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# CONSTRUCTIVE ANALYSIS AND DIGITAL 3D RECONSTRUCTION OF THE YUANMINGYUAN RUINS: WANFANGANHE PAVILION (CHINA)

## *ANÁLISIS CONSTRUCTIVO Y RECONSTRUCCIÓN DIGITAL 3D DE LAS RUINAS DEL ANTIGUO PALACIO DE VERANO DE PEKÍN (YUANMINGYUAN): EL PABELLÓN DE LA PAZ UNIVERSAL (WANFANGANHE)*

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### Highlights:

- 3D reconstruction and the production of new detailed documentation of the traditional Chinese architecture elements analysed provide new information about a project of great value.
- The documentation analysis and the virtual reconstruction have allowed us to identify errors in the measurements of the original texts.
- The translation of the original texts from Chinese has allowed completing the project, trying to reduce the language barriers and to strengthen the cultural links between Europe and China.

### Abstract:

The destruction of the Old Summer Palace in Beijing after the sacking by Franco-British troops in 1860 has been an inestimable loss in the history of architecture, described by several authors as one of the wonders of Chinese architecture. This paper presents the virtual reconstruction and geometrical analysis of the Universal Peace Pavilion for the Ancient Palace of Beijing. It is a unique project in traditional Chinese architecture both in its form and in the combination of the wooden structural elements. At present, only the foundation platform remains. In order to achieve a rigorous and accurate reconstruction, sources from China and the Forbidden City Museum have been used; the ancient Chinese texts of the Qing dynasty were translated, and the original existing documentation was compiled. The results include new unpublished documentation of the project. The current reconstruction of the Universal Peace Pavilion continues the efforts made by the "Mission Palais d'Eté" (Summer Palace Mission) between 1983 and 1985, carried out with the cooperation of French and Chinese researchers and architects. Recently, the "Cooperans" institution has resumed the research on the Old Summer Palace in order to strengthen the cultural relations between Europe and China. The digital reconstruction of the Palace makes it possible to visualise, analyse and understand a project in which only ruins remain. By documenting the remains of the ancient ruins and exporting the Wanfanganhe Pavilion to a virtual reality system, it is possible to establish a link between Chinese architecture and the interested people, breaking down language barriers. The process of measuring, three-dimensional (3D) modelling and translating the fundamental elements of traditional Chinese architecture has been carried out with precision, with the objective of generating a 3D model that represents an unforgettable part of Chinese history.

**Keywords:** 3D reconstruction; traditional Chinese architecture; wooden structures; archaeological heritage; Old Summer Palace; digital restoration

### Resumen:

La destrucción del Antiguo Palacio de Verano de Pekín tras el saqueo de las tropas franco-británicas en 1860 ha supuesto una pérdida inestimable en la historia de la arquitectura, que varios autores calificaron como una de las maravillas de la arquitectura china. Este artículo presenta la reconstrucción virtual y el análisis geométrico del Pabellón de la Paz Universal del Antiguo Palacio, con unas características únicas en la arquitectura tradicional china tanto en su forma como en la combinación de los elementos estructurales de madera. Actualmente tan solo se conserva la plataforma de cimentación. Para lograr una reconstrucción rigurosa y precisa, se ha acudido a las fuentes chinas y del Museo de la Ciudad Prohibida, traduciendo los antiguos textos del chino de la dinastía Qing y recopilando la documentación original existente. Los resultados incluyen nueva documentación inédita del proyecto. La reconstrucción del Pabellón de la Paz pretende continuar los esfuerzos realizados por la "Mission Palais d'Eté" (Misión del Palacio de Verano) entre 1983 y 1985, llevada a cabo por la cooperación de investigadores y arquitectos franceses y chinos. Recientemente, la institución "Cooperans" ha retomado las investigaciones sobre el Antiguo Palacio de Verano para fortalecer las relaciones culturales entre Europa y China. La reconstrucción digital del Palacio permite visualizar, analizar y entender un proyecto del que tan solo se conservan ruinas. Mediante la documentación de los restos de las antiguas ruinas y la exportación a sistemas de realidad

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virtual del pabellón Wanfanganhe, se establece un vínculo entre la arquitectura china y los usuarios interesados, suprimiendo las barreras lingüísticas. El proceso de la medición, modelado tridimensional (3D) y la traducción de los elementos fundamentales de la arquitectura tradicional china se ha llevado a cabo con precisión con el objetivo de generar un modelo 3D que represente una parte inolvidable de la historia china.

**Palabras clave:** reconstrucción 3D; arquitectura tradicional china; estructuras de madera; patrimonio arqueológico; Antiguo Palacio de Verano; restauración digital

## 1. Introduction

In China, there is an extensive heritage that shows the richness of its architecture throughout history. Only the ruins remain of an important part of it. Fortunately, the Chinese tradition was ordered to narrate in the ancient texts its existence and explain its history.

Wood has been one of the preferred materials in traditional Chinese architecture. Fires, looting and attacks by insects and fungi have led to the destruction of heritage and the appearance of many structures that are preserved in the form of ruins (Qian, 2009).

The development of tourism in the 19th century became an engine of economic growth in the country, favouring advances in restoration techniques, conservation and enhancement of heritage.

Thanks to the development of new digital techniques, surveys by photogrammetry, laser scanner or virtual reality, it has been possible to increase the reliability of architectural models and to awaken the interest of the government and citizens in the destroyed heritage.

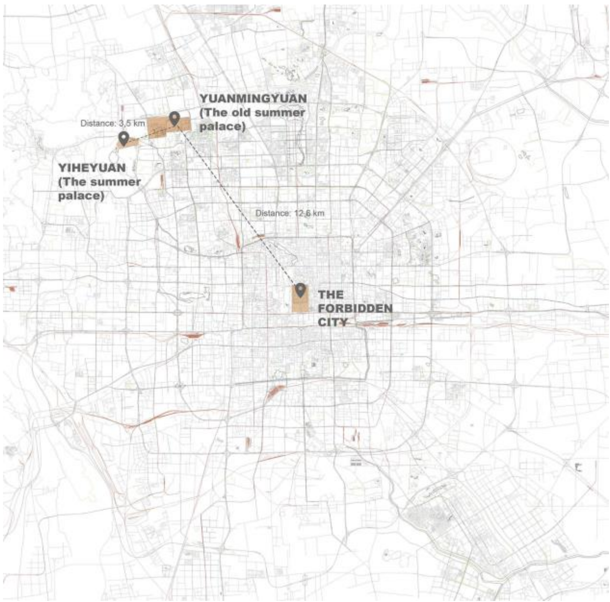


**Figure 1:** Situation plan.

In this project -the Ancient Summer Palace in Beijing- the specifications of the Chinese government have generated some difficulties in carrying out the reconstruction of the ruins of the Palace.

Yuanmingyuan Palace was born as a villa for Prince Yongzheng in 1707, on the outskirts of Beijing (Fig. 1). The villa underwent several expansions to cover an area of 3.2 km$^2$ at its peak, until it was destroyed and reduced to rubble in the Second Opium War in 1860.

The importance of the Palace in Chinese history is due to the fact that it compiled all the types of Chinese construction that existed at the time, the wide range of materials and cultural treasures, and the perfect combination of human architecture with the garden landscape (Gabaldón Guzmán, 2018). It was an architectural project that in turn, served as a catalogue.

**Figure 2:** Fire in the palace. Source: The Academy of Chinese Studies.

Its destruction generated feelings of shock and revulsion, as evidenced by the criticism of the French writer Victor Hugo, in his "Expédition de Chine" (Fig. 2):

> *People spoke of the Parthenon in Greece, the pyramids in Egypt, the Coliseum in Rome, Notre-Dame in Paris, the Summer Palace in the Orient. If people did not see it they imagined it. It was a kind of tremendous unknown masterpiece, glimpsed from the distance in a kind of twilight, like a silhouette of the civilisation of Asia on the horizon of the civilisation of Europe. [...] This wonder has disappeared. One day two bandits entered the Summer Palace. One plundered, the other burned [referring to French and British troops].* (Hugo, 1875, pp. 207-208.)

In 1949, Yuanmingyuan was reopened to the public as a national archaeological park, preserving the ruins in their present state (Fig. 3).

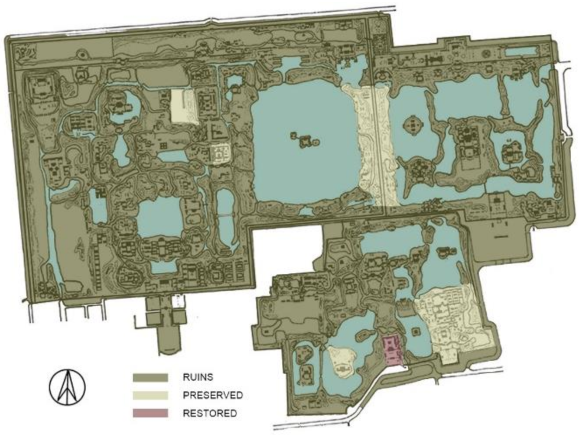


**Figure 3:** Current situation of the palace.

Using current digitisation techniques, supported by the written documentation provided by the Forbidden City Museum and the archaeological park itself, the correct reconstruction for the analysis and digitisation of the Wanfanganhe pavilion is guaranteed. The different elements that make up the wooden structure, a fundamental aspect of the pavilion that gives it a unique character in traditional Chinese architecture, have been studied in depth.

## 2. Historical background

The Old Summer Palace was an architectural and landscape project known for its extensive collection of pavilions and gardens that brought together a diversity of architectural styles and construction techniques.

The construction of summer palaces began in the 17th century with the founding and relocation of the Qing dynasty to the present site of Beijing. Climatic discomfort and the formal layout of the royal palace led the Kangxi Emperor to seek land on the western outskirts of the capital to house pavilions and gardens where he could enjoy the good weather.

The Old Summer Palace was first a villa for Prince Yongzheng, who later in 1722 occupied the throne. The name of the new villa was conceived by his father, Emperor Kangxi, which showed an ideal standard for the feudal ruling class of that time, worthy of a wise and virtuous ruler. In the original language, the words had symbolism: "Yuan" for the perfection of personal virtue and transcendence, "Ming" for wise and brilliant political performance and "Yuan" for the village.

With the ascension to the throne, the villa went from being a place of stay for the prince to a formal palace and seat of the court of the successive emperors of the dynasty, reaching at its maximum splendour an extension of more than 3 $km^2$. With the expansions to the east and southeast, the three gardens that make up the palace were formed (Fig. 4): the Garden of Perfect Brightness (Yuanmingyuan), the Garden of Eternal Spring (Changchunyuan) and the Garden of Elegant Spring (Qichunyuan).

The garden complex was composed of a total of 650 buildings forming 130 landscape scenes. Of these, 40 scenes of the Garden of Perfect Brilliance remained in history, with detailed silk paintings revealing the various picturesque views of the landscape (Fig. 5).


**Figure 4:** Components of the palace.

(a) (b)

**Figure 5:** Garden of Perfect Brilliance: a) Painting of the western part in its original state; b) Aerial view of the current state. Source: Flickriver.

Configured as a catalogue, there was a great diversity of architectural typologies: pavilions, terraces, towers, temples, village houses, halls, markets, theatres, belvederes, bridges, etc. There were 38 different types of layouts and all the types of Chinese roofs used at the time.

Its relevance is due not only to the architectural interventions, but also to the combination of landscaping and religious symbolism. This is reflected in the location where the Universal Peace Pavilion is built. It was located at the "Place of the Supreme" within the Pa Kua, with both political and religious values.

The presence of slopes between different parts of the lake where the pavilion is located allowed a natural slope for the water to flow from the northwest to the southeast. With the intention of creating scenic spaces, mounds of between 2 and 3 m were generated (Duanmu, 2008) slightly exceeding the height of human vision.

As for the levorotatory swastika shape, it refers to the word 卍 which comes from Sanskrit. Meaning "All and eternity", in Buddhism it symbolises light and endless reincarnation, a symbol of the emperor's wish for peace and tranquillity in the world.

The swastika shape allowed temperatures to remain constant inside thanks to the different orientations of the sides. In winter, the north and west sides blocked the cold wind from the northwest, leaving the south and east sides sunny. In hot summers, thanks to the cross-ventilation, the temperature inside the water was much cooler than on the shores. The harmony was a metaphor for the four seasons, the intertwining of light and dark in December and the change of yin and yang.

The pavilion was located in the centre of two axes traced by two dikes parallel to the thistle and decumanus in the form of Ruyi (talisman symbolising power and good fortune) (Fig. 6). The thistle ended in a small pavilion in the form of a Greek cross attenuating the abrupt shape of the swastika.

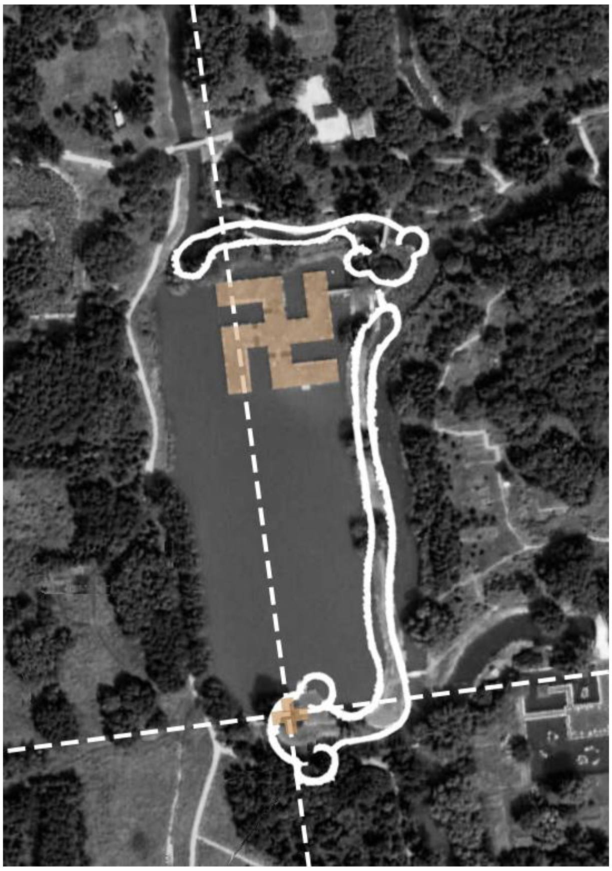

**Figure 6:** Environment map with the axes.

The destruction of the Palace was brought about by successive events during the 19th and early 20th centuries: looting and burning during the Second Opium War, the destruction of buildings and gardens by the Eight Nations Alliance, and finally its destruction related to the supply of materials (Lee, 2009). This made it a symbol of foreign aggression and testimony to the decline of the last Chinese dynasty. Currently, 90% of the Palace is in a state of ruin, and only a small part has been rebuilt.

## 3. State of the art

In 2010, Tsinghua University gathered a team of experts in the field of architecture, archaeology and virtual reality initiating the Re-Relic project for the digitisation of Chinese heritage. The research was focused on the conservation of cultural heritage and the advancement of multidisciplinary research (He, Gao & Shang, 2013).

Today, little technical information on digitised buildings can be found. The motivation for the present article is due to the lack of detailed and comprehensive documentation on the Wanfanganhe Pavilion, a unique building in the history of Chinese architecture.

The surviving documentation of the aforementioned building includes five topographical plans and a model preserved in the National Library of China (Zhu, 2004). The historical texts are kept in the museum of the Forbidden City (Duanmu, 2008).

It is worth mentioning the visual contribution of the pictures painted in 1744 under the name of the forty scenes of Yuanmingyuan, preserved in the national library of France.

The original documentation and texts are preserved only in their original language -Mandarin Chinese- having been translated for this work. On the other hand, the units of measurement used are those of the time in China, converted to the International System and incorporated in the appendix (Wang, 1996).

The work done by Renhao Liu "Studies on the Nine Poems of Wangfanganhe: Interior spaces in paintings, models and documents" (Liu, Liu & Zhao, 2016) is preserved in the archives of Tsinghua University. It collects and organises the existing information and the set of photographs in situ of the ruins, facilitating the virtual reconstruction.

Finally, it is worth mentioning the work carried out by the "Mission Palais d'Eté" (Summer Palace Mission) between 1983 and 1985, developed with the cooperation of French and Chinese researchers and architects.

Similarly, the "Cooperans" institution (2021) has expanded research on the Old Summer Palace, seeking to strengthen cultural links between Europe and China.

## 4. Methodology

The first step in the implementation of the project has been the collection of the original documents about the Old Palace and the Peace Pavilion.

Much of the information is not accessible from the outside and is restricted to researchers. The Forbidden City Museum conducts comprehensive journal publications on cultural heritage topics, being another source of information (Liu et al., 2016).

The original texts describing Wanfanganhe were written in the 18th century, using the terminology of the time and traditional measurement systems. In the history of Chinese construction, each dynasty used a different measurement. In this case, the palace corresponds to the Qing dynasty and the use of Chi, equivalent to 0.32 m.

In order to carry out the reconstruction of the project, it was necessary to organise and hierarchise the wooden structures. The three-dimensional (3D) reconstruction of the building has brought to light certain inaccuracies in the description of the original texts.

Based on the plan projection and knowing the arrangement of the columns, the vertical elements of the structure could be surveyed. From there, the division of the levorotatory shape of the swastika into 33 squares and the proportions for its modulation were obtained.

The joints of the different timber structural elements were solved using the mortise and tenon technique. The automation of modelling processes through the development of a parametric algorithm has accelerated the virtual reconstruction (del Blanco & García, 2017).

On the other hand, for the interpretation of the data obtained on the pavilion, the sections and plans of the purlins of the timber structure were consulted (Liang, 2006).

As a tool for the 3D modelling of the pavilion, it was decided to use Rhinoceros 3D v. 7. NURBS surfaces allow operating with a high level of accuracy. The 3D visualisation greatly simplifies the resolution of details of the construction elements (del Blanco & García, 2018), as well as the understanding of their geometry (Kuo et al., 2018; Aparicio-Resco, García Álvarez-Busto, Muñiz-López & Fernández-Calderon, 2021). The appearance of errors and inaccuracies in the original documentation is not surprising, considering the drawing tools of the time (Arayici et al., 2017).

Grasshopper (module included in Rhinoceros) has enabled the design of algorithms for the automation of tasks for virtual reconstruction, reducing execution time and minimising the possibility of errors in the elaboration of repetitive tasks (del Blanco García, 2022).

Recently, architects and craftsmen have made similar approaches in the realisation of the Sagrada Familia for the understanding of its complex geometries (Souza, 2021).

Also from Grasshopper, different iterations of the 3D model have been defined to be exported to real-time rendering engines and virtual reality (Parrinello, Bercigli & Bursich, 2017). The optimisation of the 3D model plays a fundamental role in order to achieve low rendering times (8 ms) and enabling a proper immersive experience through these systems (Schulze, 2021).

The transformation from NURBS to meshes is necessary to work efficiently with real-time rendering engines. This transformation may generate a decrease in model accuracy on curved surfaces. To avoid this problem, multiple iterations of the model have been made with different resolutions, which will be combined from the rendering engine (Banfi, 2020). The number of subdivisions of the mesh has been adapted proportionally to the radius of curvature of the surfaces, decreasing the smaller the curvature. The subdivision algorithm developed by Catmull and Clark (1978) has made it possible to work with a low initial number of polygons while maintaining the smoothness of the curved surfaces.

After the virtual reconstruction of the model and the aforementioned adjustments to achieve an adaptable and lightweight file, it has been possible to export it to real-time rendering engines (Pybus, Graham, Doherty, Arellano & Fai, 2019) that in turn have allowed its easy preparation for a virtual reality system (Garcia, 2021). For this purpose, Unreal Engine 5 has been the main software used, and in a more automated way Lumion 12. In this way, it has been possible to reproduce it on electronic devices with low specifications (smartphones, tablets and touch screens), to promote greater accessibility to the new documentation (Aparicio & del Blanco, 2022).

From Unreal Engine 5, we have imported the models generated with different mesh resolutions, programming when to display more or fewer polygons on the meshes. When the camera is placed close to an object, the meshes are displayed at high resolution. In this way it is possible to manually define the number of polygons to be displayed in the rendering phase, setting the accuracy of the model from the engine in real-time (Banfi, Brumana & Stanga, 2019; Trunfio, Lucia, Campana & Magnelli, 2021; Brumana, Stanga & Banfi, 2021).

This process could have been done automatically using "Nanite" (2021), the new rendering technology developed for Unreal Engine 5. "Nanite" uses a new internal mesh format to render pixel scale detail and high object counts (Karis, Stubbe & Wihlidal, 2021). However, for this reconstruction we did not use "Nanite", as doing the work manually provides more control over the final output.

Photo-realistic quality has been sacrificed to obtain an efficient scene capable of being rendered on low-spec systems or cell phones. After optimisation of the model, it has been possible to render the scene in real-time at 120 frames/s, which is equivalent to a time of 8 ms to render an image (Fig. 7).

**Figure 7:** Image capture of the real-time sequence.

To achieve these rendering times, the use of dynamic lighting has been avoided in favour of static lighting, storing the light and shadow information in "lightmaps". Also, displacement maps were not used because of the higher system requirements. The use of the "raytracing" rendering method was avoided, in favour of the traditional "rasterisation" method, due to the need to use high-end graphics cards with the RTX technology developed by Nvidia (del Blanco, 2021; Gironacci, 2021).

Once the files have been prepared, Unreal Engine allows automated export of the model to different virtual reality systems. The files have been optimised to reduce their weight for playback on cell phones, generating an immersive experience that allows revisiting the Peace Pavilion after more than 150 years (Ioannides, Magnenat-Thalmann & Papagiannakis, 2017).

An alternative procedure has employed the combination of Rhinoceros and Lumion, which can be automatically synchronised using the LiveSync plug-in. It is thus possible to work simultaneously in both software, allowing real-time visualisation while progressing through the modelling phase. Lumion is a highly automated software, with a large number of presets and elements ready for visualisation. Flexibility, customisation and interaction possibilities are less than with the previous procedure (UE5), but this speeds up the work process considerably.

It should be noted that the use of a real-time rendering engine has also made it possible to immerse oneself in the project, making it easier to detect errors, as well as pose hypotheses.

## 5. Digital reconstruction

The different elements (roof tiles, wooden roof, wooden structure and stone platform) that make up the pavilion structure are detailed below (Fig. 8).

### 5.1. Wooden structure

The structure used in the pavilion follows the "seven-purlin" stacked timber beam configuration (Fig. 9), traditional in the northern part of China. In the four wings and in the centre, the beams are joined to form a cross structure (Ma, 1991).

Two rings of columns, 68 on the inside and 92 on the outside, support the eaves. The spans between the main columns, called "rooms", follow the geometry of the square of side 4.48 m. In total there are 33 "rooms" for different uses (Fig. 10).

The measures of the pieces that compose the main structure are described in the collection Nº 227792 of the Tongji University Library, being necessary to convert the measures to international units. Each dynasty established its construction measures and structural standards applied to wooden constructions with a strict relationship between each piece (Pan & He, 2017).

The measurements of the eave columns are the ones that determine the rest of the elements, being the first to be fixed (Tab 1). Each typology of structure establishes rules that set the differences between the elements. In this case, being a "seven purlin" structure, the rules of the central "five purlins" structure located between the perimeter columns are followed.

For the construction of the pavilion, a platform is built 0.59 m above the foundation. It is visible above the sheet of water that forms the lake. The platform consists of three layers in ascending order: a layer of stone, three layers of brick and the surface layer. It has drainage channels in the centre of each side of the swastika (Fig. 12).

The eave columns are located at a distance of 1.28 m from the central structure, forming cloisters. The pavilion is connected to the shores of the lake by two bridges to the east (one of stone and the other of wood, which was later restored with stone), as can be seen in the photographs of the ruins (Fig. 11). On the south side, the dock for access by boat is located.

The connection between the columns is made by beams, with its outer side resting on the eave column and the inner side being embedded. To improve the stability of the whole, intersecting pieces called "nukis" are used following the mortise and tenon techniques. Traditional Chinese wooden structures take great care with the joints between each element, avoiding the use of nails and screws (Aira, Cabo, del-Blanco & Gonzalo, 2022). For this reason, when cutting the timber logs, the holes for the beams and the "nukis" that will cross the column are drilled beforehand (Fig. 13).

The rigid jointed-plane frames are connected by purlins, attached to purlin supports at the bottom and supported on beams. Between the main columns, reinforcement beams are embedded to balance the loads received at the top (Fig. 14). In the case of smaller buildings, this element could have been omitted.

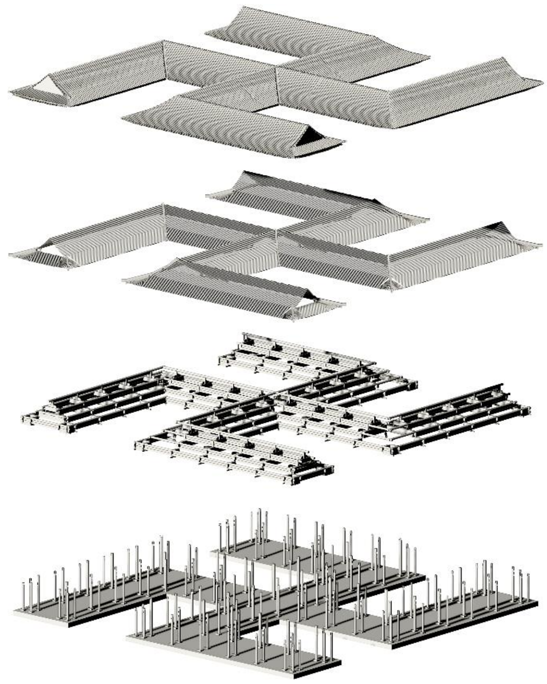

**Figure 8:** Exploded view of the complex. Wanfanganhe Pavilion.

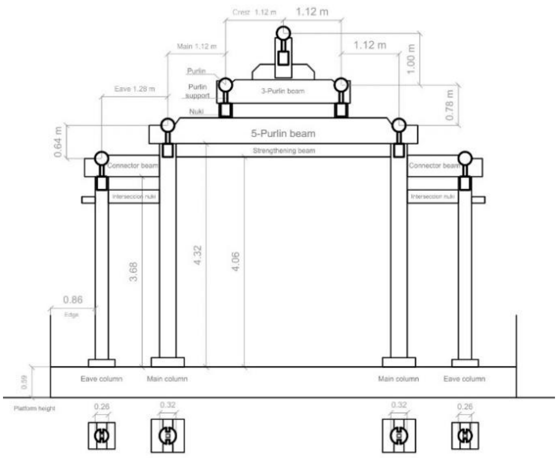


**Figure 9:** Section of the “seven purlins” stacked beam timber structure.

**Figure 10:** Plan with the arrangement of the columns.


**Figure 11:** Existing bridge ruins on the site and their location on the map: stone (1,2,3,4) and wooden (5), stone. Source: Tsinghua University digital archive.

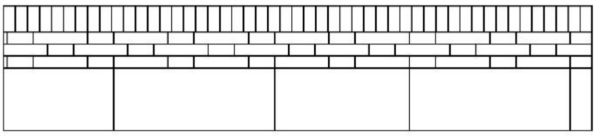

**Figure 12:** Front view of the platform that supports the palace

**Table 1:** Table of dimensions of the timber parts

| *Denomination* | | *Height (m)* | *Ø Width (m)* |
|---|---|---|---|
| 檐柱 | Eave column | 3.68 | 0.256 |
| 金柱 | Main column | 4.32 | 0.32 |
| 五架梁 | 5-Purlin beam | 0.5 | 0.384 |
| 三架梁 | 3-Purlin beam | 0.436 | 0.32 |
| 随梁枋 | Strengthening beam | 0.436 | 0.256 |
| 抱头梁 | Connector beam | 0.416 | 0.32 |
| 金枋 | Main nuki | 0.256 | 0.192 |
| 檐枋 | Eave nuki | 0.256 | 0.192 |
| 脊枋 | Crest nuki | 0.256 | 0.192 |
| 穿插枋 | Nuki intersection | 0.256 | 0.192 |
| 檩 | Purlin | / | 0.256 |
| 金垫板 | Main strap support | 0.224 | 0.07 |
| 脊垫板 | Crest strap support | 0.224 | 0.07 |
| 檐垫板 | Eave strap support | 0.224 | 0.07 |
| 脊瓜柱 | Ridge support | 0.256 | 0.07 |
| 台明 | Platform height | 0.592 | / |
| 下出 | Platform edge | 0.864 | / |
| 檐椽 | Eave rafter | / | 0.07 |
| 飞椽 | Flying rafter | / | 0.07 |

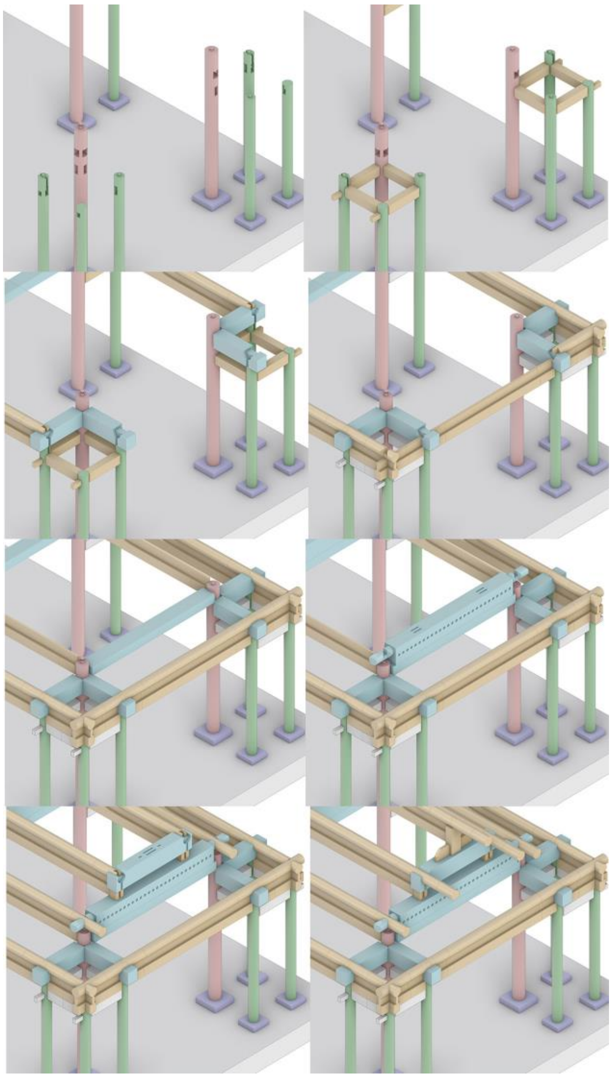

**Figure 13:** Construction process of the “seven purlin” stacked timber beam structure.

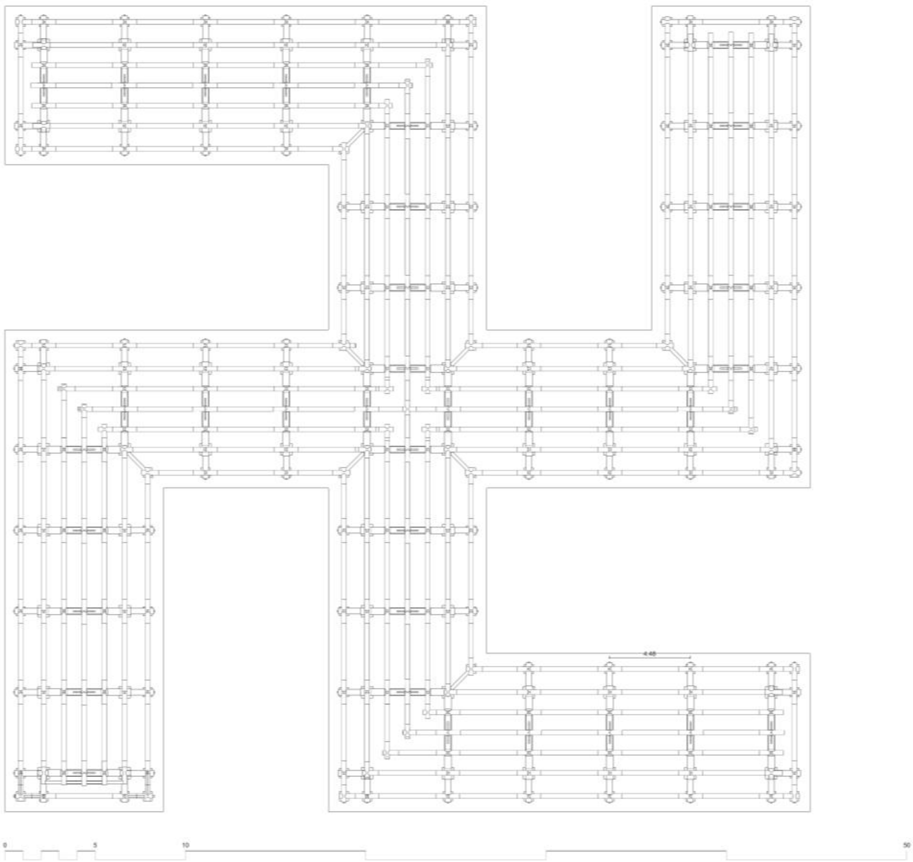

**Figure 14:** Plan of the structure.

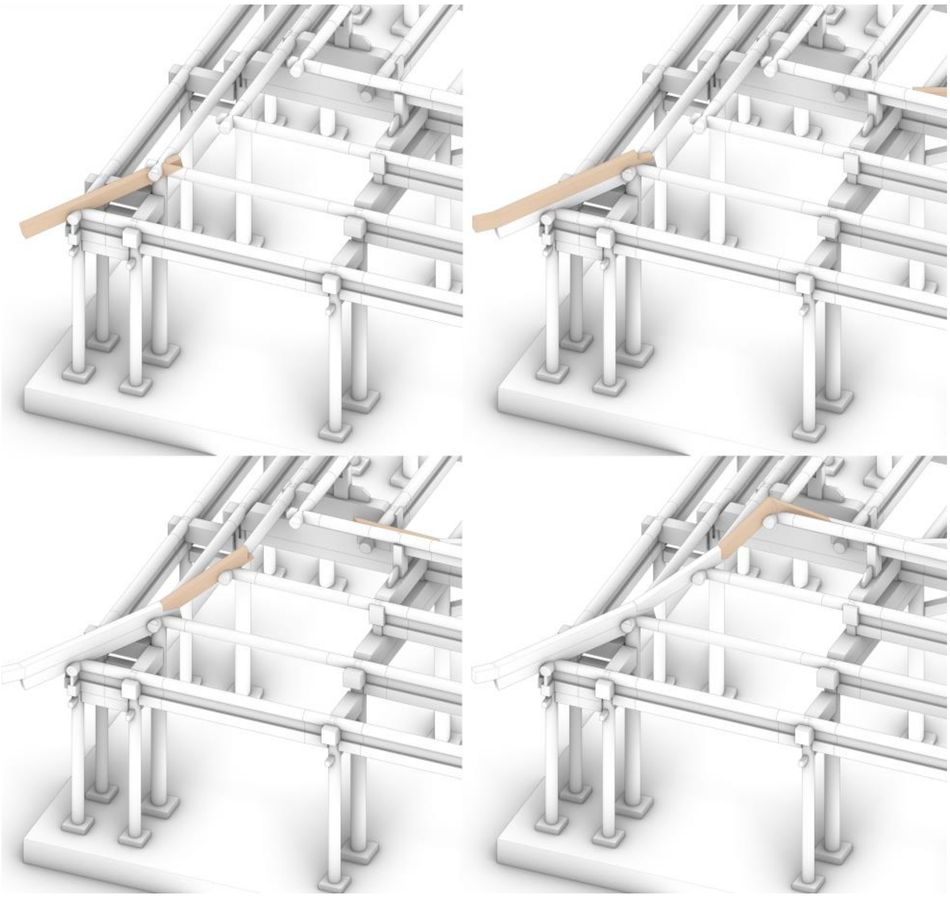

**Figure 15:** Construction process with edge beams at the corners.

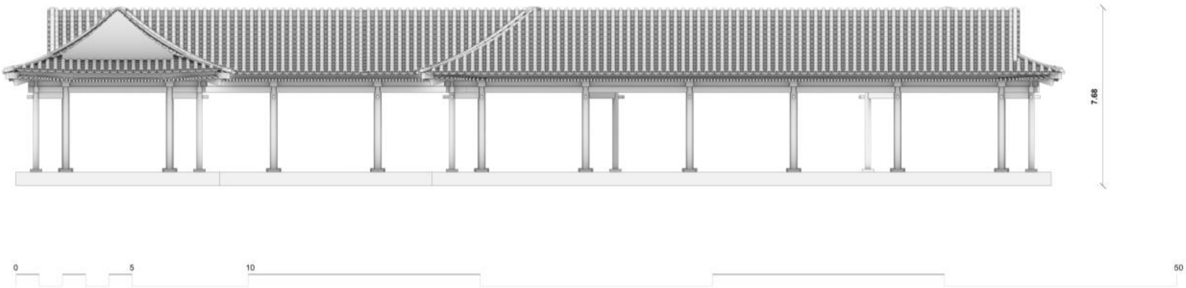

**Figure 16:** Front view of the pavilion.

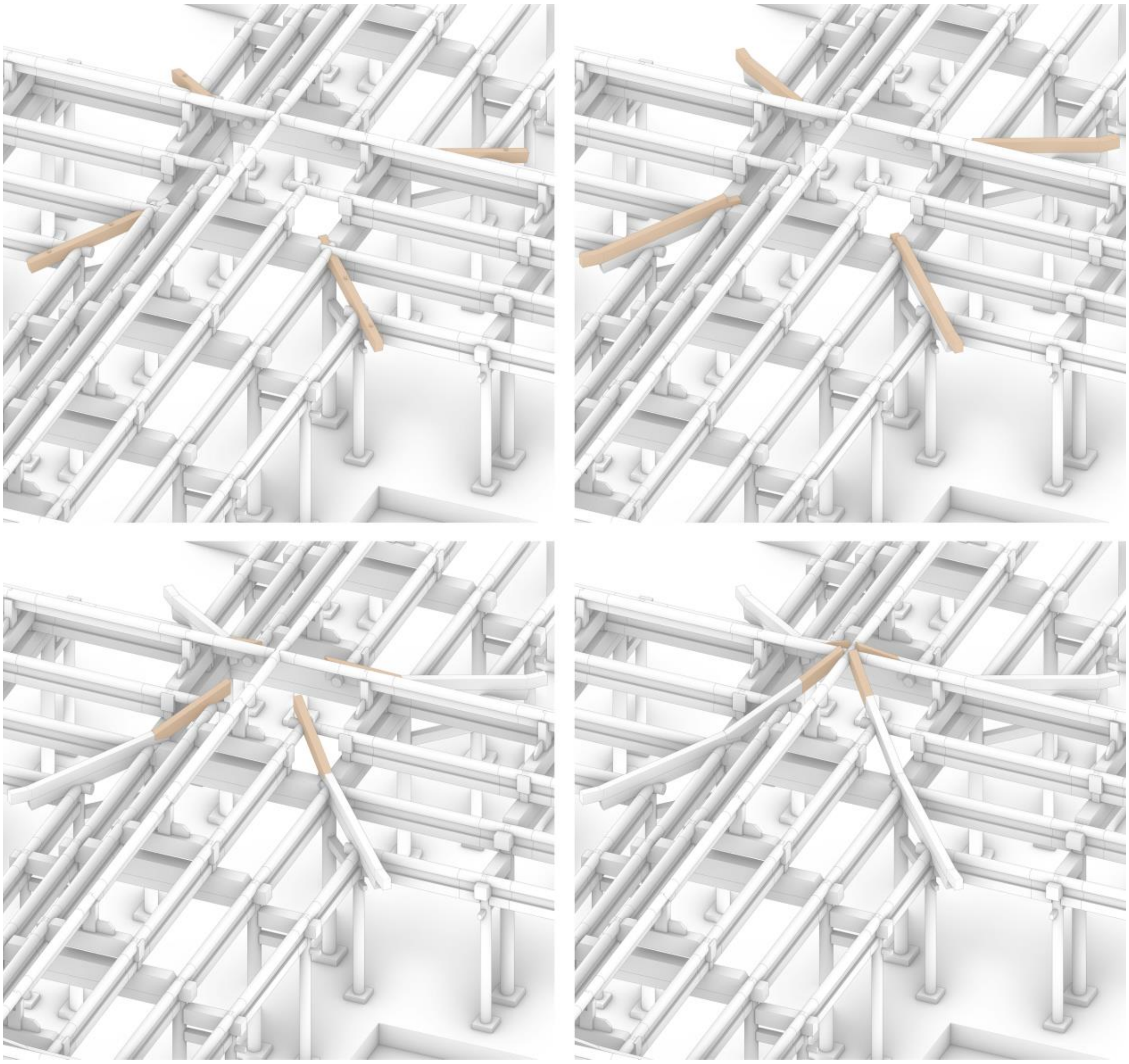

**Figure 17:** Construction process with edge beams in the central section.

The "seven purlin" stacked beam structure has five purlins in the central span forming a symmetrical triangle. The "five purlin" beams rest on the main columns and the "three purlin" beams on the "five purlin" beams. The last purlin is inserted into the "three purlin" beam by anchoring the ridge support (Fig. 15).

There are singular points due to their swastika shape, a combination of L-shape and Greek cross. At the L-shaped corners, edge beams are used for stability, and this is where purlins and beams from opposite directions overlap (Fig. 16).

In the central part, purlins from the four directions converge. The existing documentation does not allow us to define this connection. The hypothesis taken is to combine the structure defined in corner L. The hypothesis of using single purlins is discarded because of the characteristics of the structure (Fig. 17).

### 5.2. Wooden and slate roof

In the Ming and Qing dynasties, the roofs of imperial buildings could be classified into four types (Fig. 18). They could be further subdivided if they had a ridge beam or if the ridge beam was replaced by a curved ridge. By combining the different types, it was possible to obtain composite forms such as L, 工, 十, 卍, etcetera.

In the case of Wanfanganhe, two types of roofs were used: the "saddle roof" at the ends and the "suspension roof" in the middle, both with a curved ridge (Liang, 2006). Following the basis of the "seven purlins" structure, a unique beam (Fig. 19) of this type of roof is introduced to replace the "five purlins" beam. Its body resembles a beam and the two ends resemble purlins, categorising it as a beam. In the central section, the holes are drilled to support the eave rafters. As they are inclined, the perforations result in ellipses of width 1.12 times the diameter of the rafters and the height of the diameter.

To give the impression of a light roof, the ends were usually raised slightly. The corner rafters rested on sawtooth-shaped support and were embedded in the edge beam, gradually turning as they approach the corners (Fig. 20).

Round rafters were used in imperial buildings, and square rafters were also used for smaller buildings. The number of corner rafters is determined by the following formula:

$$\text{Number of corner rafters} = \frac{(\text{Corridor width} + \text{Eave overhang distance})}{(\text{Eave rafter thickness} + \text{Eave rafter width})}$$

Resulting measurements in cm:

$$13 \text{ rafters} = \frac{(128 + 86)}{(7 + 10)}$$

Once the eave rafters are in place, they are reinforced with a rectangular wood batten and serve as a support for the wood panels that are placed later (Fig. 22). To further accentuate the feeling of lightness at the tips, flying rafters are placed to give the eaves a greater inclination, then the same process is repeated until you end up with a smooth wooden surface (Fig. 21).

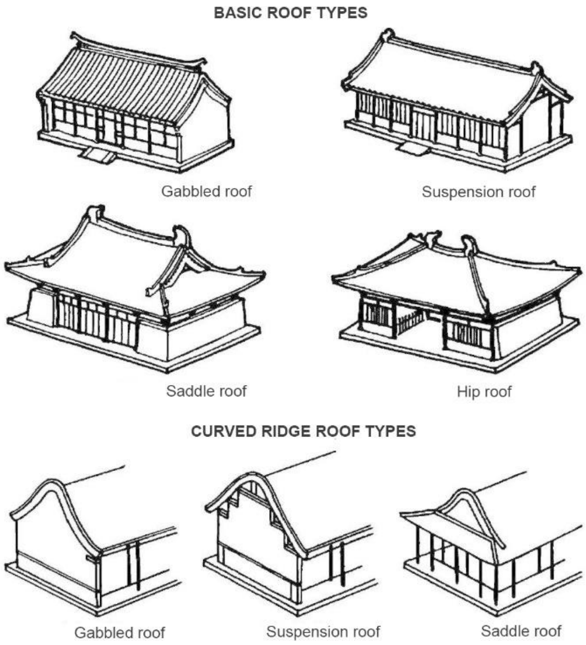


**Figure 18:** Types of roofs in the Ming and Qing dynasty. Source: Yao (1986). "Yingzaofayuan".

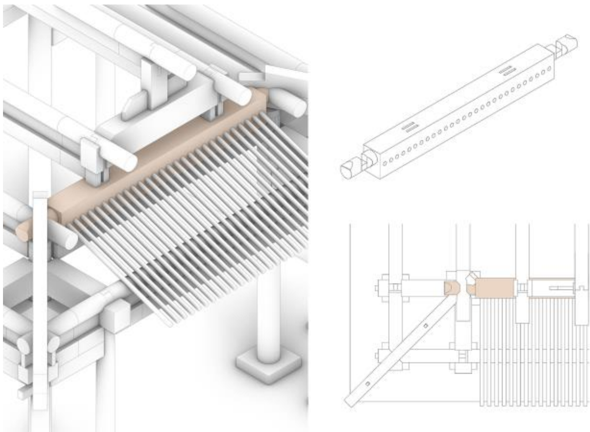

**Figure 19:** Assembly of the structural elements of the roof.

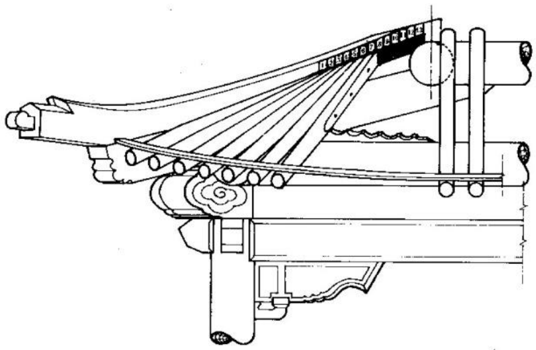

**Figure 20:** Roof construction process at the corners. Source: Ma (1991, p. 227).

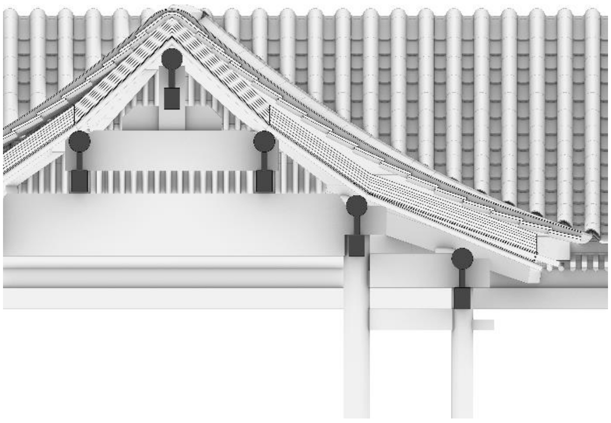

**Figure 21:** Section of the roof.

**Table 2:** Materials forming the layers under the shingles

| *Layer* | *Function and composition* |
|---|---|
| Base | Wooden panels |
| Protective layer | Mix of lime with fibres. 1 layer 15 mm thick |
| Waterproofing and insulating layer | Bamboo fibre layer. 3 layers each 40 mm thick |
| | Layer of lime powder and graphite. 2 layers of 20 mm each |
| Mortar layer | Layer of clay and lime. 1 layer of 40 mm thick |
| Roof tiles | Top tile on every other bottom tile. 40 x 33.60 cm |

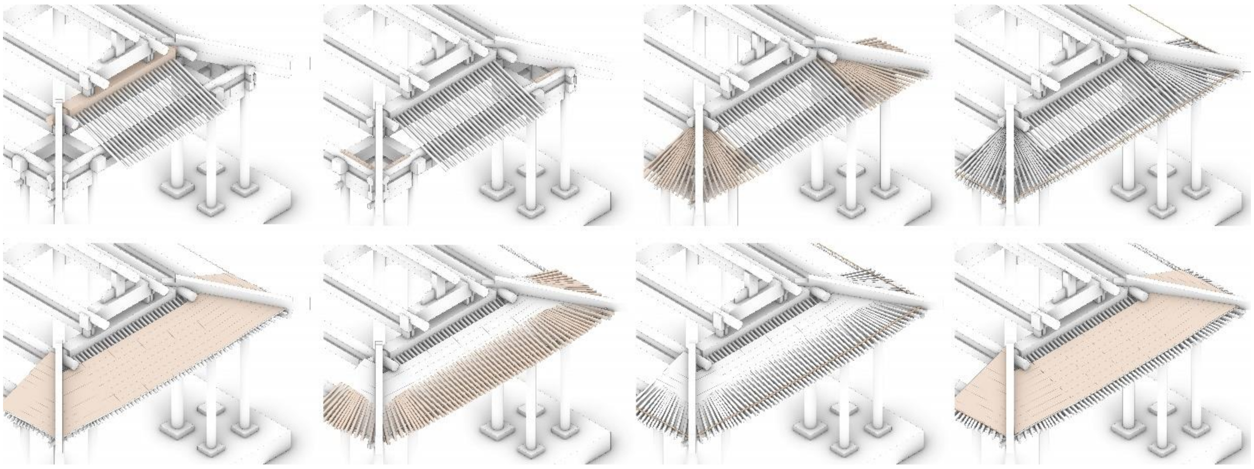

**Figure 22:** Saddle roof construction process.

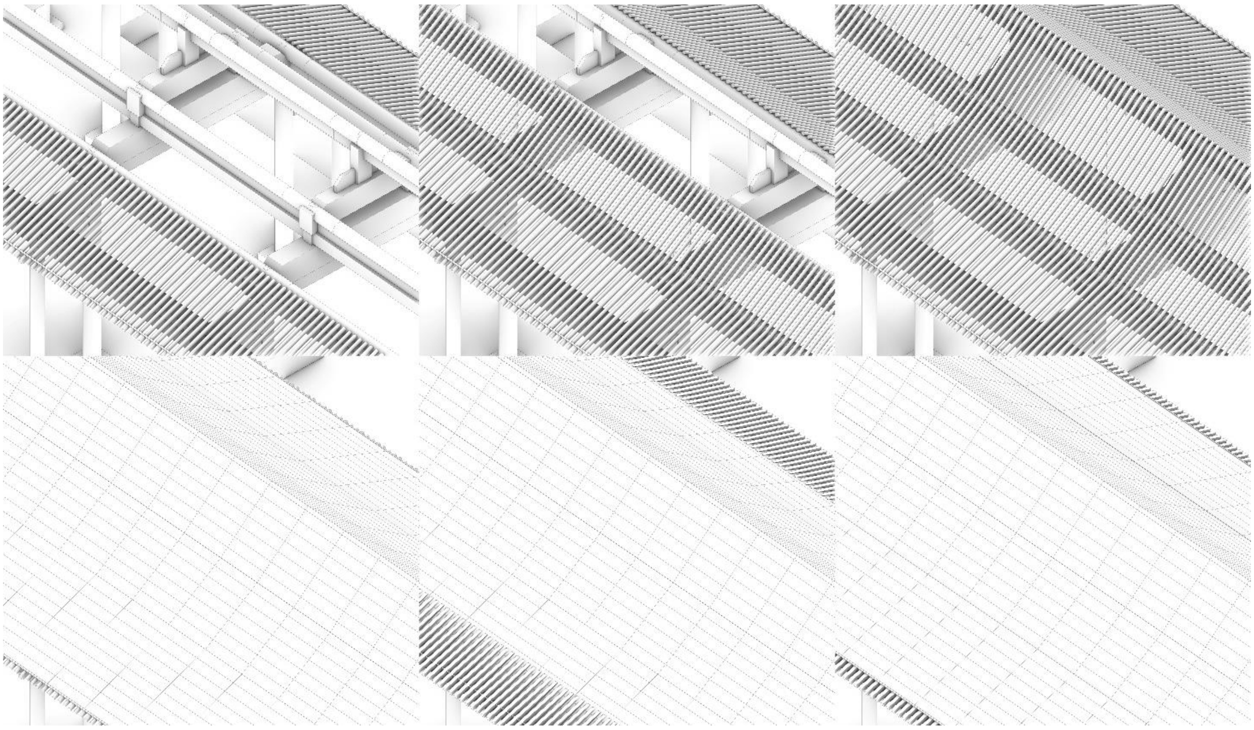

**Figure 23:** Construction process of the suspension roof.

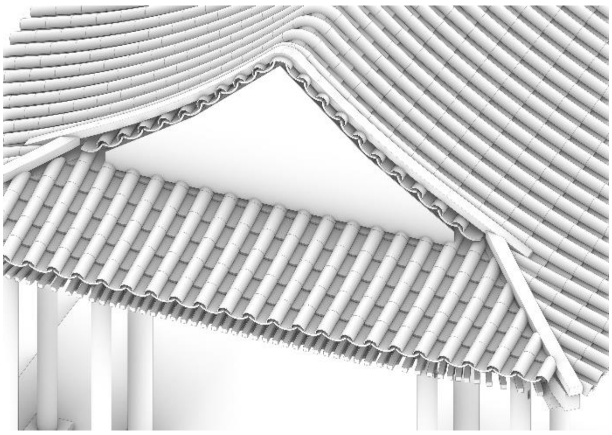

**Figure 24:** Top view of the roof.

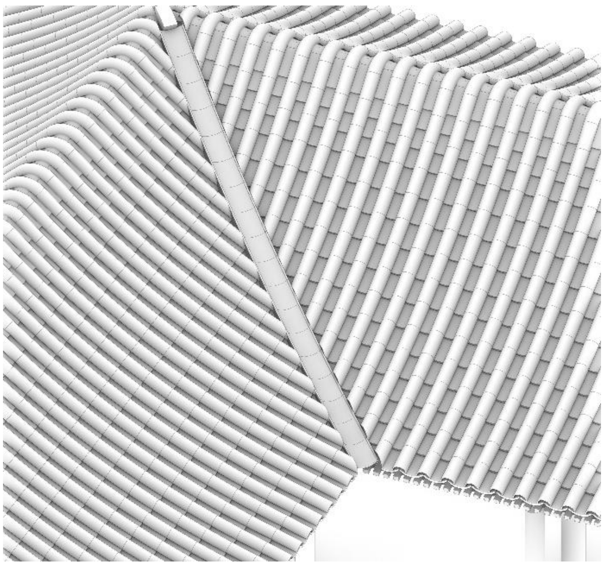

**Figure 25:** Singular point of the roof.

On the sides, the roof is gabled with straight and overhanging slopes, of the "suspension roof" type (Fig. 23). Between two purlins, a row of eave rafters is supported, thus forming 3 rows of different inclinations and connected to each other. Wooden panels are placed on top of the rafters, followed by flying rafters and finally another layer of wooden panels.

Several layers of different protection and insulation materials are added on top of the wood deck (Tab 2). The final layer consists of barrel tiles with semi-cylindrical shingles covering the joint of the curved base tiles. The arrangement of the slate tiles is such that the upper shingles cover 3/10 of the lower shingles on each side.

As the ridge roof is curved, special curved tiles are used in the centre of the structure to give the continuity of the barrel (Fig. 24). At the lower end of the roof, cylindrical tiles are used, the tops of which are decorated with simple figures.

At singular points such as the interior corners where two directions of water drainage overlap, flat U-shaped tiles (Fig. 25) are used to form the drainage gutter through which the water drains.

## 6. Discussion

Through digital documentation techniques, it has been possible to obtain an in-depth study of the ruins of the Universal Peace Pavilion in its original state.

On more than one occasion attempts have been made to reconstruct the pavilions and landscapes of the Old Summer Palace, but it has not been possible due to economic reasons. The difficulty has been aggravated by the lack of archaeological and historical documentation, lost in the looting and burning of the palace. At present, most of the three gardens remain in ruins, so the new digital documentation provides valuable information and contribution to the complete reconstruction of the Old Palace.

Being an architectural heritage belonging to the royal family, information is restricted to the professional and academic fields. The only sources accessible to the public are the comprehensive publications of the Forbidden City Museum in collaboration with the academic works of Tsinghua University, as well as the previous work of collecting and arranging the information of the pavilions (Liu, 2015).

For the study and modelling of the timber structure, being a unique shape and layout of the pavilion, it was necessary to resort to solutions with different types of purlin structures (Liang, 2006; Ma, 1991; Yao, 1986). Their combination resulted in the cross shape shown in the reconstruction (Fig. 26).

Another difficulty encountered was the constructive and geometric resolution of the roof. Unlike the rest of the spaces, the existing model of the pavilion does not show the structure under the layer of tiles. For the hypothesis proposals, it was necessary to resort to specialised texts on traditional Chinese timber construction and written documents on the pavilion (Ma, 1991; Lian, 2006; Qian, 2009).

During the reconstruction of the pavilion, some inaccuracies appeared in the original documents. For example, the height of the "three purlins" girder does not correspond to the description in the texts. According to the standard for "seven purlins" structures, the distance between the first purlin row and the second purlin row should be 1 m. This distance should correspond to the purlin radius, the height of the purlin support, the ridge "nuki" and the base support, each being 0.128 + 0.256 + 0.256 + 0.256 + 0.256 = 0.896 m. Adding the height of the "three purlins" beam would give 0.896 + 0.44 = 1.336 m. However, this distance should be 1 + 0.128 + 0.256 = 1.384 m, corresponding to the radius and support height of the purlin. In conclusion, a distance of 0.048 m would be missing in its height.

The reproduction of the pavilion using a real-time rendering engine allows a better understanding of the pavilion and favours its accessibility for all types of audiences. The performance of the scene in low specification devices has been prioritised over obtaining a photo-realistic quality, in order to facilitate its access and subsequent dissemination.

## 7. Conclusions

The reconstruction of the Peace Pavilion, Wanfanganhe, has made it possible to generate non-existent documentation about a project of great relevance in traditional Chinese architecture. By exporting the optimised model to virtual reality systems, it has been possible to generate an immersive experience through cell phones, available to most users.

Wanfanganhe presents a unique swastika shape in the history of traditional Chinese architecture. Considering the Buddhist beliefs of Emperor Yongzheng, it can be considered that he took the figure 卍 from Buddhist symbology. The infinite knot, known as Srivatsa in Sanskrit, presents a strong religious significance employed as a symbol of good luck, life and protection. The figure in Buddhism symbolises the seal of the Buddha's heart, representing eternal harmony. In this way, Yongzheng wanted to manifest the legitimacy of his ascension to the throne and his desire to be worshipped as the saviour of the people.

When comparing the dimensions of the original scale model and the virtual reconstructed model, there is a difference between their proportions, with the scale model being more slender. This is due to the fact that, at the time of making the models, the vertical proportions were exaggerated so that the spectator who observed it from a higher point of view would appreciate it taller.

The documents generated show the functionality of the wooden structures, exposing the joints hidden behind the impeccable appearance perceived from the outside (Fig. 27). They have made it possible to analyse the roof and the construction techniques employed, facilitating the dissemination of traditional Chinese architecture techniques.

This article aimed to show not only the pavilion as a whole but also the construction techniques used, as a catalogue. It remains open for future work the incorporation of an interactive system that will allow showing through virtual reality the different assemblies of the wooden structural elements. It is intended to generate a didactic scene in which non-technical users will be able to interact and not only observe.

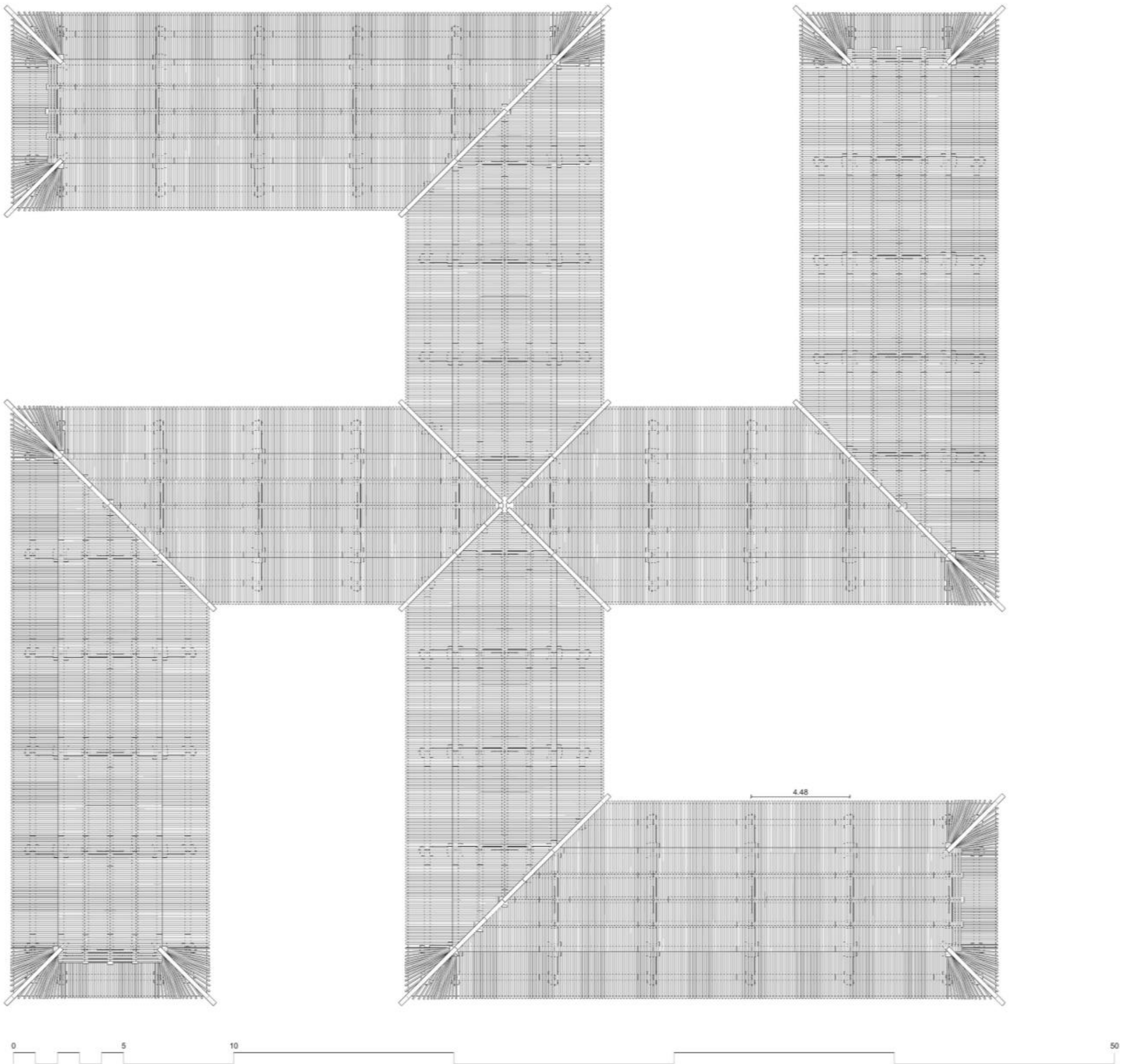


**Figure 26:** Plan of the roof structure.

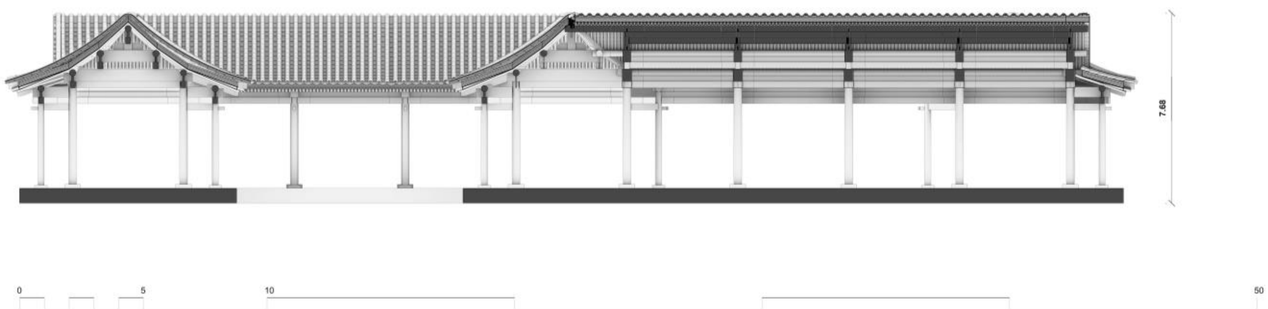


**Figure 27:** Section of the structure.

## 8. Appendix

During the compilation of this documentation, it has been noted that all the documents were exclusively in Chinese, which is an impediment for researchers or architects without knowledge of this language. Texts, construction elements and units of measurement would be indecipherable without a translation.

For a better understanding of the functioning of wooden structures and their components in ancient Chinese construction, a translation of the main elements has been prepared.

MEASUREMENT UNITS:

ZHANG (丈): Traditional measurement equal to 3.2 m and which is then divided into 10 Chi.

CHI (尺): Traditional measurement equal to 0.32 m and which is then divided into 10 Cun.

CUN (寸): Traditional measurement equal to 0.032 m and which is then divided into 10 Fen.

FEN (分): Traditional measurement equal to 0.0032 m.

STRUCTURE

EAVE COLUMN (檐柱): Column under the eaves, usually the external part of the corridor.

MAIN COLUMN (金柱): Column under the roof, usually the inner side of the corridor.

5-PURLIN BEAM (五架梁): A beam supported by 5 purlins that is supported by main columns.

3-PURLIN BEAM (三架梁): 3 purlin beams supported on 5 purlin beams by its bearers.

STRENGTHENING BEAM (随梁枋): Beam that rests on the columns and supports the load at the upper end.

CONNECTOR BEAM (抱头梁): Beam that connects the eaves column to the main column by strengthening the joints.

MAIN NUKI (金枋): Connecting element between two longitudinally arranged main columns.

EAVE NUKI (檐枋): Connecting element between two longitudinal eaves columns.

CREST NUKI (脊枋): Connecting element at the top of the structure.

INTERSECTION NUKI (穿插枋): Element to increase the stability between columns.

PURLIN (檩): A secondary structure that is carried on top of the main beams.

MAIN STRAP SUPPORT (金垫板): Element that supports the main purlin and in turn the nukis.

CREST STRAP SUPPORT (脊垫板): Element that supports the crest strap and in turn the nukis.

EAVE STRAP SUPPORT (檐垫板): Element on which the eave purlin is supported and in turn on the nukis.

RIDGE SUPPORT (脊瓜柱): Used to carry the crest eave purlin holder.

PLATFORM HEIGHT (台明): The part that extends above the ground line to raise the building.

PLATFORM EDGE (下出): The part of the base that stands out.

ROOF

EAVE RAFTER (檐椽): A batten that lies on the purlins to create the roofs.

FLYING RAFTER (飞椽): A batten that is placed on the eaves rafters to slightly lift the border of the eaves.

EDGE BEAM (递交梁): Beams on which purlins are placed at the corners.

SADDLE ROOF (歇山顶): A two-slope roof with a gable on the shorter sides.

GABBLED ROOF (硬山顶): A roof with two straight slopes without overhanging the building line.

SUSPENSION ROOF (悬山顶): Type of roof with overhanging eaves.

HIP ROOF (庑殿顶): Roof with all sides sloping.

CURVED RIDGE (卷棚): Roof without ridge beam and curved ridge.

FOOTPRINT BEAM (踩金步): Exclusive beam of the saddle roof, where the eaves rafters are recessed.

CORNER RAFTERS (翼角椽): Batten that rests on the purlins to form ceilings at the corners, raising slightly as it approaches the edges.

EAVE BORDER (连檐): The rafter that strengthens the supporting purlins of the eaves rafters and flying rafters.

WOOD PANELS (望板): Panels that are placed on top of the eave rafters.

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