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# HBIM for the protection and management: a case study of Chinese timber architectural heritage



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The creation of information models for Chinese timber architecture faces challenges due to the complexity of its structural system and components. This study aims to explore the creation and application methods of information models for Chinese timber buildings, providing technical solutions for their digital preservation. Using the Main Hall of Chuzu Temple as a case study, the study proposes a method system for constructing HBIM for timber architecture. The system includes multi-source data collection, model creation based on Revit, fitting adjustments with point cloud models, non-geometric information loading, and virtual display utilization. The research ultimately created a HBIM model for Chinese timber architecture that closely matches the current state, establishing a family library with 66 family categories and 330 families, and achieved the protection and management of the Main Hall of Chuzu Temple.

Amid the ongoing evolution of heritage conservation principles, digital technologies have introduced new tools for the documentation, management, and dissemination of cultural heritage<sup>1</sup>. These technologies help overcome the limitations of traditional conservation methods in terms of precision, efficiency, and collaboration<sup>2</sup>, thereby addressing the growing demands for systematic, sustainable, and shareable heritage practices<sup>3</sup>. Building Information Modeling (BIM) has been widely adopted in the Architecture, Engineering, and Construction (AEC) industries<sup>4</sup>, encompassing the generation, management, and exchange of information among professionals throughout project development. With the rapid advancement of surveying technologies such as Terrestrial Laser Scanning (TLS) and close-range photogrammetry<sup>5</sup>, the concept of Heritage Building Information Modelling (HBIM) was first proposed by Murphy et al. in 2009<sup>6</sup>. HBIM extends the application of BIM to the heritage field, aiming to digitally reconstruct historical buildings<sup>7</sup>, semantically model architectural elements, and integrate various types of information to support informed decision-making<sup>8</sup>.

As a crucial category of immovable cultural heritage, timber architecture holds significant scientific, artistic, and cultural value. However, its conservation faces substantial technical and managerial challenges due to the intricate structural details, the diversity of components, and the high precision required for interventions<sup>9</sup>. HBIM provides an effective solution

by integrating multi-source data, offering accurate and efficient digital support for the conservation, restoration, and presentation of timber heritage buildings<sup>10</sup>.

The creation of the model is fundamental to HBIM. Currently, the automated Scan-to-BIM workflow is the dominant approach, utilizing deep learning algorithms, Grasshopper plugins, and other technologies to perform automated or semi-automated modeling of point cloud data<sup>11–13</sup>. This process can automatically identify and segment the basic components of brick and stone buildings, such as doors, windows, and walls<sup>14,15</sup>. Additionally, some scholars have explored localized timber components, including roof trusses, floors, and staircases<sup>16–18</sup>.

In recent years, HBIM has gradually gained attention in Asian timber architectural systems. Through specific rule-based algorithms, initial steps have been taken to generate typical timber components, such as *dougong* (bracket set), from point cloud models. For example, Liu developed a method to automatically extract parameters from the 3D scanned point cloud data of *dougong* components<sup>19</sup>. A few studies have attempted to model heritage buildings holistically during restoration. For instance, Hyun-Chul Youn conducted full 3D scanning of all building components during a restoration project to create a realistic Rhino 3D model<sup>20</sup>. In conclusion, research on systematically constructing a complete timber building information model remains scarce. If the goal is to achieve a comprehensive,

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component-based expression of architectural heritage, relying solely on point cloud models is insufficient to meet the practical needs.

For architectural heritage that requires accurate representation of internal structures, creating specific building component families is crucial. However, BIM, primarily designed for modern building development, has a limited library of component families suitable for heritage buildings. Researchers have mainly focused on the parametric creation of typical building elements. For instance, Murphy M and others developed a parametric representation of classical architectural elements based on building rules<sup>21</sup>. Rania Aburamadan developed a heritage BIM shared library for typical elements in Jordanian and Arab architecture<sup>22</sup>. Sampaio A Z explored the generation of parametric families for representative components of the Lisbon Palace<sup>23</sup>. Similar research has emerged in East Asia. Jiang Y, for example, developed an intelligent automatic modeling method using Dynamo for creating *dougong* components<sup>24</sup>. Park defined the parametric relationships between Korean traditional house elements and developed a system family library for these elements.

Families are the foundation of component-based model creation. They not only express the composition and internal structure of components but also facilitate subsequent integration and management of information. Some studies have focused on enhancing the semantic expression and information integration of families by leveraging data programming, knowledge graphs, or knowledge base platforms<sup>25–28</sup>. In the field of architectural heritage preservation, most existing families focus on typical components of masonry buildings, with fewer families created for other types of heritage components<sup>1,2</sup>.

Whether through point cloud recognition and segmentation or parametric modeling of families, current modeling efforts are primarily focused on the creation of specific building components. In response to this limitation, some researchers have attempted to parametrize entire frameworks. For example, Kang H carried out parametric modeling of major load-bearing components such as columns, beams, and floors in traditional Korean timber architecture, with other parts relying on scanning data for supplementation<sup>29</sup>. Xu, on the other hand, explored an automated method for generating the drum tower frame based on traditional Chinese carpentry construction rules<sup>30</sup>.

For the architectural heritage families and entire frameworks, parametrization is typically an idealized model designed based on specific rules or algorithms, making it difficult to accurately reflect the actual state of the building. However, realism is the foundation on which future preservation efforts must be based. In addition to creating information models for architectural heritage, many scholars have also focused on the application of HBIM in 3D visualization. By integrating Virtual Reality (VR) software, game engines, and web platforms<sup>31</sup>, HBIM has been extended for practical use in heritage preservation management, educational display, and other real-world applications<sup>32,33</sup>.

Similar to BIM, the creation of HBIM also requires adherence to certain rules. Although various modeling methods are gradually emerging, there is currently no universally accepted HBIM standard across different regions. European countries have developed their own standards, including Italy's UNI 11337<sup>34</sup> and Spain's Guía BIM para Patrimonio Cultural<sup>35</sup>, which formally define the application of BIM methods in cultural heritage preservation, covering key aspects like maintenance, restoration, and digital archiving of heritage buildings. On a global scale, ISO 19650 is widely adopted and serves as the cornerstone for BIM practices in many countries, and its principles now being integrated into HBIM projects. In contrast, countries in Asia, such as China, Japan, and South Korea, have yet to establish independent HBIM standards. Instead, they generally base their HBIM practices on general BIM standards and focus on targeted explorations within specific projects<sup>36–38</sup>.

In summary, the reverse modeling approach from point cloud models to HBIM offers the advantage of faithfully representing the building's surface, but the recognition and segmentation of components are key challenges in the model creation process. In regard to East Asian timber architecture, preliminary work has been done on creating models of

*dougong* components. Using families to create heritage information models enables a complete expression of the internal structure of the building. However, most current studies focus on creating families based on an idealized design state, without considering an accurate representation of the current condition, which is fundamental to future preservation efforts. Additionally, most of the existing families are designed for masonry buildings, while those for timber structures still require further development.

The primary objective of this study is to explore the creation and application methods of the Chinese timber architecture information model, with a particular focus on meeting the need for an accurate representation of the current state while constructing component-based models. To this end, the study focuses on the Main Hall of Chuzu Temple, a representative timber building from the Song Dynasty in China, and proposes an HBIM framework for timber architectural heritage. This framework encompasses a comprehensive technical process from model creation, information integration, to virtual display. The study first creates a component library containing the majority of the hall's components based on multi-source data, then fits the point cloud model to develop an information model that accurately reflects the current state, while incorporating multiple types of non-geometric information. Finally, practical explorations of virtual display based on this model were carried out.

## Methods

### Research object

The Chuzu Temple is an integral part of the “Historic Monuments of Dengfeng in ‘The Centre of Heaven and Earth,’” a United Nations Educational, Scientific, and Cultural Organization (UNESCO) World Heritage site. The Chuzu Temple is part of the Shaolin Temple, and is located in Zhengzhou City, Henan Province, China, with geographical coordinates of 34°30'N latitude and 112°55'E longitude (Fig. 1a). The Chuzu Temple features a two-courtyard layout, oriented north to south, and covers an area of ~3000 square meters. The central axis sequentially consists of the main gate, the Main Hall of Chuzu Temple (Fig. 1b), and the Thousand Buddha Hall. On either side of the Thousand Buddha Hall are the East and West Wings, and other pavilions (Fig. 1c). The courtyard contains forty-nine steles from various periods and fourteen ancient trees of notable species.

The Main Hall of Chuzu Temple is the central structure of the temple, located on a platform with a nearly square floor plan. Built during the Song Dynasty (1125), the hall has undergone several renovations in the Jin, Ming, Qing, and modern periods. However, among existing Song Dynasty wooden structures, its construction methods are the closest to those outlined in the *Yingzao Fashi* (Song-era construction guide). The *puzuo* (bracket set) arrangement, component detailing, and decorative patterns all align with practices recorded in the *Yingzao Fashi*.

The Main Hall of Chuzu Temple is divided into three main levels. From bottom to top, they are the platform base, the main body, and the roof. The platform level includes the steps and *xiangyan* (a triangular feature at both ends of the tread), while the main body consists of three bays in both width and depth, incorporating components such as columns, windows, and walls. The roof is designed in a *Xieshan* (gable and hip roof) style, featuring a *zhengji*, four *chuiji*, and four *qiangji* (three types of roof ridges), with a relatively gentle curve. The detailed construction information of the Main Hall is shown in Fig. 2.

The Main Hall's *puzuo* are divided into external and internal *puzuo*. These systems, composed of individual components such as *dou*, *gong*, and *ang* (three main components of *puzuo*), connected by *sunmao* (a unique component connection method) (Fig. 3a), are vital to the value of Chinese timber architectural heritage. Therefore, creating these components in HBIM is essential. The external *puzuo* comprises twenty-six elements, including corner *puzuo*, capital *puzuo*, and intercolumnar *puzuo* (Fig. 3b, c). The internal *puzuo* consists of twenty-three elements, four for the interior columns *puzuo* and nineteen for the *wujia puzuo*.

The columns inside and outside the Main Hall of Chuzu Temple display unique characteristics of Chinese timber architecture heritage, such

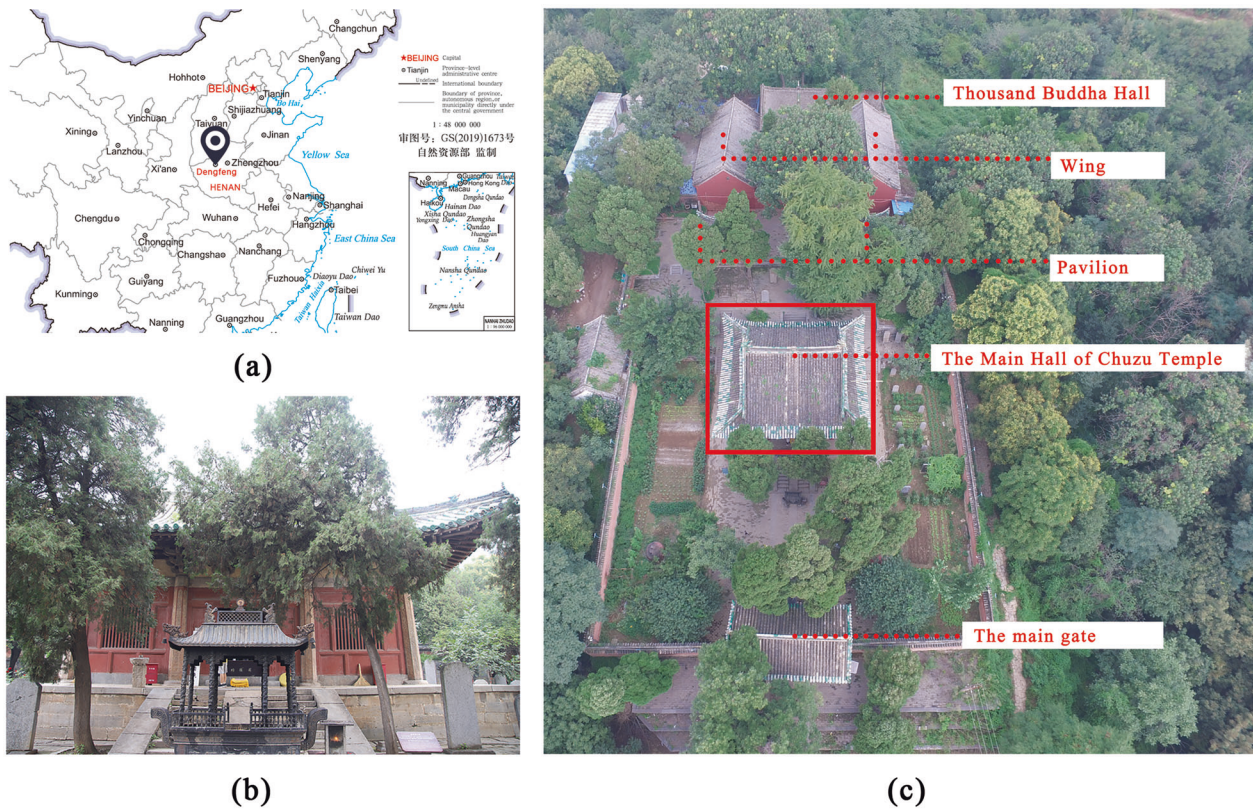
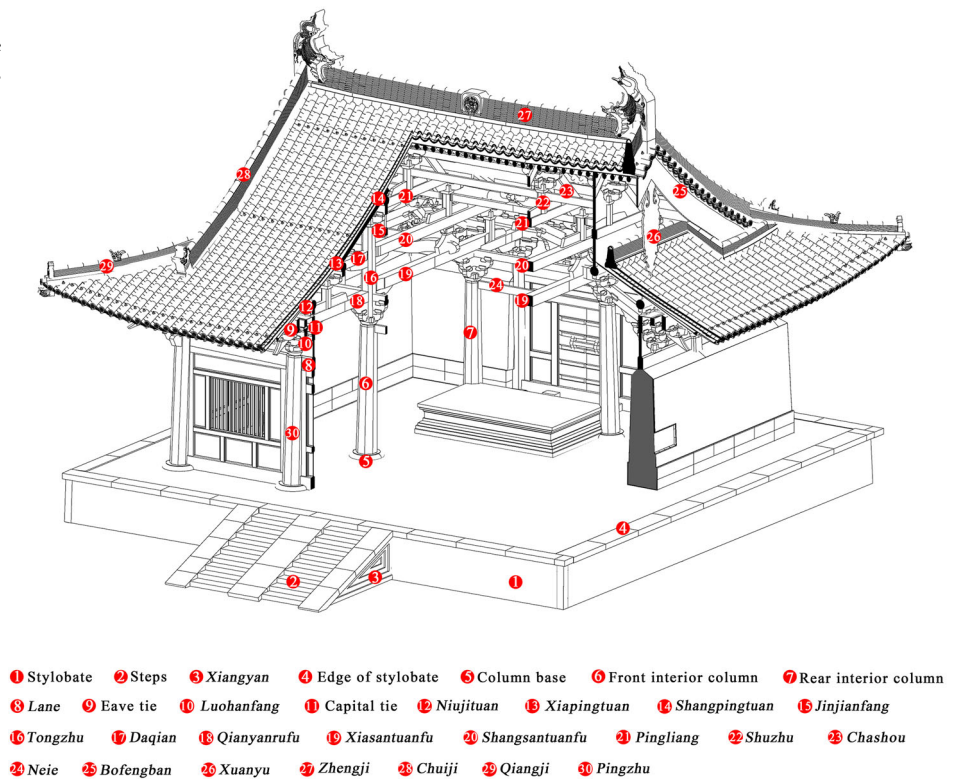
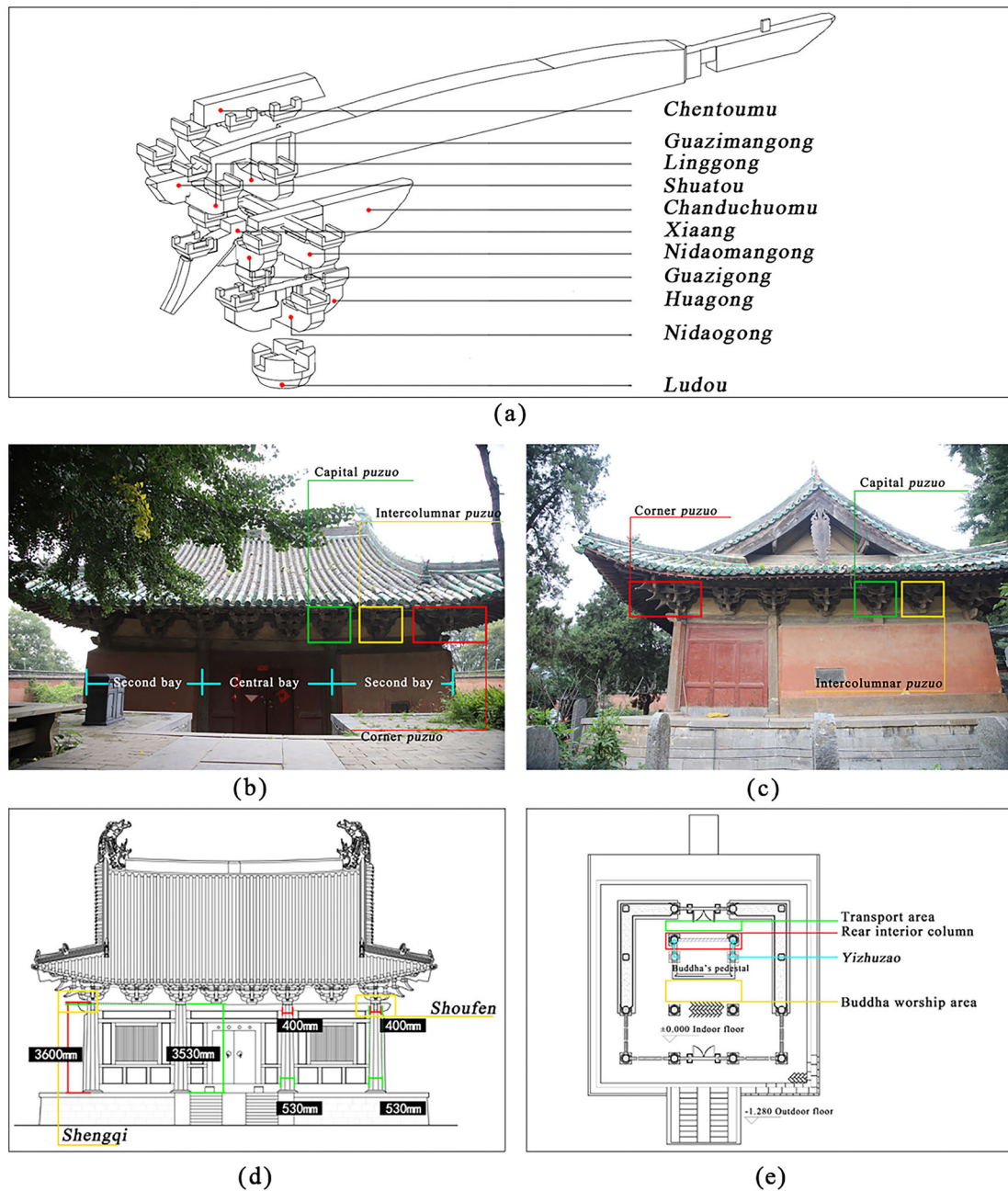


Fig. 1 | The Chuzu temple. a Location of the Chuzu Temple. b The Main Hall of Chuzu Temple. c The Chuzu Temple courtyard.

Fig. 2 | Structural system of the Main Hall of Chuzu Temple. This figure illustrates the complete structural system of the Main Hall of Chuzu Temple, with annotations identifying its key components. Special terminology is presented in pinyin (italized) for technical accuracy.





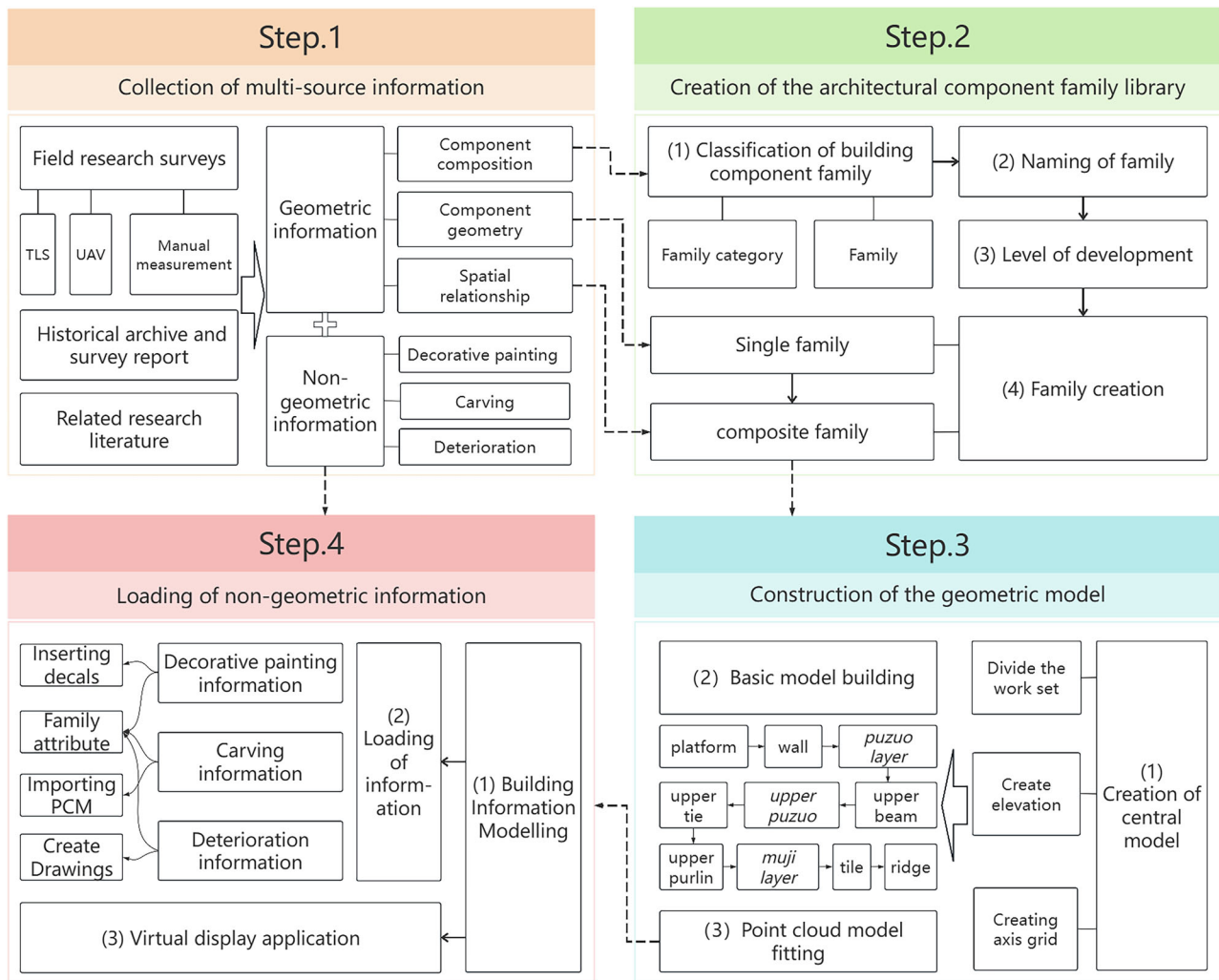
**Fig. 3 | Construction features of the Main Hall of Chuzu Temple. a** Construction composition of capital *puzuo*. **b** Rear elevation. **c** Gable elevation. **d** Front elevation. **e** Plane.

as *shengqi*, *shoufen*, and *cejiao* (three special column constructions). When creating the information model, attention should be paid to these specific construction details. All columns are octagonal stone columns, with twelve eave columns and four interior columns. The front and rear eave columns, as well as the side eave columns, exhibit significant *shengqi* from the center to the corner columns (Fig. 3d). Additionally, the stone columns retain the traditional practices of timber columns, with each column exhibiting a certain degree of *shoufen* (Fig. 3d). Except for the four columns covered by the wall, the remaining columns exhibit *cejiao*, which enhances the structural stability of the Main Hall to some extent.

Additionally, *xumizuo* (high base with decorated mouldings) is placed between the front and rear interior columns of the Main Hall, with the rear columns constructed using the *yizhuzao* (a method of column grid arrangement) technique. This approach facilitates a reasonable functional division of the originally homogeneous interior space, accommodating both

the Buddha worship area in front and the transport space in the back (Fig. 3e). The walls and components of the Main Hall are adorned with decorative paintings, and the carvings on the stone columns and the *xumizuo* are particularly lifelike. This indicates that the Chinese timber architectural heritage represented by the Main Hall possesses unique component characteristics and a complex structural system, presenting certain challenges for the HBIM creation.

Due to the geometric complexity and distinctive structural features of the Main Hall of Chuzu Temple, as well as the need to integrate various types of non-geometric information, this study proposes a structured technical framework and workflow for HBIM construction. The foundation of model construction lies in the accurate acquisition of data, achieved in this study through a multi-source information integration approach. Field measurements were combined with a review of historical data to ensure both geometric precision and contextual depth. The fieldwork involved both modern



**Fig. 4 | The technical flow of building information model for the Main Hall of Chuzu Temple.** This figure delineates the four-stage modeling process for the Main Hall of Chuzu Temple: Step.1 Collection of multi-source information, Step.2 Creation of the architectural component family library, Step.3 Construction of the geometric model, Step.4 Loading of non-geometric information.

surveying technologies—such as TLS and Unmanned Aerial Vehicle (UAV) photogrammetry—and traditional manual measurements. Historical data primarily included archival records, survey reports, and relevant academic publications.

This study employs Revit, a widely used HBIM software, as the primary tool for constructing the information model. The core of the modeling process lies in the creating building component families<sup>39</sup>. Although Revit currently lacks a built-in library specifically for Chinese traditional timber architecture—particularly the family systems of the Song Dynasty structures—custom loadable families can be created based on the acquired geometric data and structural relationships. Moreover, each family in Revit features an expandable property panel, allowing users to enter and customize non-geometric information according to the specific needs of heritage conservation and research<sup>40,41</sup>.

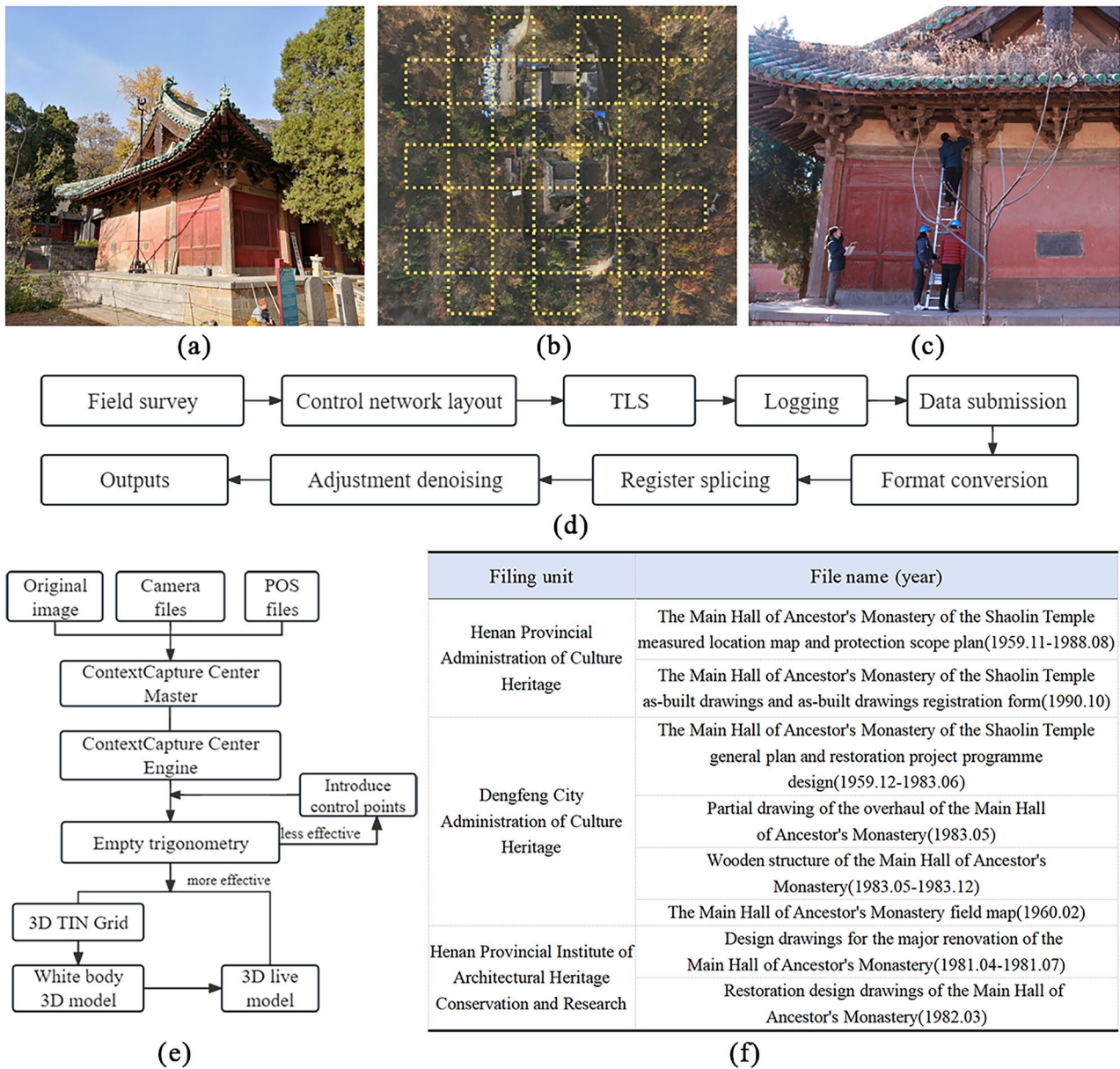
The study divides the creation of the information model for the Main Hall of Chuzu Temple into four main steps (Fig. 4).

1. Collection of multi-source information. An on-site survey of the Main Hall of Chuzu Temple was conducted using methods such as TLS, UAV photogrammetry, and manual measurements. These preliminary investigations, combined with historical archives, survey reports, and related research literature, provided both geometric information and non-geometric data. This foundational work forms the basis for the subsequent model creation.

2. Creation of the architectural component family library. First, the building components are categorized, and a naming convention is established. Based on the preservation needs of timber architectural heritage, the Level of Development (LOD) for different components in this model is proposed. A single component family is created based on these criteria, which is then used to complete a composite component family, ultimately establishing the component family library.
3. Construction of the geometric model. A central model is created to facilitate collaborative modeling among multiple parties, with tasks allocated based on the division of worksets. The components are built up layer by layer to complete the basic model. Subsequently, the point cloud model is imported for fitting, and the characterization of component deterioration is referenced to finalize the model representing the current condition.
4. Loading of non-geometric information. The integration of non-geometric information was achieved by adding family parameter information, creating drawings, and linking point cloud data. This integration of various types of information into the HBIM facilitates the work of heritage preservation, research, and management professionals.

**HBIM creation**

The geometric information of the Main Hall can be divided into two categories: one consists of data related to the exterior and interior surfaces of the



**Fig. 5 | Geometric information acquisition. a** TLS. **b** UAV flight paths. **c** Field survey. **d** TLS workflow. **e** Workflow for UAV data processing. **f** Conservation and restoration project information.

building, and the other includes the forms, dimensions, and connections of various components within the structure. The former geometric data can be obtained through TLS and UAV photogrammetry<sup>42,43</sup>, with supplemental manual measurements conducted to verify or refine the dimensional accuracy of specific components. The latter geometric data was derived from an analysis of historical archival drawings and research literature related to the Main Hall, conducted by experts in traditional Chinese architecture. These methods were employed to construct a geometric model that accurately reflects the current condition of the building. The acquisition of non-geometric information is primarily based on field surveys and supplemented or validated through archival documents and scholarly research on the conservation of the Main Hall of Chuzu Temple.

Using TLS and UAV photogrammetry allows for the precise and comprehensive collection of surface data for both the building and its surrounding environment<sup>44,45</sup>. The project uses the FARO Focus S70 3D laser scanner to capture geometric data of both the interior and exterior surfaces of the Main Hall. This phase-based scanner features a high scanning speed and a measurement range of 0 to 70 m. Before scanning, a systematic layout

of scanning stations was designed, with a total of 110 stations deployed, achieving over 90% data coverage. The scanning resolution was set to 6 mm. To ensure comprehensive data collection for the upper beams and roof structure, a boom arm was used on-site to extend the scanning range vertically (Fig. 5a).

After scanning the entire Main Hall, the acquired point cloud data was registered, merged, and denoised (Fig. 5d). Point cloud registration was carried out using cloud-to-cloud reference points in FARO SCENE software. High-precision alignment and fusion of multi-station point clouds were achieved by identifying and extracting the 3D coordinates of control points, with a Root Mean Square Error (RMSE) controlled within 3 mm<sup>46</sup>. Noise reduction was performed using the Clipping Boxes and Export Filter tools in FARO SCENE software. The final point cloud model achieved millimeter-level accuracy, consisting of approximately 1.1 billion points.

In addition to using TLS for detailed documentation of the Main Hall, the DJI Phantom 4 RTK was employed to capture data of the outdoor ground surface, building façades, roofs, and surrounding environment (Fig. 5b). Images were captured from four oblique directions (east, west,

**Table 1 | Classification of family components of the Main Hall of Chuzu Temple**

No.	Classification of building components	Family category	Family
1	Platform	1	2
2	Main body section	9	27
3	<i>Puzuo</i> layer	8	105
4	Upper beam	8	11
5	Upper <i>puzuo</i>	11	74
6	Upper tie	2	6
7	Upper purlin layer	5	12
8	<i>Muji</i> layer	6	40
9	Interior wooden decoration	1	1
10	Interior furniture	1	1
11	Tile	7	30
12	Ridge	7	21

south, and north) as well as a vertical direction, with both forward and side overlaps set to 80%. A total of 10 control points were deployed using a combination of RTK and total station to ensure high positional accuracy. The UAV photogrammetry produced three types of data: raw images, camera parameter files, and position and orientation system data, with a total of ~3000 images captured. The data were processed using Context Capture software (Fig. 5e). During the aerial triangulation process, automatic image matching combined with control point adjustment was employed to complete image alignment. The accuracy of 3D reconstruction was controlled within  $\pm 1$  cm.

To integrate TLS and UAV data, Geomagic Studio was used to align and merge multi-source point clouds. The unified point cloud data was then imported into Autodesk Recap for format conversion and simplification before being integrated into the modeling process using Autodesk Revit. In addition to data acquisition using TLS and UAV photogrammetry, manual measurements were employed to supplement and verify geometric information in areas where technical methods were limited (Fig. 5c). Specifically, manual measurements were used to: (1) obtain dimensional data of components that were occluded or inaccessible to laser scanning due to structural obstructions, and (2) verify or refine dimensions in areas where material color, reflectivity, or lighting conditions caused point cloud data to be unclear or incomplete.

The construction of Chinese timber architectural heritage, exemplified by the Main Hall of Chuzu Temple, primarily consists of internal *sunmao*, particularly the *puzuo* made up of *dou*, *gong*, *ang*, and the interlocking upper beams. Relying solely on point cloud data makes it difficult to clearly delineate the various building components, and the connections between them are even harder to discern<sup>23</sup>. Therefore, to analyze the internal structural connections of the Main Hall, it is essential to utilize archived preservation and repair drawings from the Henan Provincial Administration of Cultural Heritage, the Dengfeng City Administration of Cultural Heritage, and the Henan Provincial Institute of Architecture Heritage Conservation and Research (Fig. 5f). This information, combined with field survey, enables professional architectural heritage researchers to analyze and verify the internal divisions and connection relationships of the components, thus providing accurate guidance for the entire modeling process<sup>47</sup>.

Additionally, related research literature on the Main Hall of Chuzu Temple offers important references. These studies primarily fall into three categories: basic surveys and mapping<sup>48,49</sup>, structural and morphological analysis<sup>50–54</sup>, and heritage conservation research<sup>55–57</sup>. The first two categories contribute to the refinement and validation of the geometric information of the Main Hall, while the latter provides a valuable foundation for integrating non-geometric data such as material deterioration and past interventions.

The architectural components of the Main Hall are diverse, requiring categorization before creating the component family library. Based on the structural characteristics of the Main Hall, the components are divided into 12 major categories: platform, main body section, *puzuo* layer, upper beam, upper *puzuo*, upper tie, upper purlin layer, *muji* (roof structure) layer, interior wooden decoration, interior furniture, tiles, and ridge. Subsequently, the 12 major categories are classified according to the family category and hierarchy in Revit software (Table 1). As a result, the components of the Main Hall are classified into 66 family categories, totaling 330 families.

The construction of ancient Chinese timber structures is intricate, accompanied by a wide range of terminology. Given the practical needs of preserving and managing historical buildings, assigning unique codes to architectural components is essential. This practice clarifies the characteristics of each component, resolves issues of vague naming and difficult positioning, and facilitates their use in later restoration and management efforts.

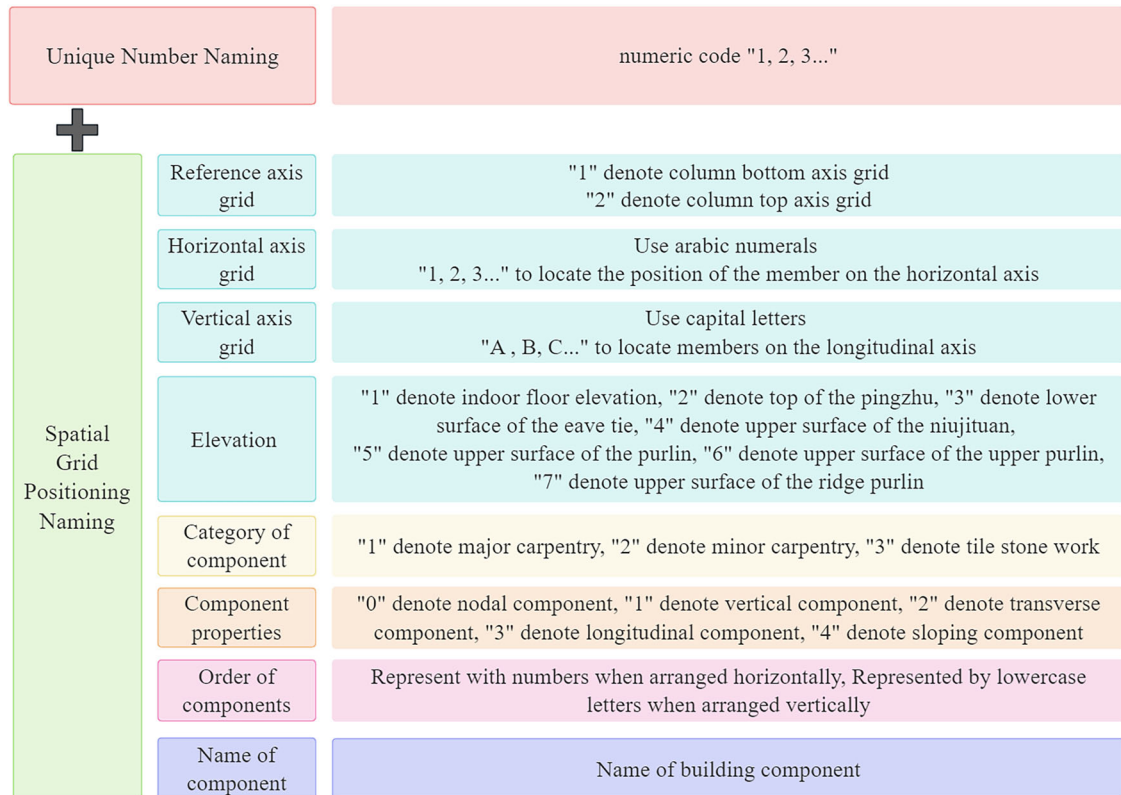
The naming of the components in the Main Hall integrates two approaches: a unique numerical identification system and a spatial grid positioning system. The unique numerical identification system assigns numerical codes to all architectural components, simplifying their location, retrieval, and quantity statistics. The spatial grid positioning system indicates the spatial location and categorical attributes of each component. This includes eight specific information elements: reference axis grid, horizontal axis grid, vertical axis grid, elevation, category, properties, order, and name (Fig. 6).

The information data of timber architectural heritage is extensive and intricate, leading to a significant workload in building the information model. However, not all component information is of equal importance. Detailing every component could result in an excessive workload, potentially reducing efficiency in future use. Conversely, overly simplified component information may fail to meet the requirements of the model's future applications<sup>58</sup>.

The concept of LOD was first introduced by the American Institute of Architects (AIA), which formally defined five levels—LOD100–LOD500—in the AIA Document E-203 (2013), to specify the degree of detail at different stages of a BIM model. Brusaporci et al. highlighted the difficulty of applying LOD standards designed for new constructions directly to heritage buildings, emphasizing the need for standardized LOD protocols tailored to the complexity of heritage modeling<sup>47,59</sup>. In the realm of built heritage, the LOD framework must remain flexible, enabling professionals to adjust the level of detail according to specific project requirements and application scenarios<sup>60,61</sup>. For example, Chow et al. proposed customized LOD definitions for historic buildings<sup>62</sup>, while Pinto-Puerto et al. introduced new concepts such as Level of Knowledge (LOK) and Level of Information (LOI), placing greater emphasis on the semantic information hierarchy inherent in heritage assets<sup>47,63</sup>.

To ensure modeling efficiency and enhance the use and management of the model, it is essential to classify the information detail levels of the building components prior to constructing the information model. Building on the original concept of LOD<sup>14</sup>, this study defines and categorizes LOD levels from 100 to 400 based on the structural characteristics of traditional Chinese timber architecture, incorporating both geometric and non-geometric information (Table 2). For the Main Hall, the components are classified into six types: walls, doors and windows, structural columns, timber beam frames, *puzuo*, and roofs. Considering the contribution of these components to the heritage value and future information usage needs, the modeling depth requirements for walls, doors and windows, and structural columns are set at LOD300, while those for timber beam frames, *puzuo*, and roofs are set at LOD400.

In Revit, there are three types of families: system families, loadable families, and in-place families. Currently, the settings for system families in Revit are developed based on the structural composition and design requirements of modern buildings. Some scholars have researched the parametric creation of families for classical European architecture, but this



**Fig. 6 | Building component coding meaning.** This figure shows the specific expressions of Unique Number Naming and Spatial Grid Positioning Naming, among which the latter includes eight information elements: Reference axis grid,

horizontal axis grid, vertical axis grid, elevation, category of component, component properties, order of components, name of component.

**Table 2 | Modeling requirements at different levels of detail**

LOD	Geometric information	Non geometric information
100	relative position, rough shape	—
200	relative position, dimension, basic form	material
300	relative position, dimension, detailed construction	material, construction method
400	relative position, dimension, detailed construction, component status	material, construction method, deterioration information

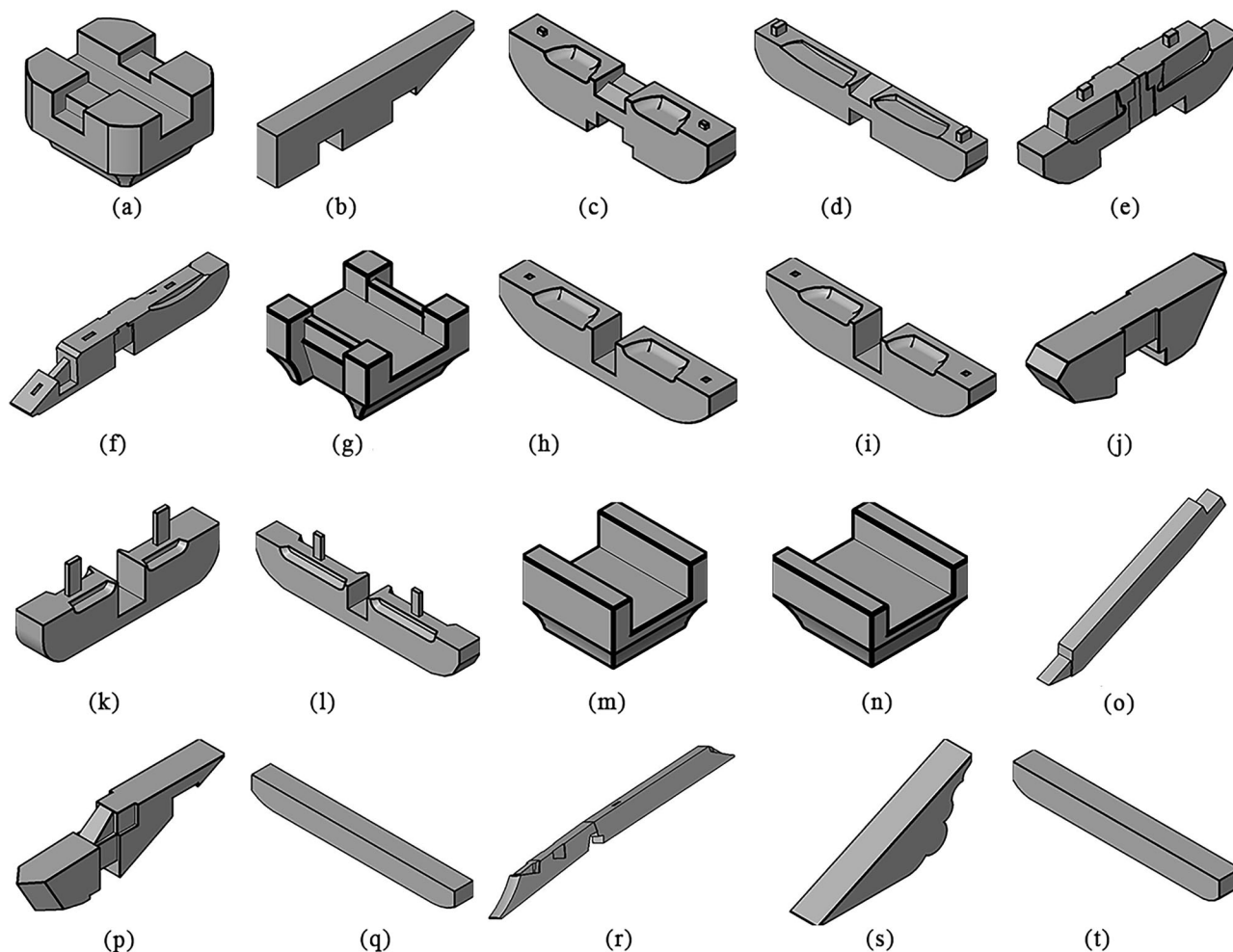
approach clearly does not meet the requirements for building information models of East Asian architectural heritage. However, Revit provides another method for family creation, allowing users to customize families in the family editor and subsequently load them into the project for use. These are known as loadable families and are characterized by high flexibility, making them the primary construction method for the architectural components in the Main Hall information model. Components such as platform and floor share similar parametric elements and are created using the system family “floor” in Revit. Conversely, components such as roof board, which require dimensions and shapes to be determined based on adjacent components, are created using in-place families.

The architectural families of the Main Hall consist of various components, which can be categorized into two types: single component families (indivisible building components) and composite nested families (families formed by combining single component families). For example, the process of creating a single-component family for *nidaogong* (a type of *gong* member in bracket set) of the intercolumnar *puzuo* is as follows: the *nidaogong* is positioned atop the *ludou* (a type of *dou* member in bracket set) and aligned centrally along the line between the inner and outer *puzuo*. Based on the geometric dimensions of the *nidaogong* obtained from prior research, a reference line or plane is established using the 3D point cloud model. The

modeling process begins with 2D drafting, followed by creation of a 3D solid model of the *nidaogong* using operations such as extrusion, lofting, and merging. Finally, appropriate materials and colors are applied to the model.

The process of creating a composite nested family can be illustrated using the intercolumnar *puzuo* as an example, employing a method similar to that used for the *nidaogong* to complete the other components of the intercolumnar *puzuo* (Fig. 7). Based on the preceding analysis of the geometric dimensions and structural characteristics of the intercolumnar *puzuo*, corresponding reference planes are defined. Each single component family is then loaded and sequentially positioned at its designated spatial location, layer by layer, completing the assembly of the intercolumnar *puzuo* (Fig. 8).

Based on the structural characteristics of the Main Hall, seven elevation levels are defined from bottom to top: indoor floor, top of the *pingzhu* (central bay column), lower surface of the eave tie, upper surface of the *niujituan* (a type of purlin), upper surface of the purlin, upper surface of the upper purlin, and upper surface of the ridge purlin. A grid system is then created, in addition to the base grid for the columns, a second shared grid is set up at the surface of the top of corner column to facilitate the accurate positioning of the *puzuo* layer and upper components. Based on the established family library, the construction of the platform, main body



**Fig. 7 | Intercolonnar *puzuo* component member. a Ludou. b Chentoumu. c Guazigong. d Guazimangong. e Huangong. f Huatouzi. g Jiaohudou. h Linggong(angshang). i Linggong. j Mazhatou. k Nidaogong. l Nidaomangong. m Qixindou. n Sandou. o Shangang. p Shuaitou. q Timu. r Xiaang. s Xuexie. t Timuzhengxin.**

section, and *puzuo* proceeds (Fig. 9), it is essential to check the relationships between adjacent components and control the overall dimensions.

There are discrepancies between the current state of the Main Hall and the design model. The hall's materials are quite diverse, predominantly using natural materials. Due to its long history and exposure to the elements, the overall structure has experienced twisting and misalignment, with some components showing signs of deterioration or loss. To meet the modeling precision requirements for the Main Hall's architectural components, adjustments are made to the geometric dimensions, shapes, and spatial coordinate positions of the component families. This ensures that the geometric accuracy of timber beam frames, *puzuo*, and roof components reaches LOD400.

In Revit, the component models were aligned with the point cloud<sup>64</sup>, with a deviation of no more than 3 mm (Fig. 10). The resulting fitted geometric models accurately represent the existing conditions, helping preservation researchers and managers in gaining a comprehensive understanding of the building's current state. This provides reliable geometric data to support future monitoring, maintenance, and conservation efforts.

#### Loading of non-geometric information

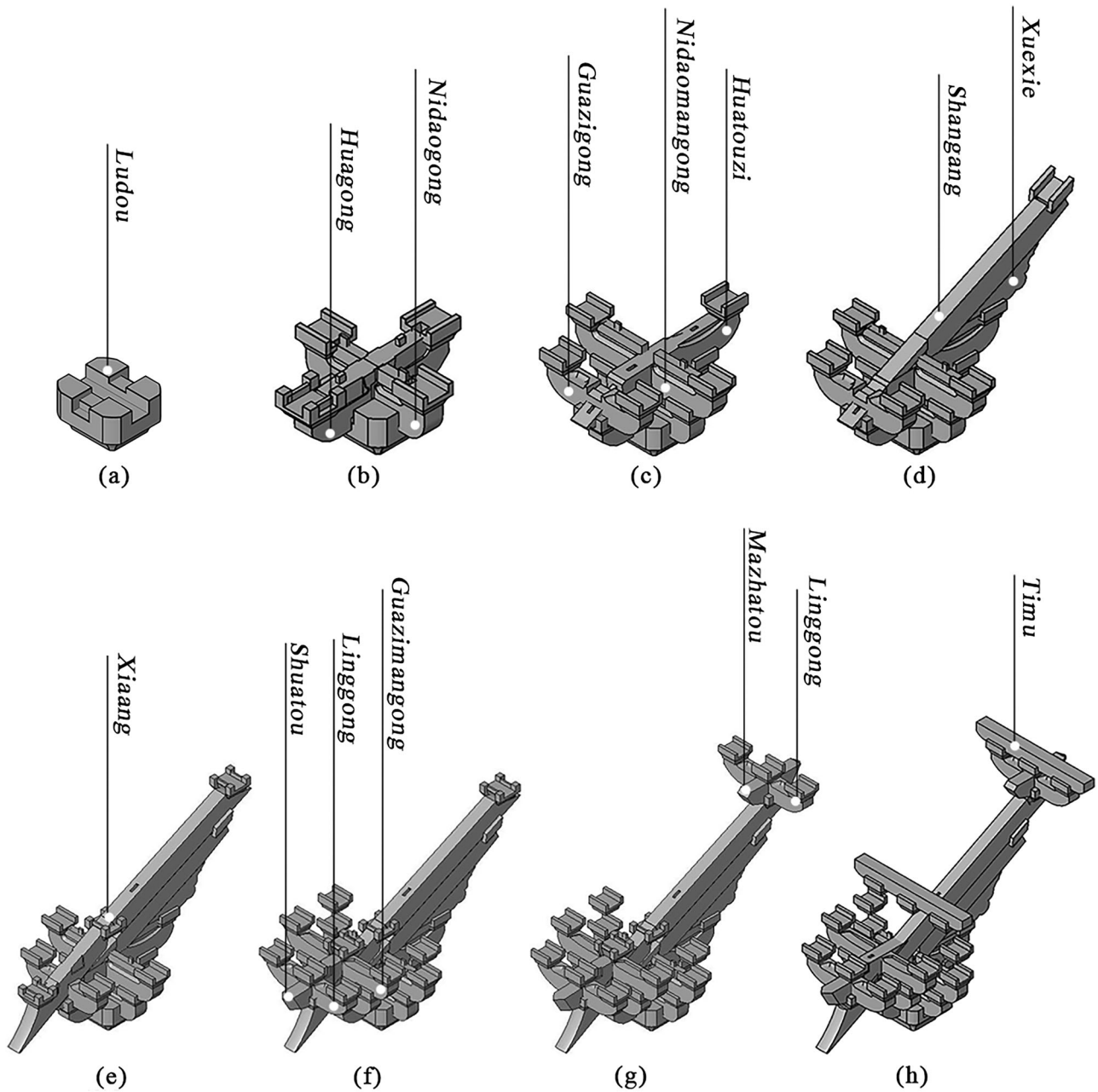
The Main Hall features intricate decorative paintings, including twenty-four images of Zen patriarchs on the east, west, and north walls, as well as *xuanzi caihua* (a decorative painting style) on the inner and outer eave *puzuo* and other architectural components. The painting techniques are refined, and the figures are vividly depicted. Two methods are used to integrate

decorative paintings information into the model: (1) adding family attribute parameters. By including file paths in the corresponding family type attribute URL parameters, high-definition scans of the decorative paintings can be linked to the model, or the file paths can be added to the family attribute field for external viewing on a third-party platform. (2) Inserting decals. This approach allows the images to be displayed directly within the information model, although its accuracy is relatively lower.

The Main Hall features finely crafted inner and outer stone columns, as well as *xumizuo*, representing rare masterpieces from the Song Dynasty. The integration of carving information also involves two methods: (1) The first method is similar to that used for decorative paintings. File paths are included in the family attributes of the corresponding components, linking them to high-precision point clouds or high-definition images of the carvings. (2) Importing the point cloud model. During the construction of the Main Hall information model, the point cloud model is imported to provide an approximate representation of the carvings' current state. This model can be viewed later using the point cloud display (Fig. 11).

The architectural components of the Main Hall exhibit complex and diverse forms of deterioration, posing significant threats to their structural integrity. Given the varying levels of modeling detail for different components in the Main Hall information model, this study explores methods for incorporating deterioration information for timber beam frames, *puzuo*, and roofs. The following elaborates on two methods for integrating deterioration information, using the *puzuo* layer as an example.

The first method for loading deterioration information involves expressing the condition through the creation of annotated views in



**Fig. 8 | Modeling process of intercolumnar puzuo. a** First layer. **b** Second layer. **c** Third layer. **d** Fourth layer. **e** Fifth layer. **f** Sixth layer. **g** Seventh layer. **h** Eighth layer.

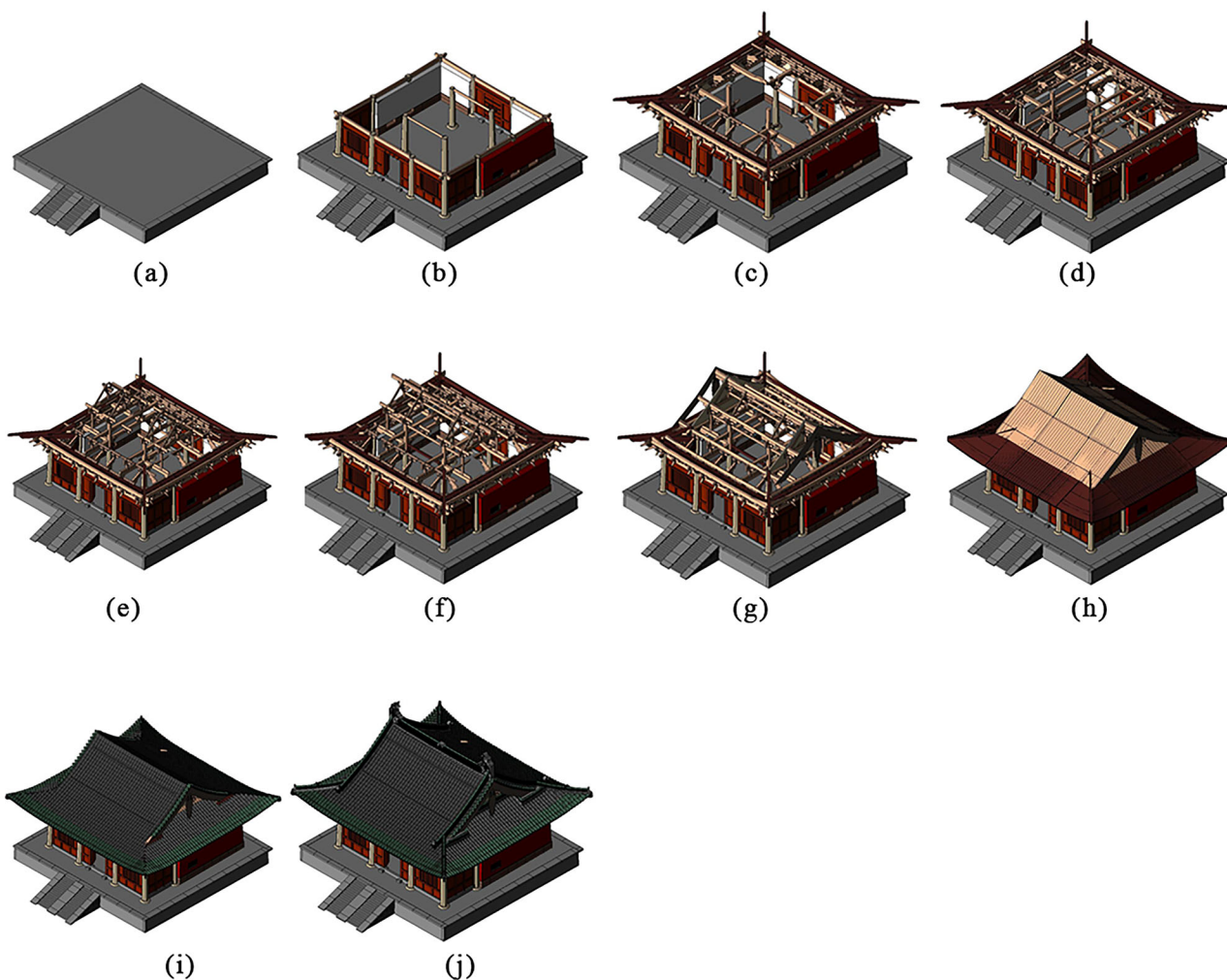
drawings, aligning with the drawing-oriented work habits of architectural professionals. The generation of deterioration drawings for the Main Hall involves three main steps: First, adjust the perspective and view range of the 3D information model based on the location of the deterioration, and capture the necessary images. Second, create a new drawing by inserting and arranging the prepared views and images. Finally, add annotations to describe the specific condition of the deterioration. To facilitate later reference, each drawing is named using the format “deterioration, category-number-specific, architectural component”, which conveys key information about the drawing. The creation of deterioration drawings for the Main Hall not only aligns with the working habits of architectural professionals but also establishes an interactive relationship between the deteriorated components in the 3D information model and their corresponding 2D deterioration drawings.

The second method for loading deterioration information involves creating text parameters within the family attribute properties to represent the specific deterioration conditions of each architectural component in the

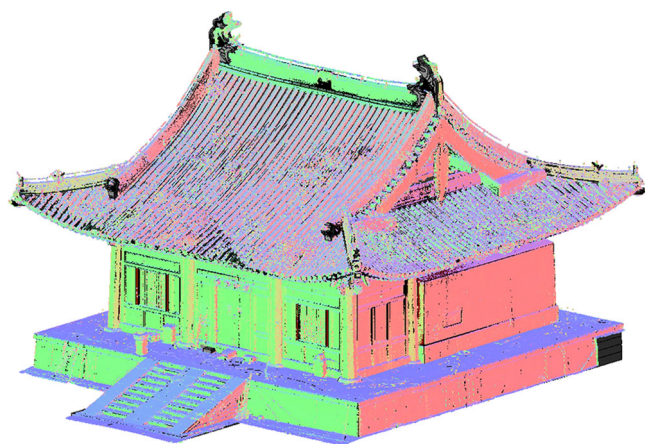
Main Hall. This information is stored in the family model files and can be added or updated as needed. Once the information is loaded, selecting a specific component in the 3D information model of the Main Hall will display the detailed deterioration conditions in the property panel (Fig. 12). Additionally, the Revit’s schedule tool can be used to generate a deterioration details schedule by adding relevant information fields, allowing for a quick summary of the deterioration conditions of all architectural components in the Main Hall. The filter, sort, and group tools in the schedule’s property panel allow for basic filtering, grouping, and statistical analysis of the deterioration data. The schedule can also be exported as a .txt file, which can then be converted and imported into specialized data analysis software for further study.

**Virtual display application**

The virtual roaming experience is created using the game engine software Unreal Engine, which requires the import of three types of data. First, data of the Main Hall, derived from its information model, is imported. Second,



**Fig. 9 | Modeling process of the Main Hall of Chuzu Temple.** a Platform. b Main body section. c *Puzuo* layer. d Upper beam. e Upper *puzuo*. f Upper tie. g Upper purlin. h *Muji* layer. i Tile. j Ridge.



**Fig. 10 | Information model of the main hall of Chuzu Temple.** This figure shows the comparison between the 3D Model and Point Cloud of the Main Hall of Chuzu Temple. Red represents the  $y-z$  plane, green represents the  $x-z$  plane, and blue represents the  $x-y$  plane.

data from other buildings within the courtyard is included. Models of the main gate, east and west wing rooms, and the Thousand Buddha Hall are constructed in 3 ds Max based on field survey results, and subsequently imported into Twinmotion for material application. Third, environmental

data is sourced from Geographic Information System (GIS) platforms to obtain geographic and spatial information of the surrounding area. By importing these three types of data into Unreal Engine, a realistic environmental atmosphere is constructed through scene arrangement.

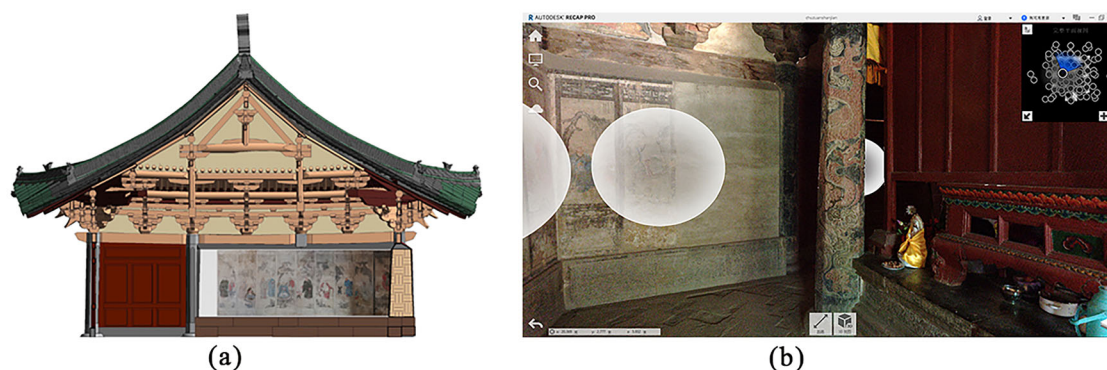
Based on the completed HBIM model and the game engine platform, the entire construction process can be virtually simulated. By reasonably disassembling and classifying the architectural heritage information model, and exporting it in specialized formats to Navisworks, virtual construction animations can be generated. The classification of building components is crucial for the subsequent production of 3D animations. Additionally, the software loads various model parts by linking file paths, which improves performance by reducing file size and helps resolve operational issues caused by the model complexity.

In the practical implementation, the information model of the Main Hall was divided into 45 parts, including the platform, column bases, and columns, which were then imported into Navisworks to create new operational files. The TimeLiner tool was used to simulate the construction process of the architectural heritage in Navisworks (Fig. 13). By combining the simulation with animation, virtual construction can be presented along with real-time roaming, enhancing the overall effect of the animation.

## Results

### Point cloud model and drawings

Using UAV photogrammetry, data on the courtyard and surrounding environment of the Main Hall was collected and processed to generate a



**Fig. 11 | Loading decorative paintings and carving information. a** Decorative painting information. **b** External link for carving information.

three-dimensional reality model. This model serves to supplement and verify roof data while also providing contextual scene information for surrounding virtual display applications of the Main Hall.

Additionally, TLS was employed to gather information about the Main Hall itself. Following registration, stitching, and point cloud denoising, a crucial reference for constructing the information model—the three-dimensional point cloud model—was obtained. To facilitate data acquisition during the model construction process, the point cloud model was sliced to produce two-dimensional sliced drawings, including sections, elevations, plans, roof framing, and top view. This approach greatly enhances the reliability of the overall dimensions of the Main Hall. The point cloud model and sliced drawings accurately reflect the current condition of the Main Hall and serve as the primary basis for creating and fitting the information model (Fig. 14).

### Family library

The family is central to the creation of the architectural heritage information model. Based on the composition and spatial relationships of building components, a family library was established, encompassing both single component families and composite nested families. This library serves as the foundation for constructing the information model of the Main Hall.

The family library for the Main Hall includes twelve major types of building components. Each major type contains multiple family categories. For example, the upper purlins include five family categories: *bofengban* (located at the ends of the roof), tie, *jitian* (a purlin at the top of the roof), *shengtoumu* (a triangular piece of wood), and *xuanyu* (located right in the middle of the mountain face of the roof). In total, the library consists of 66 family categories, each of which contains multiple individual families, reaching up to 330 families in total. Most components in the family library are loadable families, created through customizations in the Revit family editor, allowing them to be imported into other projects. The family library for the Main Hall offers a comprehensive set of family templates for constructing information models of Chinese timber architecture (Fig. 15).

### HBIM

Based on the structural characteristics of the Main Hall and aligned with the elevation and axis grid, the model was constructed layer by layer in the following sequence: platform, main body section, *puzuo*, upper beams, upper *puzuo*, upper tie, upper purlins, *muji* layer, wooden decorations, furniture, tiles, and ridges. The result output is the completed design model of the Main Hall of Chuzu Temple.

Then, the model was fitted to the point cloud data to sure that all components met the required modeling depth, resulting in the finalized information model of the Main Hall. This model not only includes geometric information such as dimensions, spatial positions, current conditions, and structural relationships, but also integrates non-geometric information (Fig. 16).

### Deterioration drawing

Based on the modeling accuracy requirements of the information model of the Main Hall, the study produced detailed drawings for each deteriorated component in the timber beam frames, *puzuo*, and roof structures. A total of 23 deterioration drawings were produced, including 5 for the timber beam frames, 15 for the *puzuo*, and 3 for the roof. These drawings provide a relatively comprehensive visual representation of the deterioration situation, supporting the protection, restoration, and further research efforts for the Main Hall.

Figure 17 presents the deterioration drawing of *puzuo* No. 1, which includes the position of the *puzuo* within the *puzuo* layer, specific locations of the deterioration, characterization (corresponding 3D model and real-scene photographs), and detailed textual descriptions. The drawing indicates that this *puzuo* is located in the southwest corner of the *puzuo* layer, with deterioration observed at the *guazigong*, *linggong*, *pingpandou*, and *sandou* (constituent components of *puzuo*) components, including six cracks and two fissures.

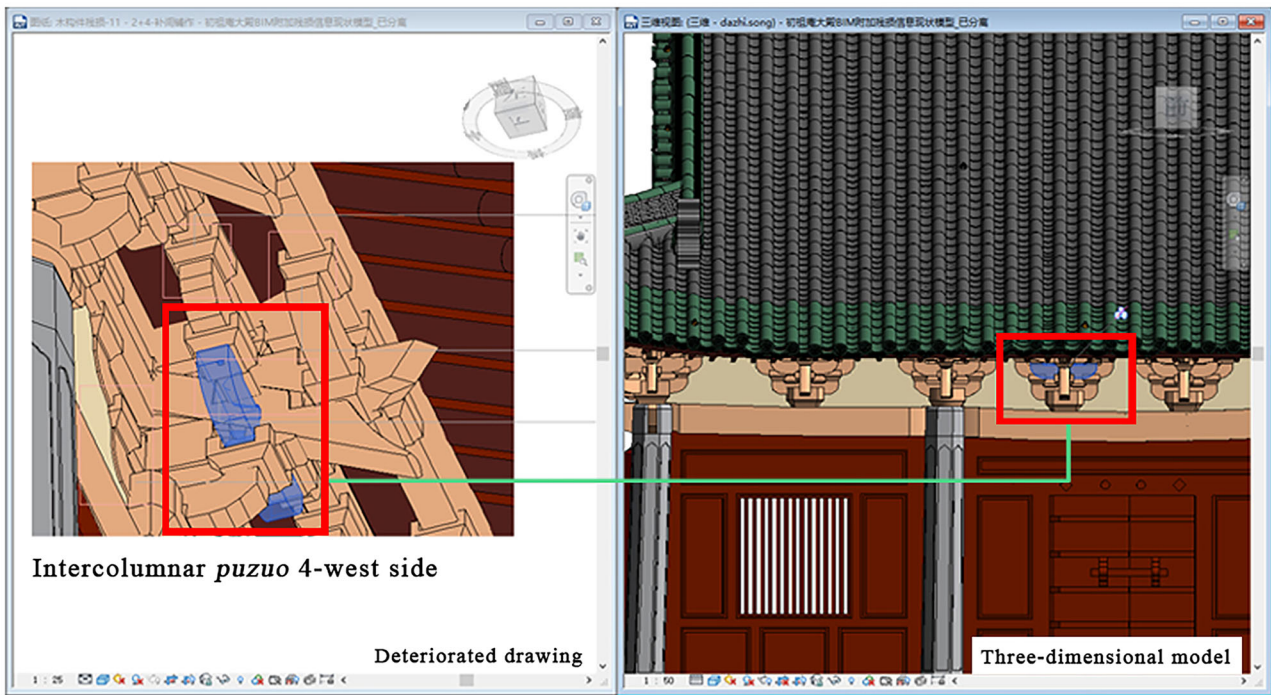
### Virtual display results

Based on the data of the Main Hall, courtyard, and surrounding environment, a virtual tour scene was developed using a game engine (Fig. 18). Through virtual reality devices such as head-mounted displays and position trackers, general visitors can engage in an immersive exploration of the architectural style of Chinese timber structures.

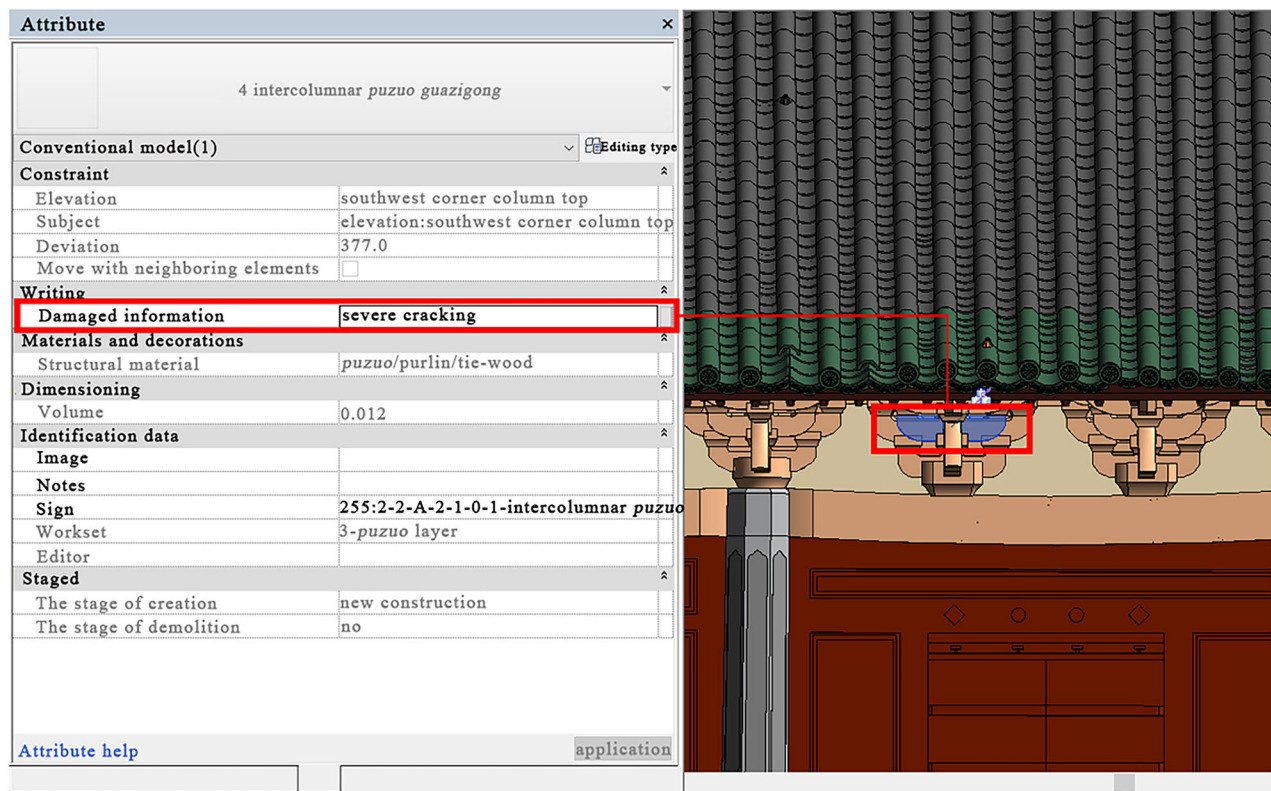
Leveraging the completed HBIM model and the game engine platform, a simulated demonstration of the virtual construction process of the Main Hall was developed. Figure 19 presents several key frames from the virtual construction video of the Main Hall. The intuitive presentation of the architectural structure delivers a visual impact, allowing viewers to truly appreciate the intricacy of traditional Chinese timber construction. The virtual display offers direct references for conservation and restoration professionals, while also providing the public with an innovative means of understanding the craftsmanship involved in Chinese timber architecture. It represents a significant approach to balancing the protection, restoration, and utilization of architectural heritage.

### Discussion

Scholars in Europe and the United States primarily approach HBIM from a measurement-oriented perspective, with concept definitions and modeling logic centered on three-dimensional point cloud data. The construction of heritage information models is largely based on reverse modeling using point cloud data<sup>65</sup>. Many researchers have explored automatic point cloud segmentation to facilitate the semi-automated generation of HBIM<sup>66</sup>. Reverse modeling is driven by the intrinsic characteristics of existing architectural heritage. In Western masonry heritage, the geometrical forms of building components are relatively prominent, with most connections involving vertical stacking or compression and fewer interlocking joints. Some researchers have applied deep learning techniques to enable the semi-automated segmentation of basic



(a)



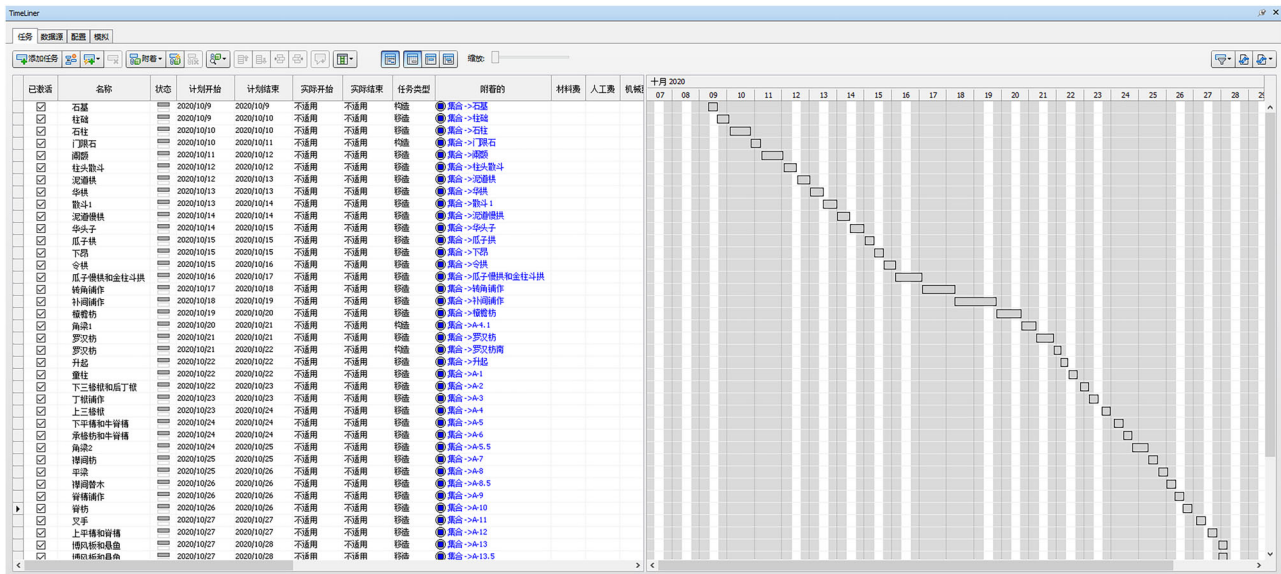
(b)

**Fig. 12 | Loading result of deterioration information.** **a** The Deteriorated drawing interact with the three-dimensional model. The deteriorated drawing is shown on the left, while the three-dimensional model is displayed on the right. **b** Attribute of *Guazigong*: deteriorated information.

components within point cloud models<sup>67</sup>, allowing for modular separation suitable for reverse modeling.

In contrast, Chinese timber structures, such as the Main Hall of Chuzu Temple, feature unique construction techniques and complex structural compositions. Although point cloud data offers high precision, it only

captures surface-level geometric information. Chinese timber architecture primarily relies on *sunmao* joints for structural connections. Whether using parametric modeling or the segmentation of point cloud data to create the information model, current technologies face significant challenges in achieving this.

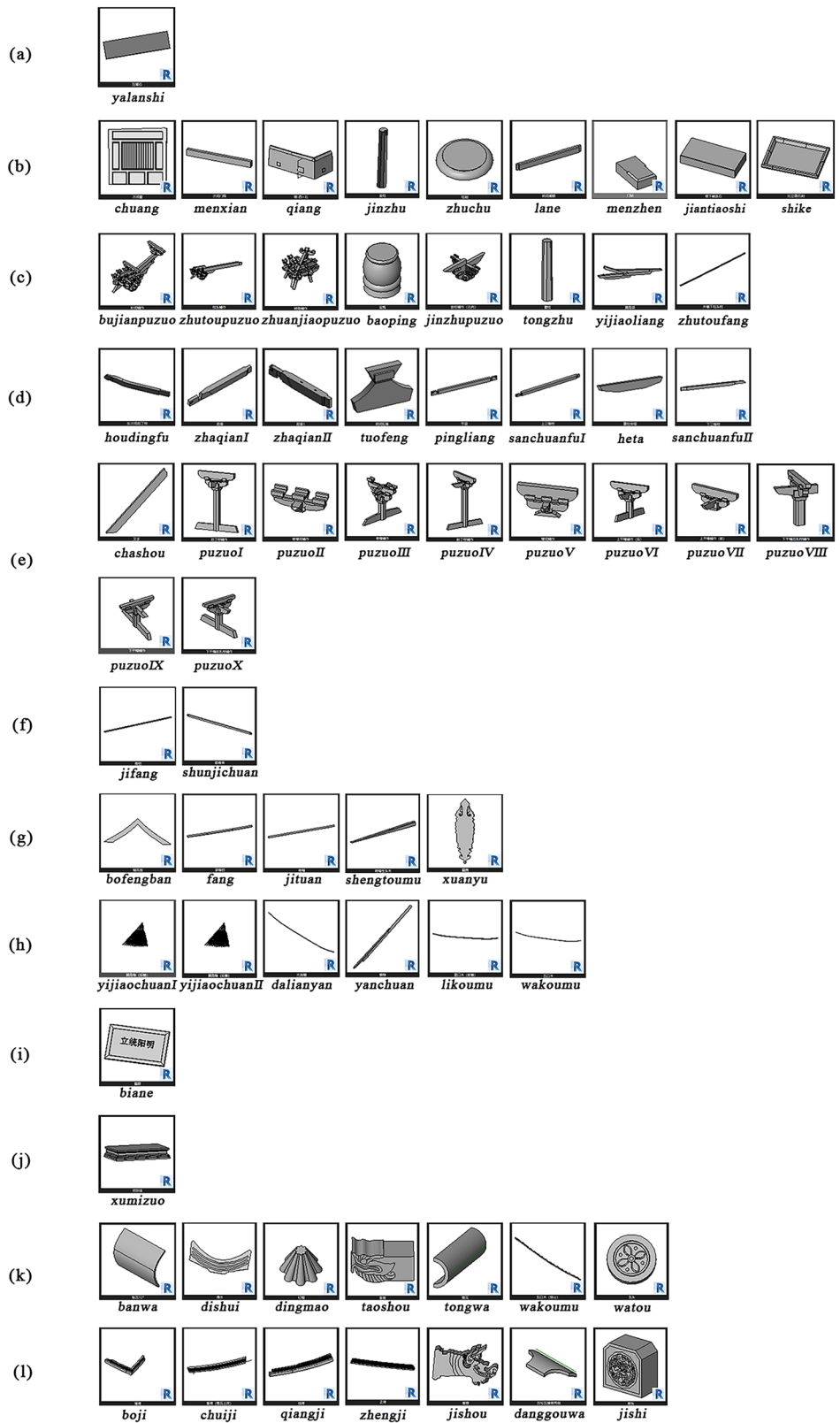


**Fig. 13 | Virtual construction process diagram.** This diagram shows that during the virtual construction process, the construction is divided into 45 stages according to the logic of building the main hall of the Chuzu Temple, and is arranged in a time sequence.



**Fig. 14 | 3D reality model and point cloud slice drawing.** a 3D reality model. b Point cloud slice drawing. It includes longitudinal section, plane, roof framing, top view, east elevation, south elevation and cross section.

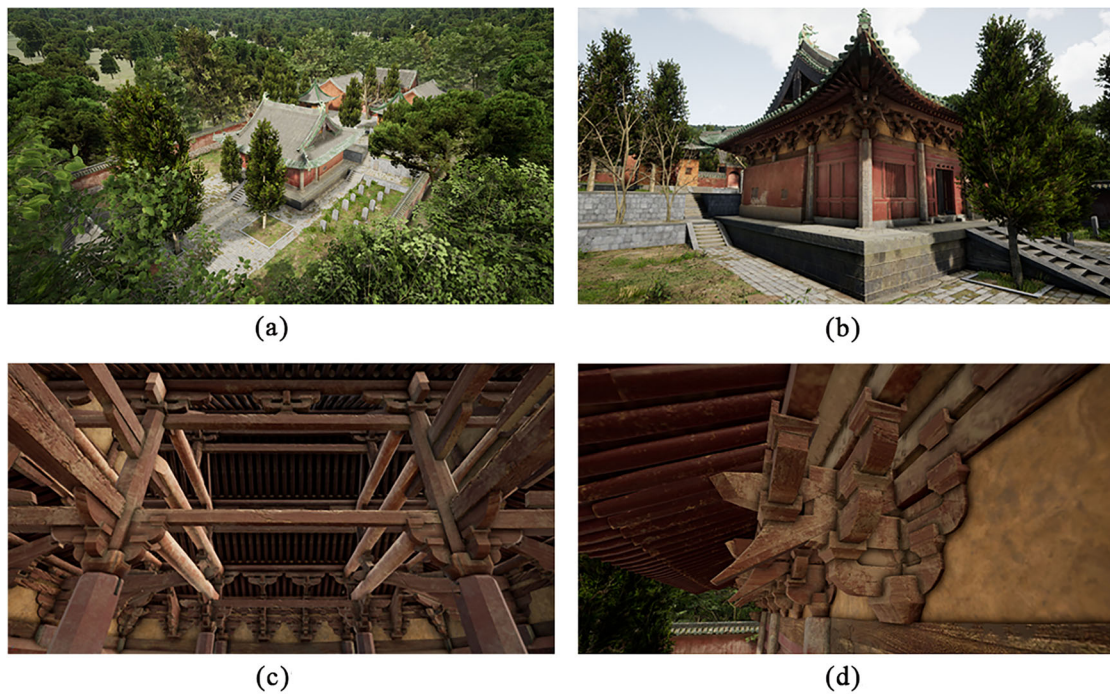
**Fig. 15 | Component family of the Main Hall of Chuzu Temple. a Platform. b Main body section. c Puzuo. d Upper beam. e Upper puzuo. f Upper tie. g Upper purlin. h Muji layer. i Wooden decoration. j Furniture. k Tile. l Ridge.**



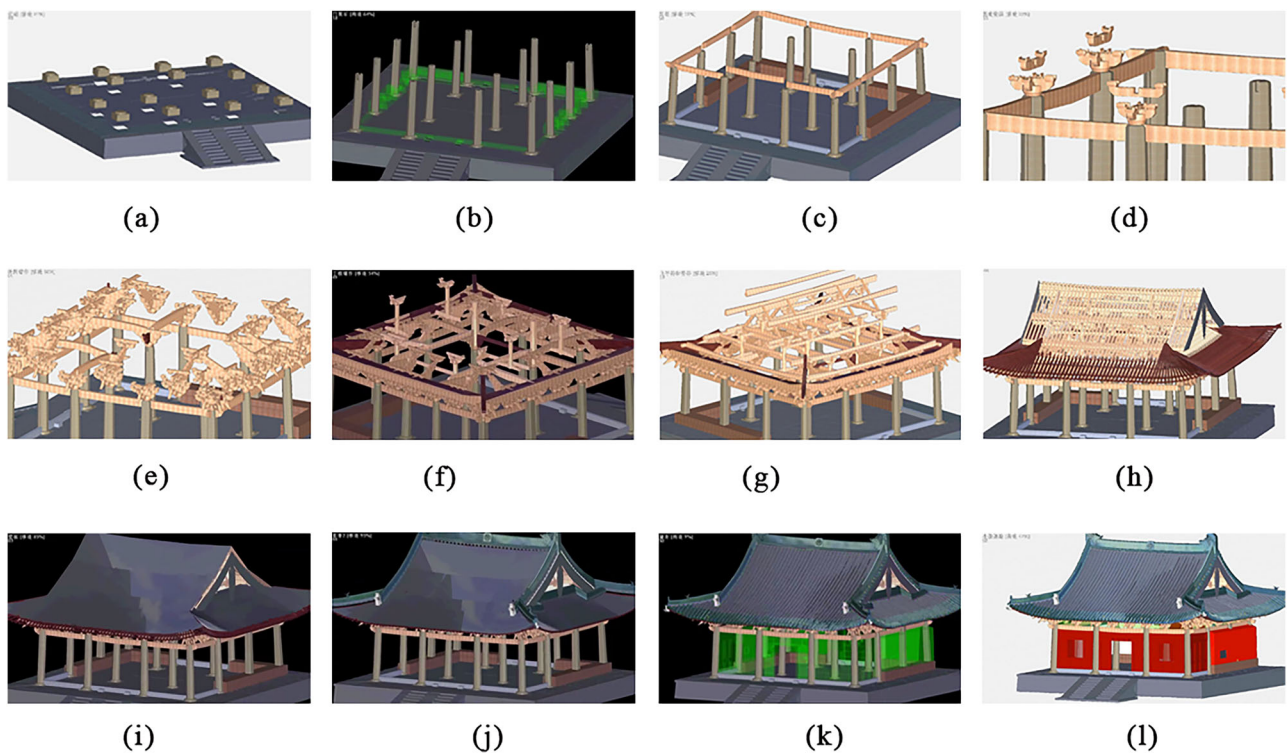
Therefore, for Chinese timber structures like the Main Hall, in addition to relying on point cloud data that captures the building’s exterior, it is essential to infer internal construction methods based on survey data and historical documentation. By creating a family library of building components, the information model can be constructed and subsequently refined using point cloud data to ensure accurate representation of the current state

of the Main Hall<sup>41,68</sup>. This component-based approach enables the three-dimensional representation of all component sizes and structure details while also supporting the integration of material properties, deterioration data, and other relevant information. The information model developed using architectural component families serves as the foundation for the implementation of the data integration platform.





**Fig. 18 | Virtual roaming important nodes of the Main Hall of Chuzu Temple.** a The Chuzu Temple courtyard. b The Main Hall of Chuzu Temple. c Timber framework. d *Puzuo*.



**Fig. 19 | Virtual construction important nodes of the Main Hall of Chuzu Temple.** a Platform. b Column. c Lane. d *PuzuoI*. e *PuzuoII*. f Beam frameI. g Beam frameII. h Rafter. i *wangban*. j Ridge. k Tile. l Wall.

summarizing and generalizing the foundational styles of architectural components, it becomes possible to develop a parametric family system specifically tailored to Chinese timber heritage buildings.

As research on architectural heritage conservation deepens, many scholars have undertaken more rigorous scientific investigations, resulting in a wealth of data such as structural stress measurements, environmental

monitoring results, and maintenance records. Analyzing the interconnections among these datasets can provide a scientific basis for the repair and protection of heritage buildings<sup>78</sup>. However, for most heritage sites, different types of information are often managed by separate departments, resulting in fragmentation that hampers the extraction of their full value. Integrating diverse information is urgently needed for government agencies, the public,

and conservation researchers alike, which is an inevitable outcome of the big data era. In addition, cross-platform compatibility is essential to promote the dissemination and practical application of modeling outcomes. By adopting the IFC data standard, interoperability among HBIM platforms such as Revit, Archicad, and FreeCAD can be achieved, thereby minimizing information loss and ensuring consistency across systems.

The Main Hall has successfully integrated non-geometric information. In subsequent work, maintenance information can be incorporated through full life cycle management in Revit<sup>79,80</sup>. Additionally, experiments and simulations have been conducted on the structural stress of both the *puzuo* and the overall framework to analyze their stress characteristics. Monitoring and simulation analyses of the surrounding microclimate have also been carried out, providing preliminary insights into the relationship between current deterioration and microclimate conditions. Integrating such information into the information model is crucial for understanding deterioration mechanism and informing protection and restoration efforts<sup>81</sup>. Achieving this may require collaboration with computer science professionals. Furthermore, the future integration of the Internet of Things (IoT) could support further development of preventive conservation strategies. The information model of the Main Hall of Chuzu Temple, developed based on family components, provides a solid foundation for implementing these functions.

The application of HBIM in the documentation, conservation research, and repair management of cultural heritage represents its most fundamental and essential function. Beyond this, the potential of HBIM in public communication and virtual presentation is also recognized, as it can enhance public awareness and engagement, thereby indirectly supporting heritage conservation. As such, educational displays and tourism promotion are regarded as important components of preservation strategies<sup>82</sup>. With the advancement of modern 3D visualization technologies, virtual display applications for cultural heritage have emerged, including VR, Augmented Reality (AR), Mixed Reality (MR), and holographic projections<sup>83</sup>. These technologies have primarily been applied in museums, exhibition halls, and educational institutions, significantly enhancing user immersion. They also have potential for broader application in contexts such as archaeological sites, scenic areas, and historical architectural complexes.

This research has effectively explored virtual display applications, including virtual tours and virtual construction, using the completed information model of the Main Hall and collected environmental data via relevant game engine platforms. This approach greatly reduces repetitive tasks and expands the application potential of the information model. In the future, we plan to gradually apply this approach to other monuments within the “Historical Monuments of Dengfeng in ‘The Centre of Heaven and Earth,’” such as the Talin and the Songyue Temple Pagoda. The goal is to leverage digital technology to foster new forms of productivity and support local tourism development.

Building upon this study, the scalability of heritage building information models demonstrates significant potential for application, particularly within an integrated BIM-GIS framework that allows for the comprehensive management of both heritage assets and their surrounding environments. By optimizing the BIM model for lightweight performance and uploading it to a cloud-based platform, tiered, permission-based access can be provided to various user groups, including heritage conservation agencies, research institutions, and public education platforms<sup>84</sup>.

However, several challenges remain in this process. On the one hand, lightweighting often involves data simplification or compression. Achieving efficient transmission and online visualization while maintaining relative data completeness and semantic integrity remains a key technical challenge. On the other hand, BIM and GIS differ in semantic structures and operational logic, and their effective integration requires unified standards and further development efforts<sup>85</sup>.

In the future, heritage building information models are expected to be integrated with existing national or regional data platforms—such as environmental monitoring systems and cultural heritage databases—to enable more comprehensive and real-time dynamic management.

However, the lack of systematic standards and practical experience in areas such as data-sharing mechanisms, platform compatibility, and security management currently limits the broader application of such models across regions and institutions.

Furthermore, to ensure the effectiveness and feasibility of heritage building information models in practical applications, a systematic evaluation mechanism should be introduced in future work. The model’s functional adaptability, operational usability, and application efficiency should be assessed from multiple perspectives, including expert feedback, user testing, and performance benchmarking. Through a multidimensional post-evaluation framework, the model can be appropriately adjusted and iterated to further enhance its practical value.

This paper takes the Main Hall of Chuzu Temple as the research subject and investigates the application and implementation of HBIM technology in the conservation and management of wooden heritage buildings. Through modern surveying techniques, various data related to the Main Hall were collected, and the building’s geometric characteristics were identified in conjunction with relevant historical materials. The information model of the Main Hall was then created using a family library developed in Revit and fitted with the point cloud model. Approaches for integrating non-geometric information were also examined. Finally, based on this information model, virtual display methods for the Main Hall were explored. The key findings of this study are summarized as follows:

A methodical system suitable for the creation of HBIM for Chinese timber architectural heritage has been established. This system encompasses data collection, model construction, and information integration, and is demonstrated through the case study of the Main Hall of Chuzu Temple. It provides a technical foundation for the development of information models for timber architectural heritage.

An HBIM has been created that closely reflects the current condition of the Main Hall of Chuzu Temple. This model captures not only the surface details of the architectural components but also their structural connections. It provides comprehensive data support for the research, conservation, and restoration of the Main Hall.

A complete library of architectural component families for the Main Hall of Chuzu Temple has been established. This library comprises 66 family categories and a total of 330 families. This work contributes to the development of a comprehensive HBIM family library for Chinese timber architecture, thereby enriching the component library for heritage architecture within the Revit environment.

Various methods for integrating multiple types of information into HBIM have been explored. By utilizing family attributes, creating drawings, and linking point clouds data, non-geometric information such as decorative paintings, carvings, and deterioration has been successfully integrated into the HBIM model, offering a practical approach for non-geometric data incorporation.

Terminologies		
<i>Ang</i>	昂	A long slanted lever arm balanced on the ludou. Its “tail” bears the load of a purlin and is counterbalanced by the eave load at the lower end, in Tang and Song construction.
<i>Bofengban</i>	博风板	Located at the ends of the roof, used to shield the purlin, see Fig. 2.
<i>Cejiao</i>	侧脚	The tops of the columns lean toward the building’s center.
<i>Chuiji</i>	垂脊	In gable and hip roof, this refers to the ridge that intersects perpendicularly with the main ridge, see Fig. 2.
<i>Dou</i>	斗	Bearing block.

Gong	拱	Bow-shaped timber, set in a bearing block, it supports a smaller block at each upraised end and often in the center, like bracket arm.
Guazigong	瓜子拱	A type of <i>gong</i> member in bracket set, see Fig. 3a.
Huagong	华拱	A type of <i>gong</i> member in bracket set, bracket extending forward and back from the <i>ludou</i> , at right angles to the wall plane, see Fig. 3a.
Jituan	脊榑	A purlin at the top of the roof.
Linggong	令拱	A type of <i>gong</i> member in bracket set, often intersected by a <i>shuatou</i> cross, see Fig. 3a.
Ludou	栌斗	The principal bearing block, lowest in a bracket set, see Fig. 3a.
Mujiceng	木基层	It refers to the part of the wooden structure above the purlin and below the tile of the entire wooden frame of the house, including rafters, boards, etc.
Nidaogong	泥道拱	A type of <i>gong</i> member in bracket set, mounted in the mouth of the <i>ludou</i> , parallel to the wall, see Fig. 3a.
Niujituan	牛脊榑	The purlin between the lower <i>pingtuan</i> and the eave tie, see Fig. 2.
Pingpandou	平盘斗	A type of <i>dou</i> member in bracket set.
Pingzhu	平柱	Central bay column, see Fig. 2.
Puzuo	铺作	Bracket set, referred to as <i>puzuo</i> during the Song Dynasty and as <i>dougong</i> from the Qing Dynasty onward, see Fig. 3a, b, c.
Qiangji	戗脊	In gable and hip roof, the ridge that intersects the <i>Chuiji</i> , see Fig. 2.
Sandou	散斗	Bearing block, usually placed on the ends of a bracket arm to support timbers parallel to the building plane.
Shengqi	升起	Gradual elevation of the column from the central bay column to the angular columns on both sides, see Fig. 3d.
Shengtoumu	生头木	It is a triangular piece of wood between the eave purlin and the corner eave rafter.
Shoufen	收分	The cross-section of the column gradually shrinks according to certain rules, see Fig. 3d.
Sunmao	榫卯	Mortise and tenon
Wujia puzuo	屋架铺作	Bracket set on the upper roof frame
Xiangyan	象眼	The stones on the left and right sides of the treadway are stacked inward to form an inward-looking triangular hole, which is the <i>Xiangyan</i> , see Fig. 2.
Xieshan	歇山	Gable and hip roof, see Fig. 2.
Xumizuo	须弥座	High base with decorated mouldings, the plane is usually square, wide at the top and bottom, narrowing in the middle layer by layer, with the narrowest layer in the middle, called the girdle.
Xuanyu	悬鱼	Located right in the middle of the mountain face of the roof, which reinforces the two side <i>bofengban</i> , see Fig. 2.

Xuanzi caihua	旋子彩画	It is one of the ancient decorative painting styles on ancient Chinese buildings, named for the spinning flower pattern painted on it.
Yizhuzao	移柱造	The practice of shifting a number of interior columns to increase or decrease column spacing to achieve the desired space and function, see Fig. 3e.
Yingzao Fashi	营造法式	It was the first official work in China to deal in detail with the practice of architectural engineering, and was a collection and summary of the experience of architectural design and construction at Song Dynasty.
Zhengji	正脊	Main ridge, see Fig. 2.

### Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

### Abbreviations

BIM	Building Information Modelling
HBIM	Heritage Building Information Modelling
AEC	Architecture, Engineering, and Construction
UNESCO	United Nations Educational, Scientific, and Cultural Organization
TLS	Terrestrial Laser Scanning
UAV	Unmanned Aerial Vehicle
RMSE	Root Mean Square Error
LOD	Level Of Development
LOK	Level of Knowledge
LOI	Level of Information
VR	Virtual Reality
AR	Augmented Reality
MR	Mixed Reality
GIS	Geographic Information System

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### Author contributions

J.Z., H.L. and S.Y. proposed the overall modeling scheme, carried out model creation, and wrote the paper. L.Z. and W.Z. completed the virtual presentation part, and Y.L. and X.W. carried out the pre-information collection and model construction. All authors reviewed the manuscript.

### Competing interests

The authors declare no competing interests.

### Additional information

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