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Parametric modelling in BIM for structural analysis of masonry vaults

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Abstract. The use of BIM for historical heritage structures has started to be widely diffused and referred as H-BIM. These models are usually aimed at the management and conservation of monuments; however, these can also contain the information necessary for the characterisation of a numerical structural model. This paper is focused on the interoperability between H-BIM and numerical models applied to masonry vaults, structures that typically require local safety assessments. Different degree of geometry subdivision for structural analysis of masonry vaults, has been identified and related to various numerical modelling approaches and HBIM classification. Based on this, an automatic parametric procedure specific for lunette vaults has been developed. This allows to obtain automatic three-dimensional geometric models that can be efficiently implemented in the H-BIM environment and to obtain and manage the geometric characteristics as input to the numerical modeling. Finally, the application of the methodology to the National Palace of Sintra is presented.

Keywords: Building Information Modeling, Masonry Vaults, Structural analysis, Finite Element Modeling, Parametric modeling.

1 Introduction

The BIM methodology applied to historic buildings has reached a high level of diffusion in the international context [1]. H-BIM models, through a centralized database, can provide all the knowledge required for the application of structural analysis methodologies, not only the geometric characteristics, but also the whole spectrum of knowledge and diagnostics [2].

However, BIM software have limitations in the structural field, especially for historic masonry buildings, which are characterized by complex and irregular geometries and large sizes. As a result, simplified models and external software are needed for in-depth structural checks.

In particular, masonry vaults due to their complex geometry represent a challenge in both H-BIM [3] and structural modeling. Those are characterized by damages that typically depend on settlement or seismic actions and require local safety assessments.

Structural analysis of masonry vaults is a widely debated topic in the scientific literature, and various modeling techniques have been proposed [4]. The adoption of an approach and the reliability of the results depend on the level of knowledge acquired. Therefore, it is essential to conduct a specific field campaign to obtain the necessary information for calibrating calculation models, including the historical-constructive characteristics of the parts, mechanical properties of materials, presence of pre-existing crack frameworks, and survey of the masonry pattern.

To address these challenges, a digital modeling methodology for masonry vaults has been proposed specifically for structural analysis.

Three different geometric modelling methods have been identified depending on the grade of subdivision of the structural parts specific to masonry vaults. These are connected to various numerical modelling strategies depending on the objectives of structural assessments required. Based on these, a generative algorithmic modelling for lunetted masonry vaults has been developed. The definition of specific input parameters allows geometric models to be interpreted by both BIM and calculation software, enabling the application of different numerical modelling strategies.

Finally, the procedure has been applied to the case study of the lunetted vault present in the entrance portico of the National Palace of Sintra. The methodology provides a promising approach to digital modeling of masonry vaults for structural analysis, overcoming the limitations of the common tools used in a BIM approach.

2 H-BIM geometrical modeling of complex historical structure background

In the case of historic masonry buildings, BIM modeling typically involves creating a three-dimensional model from a point cloud through the modeling of building elements referred as the Scan-to-BIM procedure.

While data collection and pre-processing systems are becoming increasingly automated, the most significant critical aspect of the Scan-to-BIM procedure is the modeling methods [5]. BIM software designed for the Architecture, Engineering, and Construction (AEC) sector have limited tools for modeling existing and historic buildings that are typically characterized by high complexity on multiple levels, including geometric, material, historical, and construction.

As an alternative to the time-consuming classical modeling methodology, various research groups have proposed several specific alternatives for different objectives. These methodologies can be summarized into three main groups [6]: reverse modeling, direct modeling, and generative modeling. Reverse modeling involves generating a polygonal surface mesh from the processed point cloud, while direct modeling involves extracting a series of profiles from the point cloud and using them as a reference for the creation of complex surfaces, usually NURBS [9]. Generative modeling,

on the other hand, involves generating a model through geometric operations algorithms developed in visual scripting environments, based on specific input parameters.

The above strategies lead to non-parametric models but partially solve the problem of geometric complexity. Generative modelling using visual scripting environments such as Dynamo or Grashopper is growing in popularity [9], particularly in the case of masonry vaults. Algorithmic modeling provides the advantage of automatically generating a geometric model specific to the individual object, and with appropriate adaptations, these models can be used to conduct structural analyses through the finite element method.

3 The degree of geometry subdivision

The development of a BIM model for a historical building requires a preliminary assessment to define the objectives of the model to be realised, depending on the model's aims and available resources. This can be done by targeting a specific level of detail (LOD) that the model requires and the level of information (LOI) that the object contains or is connected to [10].

Similarly, as mentioned above, structural analyses of masonry vaults require models that can be characterized by varying degrees of geometric complexity.

Typically, the most significant structural components are the vault shell, the presence of backfill and upper infill, the masonry pattern, and the potential presence of ribs. Based on these, three different degrees of subdivision (DoS) of the geometry with increasing complexity have been identified: zero, 1, and 2 (see Fig. 1). These start with the degree zero (DoS0), where the geometry is represented as a unique generic volume, and end with degree 2 (DoS2), where the vault is divided into the blocks and all construction materials.

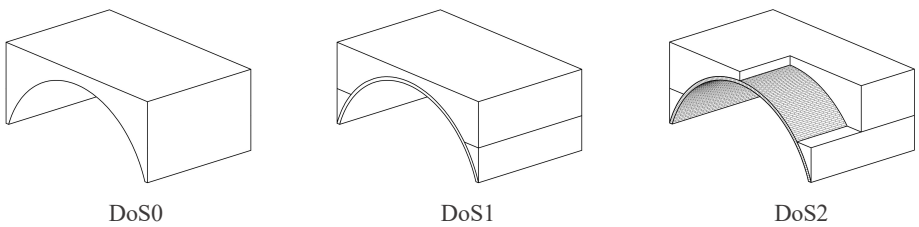


Fig. 1. Example of the three degrees of geometric subdivision on a masonry barrel vault.

Each degree of subdivision is better suited for different analyses and modeling strategies. For instance, a model with a DoS0 is intended for use in global analysis models, where the accuracy of the object and the differentiation of the parts is less significant. In contrast, a model with a DoS1 is subdivided into the most significant structural elements. This model of intermediate geometric simplification is useful in evaluating the local behavior of the vault in relation to the context while considering external connections appropriately. Finally, the DoS2 involves fine modeling, where

the geometry is discretized into the stone blocks that compose the vaulted system. This aims at local evaluations of the complete vaulted system or portions requiring specific in-depth studies.

The different degrees of subdivision can be referred to as different levels of detail (LOD) in the HBIM environment. For example, a model with a DoS0 can represent a LOD100. On the other hand, a model with a DoS2 may be useful for higher LODs where it is necessary to catalog individual construction elements for restoration operations (e.g., degradation maps, material maps, etc.).

4 A methodology for parametric modeling of masonry vaults

The different DoS discussed in the previous section can be achieved through various modelling methodologies and extended to most kinds of vaulted structures. While BIM tools can be used to achieve a geometry with a DoS0, the other degrees, require more advanced modelling approach, such as generative modelling. This approach covers a broad range of geometric complexities and enables the development of models based on different solutions.

A methodology employing automatic generative modeling procedures for masonry vaulted structures has been proposed (see Fig. 2). The main objective of the procedure is to obtain geometric models intended for two different purposes: one designed for the BIM environment and the other for structural analyses. Generative geometry allows for the processing of both models in parallel, calibrating geometries specifically for BIM objectives and various numerical modelling strategies. The finite element method (FEM) has been adopted as the analysis method.

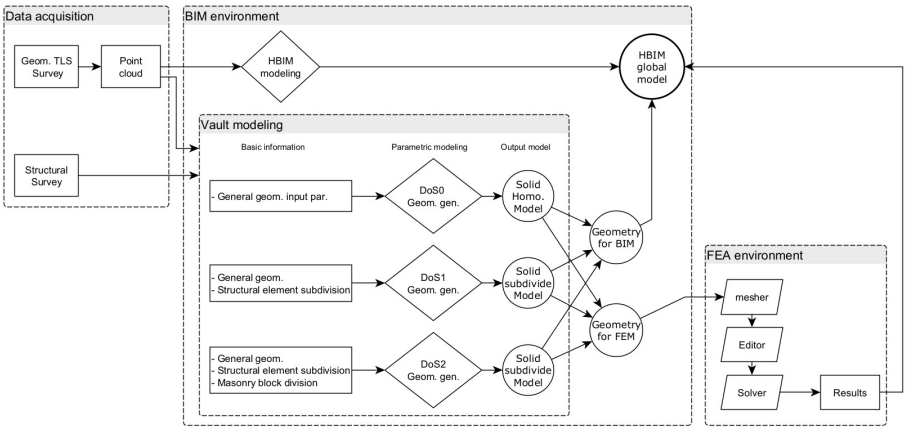


Fig. 2. Proposed methodology for BIM and structural modelling of masonry vaults.

In summary the methodology involves three stages: i) Data acquisition: specific input parameters derived from geometric and structural survey operations, should be extracted from the point cloud through local measurements or automatic procedures [11]. ii) Vault modelling: based on the input parameters, the vault is modelled using

specific geometry generator algorithms that provide two outputs – one for the global HBIM model and one for structural analysis. iii) FEA: the model is processed for discretization, calibration, and analysis procedures by external software.

4.1 A generative modelling procedure for lunette masonry vaults

Based on the discussed methodology a generative algorithmic modelling approach specific for lunette masonry vaults aimed to obtain models of DoS1 has been developed. Lunette vaults are characterised by a main vault, usually barrel or pavilion, with openings on the sides (lunettes) that provide natural light to interior spaces but constitute structural weak elements.

Dynamo [12], the Revit's [13] internal visual scripting environment, has been adopted. The developed algorithm consists of the following phases: definition of input parameters, definition of plan guidelines, geometry generation, assembly, and output (Fig. 3).

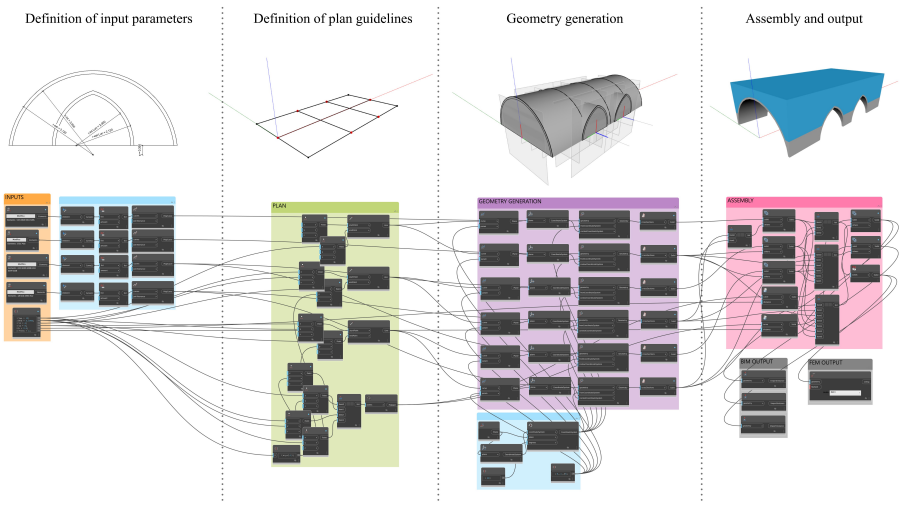


Fig. 3. Dynamo code developed to achieve a DoS1 on a generic lunette vault model.

The extrusion profiles of the main vault and lunettes need to be defined as input parameters. These can be defined parametrically through code, directly in Dynamo, or using elements drawn in the BIM environment. In the latter case, the possibility of adopting different vault profiles is extended. Dimensional parameters are also required for the definition of vault and lunette dimensions, positions of the extrusion axes, height of the backfill and height of the floor.

The procedure uses tools such as extrusion in specific directions of profiles to create solid or shell geometries. These are assembled through various Boolean operations. This methodology, although simplified, allows adaptation to various case studies and the possibility of easily modifying blocks of code according to different needs.

The use of Dynamo allows an easy exchange of information with the Revit model. The geometry can be easily exported and transferred to the comprehensive H-BIM model as a non-parametric object that is subdivided into the required structural part. The HBIM model works as centralized database, collecting not only geometric information as well as reports, related to surveys conducted on site. These models can also be used to aggregate other historic information pertaining to the site and will inform future interventions and analyses. Regarding the structural model, it is possible to transfer geometries from Dynamo to the commercial finite element analysis software Abaqus [14] through the SAT extension; a spatial ACIS solid modeling format.

Finite element models require geometries without intersections or overlaps between parts. The use of generative procedures in this context enables the control of part definition and avoid geometric definition problems typically encountered in direct export from BIM software. In addition, it makes it possible to manage all the model synthesis and simplification operations necessary for the development of structural models. As an example, figure 4 shows several geometric models developed using a generative procedure and discretized into various types of finite elements adopting the Abaqus meshing tool. It is noteworthy that minor modifications to the code allow the parallel development of simplified models designed for finite element modelling, which in this case, follows a homogeneous masonry approach.

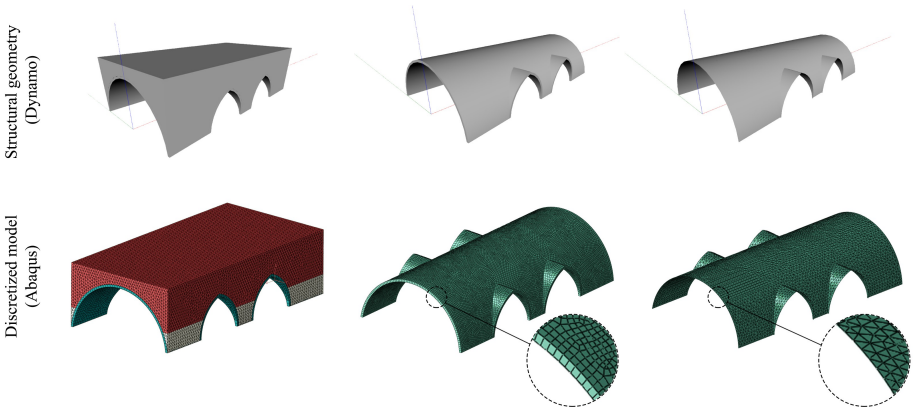


Fig. 4. Example of a DoS1 lunette vault model and different FEM modelling strategies connected.

5 Case study: Sintra National Palace

The Palace of Sintra is one of most significant royal residence of Portugal. It is an unreinforced masonry building that has been subject to a series of architectural transformations over the centuries, that have conferred a high geometric and material complexity that distinguishes this fascinating structure.

The palace has been the subject of several laser scanning survey and diagnostic campaigns [15] that led to the creation of an HBIM model of the entire complex (see

Fig. 5a) [16]. The lower floors of the building present various vaulted masonry structures. The most significant for its size and complexity is the lowered barrel lunetted vault that covers the entrance of the main façade (see Fig. 5b).

a) b)

Fig. 5. a) The BIM model rendered in twinmotion. b) The lunetted vault case study.

The vault is 24.3 m long and 3.5 m span; from the arch impost to the upper floor, it measures 2.8 m. The lunettes have a gothic arch section and cross the main barrel only on the inner side. These allow internal opening to some basement rooms that border the vault.

To model the vault, the generative procedure described above has been adopted. Necessary input parameters have been extracted from the point cloud and structural survey operations, including non-destructive ground penetrating radar (GPR) surveys [15] to assess the dimension of non-detectable internal structural elements.

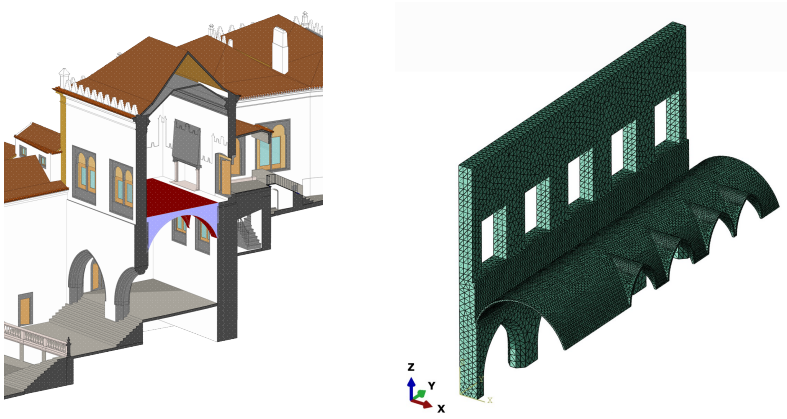
The Dynamo script has been easily adapted to the case study and the resulting geometric model, divided into the structural shell of the vault, backfill, and infill, has been imported into the BIM environment and classified as different structural elements with different characteristics (see Fig. 6a).

As discussed in section 3, utilizing an DoS1 allows for various geometry modeling strategies based on the specific assessments conducted, whether global or local in nature. In this case, a study has been conducted on the structural behavior of the vaulted structure in relation to a vertical settlement of one of the façade pillars. Although the vault currently exhibits no significant crack pattern, the vault-facade system remains a critical area of the building, as demonstrated by its previous collapse during the famous 1755 Lisbon earthquake [17], [18].

A generative process has been used to create a model of the structural portion of the vault as a solid element. This has been combined with the simplified facade portion exported from the global HBIM model.

Numerical modeling has been performed using Abaqus, with a homogenous macro modeling approach representing the masonry as a continuum material. The numerical model has been discretised in 95,292 tetrahedral four-nodes elements (C3D4) of 0.4 m length for the façade and 0.2 m for the vault. The discretised model is shown in

figure 6b. Contact faces with adjacent structures have been considered as fixed. The backfill and fill have been considered as loads.



a) b)

Fig. 6. a) The Vault inserted in the global HBIM model. b) The finite element model of the vault-façade system analysed.

The capacity of the masonry structure in presence of a vertical settlement of the façade pillar has been assessed considering the non-linear behavior of the masonry.

Two different materials have been assigned to the façade and the vault. Mechanical parameters of the facade masonry have been estimated through flat jacks test as reported in [15]. Regarding the vault masonry, in absence of specific investigations, the average values suggested by the Italian standard for the masonry class "solid brick and lime mortar masonry" have been adopted [19].

The nonlinear behaviour has been represented through the concrete damaged plasticity model (CDP), which is based on an isotropic material with a plasticity-damage relation that assigns distinct tensile and compressive strength (f_t and f_c) and different post-peak behaviors with damage parameters (d_c and d_t). Tensile softening has been described through a stress-displacement relation, with an appropriate fracture energy (*Gft*) value calculated according to [20]. Damage parameters d_t and d_c follow a linear evolution law, where the ultimate condition corresponds to 90%. Mechanical parameters adopted for each material are summarized in table 1.

Table 1. Mechanical parameters adopted.

	Young's modulus [MPa]	*Poisson [-]*	*Density [kg/m³]*	*fc [MPa]*	*ft (fc/20) [MPa]*	*Gft [N/m]*
Façade	2550	0.29	2000	4.04	0.20	13.2
Vault	1400	0.20	1800	3.45	0.18	12.2

The findings of the analysis for a vertical subsidence intensity of 1.3 cm are presented in figure 7. The results reveal that the vault and the façade experience localized dam-

age that is linked to the two lateral gothic arches in this configuration. Moreover, damage is observed at the upper floor openings as well.

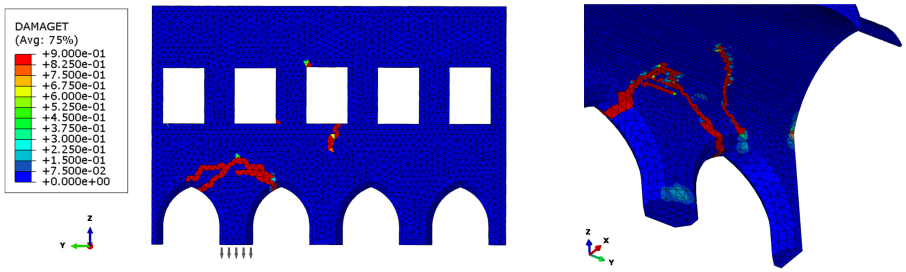


Fig. 7. Tensile damage for a vertical settlement of 1.3 cm intensity of the first pillar.

6 Conclusions

The research presented represents an initial step towards achieving interoperability between BIM environment and structural analysis, for unreinforced masonry structures.

A methodology has been proposed for creating geometries of masonry vaulted structures suitable for both H-BIM and structural analysis, with different levels of detail and application possibilities defined. The generative modeling procedure allows for the generation of geometric models for use in H-BIM and the application of the finite element method.

From experience gained in this research, it can be concluded that the use of generative modeling for masonry vaults allows for the efficient management of both H-BIM and structural models. The proposed procedure for lunette vaults leads to simplified models with lower geometric accuracy compared to direct modeling procedure. However, by appropriately setting the input parameters, a sufficient level of geometric accuracy can be achieved for structural analysis purposes. Moreover, the automation of the process and the parametrization of structural elements allow adaptation of the codes to different case studies, reducing geometric modeling time in both environments. The different classes divided by geometric complexity offer the possibility of applying different structural modeling strategies for vaults. In particular, the procedure demonstrated good interoperability by adopting a finite element macro-modeling approach considering the masonry as a homogeneous material. Future applications could extend the methodology to other numerical modeling strategies, such as FEM micro-modeling or discrete element modeling (DEMs).

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