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A virtual reconstruction method for corridor gable buildings based on the knowledge of structural dynamics: taking Leiyin Cave as an example

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Abstract

Virtual reconstruction of ancient buildings often has incomplete records of the original design and construction details, and can only be reconstructed based on limited data, drawings and photography, which is different from the actual conditions. The unique overhanging structure of the corridor gable building makes it vulnerable to damage in extreme weather conditions. In order to ensure that the virtual reconstruction results can not only reproduce the original appearance of history, but also ensure that the reconstructed model maintains structural stability in the long term. This paper proposes a reconstruction method of the original appearance of the corridor gable building remains based on structural dynamics analysis. This method comprehensively uses three-dimensional reconstruction, structural engineering, dynamic analysis, and computer simulation technology to ensure the structural accuracy and historical authenticity of the virtually reconstructed corridor gable building. First, through data collection and analysis, combined with ancient architectural construction techniques, a preliminary three-dimensional model was created, which included all structural elements and details. Several groups of reconstruction schemes are determined based on material properties. Then, using finite element analysis software, perform dynamic analysis on the three-dimensional model. Evaluate the stability of the reconstructed structure and optimize the material selection plan to ensure the feasibility and accuracy of the virtual reconstruction. Taking the virtual reconstruction of the eaves in front of Leiyin Cave as an example, it shows that this method is effective and feasible to achieve the virtual reconstruction of corridor gable buildings. It provides new ideas for virtual reconstruction of ancient buildings and has important practical application value.

Keywords Corridor gable buildings, Virtual reconstruction, Dynamic response analysis, Remains, Wood selection

Introduction

As a unique symbol of historical architecture, the corridor gable building carries the traces of time. At the same time, it has been subjected to solar radiation and rainwater erosion for a long time, and there are different forms of damage at the same time. Most of the structures that remain today are damaged structures, or even only architectural remains (the remains predominantly consist of column bases and partial wall structures, which provide insights into the original architectural layout) [1]. In order to reconstruct the corridor gable building while

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restoring the original style, it is necessary to formulate scientific reconstruction methods [2]. To address this problem, many researchers rely on surface measurements and intuitive observations to target textures, cracks, warping, hollows, etc. Surface reconstruction is carried out based on appearance characteristics. For example, Pescari Simon [3] studied the opera house wall materials in response to the problem of cracks in the masonry degradation of the opera house, and sought more suitable reconstruction materials for wall cracks. However, traditional reconstruction methods are limited by technical means. In the absence or inaccuracy of a large amount of literature, it is difficult to gain a deep understanding of the important science, materials, structure, technology, and other authenticity value information contained in the evolution of the ontology [4].

The emergence of virtual reconstruction technology breaks this bottleneck. Through virtual reconstruction, researchers can infer many details, such as the spatial layout, building materials, and construction techniques of ancient buildings [5, 6]. Virtual reconstruction technology combines digital technology and computer science to allow more authentic buildings to be visually presented through three-dimensional reconstruction [7, 8], which has considerable impact on CH management, analysis, reconstruction, and reconstruction [9]. Several digital techniques, such as digital photogrammetry and laser scanning can be used to capture the shape, size, and surrounding landscape elements of CH objects and locations in their current state [10]. Digital photogrammetry has been used for 3D reconstruction of objects based on multiple images [11]. Active sensors can generate dense 3D point cloud data required to create high-resolution geometric models, and are more suitable for creating high-precision textured 3D models [12]. Laser scanners are efficient devices that can acquire large amounts of high-quality geometric data in a short time, providing high-precision digital representations of real-world objects and environments. By processing and registering this data, 3D models with detailed geometry can be created. This enables laser scanners not only to accurately measure complex objects, but also to perform effective modeling [13]. The software Topcon ScanMaster 3.0.6.0, Geomagic Studio 2013, and Auto Recap were utilized by Gao Xixi [14] to realize point cloud data splicing, data preprocessing, and format conversion for the 3D reconstruction of Qingdao Guangxing Yard, with the aim of restoring and recreating the damaged ancient buildings. In order to more comprehensively restore and represent the overall appearance of ancient buildings, 3D reconstruction research based on the fusion of multi-source data has gradually emerged. Guo Qiu [15] and others combined 3D laser scanner and tilted photography technology, using a feature point matching algorithm to achieve the accurate fusion of multi-source data to restore Li's family temple, which has had a positive effect on the reconstruction, display, and inheritance of ancient architecture. A visualization method was proposed by Tysiac Pawel et al. [16] to establish a high-quality 3D model of a heritage building by combining ground-based laser scanning and unmanned aerial photogrammetry techniques and aligning the acquired point cloud data. These modeling methods, based on precision measurements and multi-source data fusion, can establish a realistic three-dimensional model with complete detail expression and good model accuracy, which opens up a new direction for the digital protection of ancient buildings [17, 18].

Although three-dimensional reconstruction based on digital technology can achieve higher fidelity and accuracy of architectural information, it is limited to the preservation and display of architectural information. For buildings with complex structures, improper reconstruction methods not only destroy the originality and authenticity of ancient buildings, but there is also the risk of accelerated damage and destruction, so how to ensure the authenticity and stability of reconstruction [19] is a major challenge facing the inheritance and sustainable use of ancient buildings [20]. Pachta Vasiliki [21], in order to determine the principles of construction of a historical school in the municipality of Agia, in the region of Thessaly, central Greece, conducted a structural analysis using mapping and surveying combined with a three-dimensional finite element model to determine the tectonic patterns. Siliang Chen [22] utilized detailed three-dimensional data information to determine the estimated dimensions and repair dimensions of the Bare Cliff Trestle based on the principle of bridge erection and considering the analysis of the mechanical characteristics of the slab road form. Han Xu [23] conducted an investigation into the construction techniques and spatial patterns of Buyi ethnic granaries by utilizing field research and interviews with local artisans. This approach facilitated an analysis of the reconstruction methods and construction processes of Buyi ethnic timber granaries. Through this methodology, Han Xu was able to gain a deep understanding of the traditional building techniques and cultural significance of Buyi granaries.

Within the existing virtual reconstruction research, different studies have their own focuses, and there is also a certain overlap in research content [24]. However, current research mainly focuses on existing buildings or buildings with relatively simple structures. Most ancient buildings are mainly constructed of wood. The strength, stability, durability, and corrosion resistance of wood are essential for its service life. Moreover, the stress characteristics of the structure are complex. An important feature of the structure is the use of mortise and tenon joints, that is, the ends of the beams are made into mortises and inserted into the reserved mortises on the column heads. The mortise and tenon structure can form a statically indeterminate structural system, absorb less vibration force, and have strong impact and earthquake resistance [25, 26].

The selection of wood is crucial to structural safety. Correctly selecting the right wood can not only ensure the stability and durability of the building, but also effectively resist the erosion of external environmental factors. In the reconstruction work, strictly controlling the quality standards of wood and selecting high-quality wood are important guarantees to ensure the safety of the building structure [27]. Therefore, when we virtually reconstruct a building that has disappeared, we must not only restore it with high accuracy while maintaining its original appearance, but also consider the physical properties of wood and ensure that the reconstructed building can effectively withstand earthquake loads and prevent damage and collapse during an earthquake. Such comprehensive considerations will ensure that the virtual reconstruction is not only faithful to the original building's appearance, but also has the necessary structural safety.

This article proposes a virtual reconstruction technology that takes into account dynamic knowledge to meet the needs of virtual reconstruction of corridor gable buildings. This method relies on finite element analysis technology to accurately simulate the dynamic response under earthquake action in a computer simulation environment, identify potential structural weak points, and adjust the design plan accordingly, such as optimizing material selection, enhancing node strength, etc., thereby this significantly improves the overall seismic performance and safety of the structure. This method not only ensures that the historical aesthetics and cultural value of the structure are preserved, but also ensures the safety of modern use, takes into account the needs of historical preservation and modern functions, and lays the foundation for further improvement of the virtual reconstruction theoretical system.

The proposed work makes several contributions:

- The site was reconstructed using an integrated approach from archaeology, structural engineering and computer science. This approach ensures a comprehensive understanding and reconstruction of the historic structure, taking into account both historical accuracy and structural integrity.
- Finite element analysis not only verifies the stability of the reconstruction model, but also provides a basis for the selection of reconstruction materials. By designing and experimenting with a variety of wood selection schemes, the superiority of fir in earthquake resistance is confirmed.
- Through digital technology, every detail and structural characteristics of the building are meticulously restored, significantly improving the accuracy and operability of the reconstructed model.

The paper is organized as follows: The "Methods" section describes the reconstruction requirements, evidence acquisition, and reconstruction methods in this work. The "Case study" section describes in detail the reconstruction process of the Leiyin Cave Temple. The "Discussion" section discusses the reconstruction value of this method and the difference from other methods. Finally, our research results and contributions are summarized.

Methods

Virtual reconstruction principles

Virtual reconstruction refers to the reconstruction of historical geometric forms and textures of ancient buildings based on high-precision three-dimensional models in computers. When performing virtual reconstruction, a series of principles need to be followed, including (1) the principle of historical accuracy, which means that the reconstruction work should be based on reliable historical data, including documents, images, archaeological excavations, etc., to ensure that the reconstructed content is consistent with historical facts. conform to. (2) The principle of minimal intervention refers to interventions that best combine compliance with structural requirements with the greatest possible protection and enhancement of heritage values and respect for the authenticity of the structures [28]. (3) The principle of multidisciplinary cooperation means that virtual reconstruction should be an interdisciplinary cooperation process, requiring the collaboration of archeology, architecture, and civil engineering. In undertaking the virtual reconstruction of an ancient building, the first thing that must be done is the decision to restore the building to a specific point in its history. Since ancient buildings may have been reconstructioned and modified many times over the course of their history, choosing a specific point in time means being able to clarify the goals and reference standards for reconstruction. This decision should be based on thorough historical research, including a comprehensive analysis of relevant documents, images, physical evidence, and consideration of the building's cultural, social and artistic value at different stages in its history. Through this method, virtual reconstruction not only reproduces the specific historical status of ancient buildings, but also ensures its authenticity and academic rigor in cultural inheritance.

Evidence acquisition

Due to the lack of historical records, it is very easy to cause incomplete information, making it difficult to effectively and accurately trace the original historical appearance. The lack of reconstruction basis is a major challenge in the reconstruction process. In virtual reconstruction projects, we usually put forward different requirements for the selection of reconstruction evidence based on the characteristics, preservation status and historical value of the research object [29, 30]. The creation of evidence provides a scientific basis for virtual reconstruction. In 1994, Tayfun Oner founded the Byzantium 1200 project. In 2011, the current level of knowledge of virtual reconstruction was pointed out, and a distinction was made between buildings that actually exist, those based on archaeological excavations, and those reconstructed based on different data. Until 2018, the "multi-scale evidence concept" was proposed by Portus Theodosiacus and used in the Byzantine 1200 reconstruction project. The original intention of this concept was to use 10 highly saturated colors to distinguish the sources of evidence. However, the color changes were too rich, which reduced the recognition rate and could not intuitively reflect the gradient changes of evidence. At the same time, Rafael Ortiz-Cordero et al. also discussed this issue. Therefore, he reduced the level of evidence on the basis of the London Charter and the Principles for Virtual Reconstruction of Seville Cultural Heritage, and changed the color tone to avoid the problem of excessive color saturation [31]. Li Zhen [32] reorganized the evidence scale and established a three-layer gradient pattern with 10 categories of evidence levels of the same color. The evidence scale can be summarized as existing remains, direct evidence, and indirect evidence. As shown in Fig. 1. Therefore, in order to improve the transparency of the reconstruction base record, this study mainly adopts this hierarchical classification method, using a unified gradient color to indicate the degree of credibility of a single piece of evidence. Cold colors indicate low levels of authenticity, while warm colors indicate high levels of authenticity.

Virtual reconstruction

When performing virtual reconstruction of ancient buildings, structural analysis can be used to describe the impact of different actions on the reconstruction results. By simulating the response of historic buildings to various dynamic loads, it is possible to predict how their structures will perform under future loads. This is vital to ensure the long-term durability and safety of the building. Structural dynamic time history response analysis is a method to evaluate the performance of a structure under dynamic loads, especially used to examine the response caused by earthquakes, wind, etc. The analysis is performed by applying vibration loads to the structural model and simulating its response under these loads. This method involves building an accurate structural model that reflects the mass, stiffness, and damping properties of the structure in detail. When performing dynamic response analysis, it is necessary to define the input load, which is usually the seismic acceleration obtained based on historical data. It can accurately reflect the earthquake vibration characteristics of a specific location. The results of the analysis include the displacement, velocity and acceleration of the structure under load. With this data, reconstructor can evaluate how the structure performs in actual dynamic environments and determine whether it meets safety standards. In addition,

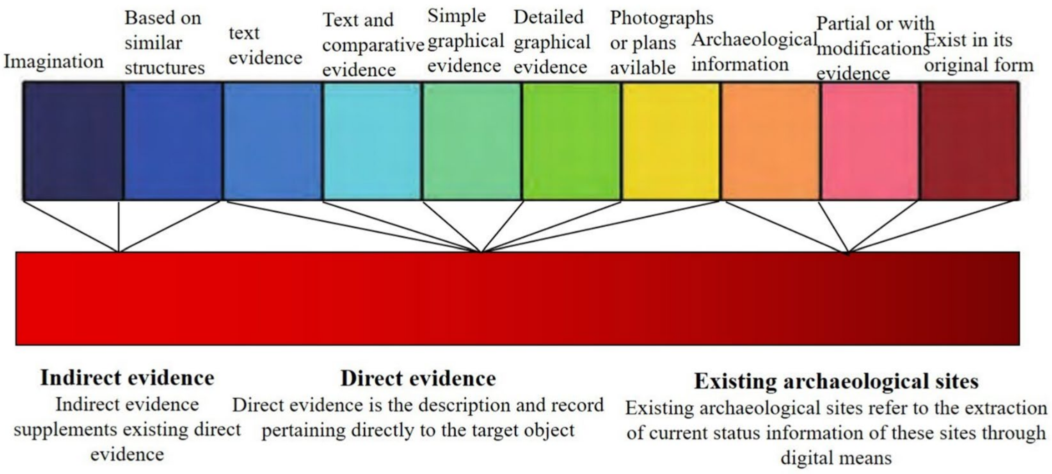


Fig. 1 Classification of evidence (Image source [32])

this analysis can also reveal potential weaknesses in the structure and provide scientific basis for design improvement and reinforcement.

Drawing on cutting-edge developments in virtual reconstruction theory, archaeological information and current information technology. Obtain information about a structure's function, purpose, history, cultural background, geographical location, etc. through archaeological surveys. Historical photographs and documents can determine key information such as a building's appearance, orientation and bays. Ancient buildings often followed specific principles of proportion and aesthetics, which provide us with the basis for reconstruction. Then, combined with ancient construction techniques, we selected appropriate building materials and designed the structure of beams and columns, especially using mortise and tenon technology at the connections to enhance the sustainability and earthquake resistance of the building. These detailed reconstruction information provides scientific qualitative and quantitative evidence for restoring the original appearance of the ruins. When integrating these detailed data and information for reconstruction, some contradictions may arise. For example, traditional Chinese ancient architecture follows certain aesthetic proportions, but when investigating architectural remains on the ground, it may be found that the construction method does not fully conform to these proportions, or there is a contradiction between historical research and structural analysis. These contradictions will lead to the emergence of multiple reconstruction schemes. Therefore, it is necessary to define structural elements, including geometry, materials, overall structural organization, architectural details, connections, locations, and settings, while respecting the principle of authenticity of ancient architecture, to ensure the high level and structural stability of the reconstructed structure. The virtual reconstruction framework is shown in Fig. 2.

Case study

Study area: Leiyin Cave

Located in Fangshan District, Beijing, Shi Jing Mountain Leiyin Cave was constructed in the 12th year of the Sui dynasty. Situated approximately 244 m high from the foot of the mountain and 357.03 m above sea level. There is no building in front of the Leiyin Cave now, and only the remains of late construction remain, as depicted in Fig. 3. This is the origin of Fangshan Stone Sutra carvings and the place where Buddha relics were unearthed. It has important political, economic and historical and cultural values.

The technical flow chart

Through literature review, on-site investigations, and field surveys, a comprehensive set of multi-scale and multi-dimensional data is gathered to establish a realistic digital model of the existing architecture scene. Then, based on the location and size of the remains combined with historical photos, the geometric dimensions, bays, depth and other structural features of the building were determined, thereby determining the initial three-dimensional model of the corridor gable building. Through material selection, several reconstruction plans were established. Subsequently, structural dynamic analysis is conducted

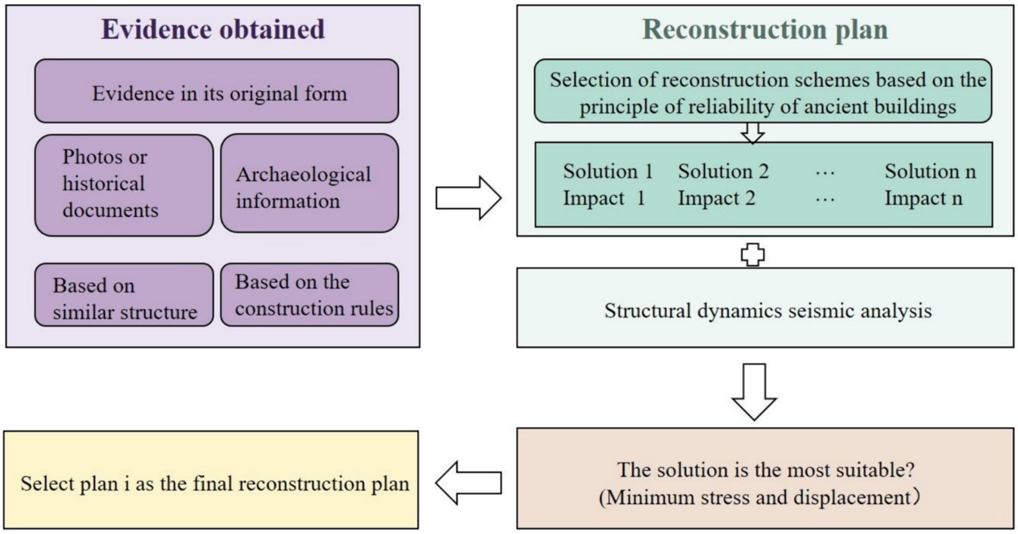


Fig. 2 Virtual reconstruction framework

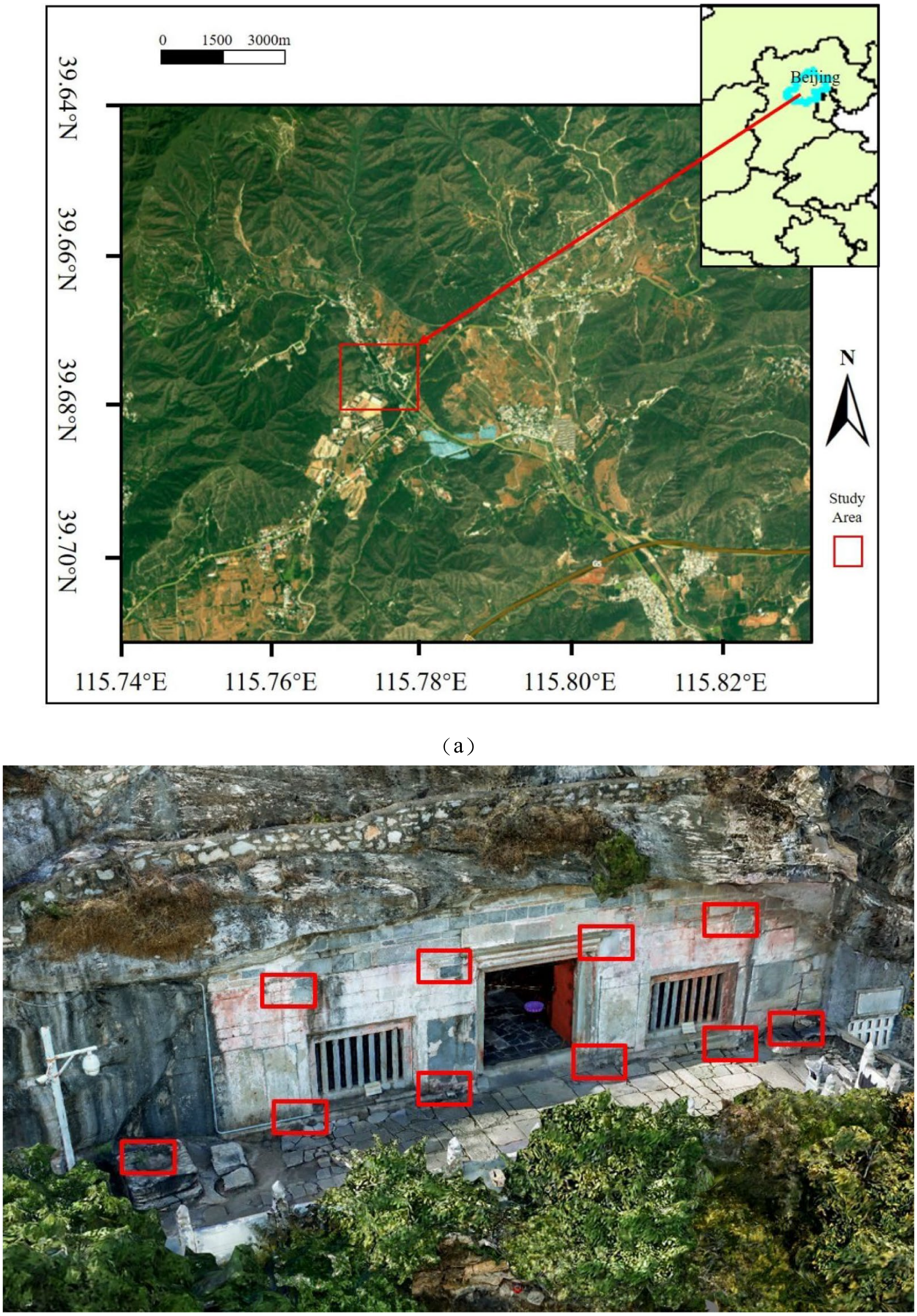


Fig. 3 **a** Location, **b** remains outside the Leiyin Cave

to delve into the structural integrity of the corridor gable building. The extracted apparent information as well as a series of attributes of the corridor gable building, such as size and material, are added to the finite element simulation software to establish the physical entity model. The seismic performance of designed corridor gable building architecture is analyzed based on the results of the analysis of the mechanics of the structural dynamics response both of the whole building and of individual components. Select the best reconstruction plan. This ensures that the reconstructed corridor gable building maintains its original historical appearance and possesses sufficient structural strength. The specific technical process is shown in Fig. 4.

Data acquisition at different spatial scales

The Leiyin Cave originally consisted of a fracture layer about 4 m thick. Over time, water seeped along the rock fissures, dissolving these fractures, which gradually enlarged the scale of the cavern. About 1400 years ago, through human modification, this naturally formed cave was transformed into the Leiyin Cave seen today. UVA (Unmanned Aerial Vehicle) and 3D laser scanning are two commonly used methods in digital protection. UVA can be used to quickly measure and collect data for the entire Leiyin Cave area, especially for hard-to-reach areas. By providing color images and texture information, it can intuitively display the appearance and status of the Leiyin Cave. 3D laser scanning can capture the shape and size of the Leiyin Cave architectural remains in detail, and is suitable for the detailed design and analysis of the reconstructed structure. For the reconstruction of the Leiyin Cave corridor gable buildings, a variety of surveying and mapping methods are used for data collection to ensure the quality of the reconstructed model[33]. The entire data acquisition process is shown in Fig. 5.

To ensure the adequacy and accuracy of the data, a method of large overlap and high-density data collection was adopted. Specifically, the images had an overlap of 70% in the flight direction and about 75% laterally, with a flight altitude controlled at 350 m. This high degree of overlap in data collection strategy is designed to ensure precision and efficiency in subsequent data processing. Using UVA images alone may encounter some occlusion problems. In order to generate a more detailed and complete 3D model, the camera images can provide detailed information on the occluded areas. The decorative details and textures of the building can also be supplemented to provide detailed side views and close-ups. ContextCapture automatically analyzes the imported images to identify similar features across different images, generating a dense point cloud. Based on this point cloud, ContextCapture further creates a more detailed three-dimensional mesh model. This model includes the surface details of the terrain and applies texture mapping using data from the original images, ultimately producing a realistic 3D model that offers a more authentic visual experience, for easy visual display.

When we performed a 3D scan of the exterior of Leiyin Cave, considering that the maximum distance between the scanner layout point and the work object is no more than 20 m, we chose to use the FARO S350 3D laser scanner, which is suitable for medium and short distances. The device has an extremely high

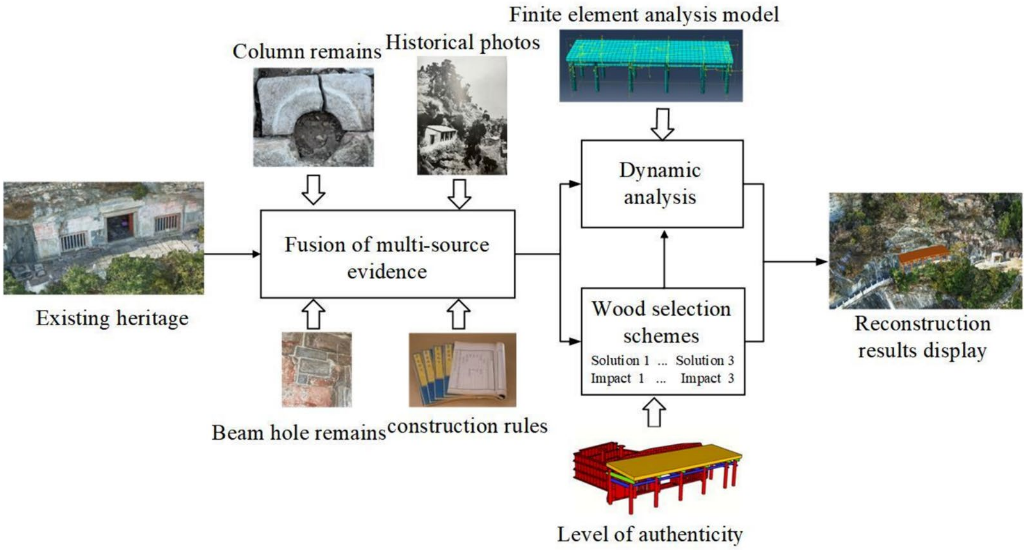


Fig. 4 Work flow chart of Leiyin Cave

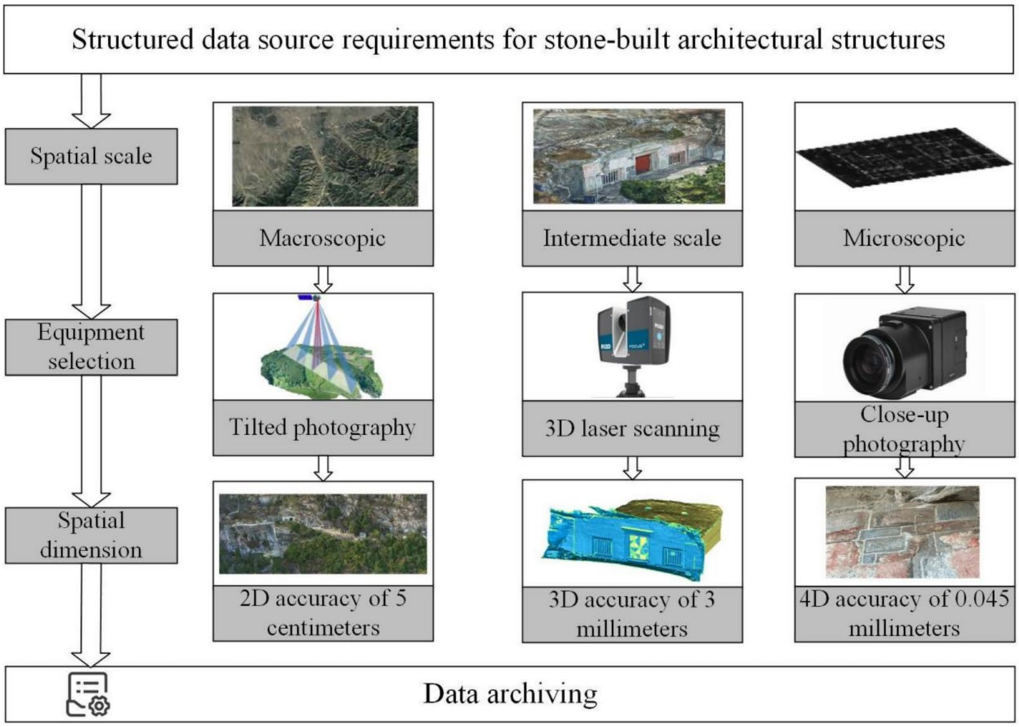


Fig. 5 Data acquisition at different spatial scales

measurement rate of 976,000 points per second, an accuracy of up to ± 1 mm, and an angular accuracy of 19 arc seconds. This configuration ensures high efficiency and accuracy of data collection. In order to collect data more efficiently, we are also equipped with a 9-m-high scanner lifting pole, which adopts a hydraulic lifting mechanism and is capable of multiple heights and all-round data collection, thus ensuring that Leiyin Cave can be fully recorded with three-dimensional information. Together, these measures ensure high-quality data collection and recording, providing accurate basic data for subsequent analysis and research.

Cloudcompare software is used to process the data obtained by 3D laser scanning. Unprocessed point clouds contain noise points such as people and obstacles. The software is used to perform denoising and filtering operations on the point clouds to remove noise points and isolated points. Massive point cloud data is simplified to reduce redundant information and improve visualization efficiency. The ICP algorithm is used to align the point clouds. Finally, the preprocessed point cloud is used to generate a triangular mesh model through the Delaunay Triangulation method, ultimately achieving the purpose of accurate measurement of architectural remains.

Three-dimensional reconstruction

Ground column

Outside the Leiyin Cave Hall, the original columns no longer exist, only the column foundation stones remain. The platform outside the hall is bounded by the door. There are two places on the north and south sides that destroy the original solid stone floor. The diameter of the columns here is about 30 cm, and the wood used is not thick, which shows that the regulations of the building are not very high. On the north wall outside the hall, there are six neat rows of column holes. These column holes are located on the inside of the corridor eaves building. It is speculated that the columns in these column holes were originally used to support the weight of the roof above the eaves.

The outermost columns of the corridor eaves building are mainly responsible for bearing part of the weight of the structure. These columns are called eaves columns. Although there are no detailed pillar remains outside the temple, it can be determined from historical photos from 1925 and the arrangement of the columns that the eaves were originally a building composed of 2 rows, 6 columns, and 5 bays. In addition, according to measurements, the north–south width of the corridor eaves

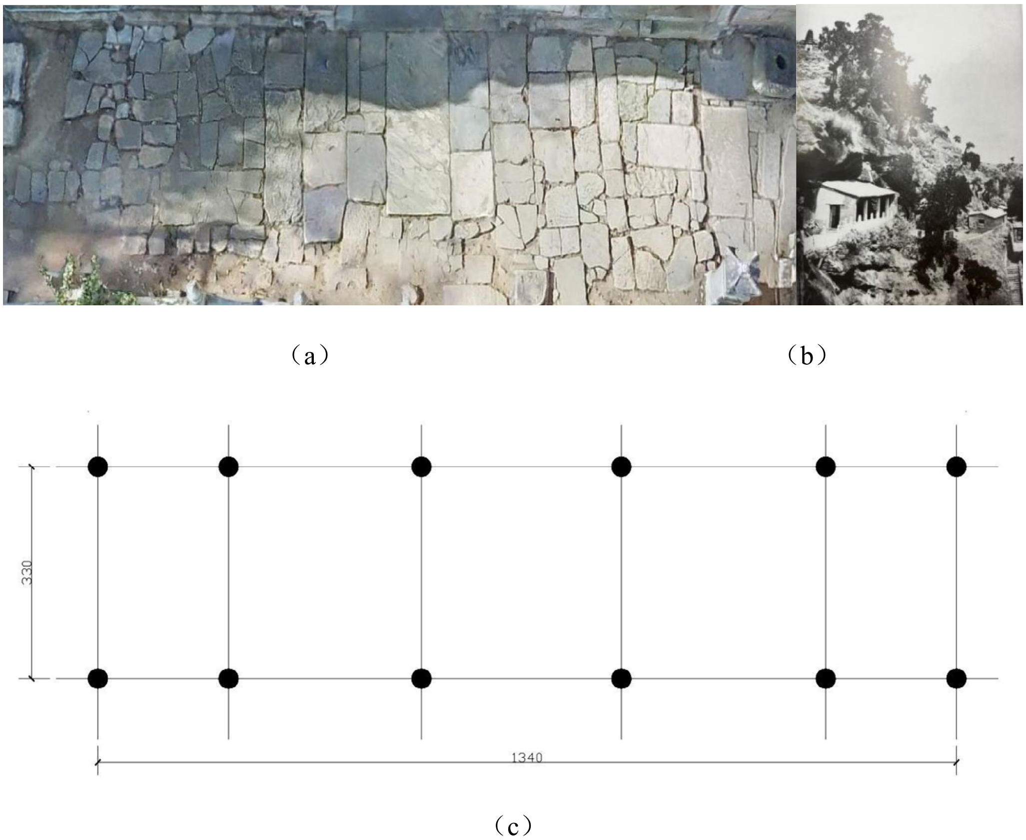


Fig. 6 **a** Orthophotograph outside the temple, **b** Historical photographs, **c** Column network distribution diagram

building is approximately 330 cm, and the east–west width is approximately 1340 cm, as shown in Fig. 6.

Wall beam holes

On the upper part of the outer wall of Leiyin Cave, from the regular masonry to the top of the natural cave, stones of different specifications, old and new, are used for sealing. The clear boundary between the regular and irregular stones on the wall shows that this part was later filled with wall tiles. There are also traces of four neatly arranged holes on the wall. The positions of these holes correspond to the top and bottom of the pillar stones at the bottom, indicating that these holes were reserved for the beam holes used to place the cantilevered beam structure when building the Leiyin cave wooden structure roof.

In order to facilitate data analysis and processing, the 3D point cloud data was imported into Geomagic software for processing, and a mash model was generated. Through this model, we were able to confirm that the dimensions of the beam hole are 20 cm long and 11 cm wide; the height of the column is approximately 285 cm. The spacing between the columns is: 282 cm in the middle, 271 cm and 289 cm on the left and right sides respectively. These data provide important information for understanding the layout and dimensions of the original structure of Leiyin Cave. as shown in Fig. 7.

Overall structural design

The building in front of the temple serves to protect the sutra plate of Leiyin Cave and the Thousand Buddhas from wind and rain erosion. It effectively blocks direct sunlight and prevents rainwater from directly washing the Buddha statues [34]. Furthermore, clear visibility of the building's structural framework and interior Buddha statues is enabled, thus fostering a sense of structural aesthetics [35].

The structural design of the Leiyin Cave corridor gable is based on measured data and references from "Chinese ancient architecture woodwork construction technology." It is determined that the porch eave wooden structure consists of hypostyle columns, eave columns, Baotou beams, eave tiebeams, penetrating ties, roof, and purlins, among other components, in order to project the dimensions of each structure. According to the book, the column diameter should be between 1:7 and 1:11 of the column height. When reconstruction the gallery eaves architecture of Lei Yin Cave, several important

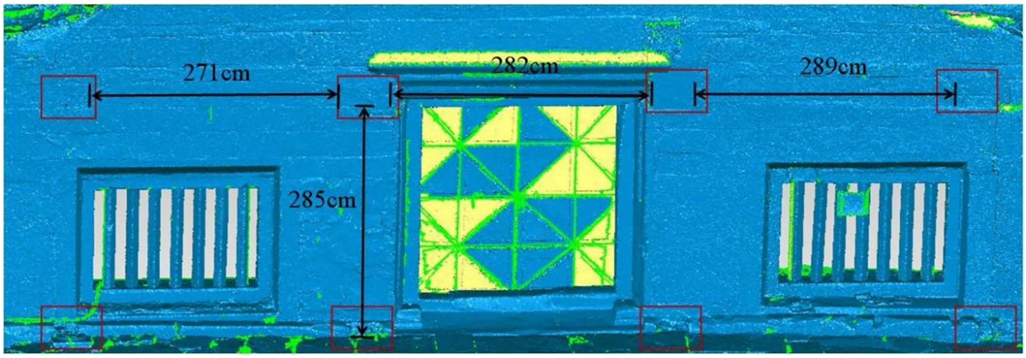


Fig. 7 Remains of a beam hole in the wall

factors need to be considered. Firstly, the height of the building is constrained by the viewing angle of the Buddha statues and the height of the statues themselves, thus it cannot be constructed strictly according to traditional building techniques. Additionally, by referencing historical photographs and observing the height from the beam holes to the top of the cave, we can determine that the roof slope is relatively gentle. These considerations have a direct impact on the final design and structure of the building. Therefore, combined with the remains of the wall beam hole, the projected height of the eave column is 272.9 cm, and the height of the hypostyle column is 330 cm. The Baotou beams are a short beam between the hypostyle column and the eave column, which bears the gravity of the roof and the purlins. The eave tiebeam, a rectangular crosspiece, is placed between the columns for connection purposes. The penetrating tie is situated between the two columns to enhance the stability of the wooden structure. According to the transparency of the reconstruction records, the reconstructed buildings are given corresponding colors according to their authenticity level. Specific lap joints and dimensions of the design are depicted in Fig. 8.

Material solution

The selection of wood is crucial to the safety of the structure, because different types and grades of wood have different physical and mechanical properties [36]. When selecting wood for ancient buildings, it is necessary to select the most suitable wood according to local conditions based on the actual needs on the basis of meeting the wood structure specifications. Common types of wood used in ancient buildings include pine, cypress, nanmu, fir and chestnut. Among them, fir is stable in corrosion resistance and compression resistance, has good seismic resistance, is not easy to be eaten by insects, and has a light weight and is not easy to deform, which makes fir more stable and durable in structures exposed to outdoor environments. It is often used in the pillars, beams, edges and other parts of the wooden structures of halls and pavilions. In addition, pine wood has a relatively hard texture, can withstand greater pressure and bending force, has moderate strength, is easy to process, is economical and easy to obtain, and is often used in load-bearing components such as beams, columns, and purlins. The reconstructed structure is composed of hypostyle column, eave column, Baotou beam, eave tiebeam, Penetrating tie and purlin. Their functions are different. Therefore, according to the advantages of fir and pine, three material selection plans are designed, as shown in Table 1. The first scheme is that the load-bearing structure such as beams and columns is fir, and the rest is pine. The second scheme is that the beams and columns are pine, and the rest is fir. The third scheme is that all are fir. The physical and mechanical properties of fir are shown in Table 2, and the physical properties of pine are shown in Table 3.

Structural analysis

Combining the dimensions of the components mentioned above, ABAQUS was used to perform finite element numerical simulation calculations on the reconstruction plan. Through this analysis, we studied its structural dynamic characteristics and seismic performance under earthquake conditions to ensure the safety of the main structure [37].

Finite element model

Based on existing research, we established three 3D finite element models of the timber structures respectively. To verify the impact of mortise and tenon joints on the overall stability under seismic conditions, we specifically analyzed the connection points between columns and beams. As shown in Fig. 9, we used the EI Centro wave as the seismic excitation to conduct a seismic response analysis of the wooden structure. Considering the seismic

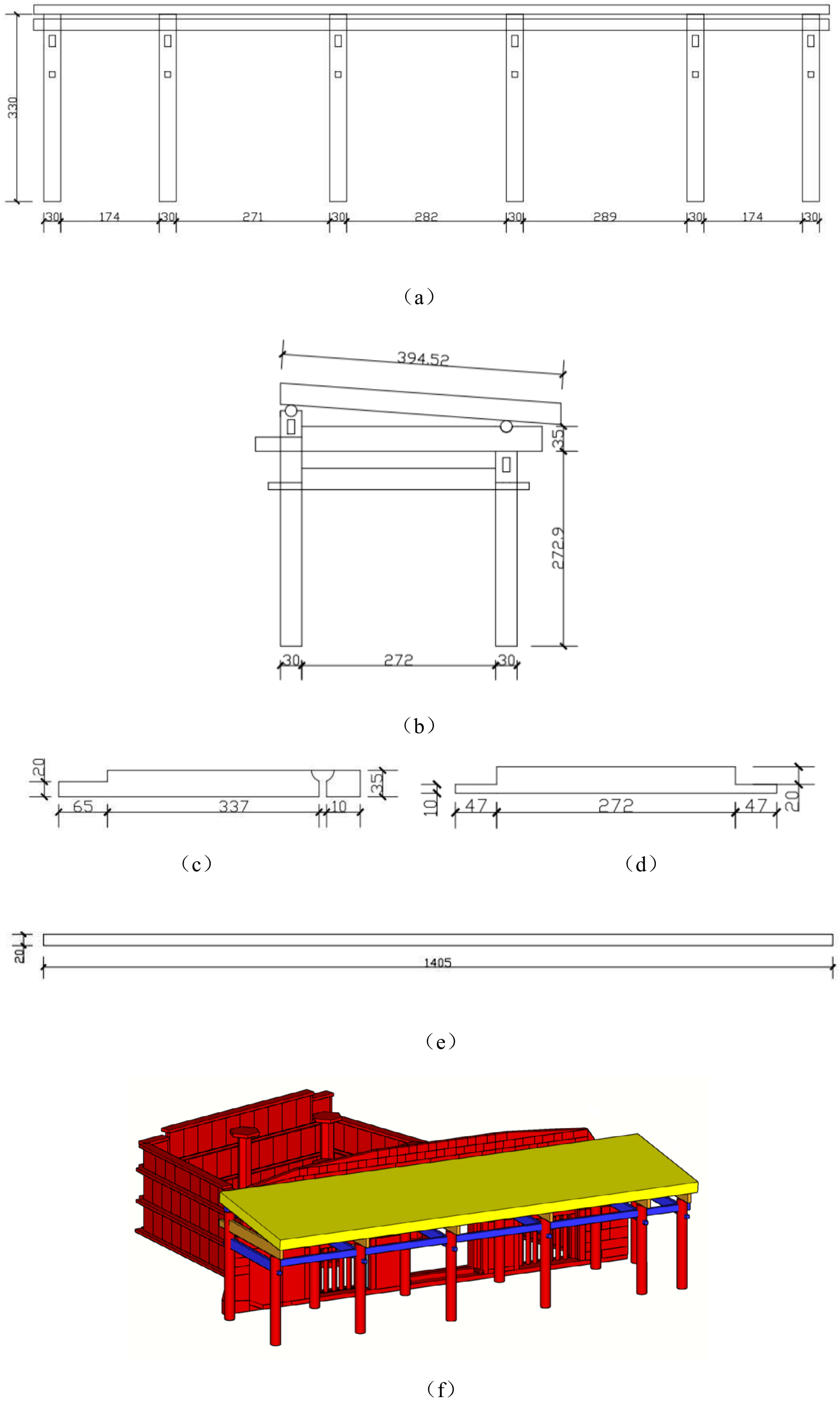


Fig. 8 **a** Front view, **b** end view **c** Baotou beam, **d** penetrating tie, **e** Eave tiebeam, **f** 3D Modeling

Table 1 Wood selection plan

Component	Hypostyle column	Eave column	Baotou beam	Eave tiebeam	Other components
Solution					
1	Fir	Fir	Fir	Pine	Pine
2	Pine	Pine	Pine	Fir	Fir
3	Fir	Fir	Fir	Fir	Fir

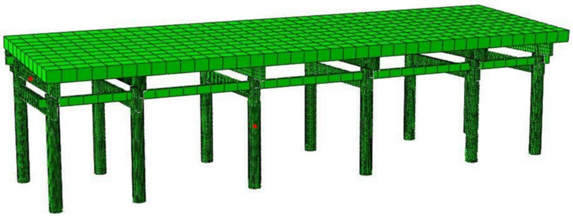


Fig. 9 Finite element analysis model and reference point selection

design intensity of 8 degrees in the Beijing area, the basic design acceleration was set at 0.2 g. This analysis helps us better understand and assess the performance and safety of wooden structures during actual earthquakes.

Dynamic response analyze

The time history analysis method is used to solve the seismic response of the wooden structure, and the principal stress and principal displacement cloud diagrams of the three schemes are obtained as shown in Fig. 10. From the displacement cloud diagram and stress cloud diagram, it can be observed that the displacement and stress values of the three plans are within the allowable range. Under the action of an earthquake, it will not be damaged due to large deformation or stress concentration. By comparing the maximum displacement values of the three plans, it was found that the displacement value of Solution 3 was the smallest at 15.92 mm, followed by Solution 1 at 16.09 mm, and the displacement value of Solution 2 was relatively large at 20.48 mm. From the principal stress cloud diagram, it can be seen that the stress value of Solution 1 is the smallest at 56.8 MPa, the stress of Solution 3 is second only to Solution 1 at 56.88 MPa, and the stress value of Solution 2 is the largest at 94.93 MPa. Therefore, according to the analysis results, Solution 3 is finally selected as the optimal reconstruction plan.

Under the action of earthquake, the wood parts at the mortise and tenon joints move slightly. This movement converts part of the earthquake energy into heat energy through friction, thereby reducing the response of the structure. Figure 11 shows the displacement and acceleration response curves of the beam and column nodes in Solution 3. The nodal response curves show vibrations centered around the equilibrium position, indicating that the structure can effectively return to its original or near-original position after the initial seismic excitation, proving that the structural design and material performance are good.

Results

The model of the corridor gable is established through Sketch Up, and Smart3D is utilized to convert the vector map acquired by the drone into a three-dimensional model. Through the fusion of models, rendering, and

Table 2 Physical and mechanical properties of fir

$E_{C,L}$	$E_{C,R}$	$E_{C,T}$	$f_{C,L}$	$f_{C,R}$	$f_{C,T}$
11,059	890	493	38.1	3.3	2.9
μ_{LR}	μ_{LT}	μ_{RT}	G_{LR}	G_{LT}	G_{RT}
0.54	0.46	0.40	829.4	663.5	199.1

Table 3 Physical and mechanical properties of pine

$E_{C,L}$	$E_{C,R}$	$E_{C,T}$	$f_{C,L}$	$f_{C,R}$	$f_{C,T}$
16,272	1103	573	52.0	6.5	5.4
μ_{LR}	μ_{LT}	μ_{RT}	G_{LR}	G_{LT}	G_{RT}
0.68	0.42	0.51	676.0	1172.0	66.0

$E_{C,L}$, $E_{C,R}$, $E_{C,T}$ represent the compressive elastic modulus of wood in the smooth grain, transverse radial, and transverse diagonal directions, respectively; $f_{C,L}$, $f_{C,R}$, $f_{C,T}$ denote the compressive strength of wood in the smooth grain, transverse radial, and transverse chordal directions, respectively; μ_{LR}, μ_{LT}, μ_{RT} are the Poisson's ratio of wood in radial, chordal, and transverse sections, respectively; G_{LR}, G_{LT}, G_{RT} represent the shear modulus of wood in radial, chordal, and transverse sections, respectively. The unit of strength is MPa

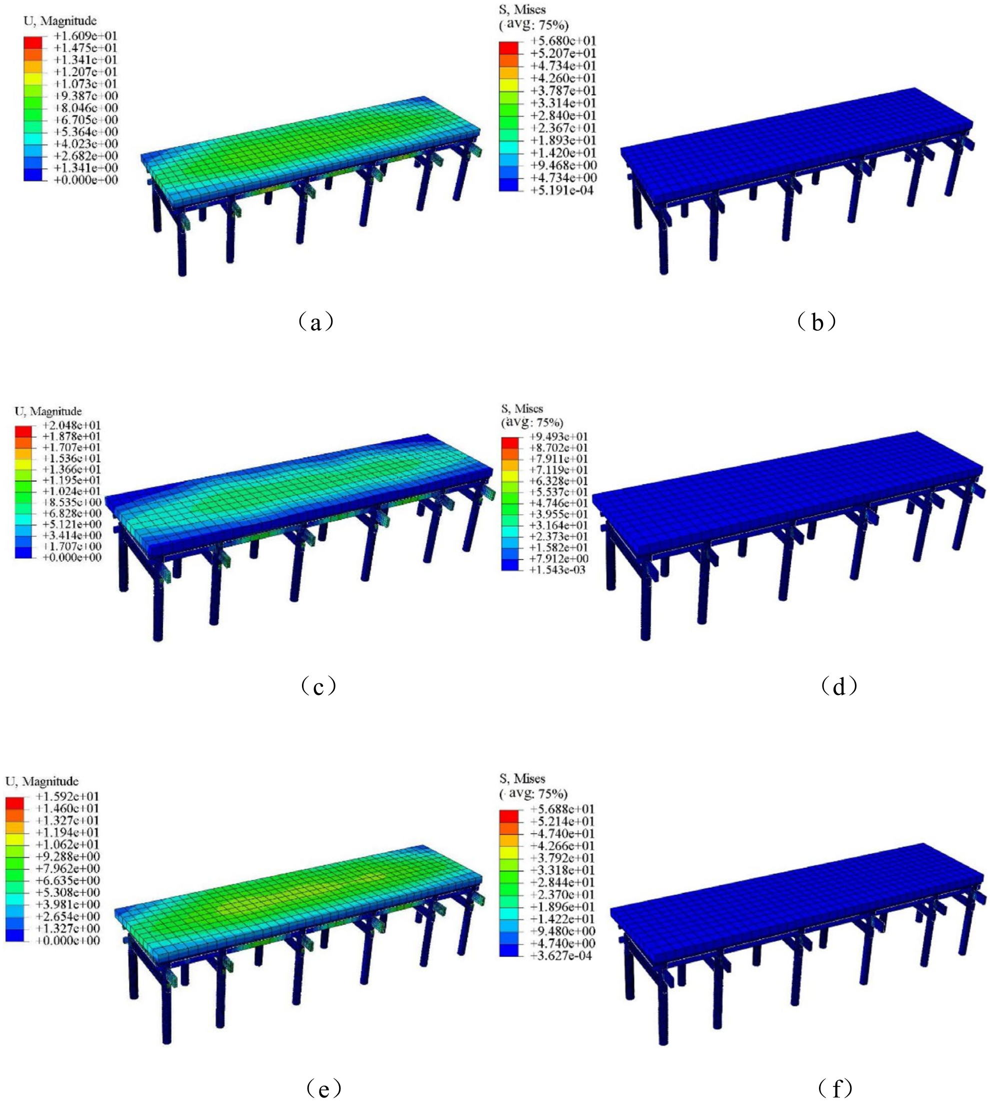


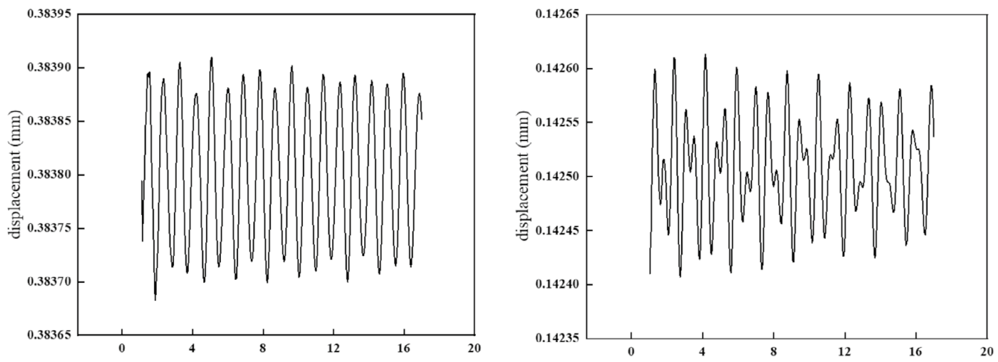
Fig. 10 **a** Solution 1 Principal displacement cloud diagram (unit:mm), **b** Solution 1 Principal stress cloud diagram (unit:MPa), **c** Solution 2 Principal displacement cloud diagram (unit:mm), **d** Solution 2 Principal stress cloud diagram (unit:MPa), **e** Solution 3 Principal displacement cloud diagram (unit:mm), **f** Solution 3 Principal stress cloud diagram (unit:MPa)

Photoshop processing, a high-definition, realistic rendering is obtained, as shown in Fig. 12.

Discussions

Reconstruction calculus checking

Throughout the Sui, Tang, Liao, Jin, Yuan, Ming, and Qing dynasties, Leiyin Cave has been preserved as the world's largest and oldest library of stone carvings. The study of Leiyin Cave continues to the present day, resulting in a large number of valuable pictures and books being left behind. As depicted in Fig. 13, it is learned from historical documents, expert knowledge, and oral interviews that the outer building of the Leiyin Cave Hall collapsed shortly after its construction. Historical photos confirm that it was rebuilt during the Republican period. Therefore, by utilizing photos as the basis for reconstruction and collecting spatial and temporal information at Leiyin Cave from various aspects, comprehensive architectural information is provided for the virtual reconstruction of the Leiyin Cave corridor. This approach enables a more comprehensive restoration of the appearance, structure, and function of Leiyin Cave after the second reconstruction, with a higher degree of credibility. This indicates that the effect diagrams truly reflect the scene at that time to a greater extent.



（a） （b）

Fig. 11 **a** Displacement response of beam nodes, **b** displacement response of column nodes

Fig. 12 Results of the virtual reconstruction for Leiyin Cave

Added value of method

The reconstruction method in this paper is different from the traditional reconstruction method [38], which takes the historical photos as the main reconstruction basis, according to the excavation of archaeological, combined with the structural dynamics analysis to improve the process of virtual reconstruction method, which not only embodies the principle of authenticity of virtual reconstruction, but also takes into account the principle of sustainability, and the method of structural assessment makes the restored building have good durability and stability to ensure that the reconstruction effect can be maintained for a long time, and will not cause further damage to the cultural relics.

Conclusion

Starting from the value demand of ancient building protection and following the principle of virtual reconstruction, this paper proposes a set of method frameworks and technical solutions for the virtual reconstruction of ancient buildings, covering data collection, model construction, detail restoration, material selection and other aspects to ensure the scientificity, accuracy and operability of virtual reconstruction.

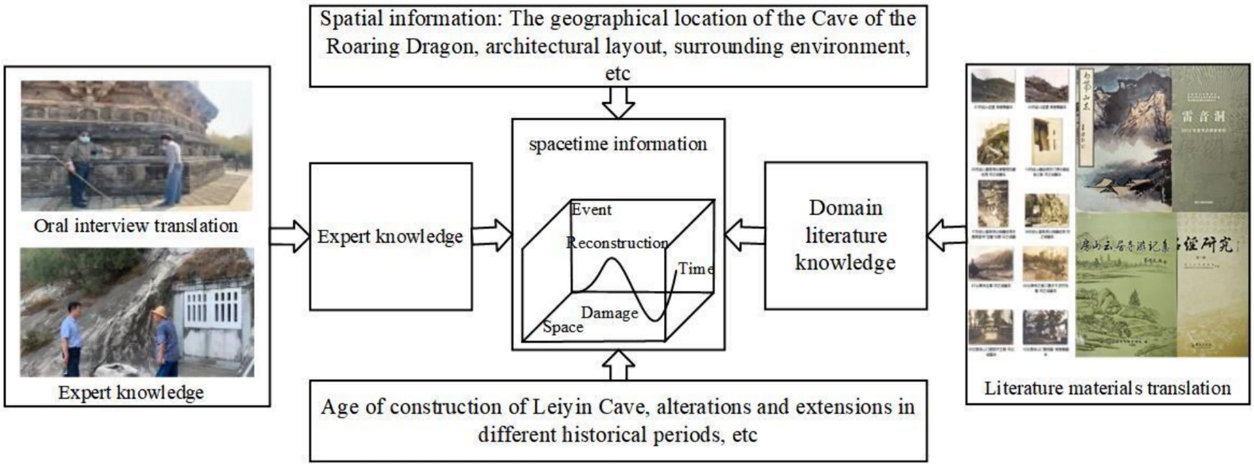


Fig. 13 Leiyin Cave space–time information

(1) As an indispensable historical witness, historical data provide key appearance and structural information for the reconstruction of the corridor gable building, thus becoming an important reference for reproducing the original appearance of the historical relics. In addition, modern digital technology provides the necessary technical support for virtual reconstruction, while traditional ancient building construction techniques provide basic guidance and theoretical foundation for structural design and reconstruction work. This comprehensive application ensures the accuracy and historicity of the reconstruction work, allowing us to preserve and pass on cultural heritage more accurately.

(2) Mechanical analysis is a key technical means to evaluate and ensure structural stability. The selection of wood properties is crucial to the stability of the structure. By integrating a series of attribute information into the finite element model, we can not only predict the stability of the reconstruction structure, but also optimize the reconstruction plan to achieve the best reconstruction effect. Such an approach ensures the long-term effectiveness of the reconstruction effort and significantly reduces the maintenance and reconstruction work that may be required in the future.

Although the virtual reconstruction of the original appearance has been achieved within the context of empirical cases through this methodological framework and technical solutions, two theoretical issues to be further investigated have emerged in the continuous pursuit of exploring more accurate and efficient virtual reconstruction techniques with the continuous progress of technology.

(1) Reconstruction evidence can improve the value and credibility of reconstruction. This article only focuses on existing remains, but future research can be further expanded to other types of buildings, and a richer reorganization of multi-source evidence can be carried out to explore a more comprehensive and systematic classification method for reconstruction evidence.

(2) Existing reconstruction methods mainly rely on manual modeling, which causes problems that are time-consuming and inefficient. Develop customized and intelligent evidence extraction and modeling tools for specific fields to more quickly analyze and use evidence to support decision-making and solve problems. This development will help improve the efficiency of reconstruction.

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Author contributions
Conceptualization: R.Z., M.H., and Y.D. Methodology: R.Z., M.H., and Y.D. Data processing: L.J. Writing—original draft preparation, R.Z., M.H., and Y.D. Writing—review and editing, All authors have read and agreed to the published version of the manuscript.

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Data availability
Data is provided within the manuscript.

Declarations

Ethics approval and consent to participate
This article does not contain any studies with human participants performed by any of the authors.

Competing interests
The authors declare no competing interests.

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