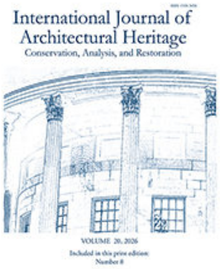

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Guidelines and Workflow for Transferring Architectural Survey Data into 3D Models for Structural Analysis Using the Case of Bagan Monuments

Valerio Sabbatini[a], Georgios Karanikoloudis[b], Luigi Barazzetti[c], Tamali Bhowmik[d], Shibu Samson[d], Michelle Duong[c], Elyse Hamp[c], Mario Santana Quintero[c], and Claudia Cancino[e]

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ABSTRACT
Structural modeling of historic construction is a complex task that requires the integration of multidisciplinary knowledge, including applied engineering and architectural disciplines. Digital documentation is fundamental to accurately capture the geometry of the structure; however, it is common practice to separate the processing of geometrical data from structural modeling operations. This separation causes the loss of helpful information such as geometric details, imperfections, eccentricities, misalignments, and material discontinuities, which may lead to erroneous interpretations. In this context, the authors have developed an approach to integrate detailed architectural survey data into 3D modeling for finite element analysis by guiding the transfer operations with the necessary simplifications and defining the workflow. In the Repair and Seismic Retrofitting of Monuments component of the Bagan Conservation Project, the efficient use and transfer of data from digital documentation and the architectural survey was applied to four monuments in the archaeological site of Bagan, Myanmar. This research connects the fields of surveying and digital recording with structural analysis, which are deeply related, especially in the conservation of built heritage, tackles problems of potential loss of critical data and the effective use of information collected on site, and focuses on the optimization of workforce efficiency.

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Digital photogrammetry; digital recording; finite element modeling; historic masonry construction; laser scanning; structural analysis

1. Introduction

As a result of the exponential development of information technologies, the existing architectural, engineering, and construction sector has also undergone a decisive change. The disciplines of architectural surveying and structural calculus have developed complex digital tools that have led to the sectorization of processes. Collecting and processing survey data are essential steps in understanding the construction of buildings and monuments. This knowledge allows the idealization of mathematical models for structural calculation. Results of structural evaluations are conditioned by the geometric survey; therefore, it is crucial to efficiently transmit and properly use collected data in structural models. Geometric modeling for structural assessment of historic constructions is a complex task, accounting for many irregularities, past interventions, accumulated damage and deformation, and decorative or nonstructural elements. Currently, there is no universal standard for the transition of geometrical data to three-dimensional (3D) models for structural analysis.

Digital recording involves data capturing operations, which can be grouped into the noncontact techniques for collecting spatial, texture/color, and reflectivity information, and the contact techniques for recording dimensional data. Focusing on the noncontact techniques, image-based techniques are passive methods in which the information is retrieved by iterative bundle adjustment, based on features automatically extracted from multiple overlapping photos. Dense clouds are then produced using dense image matching algorithms. Disadvantages can include the need to define the required resolution prior to capturing, which is related to the type of camera, lens, focal length, and shooting distance. Range-based techniques are active capture methods in which the emitted laser pulses measure the distance from the device to the surfaces. In this case, the disadvantages are the high cost and fragility of the instrumentation and possible difficulties in scanning reflective, transparent, and dark surfaces. According to Scherer (2002), the combination of multiple methods is

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recommended to overcome the drawbacks of individual techniques. For this reason, the present research deals with data collected with both image-based and range-based noncontact techniques. In principle, the data collected with contact techniques require the selection of the relevant dimension and an a priori simplification of the construction; thus, it was discarded.

During capturing operations, there is a common tendency to acquire as much data as possible, because it is desirable to exceed the information rather than fill the gaps with time-consuming interpretations of the architecture. In contrast, if the level of detail is not appropriate to completely capture the whole space, it is common to incur errors during the merging of the point clouds covering that space. In general, during data acquisition, both signal and noise are recorded; the clearer the point cloud (high signal-to-noise ratio), the faster its interpretation and the geometric modeling process. These issues can be mitigated by recording data with sufficient overlap throughout the recorded area and planning for sources of noise, such as moving elements or reflective surfaces.

Once the capturing operations are concluded, there are different options to model the geometry of the construction. Complex architectures are generally modeled as computer-aided design (CAD) programs with non-uniform rational basis splines (NURBS) functions. NURBS is a mathematical model using basis splines (B-splines) commonly used in computer graphics for representing curves and surfaces. It offers great flexibility and precision for handling both analytic – defined by common mathematical formulas – and modeled shapes. Rhinoceros (McNeel 2019) is a commercial 3D computer graphic and CAD software based on the NURBS mathematical model, which focuses on producing mathematically precise representation of curves and free-form surfaces in computer graphics, as opposed to polygon mesh-based applications.

There is a distinction between the actual geometry defined during survey operations and the geometric model required for structural analysis. There are different strategies for structural analysis of historic masonry construction: limit analysis, simplified methods, finite element modeling (FEM), macro- or micro-modeling, and discrete element methods (DEM) (Roca et al. 2010). Each method presents its own assumptions that differently fit the real structural behavior according to the interpretation of structural arrangements. FEM has found great applicability in structural engineering since it permits a realistic and accurate description of geometry while maintaining a balance of computational demands. Furthermore, the stress state and deformations are fairly represented in the case of small displacements. The geometry of the FEM is usually defined from the architectural survey or archival line drawings, considering the structural resisting elements of interest. There is no clear path that guides the definition of the structural model; most modeling decisions are led by attempts and iterative operations aimed at improving the accuracy of the output. In some cases, the results of a finite element analysis (FEA) are validated by experimental values, whereas in most cases they are evaluated with engineering judgment, questioning the validity of the model's assumptions.

In general, the assumptions and decisions involved in numerically idealizing a structural model require the informed judgment of the model developer. Among the relevant works on the generation of FEMs starting from detailed architectural surveys, Sánchez-Aparicio et al. (2014) presented a comprehensive methodology in which point cloud data from laser scans and drone photogrammetry are merged through registration algorithms. The different surfaces created are approximated with NURBS and parametric shapes, which are used to generate a FEM, calibrated with the dynamic monitoring results. The presented method enables the detection of discontinuities in the structure and demonstrates the importance of calibrating interface elements and soil stiffness to improve the accuracy of FEM.

A different, semiautomatic procedure was presented by Castellazzi et al. (2015), aiming to define discretized structural geometry in a reduced amount of time and ready to be used for structural analysis. The procedure employs point clouds of the inner and outer surfaces of the structure to produce a complex solid, made by stacking sequential layers of voxel elements. The FEM is then generated by automatically transforming each voxel into an eight-node hexahedral finite element (FE). The results of an eigenvalue analysis show comparable outputs between the FEM generated with the semiautomated procedure and the FEM generated from a conventional CAD model, demonstrating the effectiveness of the semiautomated procedure. The reduction in modeling time is achieved at the cost of lessened manual control of geometric details of the structure, especially at the local level.

In Barazzetti et al. (2015), a two-step methodology is proposed to convert a heritage building information modeling (BIM) into an FEM, with a geometric rationalization that preserves irregularities and anomalies, such as verticality deviation and variable thickness. The results of the auto-meshing algorithm were manually edited and readapted to fit the requirements of the software for structural analysis. The work reinforces that the conversion into the FEM is not only a geometric problem; an expert operator must check the errors and perform time-consuming manual corrections. Moreover, prior to modeling, the interpretation of the construction requires an investigation of material aspects, logic of construction, and architectural and structural considerations.

Leonardi et al. (2024) present a novel approach integrating BIM and FEM. An algorithm was developed to use selected standardized information of BIM in the creation of 3D FEM using open-source libraries. The approach was applied to a building aggregate demonstrating the automatization of the process in the creation of simple solid elements. Complex geometries risk being modeled as a series of surfaces instead of a single body.

Talebi, Potenza, and Gattulli (2023) define two approaches that use terrestrial laser scanner data to define a BIM, then an automatic or manual process to realize FEM on a modern pedestrian bridge. In one approach, geometric data is exchanged by a.dxf file, and after the idealization of the structure, FEM is created by using 1D, 2D, or 3D elements. The other approach transfers geometry as points defining nodes and curves to form the edges which are used to generate the FEM. Both approaches allow the control of the geometry and FE mesh; however, they seem difficult to apply in historical construction with complex architectural features, such as vaults, domes, apses, or spires.

The work discussed in this paper is part of the Repair and Seismic Retrofitting of Monuments component of the Bagan Conservation Project in Bagan, Myanmar (Cancino et al. 2026). Documentation of four masonry monuments in Bagan selected as case studies was carried out during fieldwork in 2020, and data were processed to obtain line drawings, orthorectified images, and 3D models for FEA. The innovation of the current work lies in the implementation of a cohesive set of guidelines for the transition from architectural digital recording to 3D models for structural analysis, under real case study surveys and structural assessment tasks. Given the many inherent complexities associated with the monuments in Bagan, namely, the presence of decorative and nonstructural elements, the complex volumetric configuration, connectivity, and structural alterations, and the imposed deformation and damage, an efficient approach was adopted in which engineering and documentation teams jointly defined the necessary requirements, tolerances, and simplification approaches to create the 3D models as a first stage deliverable. This allowed the optimal transfer of data from architectural surveys to FEA and represented a way to practice the holistic, multidisciplinary, and collaborative approach that was an overarching goal for the project. To increase the significance and applicability of the work, the analyzed methods were narrowed to those that are more easily accessible and applicable by the professional community, favoring their extended use in conservation practice.

2. Framework of geometric and structural 3D modeling

Computational models for structural analysis imply the adoption of assumptions, boundary conditions, and definition of input data and are constructed in two main steps. The initial step in the 3D modeling process is the understanding and representation of geometry. At a later stage, geometry is interpreted, and the structure is idealized into a 3D structural model for computational analysis. The framework of geometric and structural modeling for existing buildings is sequential and described in the following sections.

2.1. Geometric 3D modeling

The generation of a geometric 3D model for structural analysis begins with the documentation and interpretation of existing construction through architectural surveys and digital recording techniques. The acquisition phase aims to collect dimensional, morphological, and material-related attributes of the structure, including geometrical irregularities, construction details, deformation patterns, and evidence of damage or past interventions. In historic masonry constructions, this information is commonly obtained through integrated surveying methodologies, including terrestrial laser scanning, aerial and terrestrial photogrammetry, direct architectural measurements, orthophotos, stratigraphic observations, and visual inspection. The resulting point clouds, orthorectified images, and measured drawings constitute the geometric basis from which the structural morphology of the building is interpreted and subsequently idealized into a structural 3D model suitable for FE analysis.

A 3D geometric model requires topological data, such as connectivity and associativity, relational information between objects, and geometrical data, namely, shapes and dimensions. Basic geometric 3D modeling techniques are surface and solid modeling. Surface models define geometry, not topology, and are a set of faces that can be analytical, free-form, curved, or sculptured. Solid models are based on the “half-space” concept: the closed boundary of the model separates the interior and the exterior of the modeled object. It divides space into finite (filled with material) and infinite (empty) portions. Both geometric and topological information are defined in the model, and this information also specifies whether two objects occupy the same space.

According to Borrmann et al. (2018), there are two fundamentally different approaches to modeling the geometry of 3D bodies: explicit and implicit. Explicit modeling describes a volume in terms of its surface and is therefore often also known as boundary representation (BRep). BRep represents geometry as a collection of boundary surfaces and involves defining a hierarchy of boundary elements, namely, body, face, edge, and vertex. Implicit modeling employs a sequence of construction steps to describe a volumetric body. The model stores the sequence of its creation and is therefore commonly termed a procedural approach. A common approach is constructive solid geometry (CSG), which uses predefined geometric primitives (box, cone, cylinder, sphere, torus, wedge) and Boolean operations (union, intersection, subtraction). Other modeling approaches are extrusion, rotation, sweeping, and lofting of 2D sections.

Geometric 3D modeling requires intelligent decisions on the type of modeling to meet certain geometric requirements, such as slopes and/or curvatures, interpretation and definition of distinct structural components, or the modification of attributes to benefit the derived structural model. Model surfaces and boundaries are usually segmented according to shape discontinuities. The primitive elements are formed by surfaces, as two-dimensional structures defined in a three-dimensional local reference frame with surface shape and extent. A surface shape is defined by its class (planar, cylindrical, and ellipsoidal/hyperboloidal), curvature axes, and curvature values. Choosing the most appropriate geometric modeling approach and use of boundary elements depends on the idealization operations.

2.2. Structural 3D modeling and analysis

The transition from the geometric 3D model to the structural 3D model involves the interpretation and idealization of the surveyed construction into a computational representation suitable for structural analysis. Modeling the structural geometry and detailing the connections can be remarkably demanding from a computational point of view. A geometric survey alone is insufficient to define a structural model; knowledge of geometric configuration and detailing relies on semi-, minor-, or non-destructive field-testing techniques. Thus, integrating information from surveying, testing, and monitoring is key to creating an accurate structural 3D model.

Fundamental decisions in creating a structural 3D model also include the definition of materials and the adoption of appropriate constitutive models. These decisions are influenced by the understanding of the involved loads (magnitude and distribution) and the consequential interpretation of the state of stress and damage.

Also, the internal composition of structural elements is difficult to characterize due to their heterogeneous characteristics, layering, and changes in elements over time, including multiple construction phases and additions or structural repairs. The sequence of construction and damage is crucial. Historical records clarify the construction sequence and, depending on its significance, structural elements are discretized with respect to the different phases. A phased FEA can then be performed, in which the result from a previous construction phase is used as the input in terms of displacements and stresses for the subsequent one.

Multiple assumptions and decisions should be made within the same FEM, such as the type of boundary conditions, fixed or flexible; the implementation of additional internal constraints between elements at element interfaces; and the type of interlocking between elements. All these assumptions yield different structural idealizations of the true interactions of structural components. Comparison of the results between different models, or sensitivity analyses, are valuable methods to evaluate the suitability of initial assumptions; however, it is not possible to evaluate the suitability of one assumption over another, especially in the absence of field monitoring data – static or dynamic. Assumptions must be made to interpret reality and fill knowledge gaps. Thus, the incompleteness or lack of information must be accounted for during the interpretation of analysis results. In general, working only with a single structural 3D model introduces limitations and has the potential to lower accuracy in the results. Hence, it is important to compare the analysis results of models with different assumptions.

It is also necessary to consider different types of FEA, such as linear elastic or nonlinear analysis. When the problem concerns the conditions of small displacements in comparison to the dimensions of the body, the structural model can be set in a linear elastic framework and linear elastic stress–strain relationship. When this condition fails, the problem requires a nonlinear model that captures significant changes in the geometric configuration – though not large strains – following loading and the onset of cracking or yielding in the material. In this last scenario, in which the superposition principle is not applicable, the FE method is subjected to uncertainties resulting in multiple solutions. In mathematical terms, it becomes an ill-posed problem. In the nonlinear analysis, the external perturbation is gradually incremented by seeking iteratively for a solution within a set tolerance (Lourenço and Gaetani 2022). The further the response of the model moves away from small displacements, the less accurate is the prediction response of the FEM. Small displacements are an assumption of the FE method, whereas kinematic analysis, the discrete element method, or the applied element method is more suitable for large displacements.

In masonry constructions, material nonlinearity is more relevant than geometric imperfections. However, the accuracy of the solution may be improved by considering small perturbations, imperfections, and eccentricities present, which may avoid bifurcation or unstable paths that would lead to incorrect solutions. Generally, historic masonry constructions are bulky and heavy, and they respond as stiff structures up to crack formation.

The representation of cracking in a structural model depends on the chosen approach and its intended purpose. First, the discrete crack approach requires predefining the crack path along element edges and models cracking through displacement discontinuities, typically implemented via interface elements that separate the continuum. This approach diverges from the assumption of a continuous material of the FE method and presents challenges in calibrating the dummy stiffness of the interface to simulate the uncracked state. In contrast, the smeared crack approach treats the material as a continuum and allows cracks to form based on stress–strain relationships. It supports various treatments of crack orientation: as a constant single orientation, a fixed multidirectional orientation updated in a stepwise manner, or a rotating crack orientation updated continuously (Rots and Blaauwendraad 1989). However, this method is prone to stress-locking – that is, stress remains in regions where it should diminish – due to softening laws that assume displacement continuity, a limitation not observed in the discrete crack approach (Rots and Blaauwendraad 1989).

Considering the application of the two approaches, the smeared crack approach could serve to identify the crack formation and its propagation (as-built configuration), while the discrete crack approach could serve to implement existing cracks in the modeling of the damaged configuration. In both cases, the multitude of model parameters as material elastic properties, boundary conditions, and crack stiffness can be calibrated according to dynamic modal parameters or static loading data.

There is a significant difference between damaged and undamaged structural configuration, or current and original state, which is not strictly related to the geometric configuration but also involves the stress state. Choosing the state for a structural model depends on the objective of the analysis: (1) to assess the capacity and response of the original undeformed and undamaged state, having as a reference (and result) the current state of deformation and damage; or (2) to assess the capacity and response of the current state of the structural configuration, including the present damage and deformation. In general, modeling the deformed and damaged state requires careful attention to detail in the geometric model but offers more realistic results. Figure 1a shows an illustrative example of a masonry wall influenced by its load history that caused deformation, damage, loss of material, and a propping intervention.

When representing the original state, the structural model accounts for the undamaged configuration, neglecting the effects of the load history. The model of the undamaged configuration is conceived as the construction was built at the time of its completion. The geometry is deduced mostly from the current state but also from archival information. Deformations and damage connected to the load history must be disregarded because they will be compared with the outcome of the structural analyses that aim at simulating the actions experienced during construction. Additions to the building and subsequent interventions could be disregarded or respected, by simulating the evolution of the stress state with phased analyses. In this context, construction defects and geometric irregularities should be accounted for, since historic constructions always differ from the regular geometries conceived in the design phase. Figure 1b shows an illustrative example of the same masonry wall in its original state.

An undamaged structural model is generally computationally simpler than the damaged structural model, since present damage and deformation are disregarded. Figure 1c shows an illustrative example of finite element modelling of the original state.

Instead, the present damage and deformation are used as reference for the FEA results. Figure 1d shows an illustrative example of finite element analysis on the original state model simulating the causes which led to the present damage and deformation. The outcome of the simulation is comparable to the present state of the masonry wall. The evaluation of similarity can be facilitated by exploiting the detailed geometric data derived from the survey.

Structural modeling may also incorporate the present damaged configuration. In this context, the complexity of the FEM increases because the model must incorporate the deformed geometry. Moreover, damage and

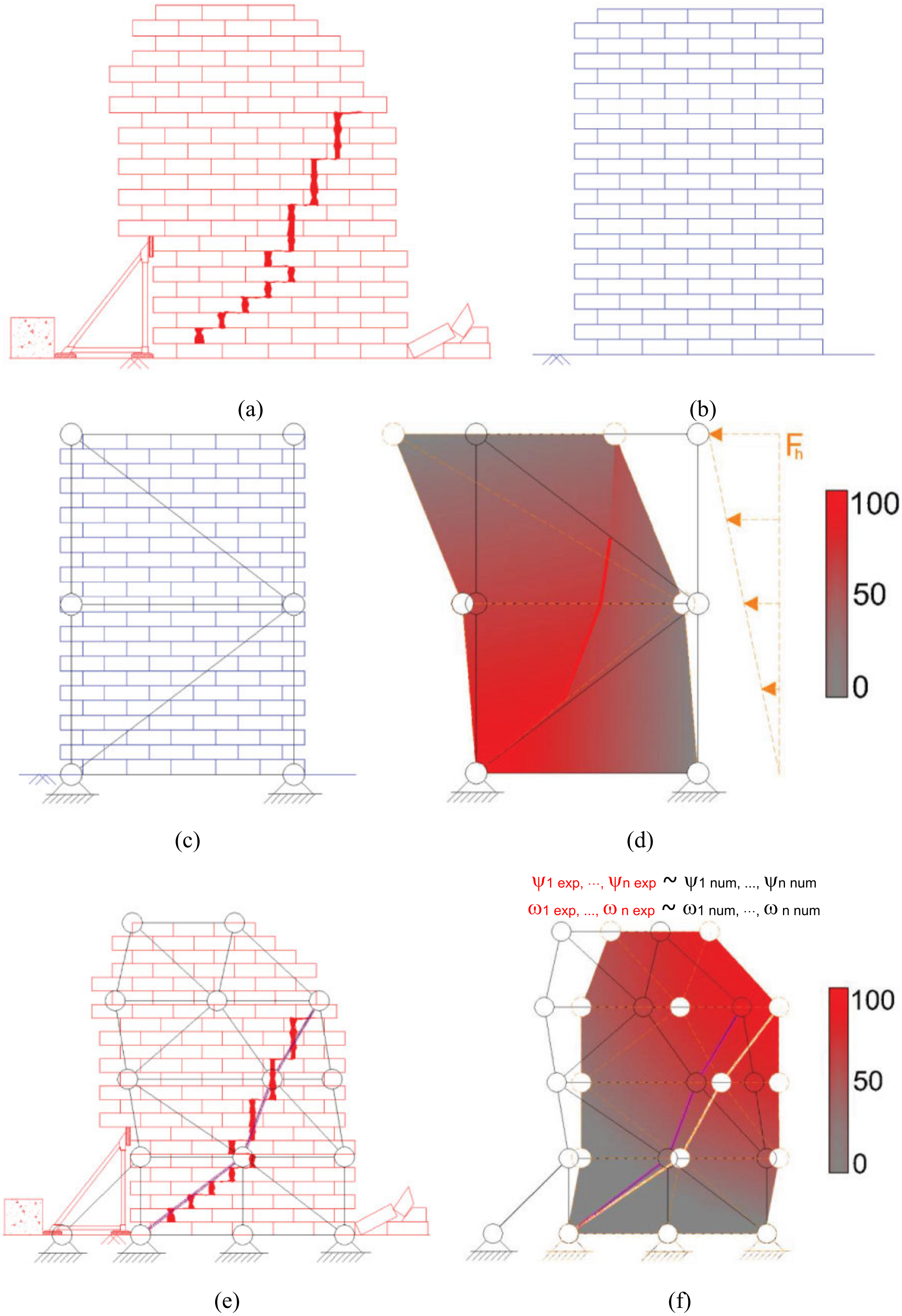

Figure 1. Illustrative examples of the structural state and modeling : (a) the current state of a masonry wall including cracks, deformations, loss of material, and propping intervention; (b) the original as-built configuration disregarding deformations, structural interventions, and damage; (c) structural model derived from the assumed undamaged configuration; (d) deformed configuration after numerical analysis, in orange; (e) structural model representing the current state, in purple the interface elements modelling cracking; and (f) numerical modal deformation ($\Psi_{n\ num}$) in orange, during the model updating process. Valerio Sabbatini © 2020 J. Paul Getty Trust.

structural interventions must be implemented in the model. Figure 1e shows an illustrative example of finite element modelling of the current state.

The introduction of damage, structural interventions, and deformation in the model increase the model parameters, thus uncertainties arise that can further complicate the control and validity of results. A strategy to reduce uncertainties consists in the use of testing and monitoring. The calibration of the model parameters is realized by comparing the numerical modal parameters with the experimental one from AVT Indeed, the variation of experimental modal parameters may be connected to the presence or propagation of damage in the construction. Thus, the structural model may be further calibrated to follow the change of the construction state. In Figure 1f is shown an illustrative example of FEA of the current state, the experimental modal frequencies ($\omega_{1\ exp}, \ldots, \omega_{n\ exp}$) and modal deformations ($\psi_{1\ exp}, \ldots, \psi_{n\ exp}$) are used as reference values in the updating process. The model updating is considered successful when the numerical modal frequencies ($\omega_{1\ num}, \ldots, \omega_{n\ num}$) and modal deformations ($\psi_{1\ num}, \ldots, \psi_{n\ num}$) approximate the experimental values within a set tolerance.

In massive masonry structures, deformations do not significantly affect the results. Thus, some irregularities and deformations may be neglected, although slender masonry structures such as bell towers and spires behave differently. Since masonry is a complex orthotropic nonlinear material that requires multiple parameters to be properly modeled, it is recommended to complement complex FEM and FEA with simplified analysis, which may be checked analytically. Updating a 3D structural model can be a never-ending process, so the level of accuracy should be set according to the purpose of the analysis and the level of acquired in situ data.

The workflow and modeling principles described in Sections 2.1 and 2.2 are implemented in the following sections through the case studies of the Bagan monuments, where the proposed simplification and idealization criteria are applied to generate FEM-ready structural models from detailed survey data.

3. Results

The following section aims to formalize a methodological framework for the transition from architectural survey data to FEM of historic masonry constructions, by means of the workflow and modeling guidelines. The workflow was designed to create structural 3D models of the four monuments selected as case studies by the Repair and Seismic Retrofitting of Monuments component of the Bagan Conservation Project (Saw Htwe Zaw et al. 2026). The created 3D structural models are shown in Figure 2. The monuments of Bagan constitute particularly suitable case studies because they combine complex volumetric configurations, irregular masonry morphologies, deformation patterns, multiple construction phases, and intricate vaulted systems, thereby representing challenging conditions for structural modelling. Despite the specific focus on the monuments of Bagan. The following modeling guidelines are able to address general challenges that might be encountered by similar research projects on historic heritage sites.

3.1. 3D structural modeling guidelines

Within the Repair and Retrofitting component of this project, a set of 3D modeling guidelines was developed to optimize the workflow between teams responsible for

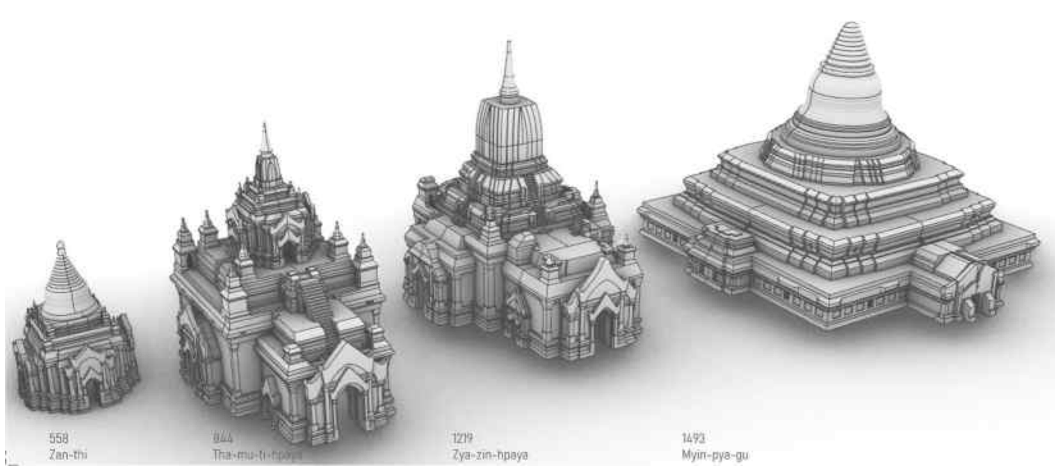

Figure 2. The four solid models of the selected buildings to be used for FEM, created using Rhinoceros. Luigi Barazzetti © 2020 J. Paul Getty Trust.

3D geometrical modeling and those using the 3D geometric models for structural analysis.

The historical masonry of Bagan is characterized by fired bricks bounded with earth-, lime, and organic-based mortars. The structural elements include massive three-leave walls, systems of vaults and arches with corbelled inner layers of lengthwise stacked bricks in the intrados, and bell-shaped domes with slender elements, such as shikaras and conical spires. The masonry and structural shapes transfer significant deformability to the constructions due to the material, the presence of multiple independent layers, and the loose connections (Elena et al. 2026).

The guidelines facilitated the creation of consistent FEMs from a detailed architectural survey. The survey data regarding the geometry of the construction included architectural details and dimensional variations that were not significant for structural analysis purposes on a large scale. Yet data regarding rotations, translations, and bulging in the structure are useful for structural assessment purposes either inserted in the FEM or to be referenced in the results. The guidelines outlined the selection of the geometric data for the definition of the 3D structural model according to two main concepts:

- Simplification: Geometric entities with strong irregularities and complex features are approximated according to specific criteria. Large, nonstructural elements add significant weight and affect the center of gravity of the structural element and thus are accounted for in the model. Their main purpose is to account for the additional mass on structural elements, and thus their shape can be simplified.
- Omission: Small geometric elements generating local loading trajectories can be omitted. In the case of undamaged, as-built configurations, load deformations can also be neglected.

In the horizontal plane, the geometric model must respect the variations of thickness of vertical resisting elements, such as walls. In the meshing stage, it is recommended to model the thickness of a wall with multiple linear or quadrilateral FEs, without mid-nodes, to accurately capture the state of stress through the thickness of the wall. The variation of thickness of the walls, and the lack of orthogonality of the corners are accounted in the modelling (in Figure 3a,b, the horizontal section of the wall and the construction plan which include geometrical defects and architectural shapes are highlighted in green). For instance, the geometrical asymmetry in plan of Myn-pya-gu is modelled, the survey data detected an offset of 16 cm between the structural parts and the symmetry axes (Figure 3c). These variations from the ideal architectural design are considered defects encountered during construction.

In elevation, the geometric model respects the assumed construction defects, such as the deviations of the vault's centerline in the vertical and horizontal direction (Figure 4a). The wall thickness in elevation is simplified as uniform, unless a variation larger than 10% is recorded (Figure 4b). For reference, with respect to Myin-pya-gu (1493), where the thickness of the walls at the base of the structure is around 4.2–4.5 m, this would correspond to about 40 cm of tolerance for variation of the wall thickness for the geometric irregularity to be accounted for in the 3D structural model.

In addition, portions of elements with cantilever action are disregarded because they alter local loading trajectories. Angular profiles are simplified with oblique trapezoidal shapes of equivalent section area (Figure 4b).

Finally, rotation or torsion in slender elements and walls, or bulging of vaults accompanied by formations of cracks are frequently documented in masonry historic constructions. These effects may be caused by excessive loading, seismic events, soil settlements, or accidental loads. When the 3D structural model refers to the undamaged as-built configuration, these irregularities are disregarded.

3.2. Workflow for 3D structural modeling

Data collected through digital recording methods were used to develop 3D structural models in a workflow summarized in Figure 5. The workflow started with the processing of survey data. Throughout the process, different software was used, accounting for different stages of the workflow. The point clouds recorded with laser scanning and aerial photogrammetry were registered and then merged in ReCap (2019). The data served two purposes: the production of line drawings using AutoCAD (2019) and the generation of 3D solid models using Rhinoceros (McNeel 2019). Rhinoceros was equipped with the 2017 plugin, which can display and edit massive point cloud data sets. The modeling guidelines discussed here were applied for the creation of geometrical models, aiming to facilitate the workflow and guide the necessary simplifications. The geometry was checked for errors and imperfections in the software SolidWorks (Street and Waltham 2020), Gmsh (Geuzaine and Remacle 2020), and Analysis Situs (Slyadnev 2020). Finally, the structural 3D models were meshed in Midas FX+ for Diana (2014).

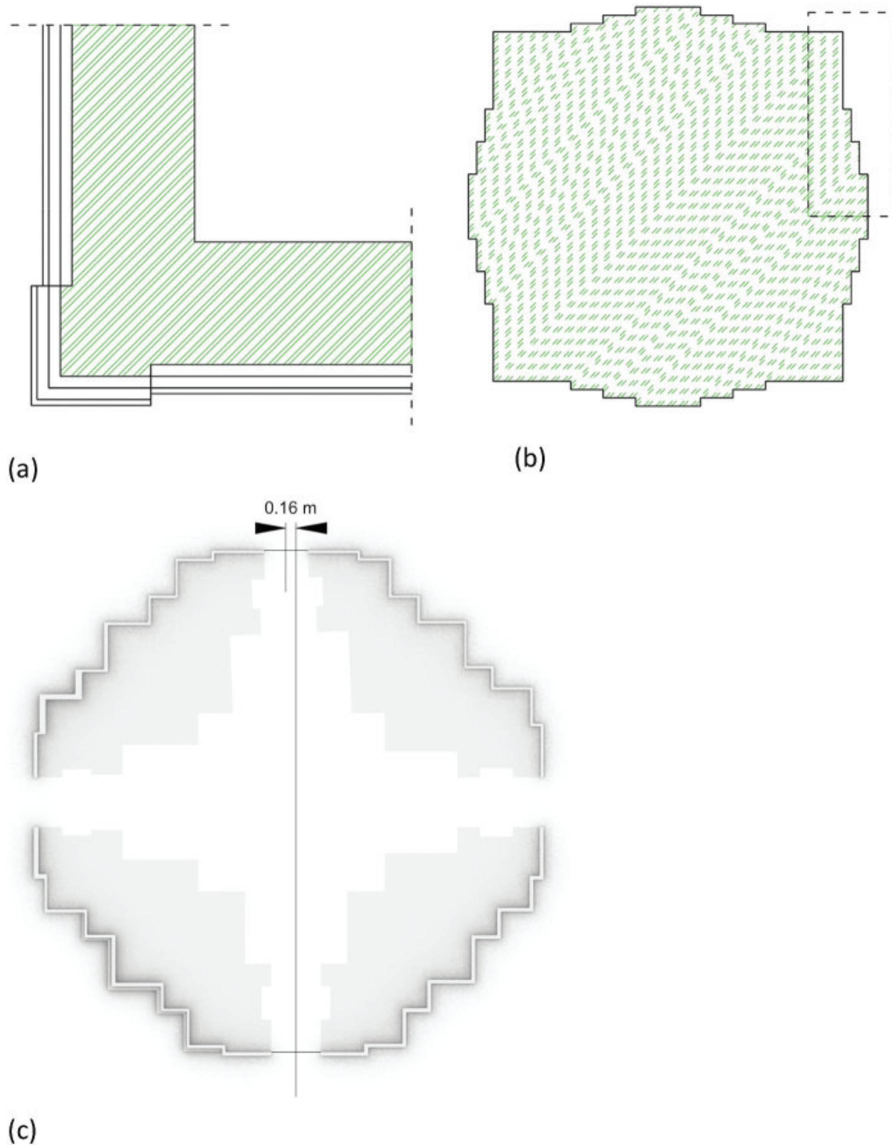

Figure 3. Modelling of horizontal features: (a) corner junctions enlarged in section (b) staggered variations in-plan (c) deviation from symmetry axis in Myin-pya-gu (1493). (a–b) Georgios Karanikoloudis and (c) Luigi Barazzetti © 2020 J. Paul Getty Trust.

3.3. 3D geometric modeling operations

The preparation of the 3D solid models for structural analysis required considerable time due to the complexity of the structures and the continuous need for testing and verification. Manual corrections were done because of the need for continuous interpretation and simplification of the geometry considering the requirements provided by the modeling guidelines. As mentioned, laser scanning and photogrammetric point clouds were valuable tools to capture the complex geometry of the monuments. Still, the model developer's interpretation was fundamental for rationalizing the geometry and creating a model suitable for structural simulation. For the creation of 3D solid models, structural elements were first discretized (Figure 6a). Structural elements were reconstructed using geometric primitives such as parallelepipeds, pyramids or pyramid trunks, and cylinders, with the defined level of detail. Special attention was paid to ensure very small tolerances of the geometry so that different adjacent solids would be recognized as continuous entities during meshing in FEM software. Incompatible tolerances within adjacent solids results in 3D solid models that are not recognized in the FEM software, so further processing will fail. As different software for numerical analysis have variable default tolerances, testing is always necessary to improve interoperability.

Since structural elements of complex geometry (e.g., vaults, arches, or collapsed parts) cannot be

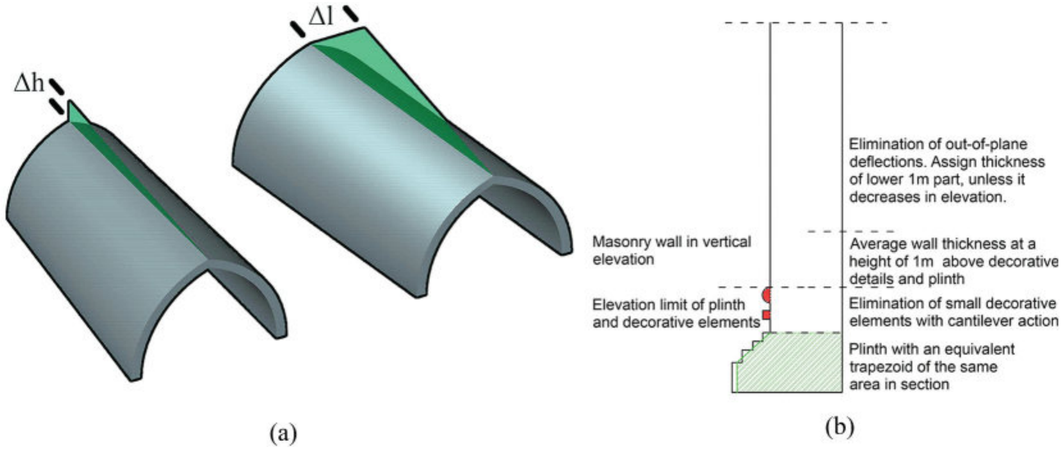

Figure 4. Modelling of vertical features: (a) Geometric variations of the centerline of vaults in horizontal and vertical directions are accounted in the model; (b) decorative elements are disregarded (in red) and plinth is simplified with an equivalent trapezoidal shape (in green). Georgios Karanikoloudis © 2020 J. Paul Getty Trust.

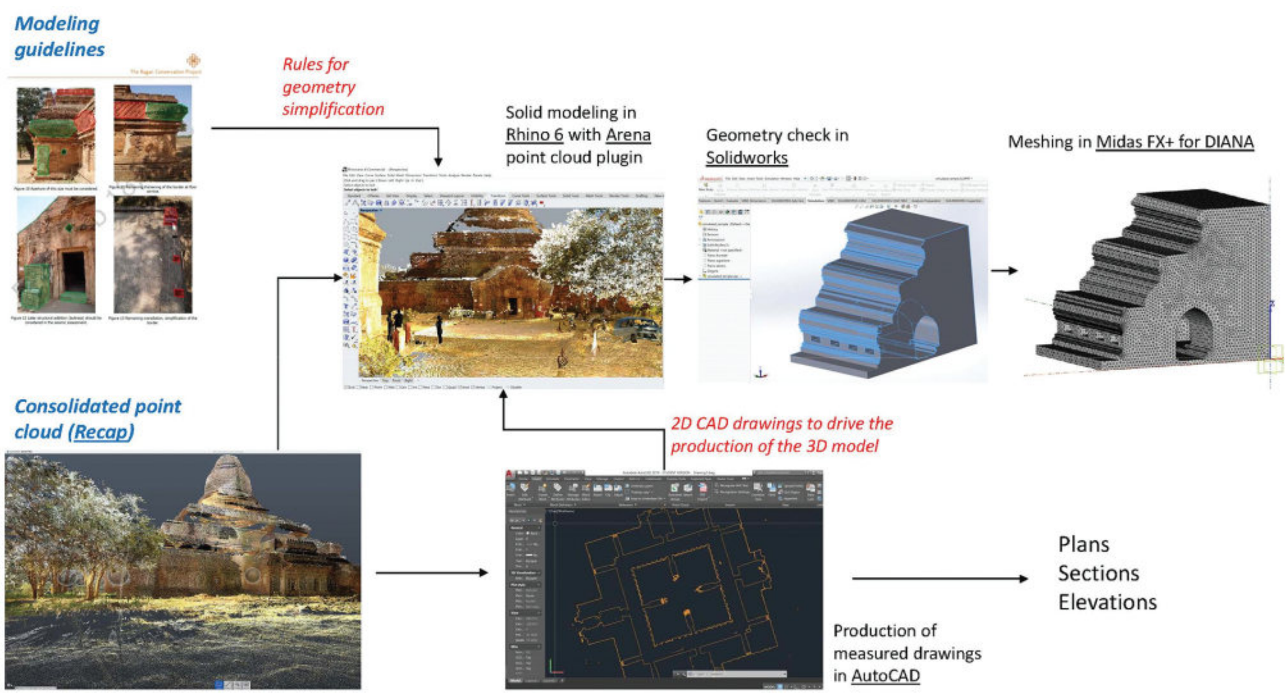

Figure 5. Workflow using architectural survey data to produce measured drawings and 3D structural models for FEM. Luigi Barazzetti and Georgios Karanikoloudis © 2020 J. Paul Getty Trust.

approximated with basic primitives, they were instead reconstructed using the preliminary generation of NURBS curves with three degrees of curvature, from which solids were obtained with more advanced operations like extrusion, sweeping, revolution, and lofting. In this case, the definition of control points during manual tracing of generative curves was aimed at reducing the number of internal subdivisions and keeping a model as simple as possible to facilitate the creation of the FE mesh.

Different solids can also be used to form a complex structural element. Boolean operations allow union, subtraction, and subdivision of different elements. The final structural element is delivered as a single solid.

In the 3D modeling operations for the monuments in the archaeological site of Bagan, which present a complex structural configuration, with corridor vaults, domes, and niches, creation of a single, continuous solid model without the internal voids was implemented as a first step. A second solid model was generated for the

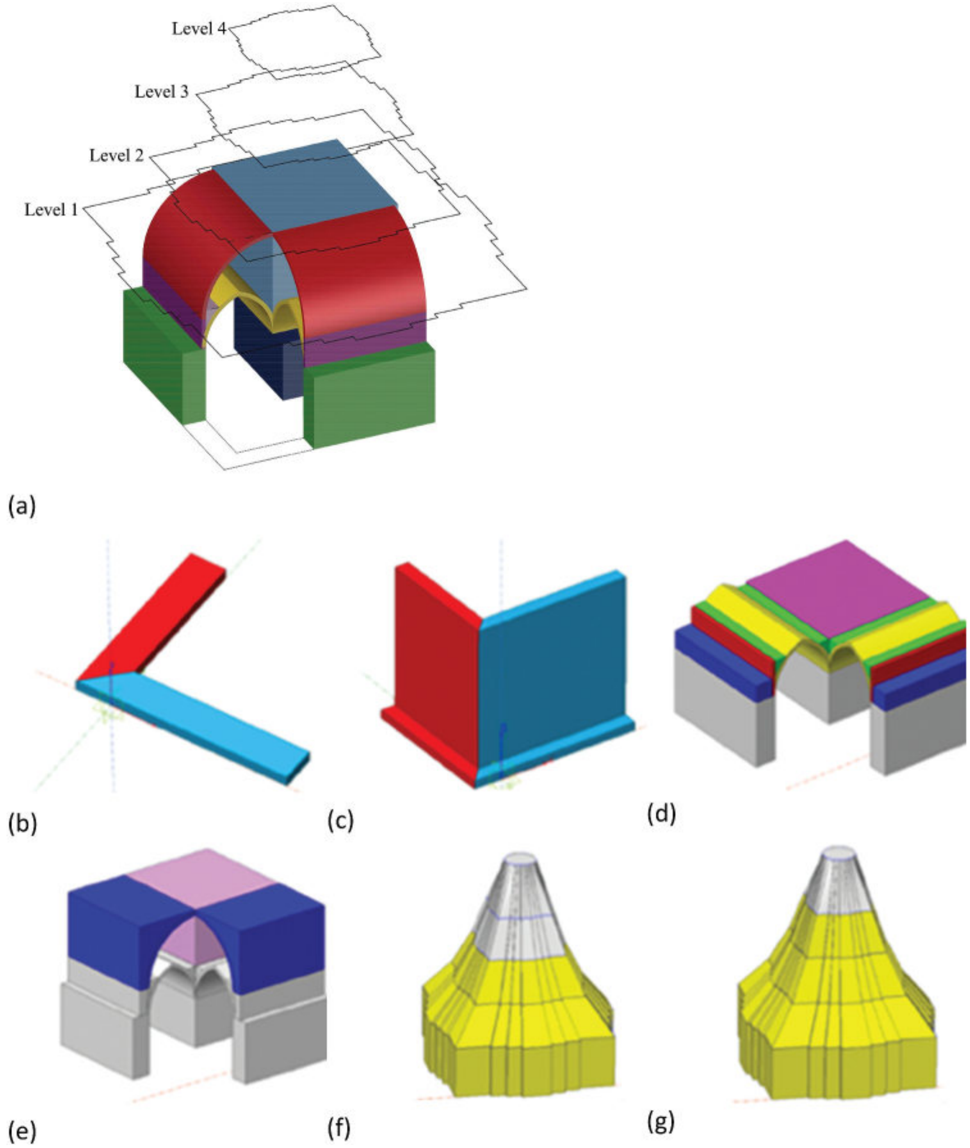

Figure 6. (a) Structural discretization for the 3D structural model of min-pya-gu (1494), divided into four levels; (b) foundation of lateral walls divided as individual solids and connected diagonally at the corners (level 0); (c) walls up to the vault springing elevation as separate solids (level 1); (d) vaults, infill, extension of side walls up to the upper level, terraces, solid core modeled separately (level 1); (e) vaults, infill, and extension of solid core modeled separately (level 2); (f) extension of solid core and terraces modeled as one solid (level 3); and (g) bell-shaped dome and spire modeled as separately (level 4). Georgios Karanikoloudis © 2020 J. Paul Getty Trust.

monument's interior open spaces (negative volumes). Boolean difference was applied to create the interior configuration of the model and obtain the final solid (Figure 7).

3.4. Model validation and mesh generation

The generation of the 3D structural model from the 3D point cloud data was performed using an iterative process that considered data processing between multiple software applications, as described in Figure 5. Software interoperability for structural modelling is a real challenge during architectural recording and structural modelling workflows, among different teams of experts, and is often a common practice for achieving geometric consistency, topological validation, and mesh compatibility.

The geometry was initially generated in AutoCAD (2019), which presented limitations in 3D modeling operations, and thus Rhinoceros (McNeel 2019) was adopted because of its greater flexibility and precision for handling complex shapes. The geometry was exported in.iges (Initial Graphics Exchange Specification, a vendor-neutral file format based on

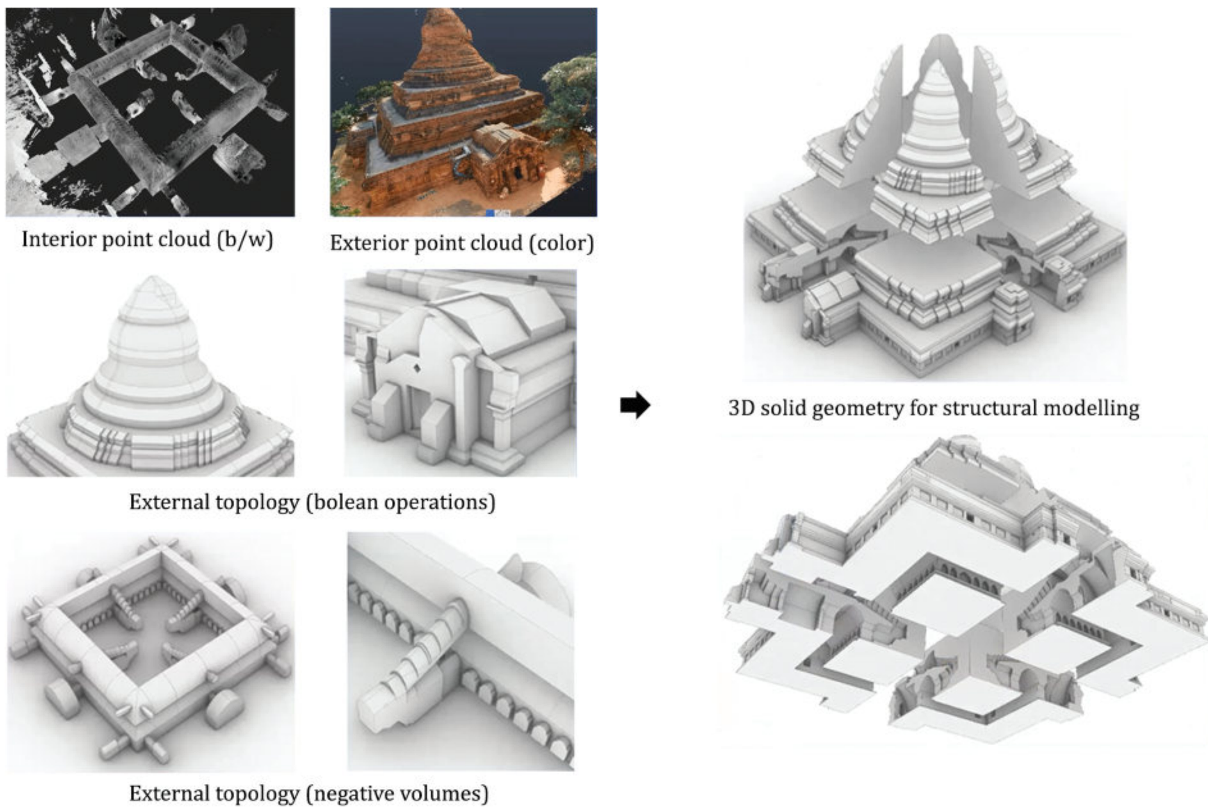

Figure 7. 3D structural model of Myin-pya-gu (1493), constructed by subtracting negative volumes. Luigi Barazzetti © 2020 J. Paul Getty Trust.

ASCII) or.step file format (Standard for the Exchange of Product Data written in an ASCII format). Then data were imported into SolidWorks (Street and Waltham 2020) and controlled for mismatched or missing parts, penetrating solids, and folded edges of the geometry. The identified errors were then corrected in the geometric model. Once the geometry was fully validated, it was imported into the software Midas FX+ ("Midas FX+ for DIANA" 2014), checked in terms of scaling and overall dimensions, and then processed with mesh generation algorithms.

As explained in Section 3.3, to have greater control over the 3D structural model the structure was discretized in groups of structural components to control the details and material differentiation and to facilitate the implementation of interface elements that may be inserted into the FEM. The creation of the FE mesh should start from the foundations and continue progressively to the top with a proposed discretization of structural elements as shown in Figure 6b. In some cases, given the complexity of the elements to be modeled, a differential modeling approach was adopted; that is, certain elements with voids were initially modeled as solid. Subsequently, the voids were modeled as solids and subtracted from the overall geometry.

After the completion of each level of the structure, the geometry was checked for geometrical errors using SolidWorks, Gmsh, and Analysis Situs software, and once the compatibility was ensured, the modeling proceeded to the level above, until the geometry of the entire structure was completed and validated. Tolerance is considered an essential part of 3D solid modeling. Different software has different tolerance levels, and compatibility tests should be always carried out.

Once the 3D structural model moves to the FEM software, the creation of the FE mesh also follows an iterative process. Mesh refinements are fundamental for the transition between coarse and refined elements according to mesh quality parameters.

Different modeling errors pertaining to illogical or physically impossible geometry were found during the modeling phase, such as nonmanifold edges, faces without closed contours, open edges, or interferences between different solids. All these errors obstruct the creation of FE mesh and must be detected and removed. Most error sources often require the operator to remodel specific parts of the structure and generate new solids bounded by surfaces perfectly connected to adjacent ones. Continuous inspection during the modeling process also allows the identification and reduction of the number of elements that are geometrically and topologically incorrect. Further issues regarding the quality of the FE mesh arise from ill-shaped tetrahedra, especially in areas of sharp edges, which can be avoided by smooth mesh size transitions. It is also fundamental to reach a proper level of detail for the representation of small entities that could result in faces with small areas, short edges, slivers (i.e., narrow elements with a high aspect ratio), and knife vertices or edges (i.e., acute angles between edges or faces). These issues of misshapen tetrahedra and small faces or edges in the mesh are not necessarily identifiable through automated checks in the modeling or meshing software and must be checked and re-modeled using the careful judgment of the practitioner.

Finally, meshing tests are carried out to ensure that the different parts can be successfully converted into tetra-meshes. Such tests were carried out for both the models as single solids and the models split into multiple solids with coincident edges and faces. As a last check, node-to-node connectivity should be verified in adjacent surfaces between structural elements.

3.5. Challenges of mesh definition from geometric to structural 3D models

Several attempts were made to study the generation of a compatible 3D structural model and the creation of FEM. This section describes the most common issues encountered in the process.

When structural elements were modeled with surfaces, often they could not be converted into a solid or extruded; thus, they were not acceptable as part of the workflow. Curved edges at the corners of 3D structural elements cannot be represented by polylines because they negatively influence the mesh creation by introducing unnecessary edge divisions (Figure 8). Therefore, it is important that edges and curves are continuous so that they do not interfere in the creation of the FE.

In the presence of curved and articulated parts that require elaborate modeling operations, small edges are frequently generated that would corrupt the mesh generation and were responsible for a nonuniform mesh. An example of meshing error caused by small, distorted elements generated from geometric defects is shown in Figure 9. The error can be resolved by reshaping the geometry and eliminating the small edge.

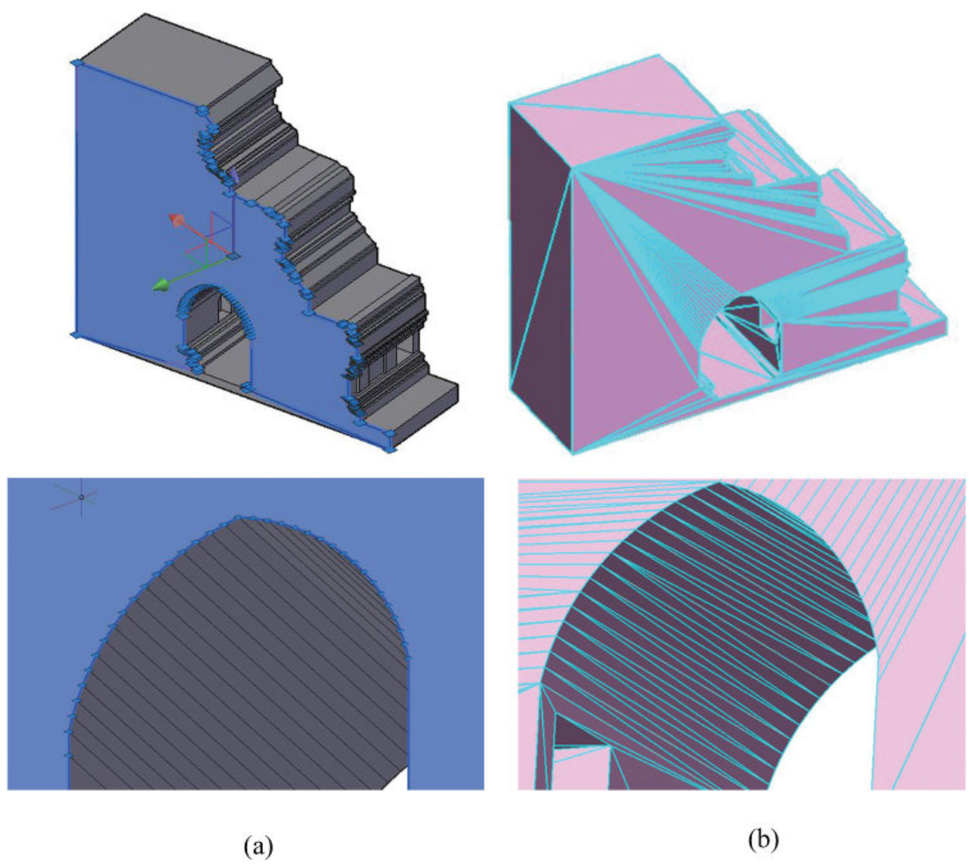

Figure 8. Problematic solid, part of Myin-pya-gu (1493), in the CAD software (a), with small divisions in vault's curvature and additional surface divisions when imported in the FEM software (b). Georgios Karanikoloudis © 2020 J. Paul Getty Trust.

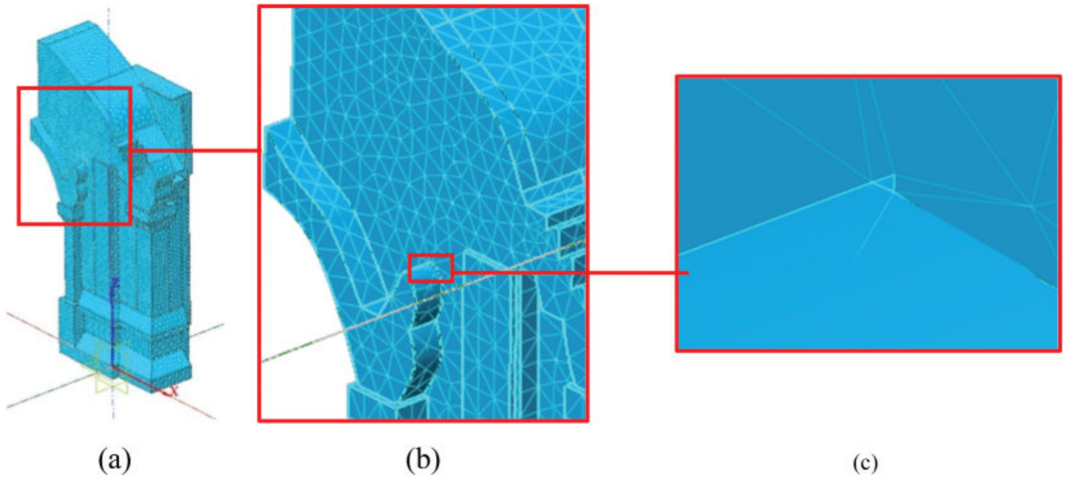

Figure 9. Errors encountered in Midas FX+ with the 3D structural model and FEM of Tha-mu-ti-hpaya (844): (a) failing 3D mesh in the part of the portal; (b) closer view of the failed mesh; and (c) small, distorted FE. Luigi Barazzetti © 2020 J. Paul Getty Trust.

The number of edges and divisions of the geometry depends on the specific modeling functions used to generate the geometry, such as extruding a planar surface or sweeping a solid profile along a reference line. In addition, when the 3D structural model is imported into the FE software, it is common that the geometry is further processed and discretized based on the material differentiation and damage. Hence, the presence of any unnecessary divisions will cause issues with Boolean operations (union, difference, intersection, split). The reduction of edges for the tested case studies was performed with the pre-processing software Midas FX+ prior to the generation of the mesh to diminish the constraint points (Figure 10a). Despite manual corrections and checks, many small edges can still exist that generate small FEs. These can be removed even after the generation of the mesh by merging the nodes closer than 1 cm and replacing them at center locations (Figure 10b).

Finally, in the pre-processing software (such as Midas FX+), further processing can be favorable by simplifying the 3D structural model during importation. For example, the simplification of B-splines to an analytical type is an automated operation that can corrupt the model, and avoiding such automatic simplification is recommended.

Software as Naviswork (Autodesk 2024) and SolidWorks include algorithms to identify problems of the geometry prior and after mesh generation. Geometry checks include the Vertex Connectivity and Normals, for which shared vertices are identified, ensuring mesh connectivity. Normals at triangle vertices are evaluated to differentiate between internal and external edges, identifying smooth or sharp surfaces. Another check is the Surface Consistency, if geometry has slightly misaligned edges faces may not weld properly, leading to gaps in the geometry. The Duplicate Geometry Detection algorithm checks for duplicate elements. The Interference (Clash) Testing acts as a form of geometric validation, looking for intersections of surfaces, lines, and points. These algorithms may be also implemented in Python or MATLAB routines. In Section 3.4 are mentioned two common geometry formats (.iges and.step), each format has its own coding to represent the model. The automated procedure must consider geometry formats compatibility in input (the decoding of the geometry to perform the testing operations) and in output (the compatibility of the updated geometry with the software designated for the finite element analysis).

3.6. Applications

This section presents the process of transferring geometric data to FEM for two temples among the four selected as case studies for the Repair and Seismic Retrofitting component. The workflow was first applied and fine-tuned with Myin-pya-gu (1493) and Tha-mu-ti-hpaya (844).[1] The refined guidelines were then implemented on the remaining two temples.

3.6.1. Application to Myin-pya-gu

Myin-pya-gu (1493) is a *gu* temple constructed in the 11th century. Further description of the temple architecture can be found in Saw Htwe Zaw et al. (2026). Digital recording of the construction was carried out

[1]Monuments are identified by their name and number, following Pichard (1992).

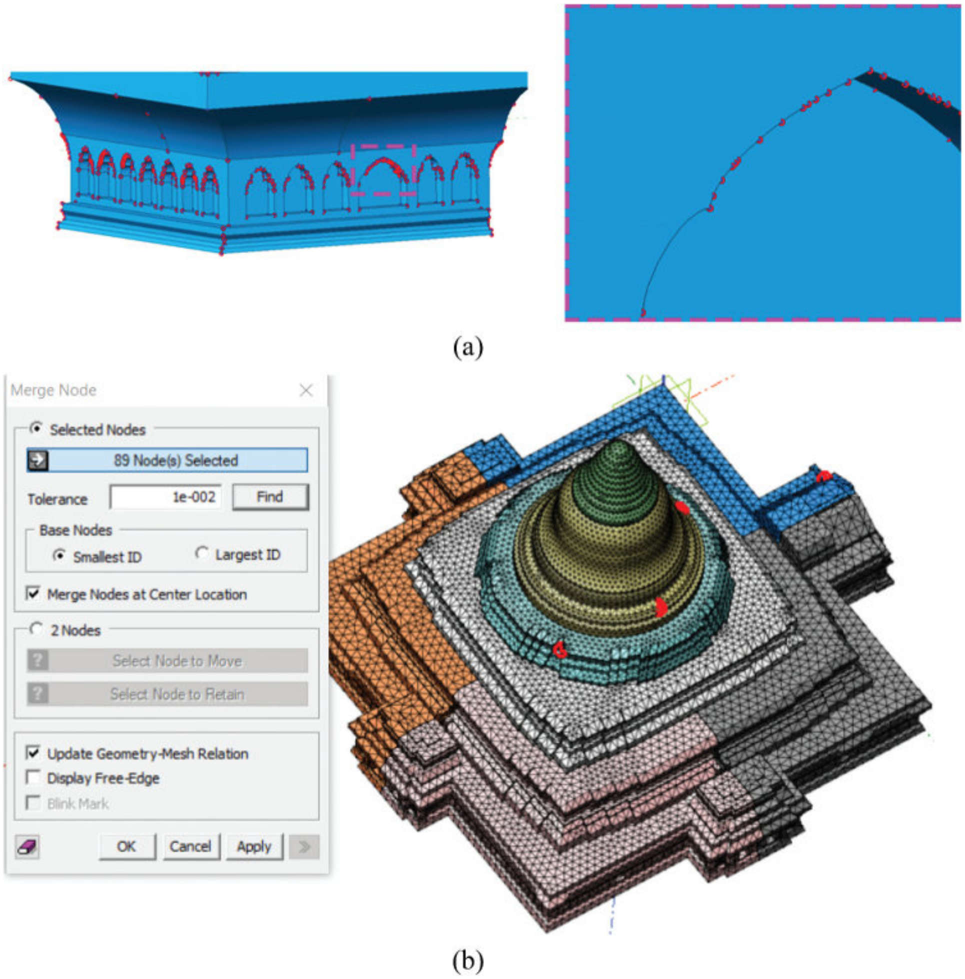

Figure 10. Operations for improving 3D structural models and FEM: (a) merging of unnecessary edges in the niches Myin-pya-gu (1493) before the generation of FE mesh, in Midas FX+; and (b) merging of FE nodes closer than 1 cm, in Midas FX+ for Myin-pya-gu (1493). Georgios Karanikoloudis © 2020 J. Paul Getty Trust.

with an approach based on surveying, terrestrial laser scanning, and aerial and terrestrial photogrammetry to produce georeferenced data of the site for structural modeling, as discussed in Duong et al. (2026).

The construction was modeled to represent the undamaged as-built configuration, not considering previous seismic damage to the structure. The main seismic damage is concentrated on the conical spire that collapsed twice during the 1975 and 2016 earthquakes, resulting in a loss of material and irregular shape of the conical spire. Therefore, this irregularity introduced by the previous seismic damage was disregarded and used to validate the structural analysis, while the missing spire was re-created by means of photogrammetry from photographic archives.

As illustrated in Figure 11, the recessed increments of the wall section were modeled following the true recorded geometry. Also, the profile of the plinth was simplified to maintain the volume of the element by interpolating a straight sloped surface (Figure 11a). Each projection was about 0.20 m, which was simplified to a single sloped surface.

As shown in Figure 11b, the recent brick masonry fill constructed in the openings of the ground level was omitted as it constitutes a later addition to the construction.

The irregular geometry of the decorative surfaces was disregarded since they were interventions from the 20th century to regularize the damaged cornice (Figure 11c). The stepped section of the cornice was simplified with an interpolating straight line. The remaining original cornice was respected (Figure 11d–f). The rectangular crenels separated by approximately 0.10 m gaps were considered irrelevant, since their load is low, and therefore disregarded (Figure 12a,b). Figure 12a shows the yellow dashed lines highlighting two vertical cracks, which were disregarded in the model and used for comparison with the numerical results. In Figure 12c–e, the ground floor in the interior spaces was disregarded,

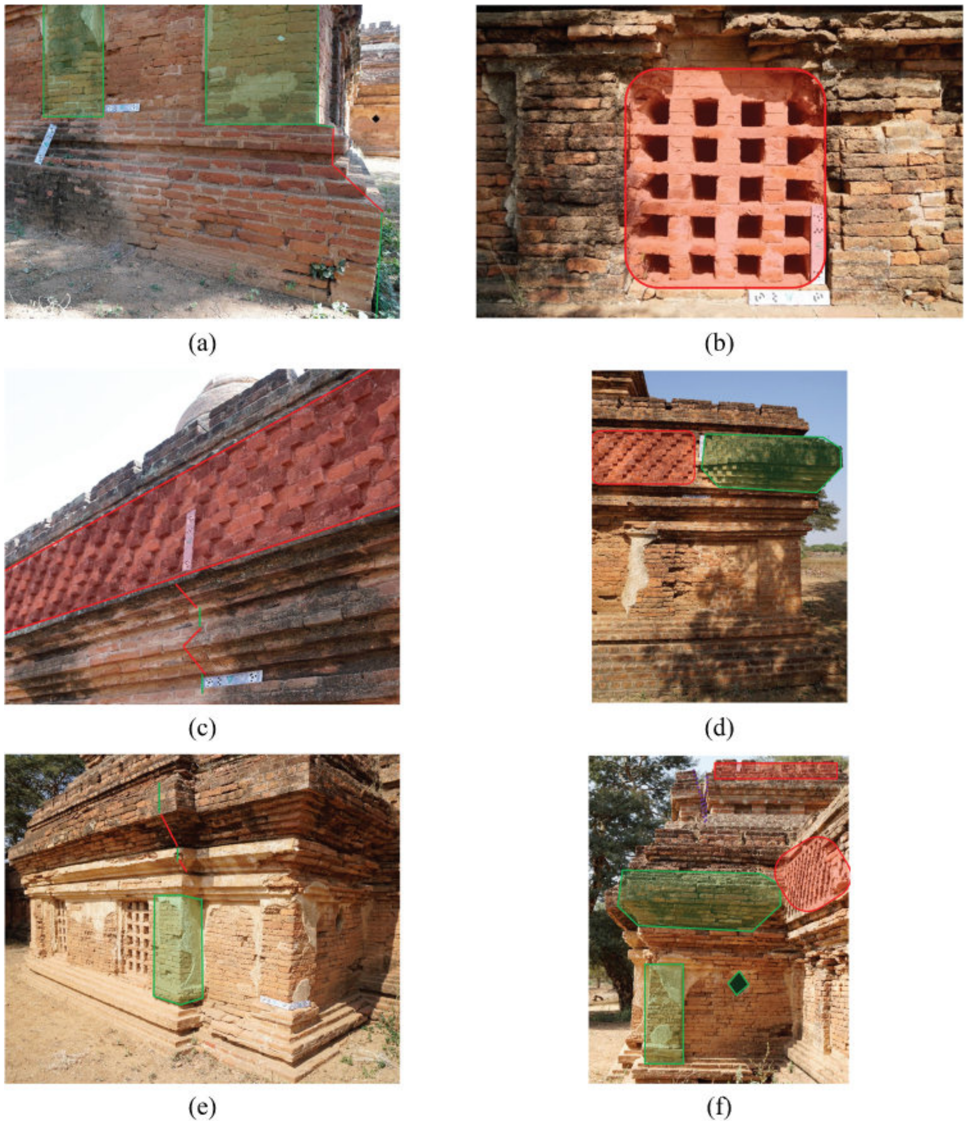

Figure 11. Employed modeling guidelines for the 3D structural model of Myin-pya-gu (1493): (a) lower portion of the exterior corner wall and plinth at the ground level; (b) the brick masonry grids built into the windows, to be disregarded; (c) higher portion of the exterior lateral wall and (d) corresponding corner; lateral forepart in front (e) and side view (f). Note the parts in green to be kept in the model and the decorated elements that are simplified in red. Photographs by Valerio Sabbatini © 2019 J. Paul Getty Trust.

while the raised floor (about 0.50 m from the ground floor) was accounted for as it was in continuity with the walls. The statues were omitted as they are decorative elements and do not interact with the structural elements. The recurrent niches were considered, given their significant number and dimensions, as part of the masonry walls (Figure 12d). The vaults were simplified with regular curvatures, but the variations of the vaults' centerlines in the horizontal and vertical directions were respected because they were considered part of the construction practice (Figure 12d).

The resulting FEM composed of pyramid linear elements, here with an FE size of 0.4 m, is shown in Figure 13a.

3.6.2. Application to Tha-mu-ti-hpaya

Tha-mu-ti-hpaya (844) is a medium size, single-story temple with a square central shrine on the ground floor and a solid core measuring about 4.60 by 4.50 m. The temple has a large shikara that was destroyed in the 1975 earthquake, reconstructed in the 1990s, and severely damaged again during the earthquake of 2016.

The survey of the construction was carried out with a similar approach used for Myin-pya-gu, i.e., a combination of laser scanning and aerial photogrammetry, using a geographic survey network to register data in a common reference system (Duong et al. 2026). The digital recording resulted in dense point clouds directly referenced to create solid models for structural analysis.

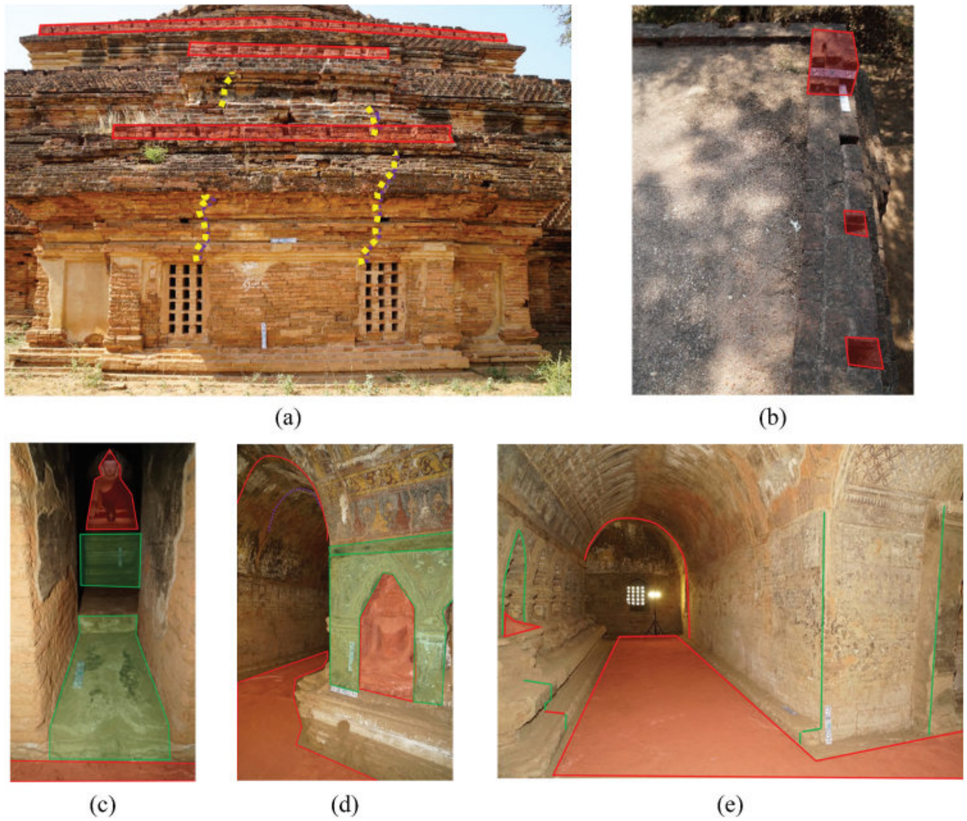

Figure 12. Employed modeling guidelines for the 3D structural model of Myin-pya-gu (1493): (a) in north elevation, yellow dashed line showing the cracks considered for validation and red shows the disregarded gaps between crenels, also from top view (b); (c) corridor with elevated floor and statue; (d, e) main vaulted corridor with paved floor, and niches with statues, part of the walls. Note that the statues and the floor in red were disregarded, and the vaults' deformations were regularized. The steps to the raised floor, the niches, and the wall profile, shown in green, were included in the model. Photographs by Valerio Sabbatini © 2019 J. Paul Getty Trust.

For the creation of the 3D structural model of Tha-mu-ti-hpaya, similar modeling decisions were made as in the Myin-pya-gu model (Figure 13a). Specifically, the detailed profiles of the cornices and plinth were simplified to single sloped surfaces. The true geometry of the pilasters was represented in the model, having a variation of 0.15 m from the regular wall thickness. Finally, the complex profile of the spire was simplified to a smooth conical shape with equivalent mass.

The resulting FEM composed of pyramid linear elements, here with a FE size of 0.4 m, is shown in Figure 13b.

The modeling principles applied to Tha-mu-ti-hpaya are illustrated and summarized in Figure 14,

4. Discussion and conclusions

Modeling for structural analysis of historical masonry structures requires thorough knowledge of the construction considering multiple sources of information, such as bibliographic research, on-site testing, and diagnostic monitoring. For the creation of 3D structural models and FEM for structural assessment, it is essential to establish a strong connection between the workflow of geometric surveying and numerical modeling.

The assumptions and decisions behind loading, boundary conditions, connectivity between structural elements, and material discretization highlight the importance of proper idealization of the structure. Thus current 3D structural model generation procedures result in additional and often unnecessary simplifications with specified control or refinement techniques.

Relevant aspects of the FEM include acknowledgment of the construction sequence to reproduce the variation in the stress state, the appropriate definition of boundary conditions, and the calibration of structural parameters, particularly in characterizing nonlinear aspects such as natural modes of vibration, stiffness, connectivity, and damage.

The application of the modeling guidelines for the case studies of Myin-pya-gu and Tha-mu-ti-hpaya was proven useful for solving the technical issues and simplifications involved in the transition from 3D geometric to 3D structural models for FEM for the

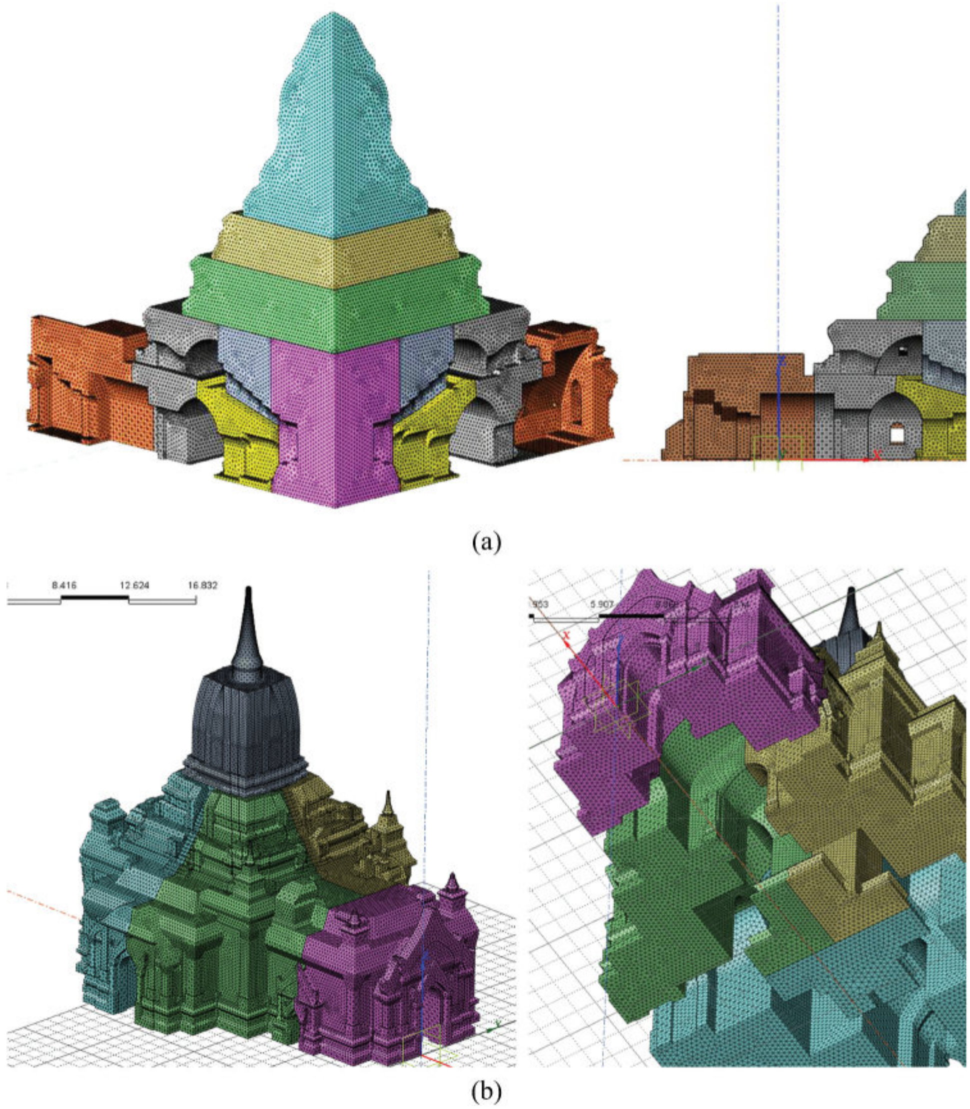

Figure 13. Generation of FE mesh, in Midas FX+ for (a) ¼ of the 3D structural model of Myin-pya-gu (1493), with a mesh size of 0.4 m; and (b) Tha-mu-ti-hpaya (844), with a mesh size of 0.4 m. Georgios Karanikoloudis © 2020 J. Paul Getty Trust.

masonry monuments of Bagan's architecture. This transition required the interpretation of multidisciplinary information acquired through surveying, testing, and monitoring. Significant insights were gained from historical analysis for the definition of construction phases, alterations, and additions, which may play a pivotal role for structural assessment, especially when significant alterations are generated over the lifetime of a structure.

Some of the issues encountered require further research, such as a comparison of models representing different states of damage and deformation against the as-built state of the structure. Historic constructions include a long series of damages and interventions that recurrently alter the geometry and stresses of the current state. Therefore, it is critical to consider the objectives of the analysis in the preparation of the 3D structural model when determining the appropriate state to represent. When the current state is to be represented, a higher level of detail and complexity is often associated with the geometric model. On the other hand, the definition of the simplified undamaged state of the structure needs careful consideration since it is accompanied by many assumptions and idealizations that may introduce inaccuracies in the model.

This paper has presented basic principles for generating geometric models of complex massive masonry structures, with the intent of conducting robust numerical analysis simulating the as-built conditions. The modeling principles are guided by the concepts of simplification and omission. Simplification is recommended to approximate the equivalent mass and volume of complex and irregular structural elements, where the weight and center of gravity can potentially influence the structural behavior, whereas a detailed geometric representation is often not as relevant.

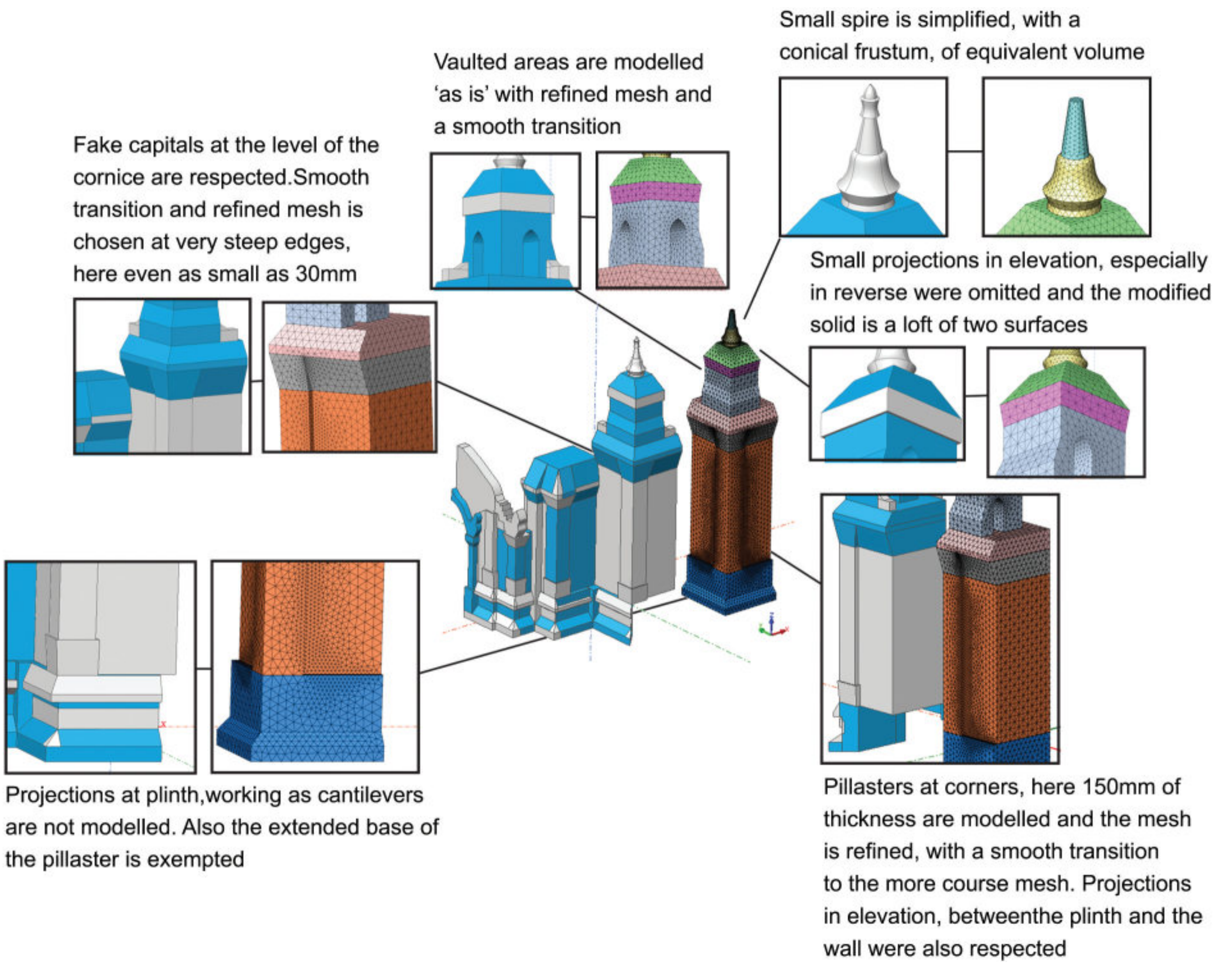

Figure 14. Modeling principles as applied to Tha-mu-ti-hpaya (844). Luigi Barazzetti and Georgios Karanikoloudis © 2020 J. Paul Getty Trust.

Similarly, omission of complex geometric elements is recommended where the local loading trajectories of non-structural parts do not affect the load paths through the overall structure or where irregular geometry represents a later stage of damage and not the as-built condition.

As modeling for structural assessment of complex historic masonry structures requires a careful balance between accurate representation and simplification of the geometry, the proposed modeling guidelines offer a valuable framework for generating 3D structural models from detailed architectural survey data, focused on the objectives of the structural analysis.

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Author contributions

CRediT: **Valerio Sabbatini:** Conceptualization, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing; **Georgios Karanikoloudis:** Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing; **Luigi Barazzetti:** Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing; **Tamali Bhowmik:** Data curation, Formal analysis, Investigation, Software, Validation; **Shibu Samson:** Data curation, Formal analysis, Investigation, Software, Validation; **Michelle Duong:** Data curation, Investigation,

Software, Visualization, Writing – review & editing; **Elyse Hamp:** Data curation, Formal analysis, Investigation, Software, Validation, Visualization; **Mario Santana Quintero:** Conceptualization, Project administration, Resources, Supervision; **Claudia Cancino:** Conceptualization, Funding acquisition, Project administration, Supervision.

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