

Article

A Parametric HBIM Approach to Geometric Uncertainty Modelling for Heritage Bridge Structural Analysis

Giulio Lucio Sergio Sacco ¹, Matilde Ridella ^{2,*} and Chiara Calderini ¹

¹ Department of Civil, Chemical and Environmental Engineering (DICCA), University of Genoa, 16145 Genoa, Italy; giulio.lucio.sergio.sacco@edu.unige.it (G.L.S.S.); chiara.calderini@unige.it (C.C.)

² Department of Modern Languages and Cultures (DLCM), University of Genoa, 16124 Genoa, Italy

* Correspondence: matilde.ridella@edu.unige.it; Tel.: +39-333-655511

Abstract

Implementing Historic Building Information Modelling (HBIM) for heritage structures is challenged by incomplete knowledge of hidden or inaccessible elements, as well as limited information on construction history, original design, and structural details, making geometric definition inherently uncertain. Simultaneously, applications such as structural analysis often require the same missing information. This study proposes an adaptive parametric Scan-to-BIM-to-FEM workflow that explicitly incorporates geometric uncertainty by generating multiple plausible and complete reconstructions from survey data and typological inference, enabling their use in parametric structural analysis. Starting from TLS survey, adaptive families were used to link measured and inferred dimensions through geometric constraints. The methodology is applied to the 19th-century masonry arch bridge of Montoggio (Genoa, Italy), currently characterized by a hybrid structural system resulting from subsequent retrofitting. Eight geometrical configurations were tested by varying uncertain parameters, including vault thickness and backing height, and were analyzed through modal and static finite element simulations. The results show a limited but non-negligible sensitivity of the structural response to these parameters, highlighting the influence of geometric uncertainties on analysis outcomes. In this light, the proposed framework provides a bridge between survey, modelling, and structural analysis, enabling HBIM to support interpretative and predictive structural assessment.

Keywords: HBIM; parametric modelling; FEM; geometric uncertainty; masonry bridges; structural assessment



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1. Introduction

Historic Building Information Modelling (HBIM) has become a fundamental approach for the documentation and analysis of heritage structures. Nevertheless, its application is inherently challenged by incomplete knowledge of construction systems, hidden or inaccessible elements, and limited documentation on alterations undergone by the building over time. Therefore, the geometric definition of HBIM models is often affected by uncertainty, while many downstream applications such as structural analysis, energy-performance simulation, conservation planning, etc., require a level of detail that is not directly observable and require the explicit modelling of hidden, inaccessible, or otherwise unobservable components.

In current practice, Scan-to-BIM-to-FEM workflows are increasingly adopted to support structural assessment; however, they typically rely on a single “best-estimate” reconstruction derived from survey data. This deterministic approach does not fully account

for the range of plausible geometric configurations that may be consistent with available evidence, potentially overlooking their influence on structural behaviour.

This study proposes an adaptive parametric HBIM methodology that explicitly incorporates geometric uncertainty within the modelling process, with the aim of assessing their influence on the structural behaviour. By combining survey-based measurements with historical and typological inference, this approach enables the generation of multiple coherent geometric configurations suitable for finite element analysis. The methodology is applied to a 19th-century masonry arch bridge in Montoggio (Genoa, Italy), where alternative reconstructions are analyzed to evaluate the sensitivity of structural response to uncertain dimensions of the internal structure of the arches. In this perspective, HBIM is framed not only as a descriptive tool, but also as an interpretative and predictive framework supporting structural assessment under uncertainty. To date, HBIM implementation strategies, including recent multisensory Scan-to-HBIM workflow, have focused on reconstructing the single most faithful as-is model. To the authors' knowledge, the use of geometric parametrization to generate alternative plausible configurations of hidden, unmeasurable features for propagation into structural analysis remains a less-explored topic. It is this specific gap that the present study addresses. The novelty of the proposed workflow lies in the use of parametrization beyond the optimization of survey-based as-is modelling, as a structurally informed modelling strategy conceived for the semi-automatic generation of multiple possible FEM-ready configurations, contributing to the assessment of how different assumptions on geometric uncertainties influence structural response.

2. Background and Research Context

2.1. HBIM and Parametric Modelling in Heritage

BIM methodology aims to support the lifecycle of a building across all its phases, from pre-design to design and ultimately to management. It consists of an organized database of information linked to a corresponding 3D geometric representation, enabling the integration of geometric and semantic data within a single environment. At any stage, the Level of Development (LOD), defined as the combination of Level of Geometry (LOG) and Level of Information (LOI), should be consistent with the specific objectives for which the BIM model is implemented [1]. This framework is rooted in the standardization enabled by industrialized building production, where components can be described through predefined parametric families and reused across different projects.

In the modelling of existing buildings, and even more in HBIM, this paradigm is fundamentally challenged. The modelling process no longer starts from design but from a survey of the current condition, typically derived from point clouds or other digital acquisition techniques, enriched with historical and architectural knowledge [2,3]. Consequently, the LOD does not represent the advancement of a design process but rather the level of knowledge achieved about the building, which must be aligned with conservation and analysis needs [1]. In this context, the model becomes an interpretative reconstruction of the structure, where geometry and information are progressively refined based on available data, historical research, and diagnostic investigations.

Such a shift introduces significant methodological implications. The absence of standardization in historical constructions, characterized by irregular geometries and unique constructive solutions, limits the applicability of predefined BIM libraries and requires the development of custom parametric objects [4]. Moreover, the knowledge of the structure is often incomplete and heterogeneous, particularly with respect to hidden or inaccessible elements, leading to the presence of epistemic uncertainty directly embedded within the model. As a result, HBIM cannot be considered a deterministic representation, but rather a knowledge-based model in which assumptions and interpretations play a central role [5–7].

A large part of current research aims precisely at reducing this incompleteness by acquiring and fusing additional data into the model. Recent continuous and multisensor Scan-to-HBIM workflows, for example, integrate survey acquisition, real-time semantic segmentation and parametric HBIM generation within a single pipeline, improving the continuity, automation and metric reliability of the as-is reconstruction and reducing the manual effort needed to translate heterogeneous survey data into semantically structured models [8]. Data-fusion strategies of this kind, combining laser scanning, photogrammetry, inertial and visual localisation and, where feasible, diagnostic investigations, progressively enrich the model with measured and inferred information. Nonetheless, as extensive this effort could be, part of the information may remain missing or uncertain, especially for hidden or inaccessible components. Enriching the model in this way reliably raises its LOI and can, in some cases, refine its LOG, but it does not constitute a definitive solution, as certain geometric features cannot be observed regardless of the acquisition strategy adopted.

However, certain applications such as structural assessment, energy-performance simulation and other specialized analyses, may require LOG and LOD higher than those readily available for the heritage building under analysis. To address this limitation, uncertain information can be represented through alternative assumptions or parameter ranges, for instance by assigning ranges to construction periods, material properties, masses and other relevant quantities, and combining them to generate alternative scenarios. In principle, a similar approach could be extended to the definition of the required LOGs; however, while this is theoretically straightforward, its practical implementation could easily become impractical due to temporal and economical constraints, unless a fully parametric description of the geometry is achieved. This asymmetry reflects the different nature of the two components of the LOD: LOI-dependent quantities are essentially numerical attributes associated with the elements, so the corresponding scenarios can be varied directly and at negligible cost; varying LOG-dependent quantities, by contrast, means modifying the geometry itself, which is not reducible to a numerical attribute and requires a more elaborate parametric pipeline to be propagated consistently across the model.

The parametric description of heritage geometry has been the subject of a substantial body of research. Early approaches relied on scripting and visual programming languages, from the Geometric Descriptive Language adopted in the seminal HBIM workflow [3] to the grades-of-generation logic and the use of Autodesk Dynamo, in order to reconstruct complex architectural elements, such as vaults and domes, directly from point clouds [8–11]. In parallel, native Revit adaptive families have proven to be a viable and more responsive alternative for the semi-automatic, knowledge-based modelling of recurrent typological elements, offering a favourable compromise between geometric fidelity and ease of updating [12]. The same parametric paradigm has also been exploited to bridge the gap between survey and structural analysis, generating analysis-oriented geometries for the finite element modelling of vaulted and massive masonry systems [13,14].

This body of literature demonstrates that the parametric modelling of heritage geometries is feasible in principle. However, the focus is always on the definition of a single model of the as-is configuration in the most faithful way and the parametrization is a tool to speed up modelling and promote reusability. This approach could face some limitations in specific scenarios, such as modelling for FE analysis, where the required LOG could vary according to technical requirements of numerical analysis and the parametrization of the geometry could be a tool to generate multiple geometrical models useful for sensitivity analysis to inform structural assessment.

2.2. FEM in Structural Assessment of Masonry Structures

The structural assessment of masonry heritage structures can be tackled through different approaches, ranging from simplified analytical methods to advanced numerical simulations [15]. Traditional methodologies include limit-analysis techniques, based on graphical statics and on kinematic approaches, which are particularly effective for the evaluation of local mechanisms. Based upon the no-tension assumptions formalized by Heyman [16], these methods can be successfully applied to isolated structural elements such as arches, vaults, and walls approached in 2D [17], as well as to more extended portions of buildings both on 2D sections and 3D [18,19]. Similarly, membrane analysis approaches can be adopted for specific structural typologies, such as thin vaults, where the stress distribution can be approximated within a two-dimensional framework [20]. However, the application of these methods to entire structural systems remains challenging, due to the complexity of interactions between structural components and the three-dimensional nature of the behaviour.

To overcome these limitations, numerical approaches such as the Finite Element Method (FEM) and the Discrete Element Method (DEM) have been increasingly adopted [21]. Among these, the DEM offers a powerful tool for explicitly simulating discontinuities and block interactions, making it particularly suitable for detailed micro- and meso-scale analyses. Nevertheless, its application is still limited by high computational costs and modelling complexity, which constrains its use to relatively small-scale, highly detailed models or if a reliable automated geometrical model generation procedure can be adopted [22]. Conversely, FEM represents the most versatile and widely adopted approach for large-scale structural assessment, mainly due to its flexibility in handling complex geometries and boundary conditions, as well as its broader availability in engineering practice [15,21].

Finite element modelling is therefore widely recognized as a fundamental tool for the structural assessment of historic masonry structures, as it allows the representation of complex geometries, heterogeneous materials, and nonlinear mechanical behaviour [23]. However, despite these advantages, the application of FEM to heritage structures is affected by significant limitations, primarily stemming from pervasive uncertainties in all aspects of the modelling process. These include uncertainties in geometry, mostly related to the internal structural configuration, in the pre-existing state of damage, in the material properties, and in the boundary conditions, all of which can significantly influence the structural response and the reliability of numerical predictions [21].

In this regard, as an example, the adoption of advanced constitutive models for masonry introduces a large number of mechanical parameters, which are rarely directly measurable in historical constructions. Reference to approaches like Masonry Quality Index (MQI) [24], building codes (e.g., the Italian *Circolare* to the *NTC*; [25]), and information about similar structures in the same area, can partially mitigate this issue by providing ranges or indicative values for material properties. In this context, parametric and sensitivity analyses represent a viable strategy to explore the influence of uncertain parameters, albeit at the cost of increased computational demand. The same approach is commonly used for other sources of uncertainties, such as boundary conditions.

Geometric uncertainties, on the other hand, are harder to approach in the same manner. This partly stems from the limited familiarity of the general user with Scan-to-FEM approaches, despite the topic being well represented in the literature. Indeed, a variety of workflows have been proposed, ranging from semi-automatic, voxel- and slicing-based mesh generation directly from point clouds [26] to symmetry- and module-based parametric pipelines [27] and HBIM-mediated procedures [13,28]. A recurrent obstacle, common to most of these frameworks, is that they remain comparatively complex to apply for users with a limited background in geometry processing [29].

However, in heritage structures, and especially in arched and vaulted ones, geometry plays a crucial role in governing structural behaviour: these elements, in fact, carry loads only through geometrical equilibrium, and variations in dimensions, thicknesses, or internal configurations can lead to significant different structural responses [30]. This is particularly evident in masonry arch bridges, in which features such as the vault thickness, the depth of the backing, and the stratigraphy and mechanical role of the backfill are seldom directly observable, yet strongly affect structural response [31]. Despite this, FEM analyses are frequently performed on a single “best-estimate” geometric model derived from survey data, without systematically exploring the range of plausible configurations.

3. Methodological Framework

The proposed methodology is structured as a Scan-to-BIM-to-FEM workflow [32,33] for heritage constructions with incomplete geometric knowledge, uncertainties and FEM specific modelling needs. In this framework, the HBIM model is not conceived as a single deterministic reconstruction of the existing structure based on a point cloud survey, but as a parametric knowledge-based [12] environment able to represent multiple admissible configurations. These configurations represent alternative interpretations of the same object, consistent with the available evidence, structural logic and typological considerations, implemented at an appropriate LOG suitable for subsequent analysis. In this sense, the workflow differs from conventional HBIM approaches primarily aimed at producing one as-is model, and partially reintroduces the scenario-testing logic typical of BIM design processes, where alternative configurations are generated and compared. Here, however, this logic is not used for design optimization, but to test the structural implications of uncertain geometric assumptions in heritage assessment.

The different configurations are generated by explicitly modelling geometric uncertainty, which are the unknown dimensions of not measurable structural elements. Since certain dimensions are limited to the measurable current state, survey data can define accessible surfaces but not hidden components, internal structures, or elements whose presence cannot be verified. Destructive investigation, endoscopic inspections and advanced techniques such as ground-penetrating radar, sonic or ultrasonic testing and thermography can reduce some of the uncertainties; however, they are not always available, affordable or compatible with conservation standards. Historical sources, archival drawings, typological studies, and analogies with similar structures may support interpretation of the structure, but they cannot be assumed as definitive evidence of the built configuration. Within this framework, two main forms of geometric uncertainty can be considered: dimensional uncertainty, related to unknown or partially known quantities such as thicknesses, widths, depths, heights, elevations, inclinations, or relative positions; and configurational uncertainty, related to the possible presence or absence of constructive elements or sub-elements that cannot be directly verified, and which would carry all the first ones. Both forms may affect the interpretation of the structural system and the reliability of analysis-oriented models. While dimensional uncertainties are more common and can generally be represented within a single parametric model; configurational uncertainties are less frequently encountered, and require the definition of alternative geometric decompositions and, therefore, more complex parametrisation strategies or alternative parametric definitions. In the case study presented in this paper, only dimensional uncertainties were considered, since no plausible configurational alternatives were identified.

Parametrization is therefore used not only as a modelling aid, but as a methodological device for representing incomplete knowledge. Measured quantities define the fixed geometric basis of the model, while uncertain dimensions or uncertain elements are represented through parameters or alternative structural decomposition. At the same time, not all geo-

metric quantities are independent: many are constrained by their relationship with other components. Once specific measured or uncertain quantities are assigned, other parts of the geometry become determined as a consequence. The model must therefore distinguish between measured dimensions, uncertain parameters, and geometric constraints.

The workflow, summarized in Figure 1, is divided into five phases: (i) the knowledge phase, which combines metric survey, historical investigation, and typological interpretation to define the available evidence and the constructive logic of the structure; (ii) the definition of the structural system, which consists of the decomposition of the surveyed volume into its principal components, distinguishing among measured dimensions, uncertain ones, and constrained relationships; (iii) the implementation of parametric families and the HBIM model, which must ensure the coherent propagation of variation in the unknown parameters in accordance with the configurational assumptions (paying particular attention to the required LOG, geometric continuity, tolerance control, component subdivision, and object organization, consistently with the requirements of the subsequent analysis), followed by the generation of the set of geometric configurations through a combination of the parameter variations; (iv) the transfer of these configurations to the chosen numerical analysis environment and their analysis; and (v) the optional import of the results back into the HBIM environment and their final interpretation in relation to the assumptions embedded in each configuration, explicitly showing how alternative plausible geometries influence the assessment process. Although this study adopts finite element modelling for step (iv), the framework is not restricted to FEM and may support any analytical procedure that requires geometric information beyond what can be directly measured. The focus of this work is the feasibility of the proposed Scan-to-BIM-to-FEM workflow rather than a comprehensive safety assessment of a case study. Consequently, the simplified numerical analyses presented herein are intended as comparative simulations aimed at evaluating the proposed workflow, rather than as a rigorous evaluation of the influence of selected geometric assumptions on structural response nor as a complete safety assessment of the bridge.

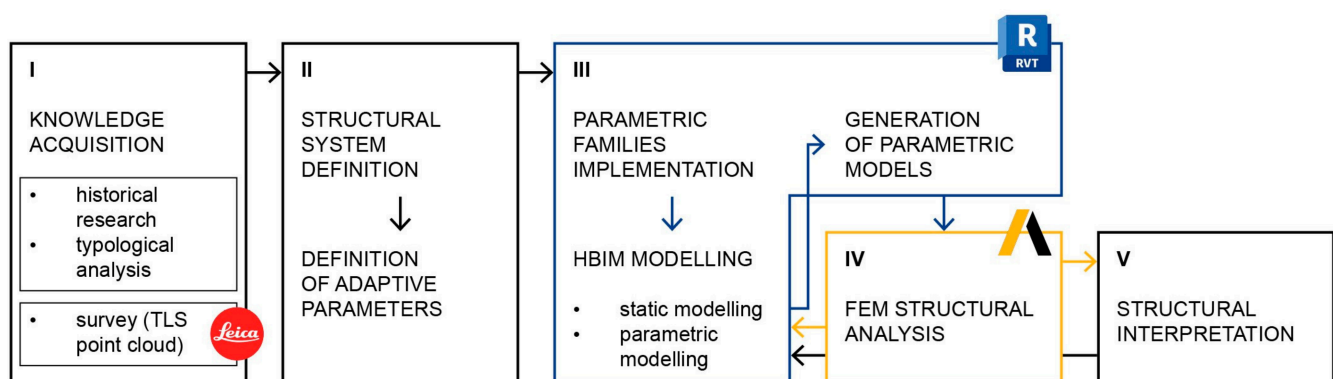


Figure 1. Schematic overview of the proposed Scan-to-BIM-to-FEM workflow.

4. HBIM-Based Parametric Modelling of Montoggio Bridge

The proposed methodology is applied to a historic masonry arch bridge, selected as a representative case study due to the presence of typical sources of uncertainty affecting heritage structures, including incomplete geometric information, irregular morphology, and limited knowledge of internal construction details. Moreover, the structure has undergone a retrofitting intervention, resulting in a hybrid system characterized by the coexistence of historic masonry with steel beams and precast concrete elements (Figure 2).

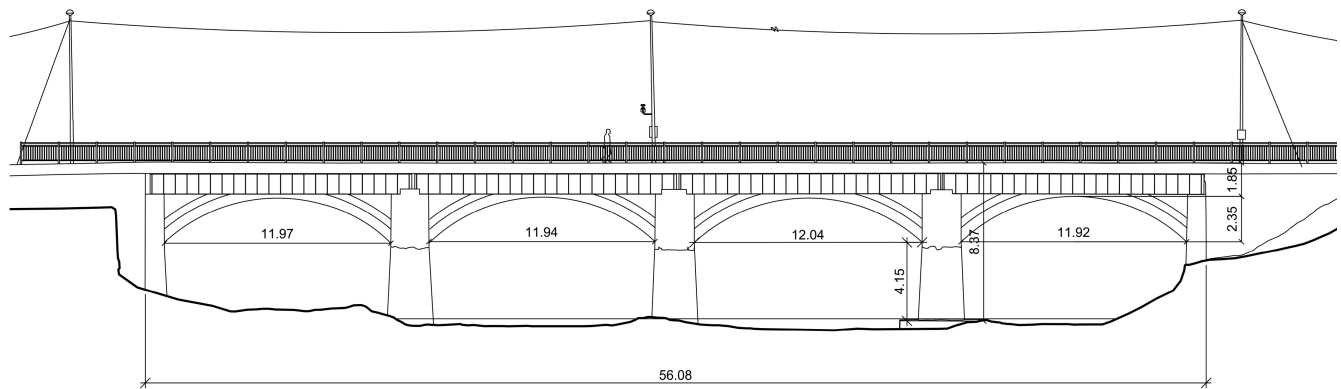


Figure 2. Montoggio masonry bridge: elevation view with dimensions. Drawn from the laser scanner survey.

The bridge, located in Montoggio (Genoa, Italy), spans the Scrivia River along the Strada Provinciale 226 (SP226), as shown in Figure 3a. It consists of four brick arches with a span of approximately 12 m each and a width of about 5.45 m, supported by three stone masonry piers, of about 4.15 m, and abutments, for a total length and height of about 56 and 8 m respectively (Figure 3b). Although its original construction date and design documentation are not available, the bridge can reasonably be attributed to the 19th-century based on its typological and constructive characteristics. Over time, the structure has undergone significant modifications and today it presents additional reinforced concrete elements at the level of the piers, supporting longitudinal steel beams and a new precast concrete deck system (Figure 3d), substantially altering the original load transfer mechanisms. Additional consolidation works, including reinforced concrete strengthening at the foundation level, are also evident. The foundations underwent similar reinforced concrete intervention (Figure 3e). However, no technical documentation related to these interventions is currently available to the authors.



Figure 3. Photos of the bridge: (a) bridge location; (b) overall view of the bridge; (c) detail of one of the masonry arches; (d) detail of a pier showing the concrete retrofit, steel beam, and deck precast elements; (e) detail of the foundation.

The survey campaign was conducted in the spring of 2024 using a Leica RTC360 terrestrial laser scanner (Figure 4a). The instrument was operated at medium-resolution setting with integrated RGB image acquisition, enabling the collection of dense coloured point clouds with full panoramic coverage. A total of 54 scans were acquired and subsequently registered within Leica Cyclone REGISTER 360 version 2024.0.1 software using cloud-to-cloud registration algorithms (Figure 4b). The resulting point cloud dataset consisted of approximately 47 million points, with a global registration error of 3 mm, providing a detailed three-dimensional representation of the bridge external geometry. The registered point cloud (Figure 4c) was subsequently imported into Autodesk Revit and used as the geometric reference for the development of the HBIM model.

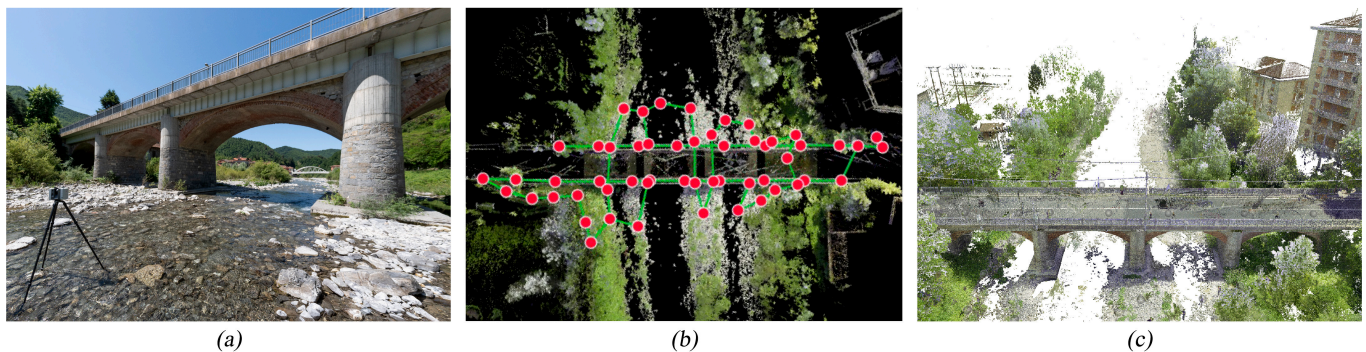


Figure 4. Survey campaign: (a) terrestrial laser scanning; (b) scan positions and registration scheme in plan view; (c) registered point cloud of the bridge.

The survey provided a highly accurate representation of the accessible external surfaces of the structure, allowing the reliable definition of the geometry of the piers, reinforced concrete supports, steel beams, deck system, and visible portions of the spandrel arches. However, several geometrical parameters relevant to structural analysis could not be directly observed from the survey data. These include the thickness of the masonry vaults, the depth of the spandrel arches and walls, and the height and geometry of the backing material. Such information may be investigated through complementary diagnostic techniques, including endoscopic inspections, localized destructive investigation, and ground-penetrating radar (GPR). However, such complementary diagnostic data were not available for the present case study, which was therefore based on the TLS survey and direct on-site observations alone.

The proposed methodology aims to address these limitations starting from the preliminary decomposition of the structure under investigation into its principal constituent components. This subdivision is defined based on both the available survey data and consolidated knowledge on the investigated structural typology, in this case derived from the relevant literature on modern masonry arch bridges [34]. The aim of this decomposition is to distinguish between geometric parameters that can be directly measured from the survey and those that must be inferred, and, among the latter, those that can be freely varied and those that are constrained by the surroundings, thereby establishing the basis for the implementation of adaptive BIM families and for the generation of alternative geometric configurations.

Figures 5 and 6 illustrate the adopted subdivision and the corresponding parametrization adopted in the modelling process in longitudinal elevation and section view, and in transversal sections respectively. Dimensions shown in black corresponds to the known, measurable quantities obtained from the survey; dimensions shown in blue are not directly measurable but are geometrically constrained by adjacent components; dimensions in orange represent the independent unknown parameters that cannot be determined

from direct evidence and therefore constitutes the editable parameters. Due to their relatively simple geometry, the piers of the bridge, the corresponding reinforced concrete supports, and the abutment were modelled adapting simple wall families and based on the point cloud.

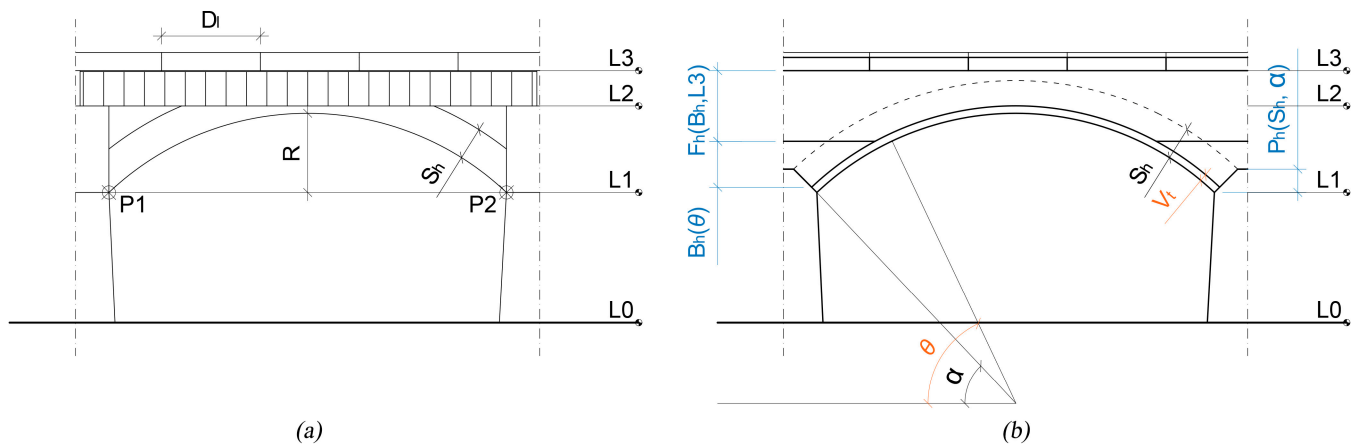


Figure 5. Parametric definition of the bridge geometry: (a) elevation view of a representative span with associated parameters; (b) longitudinal section along the bridge centrelines with associated parameters. The surveyed dimensions are reported in black, the parameters in orange and the derived dimensions in blue.

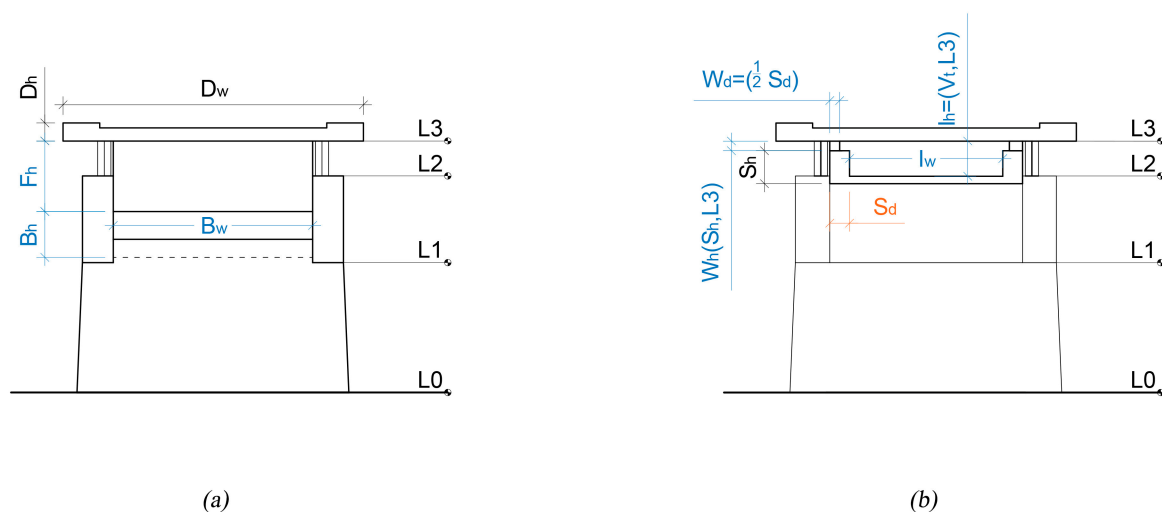


Figure 6. Parametric definition of the bridge geometry: (a) transverse section BB' at the pier; (b) transverse section CC' at the arch crown. The surveyed dimensions are reported in black, the parameters are reported in orange, and the derived dimensions are reported in blue.

In the elevation view displayed in Figure 5a, the main directly measurable measurements of the arch are displayed: the rise of the vault (R), the height of the spandrel arch (S_h), the elevations of the reference levels, and two of the four springing point (P1 and P2) at the corners of the arch. In the longitudinal section in Figure 5b, two of the three parametrized variables are shown in orange: the vault thickness (V_t) and the reference angle of the backing (θ), which is used to define the backing height (B_h). The remaining geometric quantities are obtained through geometrical relationships or mathematical constraints. For instance, the height of the infill (F_h) is derived from the height of the backing and the elevation of Level 3, while the height of the pier top (P_h) is derived from the elevation of L1, S_h and the embrace angle α .

The transverse sections in Figure 6, taken at the piers (Figure 6a) and at the arch crown (Figure 6b) further define the parametric structure of the model. In these sections, the principal unknown parameter is the depth of the spandrel arch (S_d), from which several other geometric quantities are derived. These include the width and height of the spandrel wall (W_d and W_h), which depend on S_d and the elevation of Level 3, as well as the dimensions of the infill (I_w and I_h) and the backing (B_w and B_h).

Following this geometric decomposition, three independent uncertain parameters were identified (θ , S_d and V_t). The admissible range for each parameter is derived based on literature or construction criteria. In particular, the parameter θ is based on Torre [34], who, according to historical construction treatises and practices, prescribes that the backing height (B_h) for lowered arches which span less than 120° is typically comprised between the springing point of the vault at the extrados and the crown elevation at the intrados. In the case under analysis, this condition corresponds to a range of approximately 45° to 77° measured from the horizontal. The ranges for the spandrel depth (S_d) and the vault thickness (V_t), on the other hand, are defined in accordance with the dimensions of the bricks (about $26 \times 13 \times 6.5$ cm) and the plausible brick pattern adopted to scale up and down the dimensions of these elements.

Based on this decomposition, five families were developed using the standard Adaptive Components tool available in Autodesk Revit (versions 2025 and 2026). This choice was motivated by the intention to critically assess the capabilities and limitations of this simple modelling approach that is often overlooked, while ensuring a self-contained, flexible, and easily updatable workflow. More widely adopted approaches based on external tools, such as Dynamo or Rhino.Inside.Revit, would have been comparatively straightforward to implement; however, they typically require the re-execution of scripts to propagate modifications, resulting in a less interactive and less responsive modelling process.

The developed families correspond to the principal structural components of the bridge and were organized as follows: (i) the piers and the concrete supports and (ii) the abutments, implemented as modified wall families; (iii) the longitudinal beams, modelled as assemblies of simple surfaces intended to be subsequently modelled as shells in FEM environment, using nested families for each section comprising a pair of flanges (Figure 7a); (iv) the deck system, composed of precast elements of about 3 m in length; and, lastly, (v) the main portion of the bridge (Figure 7b), comprising the spandrel arch and the vault, modelled as a single and continuous 3D element generated by sweeping a parametric section along the arch generatrix curve, as well as the spandrel walls, the backing and the infill.

Adaptive points were employed wherever possible to establish explicit geometric relationships among the different families and among the elements which constitute them, enabling coordinated and consistent updates of the model. Where direct adaptive connections were not feasible, usually due to Revit limitations, parametric constraints and formula-based relationships were introduced to ensure geometric coherence. This aspect proved to be particularly critical for the subsequent finite element modelling, where even minor inconsistencies, such as edge misalignments or the lack of coplanarity between adjacent elements, can significantly compromise mesh quality and the definition of contact interfaces. The use of formulas often causes these inconsistencies, and care must be taken to the admissible tolerances. Furthermore, several structural components, such as the beams, backing, and infill, were discretized into multiple geometric objects, despite this not strictly reflecting their physical continuity. For beams, this modelling choice improved mesh conformity in FEM, while for 3D elements it avoided robustness issues related to Revit's limited handling of Boolean operations on complex solids.

Once assembled, the described parametric families result in a span made of 16 solid elements and 2 beam assemblies, each made of 166 surface components. An exploded view of the assembly is shown in Figure 8, including the two piers and four reinforced concrete supports which are shared by adjacent spans.

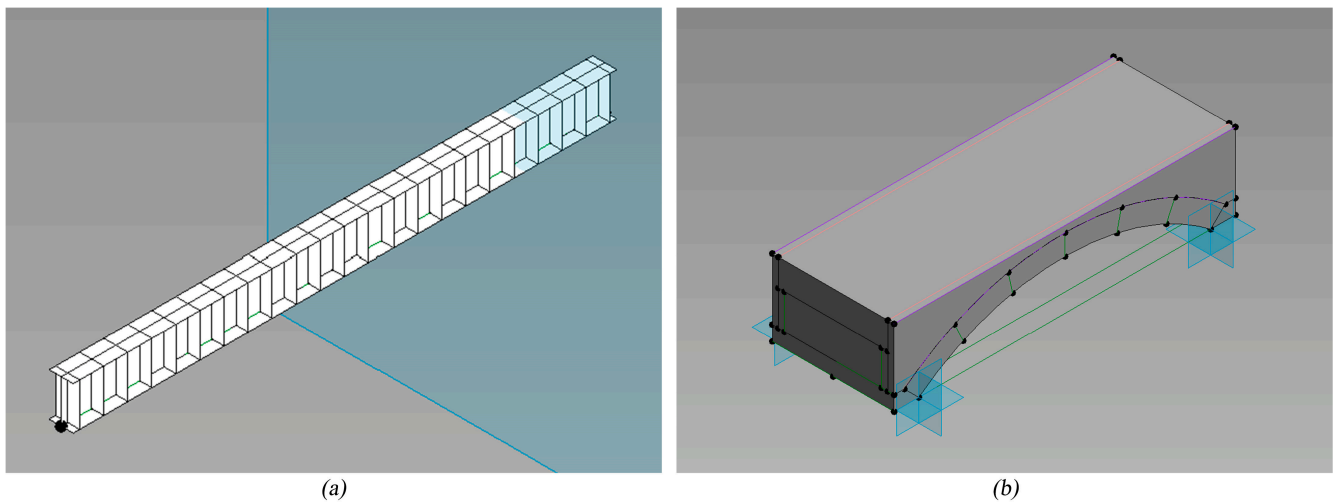


Figure 7. Adaptive family definition in Revit: (a) generic beam made of 166 distinct surfaces based on a line and numeric parameters; (b) arch span made of 9 solid blocks and based on three adaptive points plus numeric parameters and elevation levels.

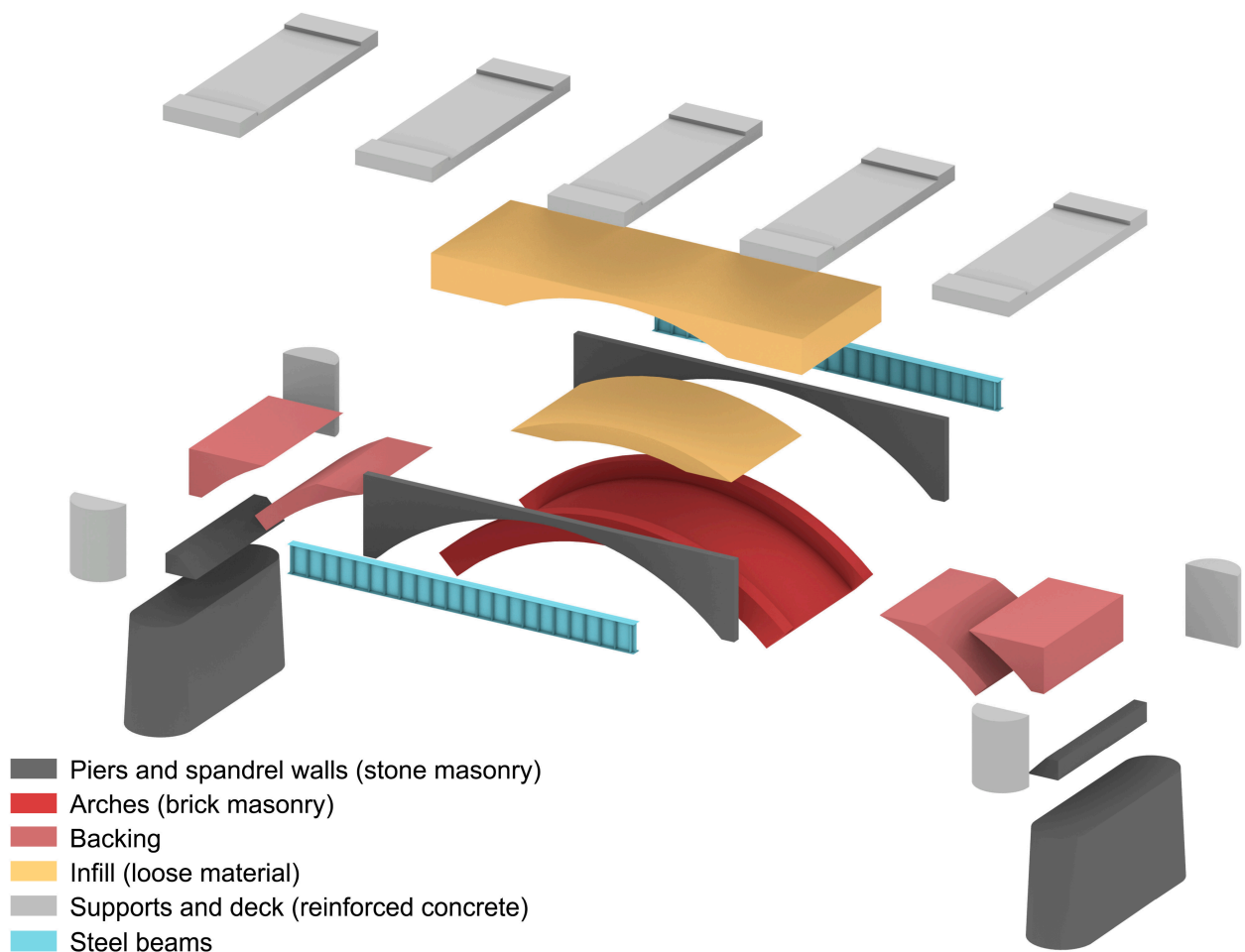


Figure 8. Exploded view of a single span of the bridge with division in elements modelled and material.

The assembly process was repeated for each span, closely tracing the point cloud geometry, until the whole bridge structure was completed. Lastly, the abutments of the bridge were manually modelled conforming to the parametric model and the point cloud survey, completing the HBIM implementation. These were modelled with only three elements: the lateral masonry walls, the soil inside and the continuation of the concrete deck.

5. FEM Structural Analysis

The full combination of two cases for each of the three uncertain geometric parameters of the main bridge, V_t , S_d and θ , is reported in Table 1; these defined the eight three-dimensional models of the full bridge adopted for the finite element analysis. For the vault thickness V_t , the two adopted values correspond either to the length of a single brick laid on the short edge or to a composite arrangement consisting of one brick laid on the short edge combined with an additional one laid on the long edge. The spandrel arch depth S_d was instead defined assuming either three or four bricks laid on the short edge. The highest backing position was taken as the upper bound of the aforementioned prescribed height for lowered arches, corresponding to the intrados crown ($\theta = 77^\circ$). On the other hand, the lower bound of 45° would have resulted in a configuration with no backing in the current case study. Such a configuration was considered unlikely from a constructive and typological perspective among the bridge build stock in the area; hence, a minimum backing height corresponding to half of the maximum one was adopted, corresponding to $\theta = 60^\circ$. The models were subsequently exported from Revit in .step format and imported in SpaceClaim 2024 R2 to be preprocessed.

Table 1. Geometric parameter combinations defining the eight finite element models.

	Vault Thickness— V_t (cm)	Spandrel Arch Depth— S_d (cm)	Backing Position— θ (-)
Model 1	25.5	40	60°
Model 2	25.5	40	77°
Model 3	25.5	60	60°
Model 4	25.5	60	77°
Model 5	40	40	60°
Model 6	40	40	77°
Model 7	40	60	60°
Model 8	40	60	77°

The FE meshes were generated in ANSYS Mechanical 2024 R2 and consisted of about 520,000 nodes and 130,000 elements. The element size was selected based on the structural element dimensions, ranging from 75 cm for the abutment to 25 cm for the span elements. A finer discretization (12 and 6 cm) was preliminary tested for the masonry arches; however, no significant influence was observed on the modal analysis results, and the coarser mesh was therefore adopted. A slight variation in the total number of elements from Model 1 to Model 8 is observed due to geometric variations in the masonry components. Quadratic elements were used throughout the models, including SOLID186 elements for three-dimensional components and SHELL181 elements for the beams, while contact interactions were defined using CONTA174 elements. The mesh of Model 1 is displayed in Figure 9.

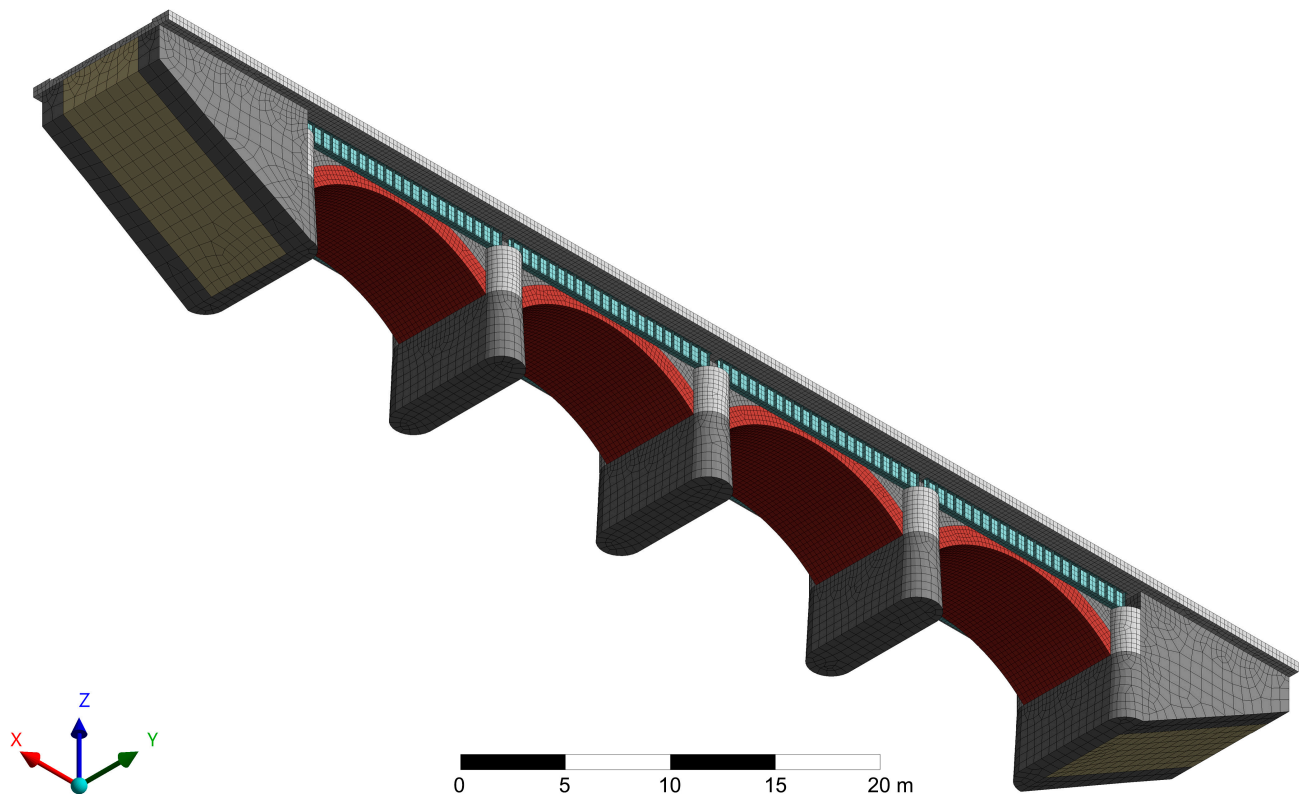


Figure 9. Mesh of Model 1 seen from below.

Regarding material modelling, a simplified elastic–perfectly plastic constitutive law was adopted for masonry and concrete elements in order to reduce computational complexity. This choice is not intended to provide a detailed representation of masonry nonlinear behaviour, nor to support a full damage assessment. Rather, it provides a sufficiently stable and computationally efficient formulation for the comparative analyses carried out in this study, where the main objective is to evaluate the influence of geometric assumptions on the numerical results. Simple linear behaviour was assigned to steel and infill components. For the former materials, this assumption is justified by the fact that no significant damage or plastic response is expected under the considered loading conditions. For the infill, a significantly reduced stiffness was adopted to represent its loose and highly deformable nature. Masonry material parameters are taken from the Italian Building Code [25], considering the average values from table C8.5.1; for the backing the lower value of brick masonry was considered. A simple Drucker–Prager yield criterion was adopted and the biaxial compressive f_{bc} and uniaxial tensile f_{ut} strength were derived from the uniaxial compressive strength provided by the aforementioned Italian building code using the same approaches adopted in [35]. A comprehensive overview of all the mechanical parameters adopted in the numerical model is provided in Table 2.

Table 2. Material properties adopted for the different structural elements: density— ρ ; E—Young’s modulus; ν —Poisson ratio; f_{uc} —uniaxial compressive strength; f_{bc} —biaxial compressive strength; f_{ut} —uniaxial tensile strength.

	ρ (kg/m ³)	E (GPa)	ν (-)	f_{uc} (MPa)	f_{bc} (MPa)	f_{ut} (MPa)
Stone masonry	2100	1.74	0.18	3.20	4.80	0.655
Brick masonry	1800	1.50	0.20	3.45	5.18	0.689
Infill	1600	0.32	0.20	-	-	-
Backing	1800	1.20	0.20	2.60	3.90	0.570

Table 2. Cont.

	ρ (kg/m ³)	E (GPa)	ν (-)	f_{uc} (MPa)	f_{bc} (MPa)	f_{ut} (MPa)
Concrete	2300	27.0	0.20	16.0	24.0	1.915
Steel	7850	210	0.30	-	-	-

Furthermore, to avoid unrealistic tensile stress transfer between the infill and adjacent structural elements, frictional contact interactions were introduced instead of a more computationally demanding fully damage-based constitutive model. The friction coefficient was taken equal to $\mu = 0.5$. All the other connections were implemented either imposing mesh continuity or bonded contact. Fixed supports were applied at the base of the piers and at the abutments.

Two types of analysis were performed: linear modal analysis and nonlinear static analysis. The modal analysis was carried out on the linearized system to compare the natural frequencies and mode shapes of the bridge models. The static analyses were performed under self-weight only and in small displacements. Although masonry was described through an elastic–perfectly plastic law and the infill interfaces through frictional contact, under self-weight the response remained essentially within the elastic range, with only limited and localized plasticity; the comparison among configurations therefore reflects differences in their elastic stiffness.

6. FE Results

The results of the parametric analyses are summarized in Tables 3 and 4, which report the structural response of the eight geometric configurations defined in Table 1. The results are presented separately for modal and static analyses, providing complementary insight into the dynamic characteristics and the deformative response of the structure.

Table 3. Modal analysis results: modes with a participation factor higher than 0.1 in at least one model among the first 24 modes. All measurements are shown both in Hz and percentage difference in respect of the minimum value of each mode (i.e., Model 1). Maximum differences are reported in **bold**.

	Mode 1 y		Mode 2 rot z		Mode 3 rot z		Mode 5 x		Mode 6 z, rot z		Mode 7 x, ry, rz		Mode 8 y		Mode 20 rot y		Mode 21 z, rot x	
	Hz	%	Hz	%	Hz	%	Hz	%	Hz	%	Hz	%	Hz	%	Hz	%	Hz	%
Model 1	7.07	0.0	10.46	0.0	10.50 *	0.0	12.24 *	0.0	12.86	0.0	14.09	0.0	15.46	0.0	26.00	0.0	26.38	0.0
Model 2	7.20	1.8	10.67	2.0	10.72 *	2.1	12.48	2.0	13.27	3.2	14.23	1.0	15.59	0.8	26.25	1.0	26.97	2.2
Model 3	7.12	0.7	10.60 *	1.3	10.68	1.7	12.34	0.8	13.00	1.1	14.15	0.4	15.64	1.2	26.14	0.5	26.62	0.9
Model 4	7.21	2.0	10.72	2.5	10.81 *	3.0	12.54	2.5	13.37	4.0	14.28	1.3	15.64	1.2	26.38	1.5	27.14	2.9
Model 5	7.13	0.8	10.63 *	1.6	10.69	1.8	12.35	0.9	13.02	1.2	14.16	0.5	15.64	1.2	26.21	0.8	26.69	1.2
Model 6	7.22	2.1	10.72	2.5	10.84 *	3.2	12.55	2.5	13.34	3.7	14.26	1.2	15.63	1.1	26.42	1.6	27.14	2.9
Model 7	7.14	1.0	10.69	2.2	10.76 *	2.5	12.43	1.6	13.13	2.1	14.21	0.9	15.65	1.2	26.32	1.2	26.87	1.9
Model 8	7.20	1.8	10.69	2.2	10.91 *	3.9	12.62	3.1	13.44	4.5	14.31	1.6	15.59	0.8	26.51	2.0	27.25	3.3

* Denotes modes with a participation factor lower than 0.1 for that specific mode and model.

Table 3 reports the natural frequencies associated with the most significant vibration modes, selected based on a modal participation factor greater than 0.1 in at least one model. Figure 10 shows the first three vibration modes with significant modal participation factors of Model 1. Since the modal participating mass of Mode 3 is negligible, the corresponding frequencies are marked with an asterisk in Table 3. The results show a generally consistent dynamic behaviour across all models. The normalized frequency variation confirms this, with a limited variations across all the modes of about 3%. As expected, higher frequencies are generally associated with configurations characterized by larger geometric dimensions in the parametrized elements. The most significant effect can be attributed to the backing

height, with Models 2, 4, 6 and 8 presenting consistently higher frequencies, while the spandrel depth and vault thickness have a minor influence. The relatively small differences between models suggest that the global modal behaviour of the structure is moderately sensitive to the considered geometric variations.

Table 4. Static analysis results: vertical displacements at the arch crown points A1–A4 and corresponding deck points D1–D4 under self-weight loading. Values are reported both in mm and percentage difference in respect of the minimum value of each control point (i.e., Model 1). Maximum differences are reported in **bold**.

	A1		D1		A2		D2		A3		D3		A4		D4	
	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%
Model 1	−2.16	0.0	−2.17	0.0	−2.22	0.0	−2.22	0.0	−2.19	0.0	−2.19	0.0	−2.22	0.0	−2.22	0.0
Model 2	−2.04	−5.6	−2.04	−6.0	−2.08	−6.3	−2.07	−6.8	−2.06	−5.9	−2.06	−5.9	−2.09	−5.9	−2.09	−5.9
Model 3	−2.12	−1.9	−2.13	−1.8	−2.17	−2.3	−2.17	−2.3	−2.15	−1.8	−2.15	−1.8	−2.19	−1.4	−2.19	−1.4
Model 4	−2.01	−6.9	−2.01	−7.4	−2.05	−7.7	−2.05	−7.7	−2.03	−7.3	−2.02	−7.8	−2.08	−6.3	−2.08	−6.3
Model 5	−2.09	−3.2	−2.09	−3.7	−2.14	−3.6	−2.14	−3.6	−2.12	−3.2	−2.12	−3.2	−2.16	−2.7	−2.16	−2.7
Model 6	−2.01	−6.9	−2.01	−7.4	−2.04	−8.1	−2.04	−8.1	−2.02	−7.8	−2.02	−7.8	−2.07	−6.8	−2.07	−6.8
Model 7	−2.06	−4.6	−2.05	−5.5	−2.10	−5.4	−2.10	−5.4	−2.08	−5.0	−2.08	−5.0	−2.12	−4.5	−2.12	−4.5
Model 8	−1.97	−8.8	−1.98	−8.8	−2.01	−9.5	−2.02	−9.0	−1.99	−9.1	−1.99	−9.1	−2.04	−8.1	−2.04	−8.1
Average	−2.06	-	−2.06	-	−2.10	-	−2.10	-	−2.08	-	−2.08	-	−2.12	-	−2.12	-

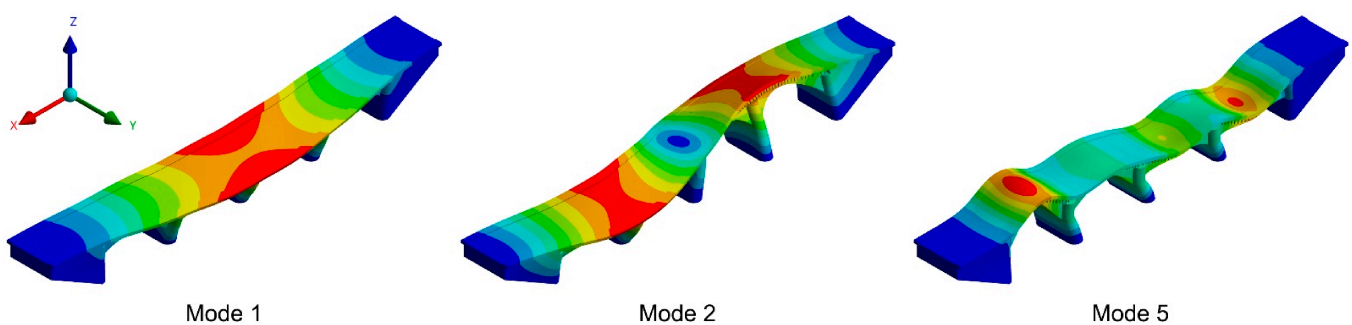


Figure 10. First three vibration modes with significant modal participation factors of Model 1, representative of all the models.

Table 4 presents the vertical displacements at central crown point of the arches (A) and the corresponding point on the deck of each span (D) under static loading. Figure 11 shows the total deformation contour plot of Model 1. In contrast with the modal results, the static analyses show a higher sensitivity to the geometric variations. The normalized displacements reported in percentage indicate an average displacement variation of approximately 9% among the crown displacements of each span. The same general trend observed in the modal analysis can be observed: displacements systematically decrease as the geometric dimensions increase. Configurations with higher backing position, greater spandrel depth, and thicker vaults exhibit reduced deformations, reflecting the increase in overall structural stiffness already observed in the modal analysis results. Among the analyzed parameters, also in this case the backing position appears to have the most pronounced influence, as it directly affects the confinement of the arch and the distribution of load, with Models 2, 4, 6 and 8 presenting the smallest deflections. However, in this case the spandrel arch depth and the vault thickness show more significant and different effects on the result, with the latter showing a minor impact.

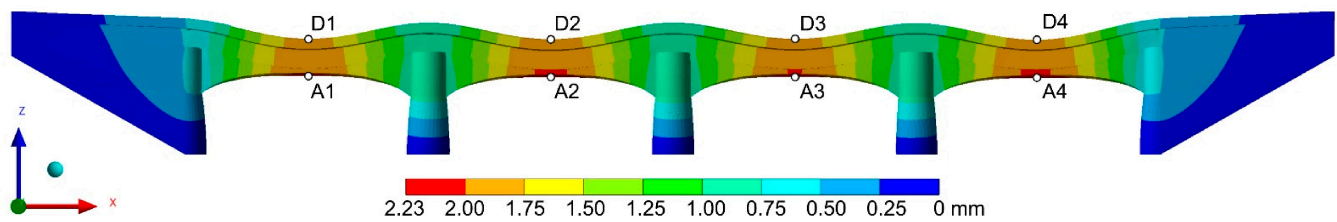


Figure 11. Total deformation from self-weight static analysis of Model 1, representative of all the models.

7. Discussion

The proposed workflow confirmed that the structural assessment of heritage masonry bridges cannot be reduced to the direct translation of survey data into a numerical model. In the case of Montoggio Bridge, the laser scanner survey provided a reliable description of the accessible external geometry, but several structurally relevant features remained physically hidden and therefore had to be inferred. The critical step was therefore not only the acquisition or reconstruction of geometry, but the definition of a limited set of unknown parameters able to translate incomplete knowledge into structurally meaningful modelling hypotheses. In this sense, the preliminary interpretative phase proved to be the methodological core of the whole Scan-to-BIM-to-FEM process, where surveyed dimensions, inferred ones, and geometrical relationships combine to define admissible geometric configurations, rather than a single “best-estimate” model, in a manner that partially mirrors the logic of the original design and construction process. The value of the parametric HBIM strategy lies precisely in making this passage explicit, traceable, and reproducible, allowing geometric assumptions to be propagated systematically into the subsequent FEM analyses.

From a modelling perspective, the use of Revit’s Adaptive Components proved to be useful mainly as an intermediate solution between manual HBIM and fully algorithmic procedures. Their responsiveness made the exploration of geometric hypotheses relatively direct, but the case study also showed that they are not a seamless or fully mature environment for a full parametric implementation. Complex dependencies required formula-based constraints, nested components, and geometric subdivisions, which should be considered pragmatic workarounds rather than ideal modelling solutions. This is likely caused by the known lack of modelling tools optimized for heritage structure geometries in BIM environments and the specific needs of structural simulation, for which modelling choices cannot be evaluated only in terms of visual or point cloud fidelity, but they must also account for meshability, contact definition, element organization, and tolerance control. In this sense, Adaptive Components implemented in this way are effective only if the model is conceived from the beginning as a FEM-oriented HBIM, rather than as a generic documentation model subsequently adapted for analysis. Moreover, they should be planned at the appropriate LOG, likely lower than the one used for visualization, degradation mapping, etc. This is consistent with recent studies on organizational BIM capabilities, which identify expertise, software infrastructure, standardized procedures, and role coordination as key conditions for effective BIM implementation [36,37]. The BIM-to-FEM transition represents a second step of the methodology. From a practical standpoint, the initial HBIM implementation was the most time-consuming phase of the workflow. In the present case study, geometric decomposition, adaptive family setup, and complete bridge assembly can be estimated at approximately one and a half working days for an experienced user. The subsequent generation and export of the eight geometric configurations required less than 10 min in total, since it only involved modifying the three uncertain parameters. The subsequent implementation of the eight FE models, including preprocessing, required approximately

half a working day after the first reference model had been established. This confirms that the main advantage of the proposed workflow is obtained after the initial parametric setup, by avoiding the need to remodel each geometric hypothesis from scratch. This advantage is expected to increase with the number and complexity of the configurations, since the initial setup cost is progressively distributed over a larger set of generated models. At the same time, the workflow also showed that interoperability remains only partially solved. Although the HBIM approach can effectively support FEM, the geometric organization required by Revit, based on families and modelling hierarchies, does not necessarily coincide with the organization expected by Ansys, where mesh generation, contact definition, and element connectivity are influenced by these details. This aspect is especially important for hybrid structures such as the Montoggio Bridge, where masonry elements coexist with reinforced concrete supports, steel beams, and precast deck components. The workflow therefore suggests that the quality of the BIM-to-FEM process depends less on the possibility of exporting geometry itself, and more on the capacity to export geometry that is already structured according to numerical modelling needs.

The finite element analyses provide an additional layer of interpretation, despite the limitations of a simplified approach. The comparison among the alternative configurations indicates that the considered geometric uncertainties influence the structural response in a coherent and mechanically meaningful way, supporting the relevance of the proposed methodology. The modal behaviour showed only minor fluctuations among the analyzed configurations, suggesting that the explored geometrical variations did not radically modify the global mass-stiffness distribution of the bridge. This can be explained by the fact that modal frequencies are global response indicators, also governed by components that remain unchanged across the models, such as piers, abutments, and non-geometrical variables such as boundary conditions. Conversely, the static analyses were more sensitive to the internal configuration of the arch system, as the evaluated crown displacements represent more local response quantities, directly tied to the geometry of the arch. In particular, the backing height results as the most influential aspect among the investigated parameters, while vault thickness and spandrel arch depth produced comparatively smaller effects. This is likely due to the fact that the backing contributes to load diffusion, confinement, and overall stiffness, so that variations in its geometry directly affect the behaviour of the arch barrel and the overlying fill and deck system. This interpretation is consistent with broader evidence on the sensitivity of masonry arch bridge response to the properties and modelling assumptions associated with filling and backing components [38].

8. Conclusions

This study proposed an adaptive Scan-to-BIM-to-FEM workflow for the explicit modelling of geometric uncertainty in the structural assessment of heritage masonry bridges. The methodology was applied to the Montoggio Bridge case study, where Revit adaptive families were used to combine survey-derived information with inferred geometric parameters, enabling the generation of eight alternative HBIM configurations subsequently transferred to FEM analysis. The workflow was conceived not as a post-processing adaptation of a conventional BIM model, but as a structurally informed HBIM implementation, developed specifically as a specialized LOG to support parametric finite element simulations. This required a preliminary knowledge-based phase in which the bridge was interpreted as a structural system, decomposed into meaningful components, and described through a limited set of uncertain but mechanically relevant geometric parameters.

The results demonstrate that the methodology is effective in practice. Once the adaptive HBIM model was implemented, alternative geometric configurations can be produced quickly with limited additional modelling effort, avoiding the need to remodel each hy-

pothesis from scratch. This represents a relevant advantage in heritage assessment, where incomplete knowledge often requires the comparison of multiple plausible configurations rather than the analysis of a single deterministic model. The BIM-to-FEM transition also proved generally effective: after the definition of a reference FEM model, subsequent configurations could be introduced by replacing the different geometric components, while preserving most material assignments, boundary conditions, contacts, and analysis settings. This enabled consistent comparison among the models and reduced the time required for FEM preprocessing.

At the same time, the proposed approach presents clear limitations. First, the initial implementation cost is significant. The identification of the important parameters and geometrical boundaries for their dimension, the construction of adaptive families, the definition of geometric constraints, and the organization of the model require specific expertise and must be planned with the FEM application as the final goal. In this sense, the workflow is not a generic HBIM procedure that can be easily reused for structural analysis at a later stage; rather, it requires early collaboration between HBIM modellers and structural/FEM specialists. Second, although Revit proved capable of producing solid and surface geometries suitable for analysis, interoperability issues remain. In particular, the family-based hierarchical structure of Revit does not always correspond to the grouping organization required in SpaceClaim/ANSYS, where organization by structural component, material, and contact behaviour is required to produce reliable models. This mismatch required manual adjustments and accounted for most of the time required in the BIM-to-FEM phase, and should be further addressed.

A further limitation is related to computational cost: while the parametric HBIM workflow reduces the modelling effort, each generated configuration still requires a dedicated finite element analysis. As a consequence, the overall cost of the procedure shifts from geometric modelling to numerical simulation, especially when high Levels of Geometry and detailed contact or nonlinear settings are adopted.

The structural results showed limited but non-negligible variations among the analyzed configurations. This outcome supports the use of multi-model geometric exploration as a preliminary stage of structural assessment: rather than directly selecting a single assumed geometry, the proposed workflow allows the analyst to identify the sensitivity of the response to uncertain parameters and to select, justify, or further investigate the most relevant configurations. Future work should therefore focus on improving BIM-to-FEM interoperability, to reduce model-update effort, thereby improving the efficiency in analyzing larger parametric datasets, encompassing wider geometric variability. Further methodological development should address the quantitative characterization of geometric uncertainty by integrating multiple sources of evidence, including diagnostic investigations, to assign a confidence levels for each parameter value and therefore to the resulting geometrical configuration. These geometry-related levels, combined with those associated with other sources of uncertainties, could be linked to the subsequent FEM analyses to assign confidence level to each structural analysis toward the definition of confidence-informed resistance domain. This, coupled with more comprehensive structural analyses, such as limit-load and pushover analyses, would provide a more rigorous basis for quantifying the effects of geometric uncertainty on structural assessment outcomes in relation to the confidence level associated with each geometric configuration.

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