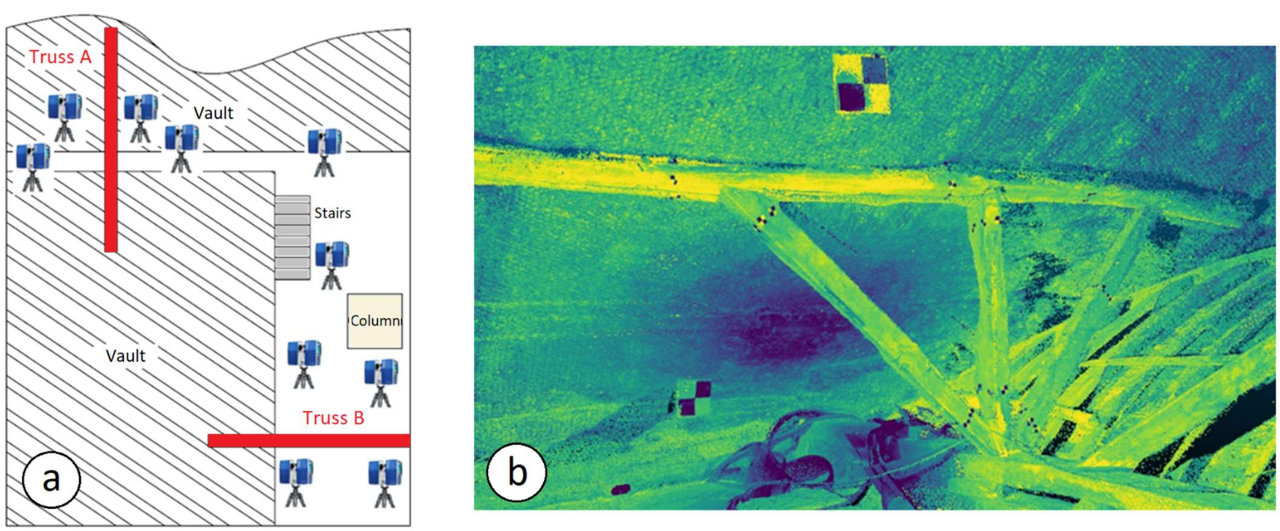

Figure 9. Laser scanner tests: a) scan location; b) truss B view in roof point cloud

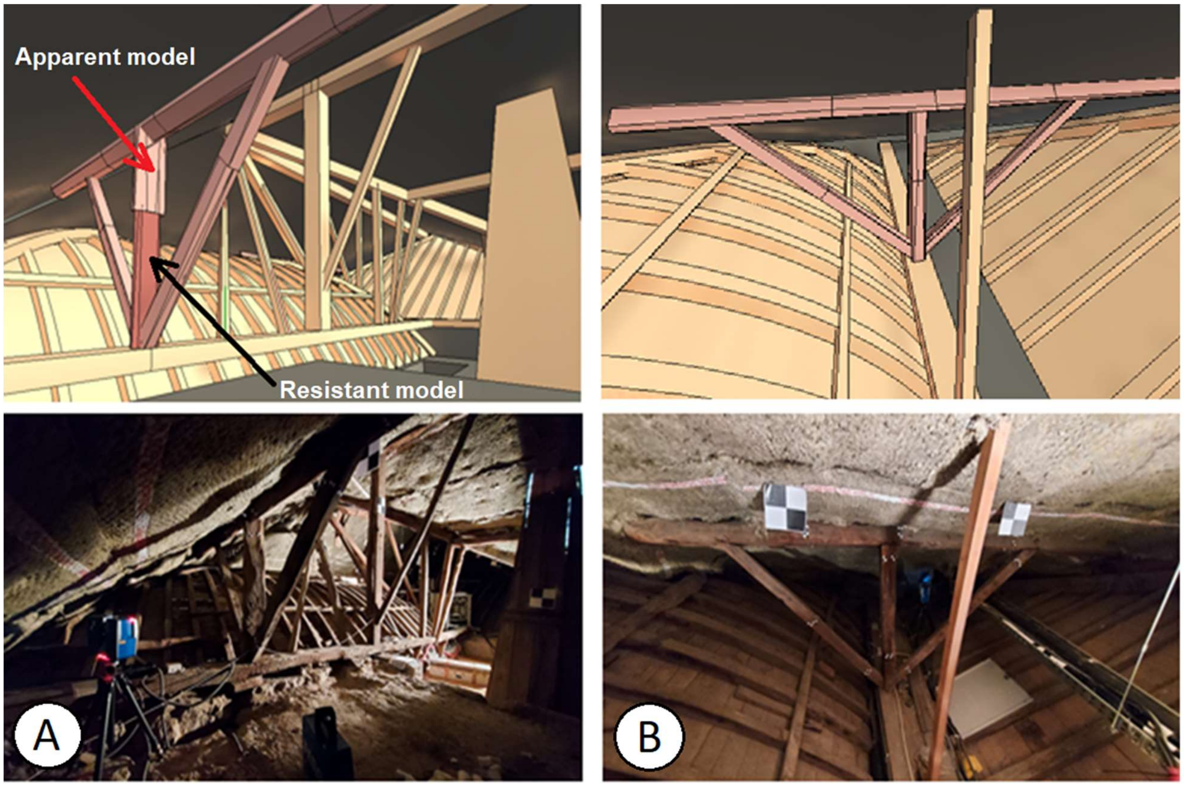

Figure 10. A and B trusses' apparent HBIM model and real view

As to carry out the structural analysis both trusses resistant models were exported to FEM software Ansys. Firstly, the material properties were introduced. The elements made of hardwood were visually graded according to UNI 11119 standard and the following properties were assumed: compression parallel to grain of 9 N/mm^2, bending strength of 10 N/mm^2, tension parallel to the grain of 9 N/mm^2, shear stress parallel to grain of 0.7 N/mm2 and bending modulus of elasticity of 9000 N/mm^2. With regard to the structural behavior and finite element model, the support conditions were chosen in a way to represent the onsite conditions and connection of the trusses with the other existing structural elements. The weight of the rafters, tiles and snow was introduced as surface loads applied to the beam surfaces in contact with the rafters. After generating the mesh, the trusses stresses were calculated, obtaining a maximum tension of 8.14 N/mm^2 and a maximum deflection of 2.53 mm in A truss (Figure 11). Therefore, the analysis concluded that both trusses still present an adequate performance.

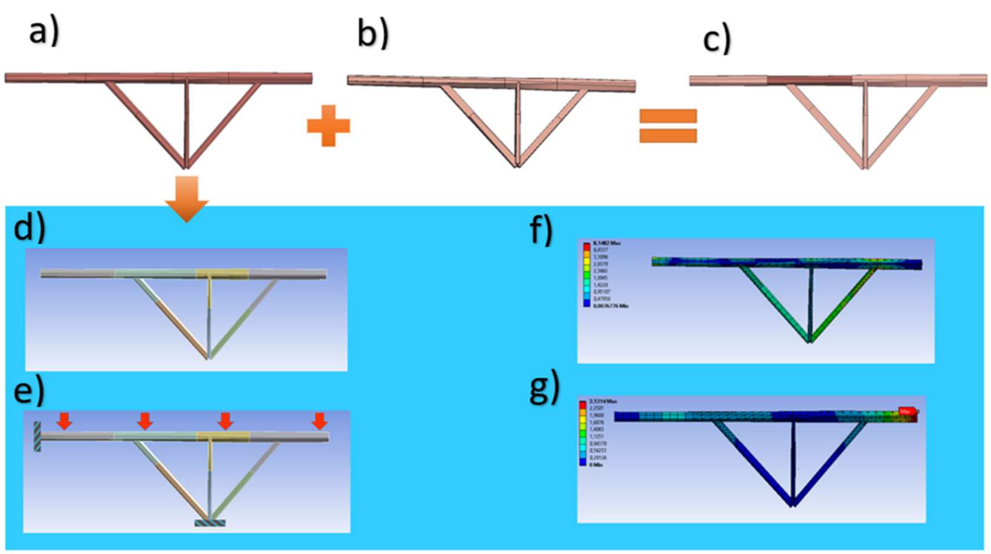

Figure 11. a) Resistant model, b) Apparent model, c) HBIM model, d) Model in the numerical analysis, e) Scheme of the loads, f) Analysis results, stresses, g) Analysis results, deflection

During the state of conservation analysis, where all the collected information (point clouds, scans, photographs, resistance drill graphs, among others) was analyzed evidencing that one of the truss B beams had a high degree of degradation (Figure 12). For this reason, a continuous review of the roof condition is necessary to avoid an increase in their degradation and therefore a possible loss of bearing capacity.

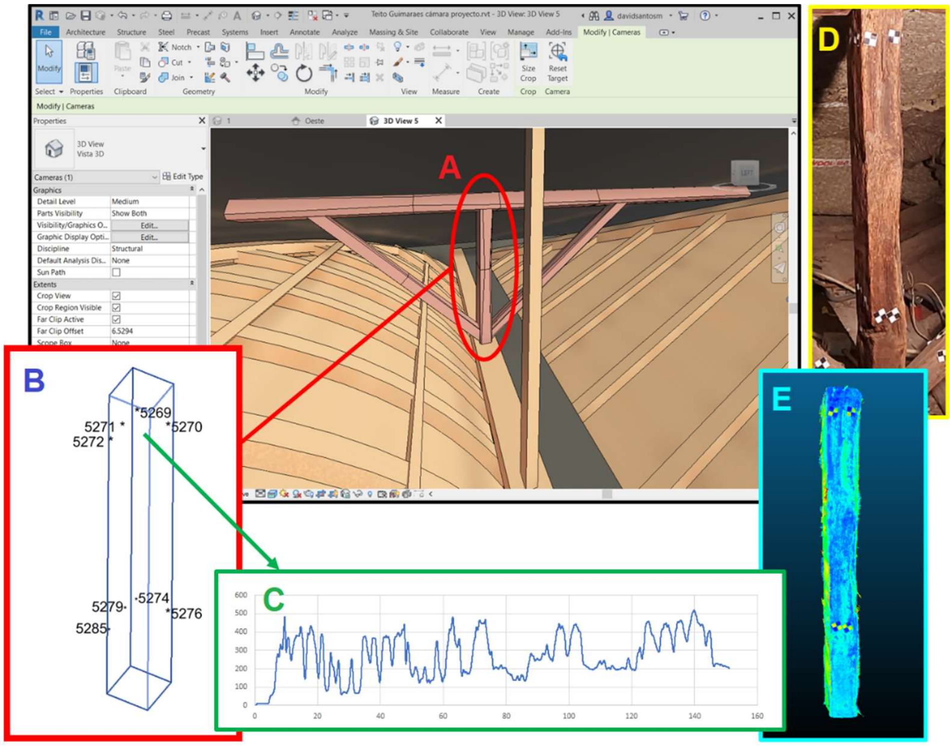

Figure 12. a) Truss B vertical beam with a high degree of degradation. b) resistance drill test positions scheme c) resistance drill test graph. d) vertical beam picture associated in the HBIM database to the model e) vertical beam point cloud associated in the HBIM database to the model.

In the same way as it was done with the laboratory case, the trusses rendered and parametric model geometry were compared. This comparison showed a volume difference between models of 3.55% and a 10 times less required storage memory for the parametric model.

5 Conclusions

Based on the obtained results, the methodology proposed in this document shows its potential for modeling timber structures with irregular and or decayed beams, from LIDAR and drilling resistance data. This methodology allows to obtain in a single HBIM model simultaneously both apparent and resistant structure's geometry and respective data. On the one hand the apparent parametric model collects all necessary data for a structure's health analysis, in addition to be able to represent irregular beams' structure geometry with a high level of detail. The volume difference between the rendered and the proposed parametric models was on average only 3.2%, whereas the memory space occupied was 10 times less. This offers a great advantage working with 3D HBIM models of historical timber structures since it is necessary fewer resources for their representation as well as for their structural analysis. On the other hand, the parametric resistant model takes into account the beams surface degradation. In this way a structure resistance analysis can be carried out considering the decreased load bearing capacity caused by decay, being able to simulate in a more accurate way the construction's structural performance.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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