Exploration and Design of the Contemporary Bracket Set Through Topology Optimization

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Abstract. Dou Gong, pronounced in Chinese, and known as Bracket Set, is a vital support component in the ancient wooden tectonic systems. It is located between the column and the beam and connects the eave and pillar, making the heavy roof extend out of the eaves longer. The development of the bracket set is entirely a microcosm of the development of ancient Chinese architecture; the aesthetic structure and oriental artistic temperament behind the bracket make it gradually become the cultural and spiritual symbol of traditional Chinese architecture. In the contemporary era, inheriting and developing the bracket set has become an essential issue. This paper introduces the topological optimization method bi-directional evolutionary structural optimization (BESO) for form-finding. Through analyzing the development trend of bracket set and mechanical structure, the authors integrate 2D and 3D optimization methods and apply the hybrid methods to form-finding. This research aims to design a new bracket set corresponding to "structural performance-based aesthetics." The workflow proposed in this paper is valuable for architrave and other traditional building components.

Keywords: Bi-directional Evolutionary Structural Optimization (BESO) · Bracket set · Structural form-finding · Heritage building · Architectural component

1 Introduction

Chinese ancient architecture has a long history and a self-contained system based on a wooden framework. The development of the timber frame has also become the central vein of China's architectural development. The bracket set plays an essential role in the Chinese wood tectonic system. It symbolizes the feudal hierarchy, and an indispensable cultural character in traditional Chinese architecture. In an era where digital design is booming, how can the conventional bracket set be combined with advanced structural form-finding methods to create a new derivative of the bracket set that incorporates ancient and modern elements? The inheritance and innovation of the bracket set have become a significant concern.

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2 Translations and Derivation Practices of the Bracket Set

From a contemporary standpoint, a few architects have attempted to translate the traditional bracket set, employing the new material and techniques to integrate it into modern architectural systems. These can be broadly divided into three categories according to the structural role, form, and cultural symbolism.

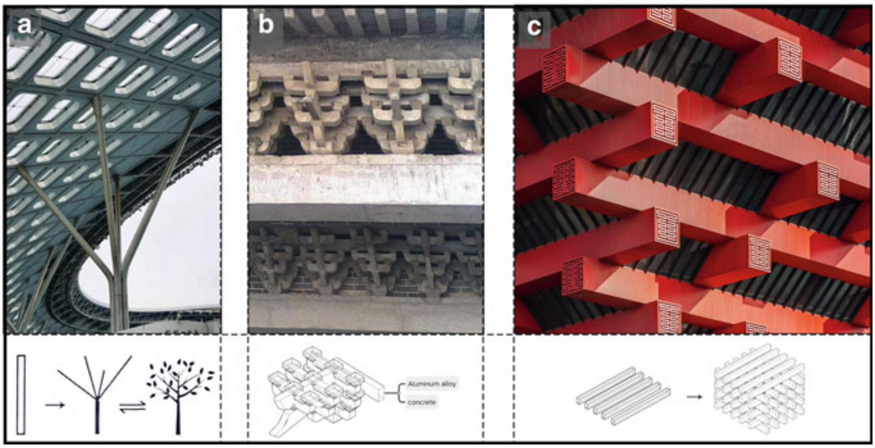

Fig. 1. **a** Tree-like column; **b** Archaize bracket set; **c** Bracket set on 2010 China Pavilion

2.1 The Dendritic Tree-Like Column with Structural Bionics Design

The application of dendritic columns in the spatial structure solves the problem that a single vertical column with an equal cross-section is challenging to set off the far-reaching eave, in accord with the function of the tiered projections of the arch. The dendritic column is upright and looks like a tree trunk. It has various branches at the top of the column, geometrically dispersed to form multiple points of support and radiating away from the centre of the column (Fig. 1a). Although the dendritic column satisfies the integration of “force” and “form”, achieved straightforward transferred force and material efficiency, it differs from the bracket set in appearance.

2.2 Archaize Bracket Set Using Contemporary Tectonic Methods

Archaize bracket set is constructed from high-strength materials such as cement and aluminium alloy, imitating or copying the bracket set from various historical periods (Fig. 1b). The same are the beams, columns, arches and pillars in archaize buildings. Still, they are not optimized for the mechanical properties of the individual materials. As a result, the overall stiffness and the structural frequency of archaize buildings are excessive, which will lead to enormous material waste and the loss of characteristics of the traditional bracket set as simple, efficient, and exquisite.

2.3 Abstract Bracket Set Cultural Symbols

This type of building has a superficial structure that exhibits layer-by-layer stacking, achieving a cultural homage to the bracket set (Fig. 1c). In the case of the China Pavilion at the 2010 World Expo, the traditional bracket set is simplified through dislocation, orthogonality, and classification in three-dimensional construction. While the mechanical characteristics of force transfer from one layer to another are retained. However, this type of abstract translation detracts from the essential structural role of the arch and the corresponding scale of its components. It serves only as an abstract derivative and a metaphor for the bracket set culture.

3 Introduction and Analysis of Bracket Set

3.1 The Evolution of the Bracket Set

The evolution of the bracket set is a nearly comprehensive presentation of the development of architectural skills and the aesthetic trends of building components in each period of Chinese history. The bracket set is not only a single structural component, but also has multiple-layered significance in cultural inheritance, decoration and beautification, class identity, measurement, etc.

The development of the bracket set can be briefly divided into five stages. Firstly, from Western Zhou Dynasty to the Han Dynasty, the image of the bracket set was depicted in various historical relics (Fig. 2a). After the Han Dynasty, it appeared between the columns. Secondly, in the period of the Wei, Jin Dynasty, and Southern to Northern Dynasties, the form of bracket set gradually became standardized, and the classic forms of inverted-V brackets appeared (Fig. 2b). Thirdly, from the Sui and Tang Dynasties to the Five Dynasties, the bracket set was vigorously gorgeous and magnificent, characterized by the huge body (Fig. 2c), and played an indispensable role in the structure. Fourthly, during Song and Yuan Dynasties, the number of brackets set increased, and the volume decreased. A certain decorative effect was introduced. The size of components started to be unified, and the modular system appeared (Fig. 2d). The last was the Ming and Qing Dynasties. By the Qing Dynasty, the bracket set adopted the modular of the mortise of cap block, which was used to standardize the dimensions of each component of it (Fig. 2e). Decorative and colouredcolored paintings appeared on the surface of the bracket set, which further strengthened the decoration and weakened the structure roles.

3.2 The Structural Function and Mechanical Prototype of the Bracket Set

The bracket set, placed between beams and columns, plays the key role of a connecting link. And the load of the roof and the upper structure is transmitted to the spreading layer of brackets set, and then to the column and foundation. As a structural "transit hub", the arch body is paved up layer by layer, and the truss and purlin on the outermost layer are propped further for a longer distance, which supports the far-reaching eaves of the structure and makes it more imposing and magnificent.

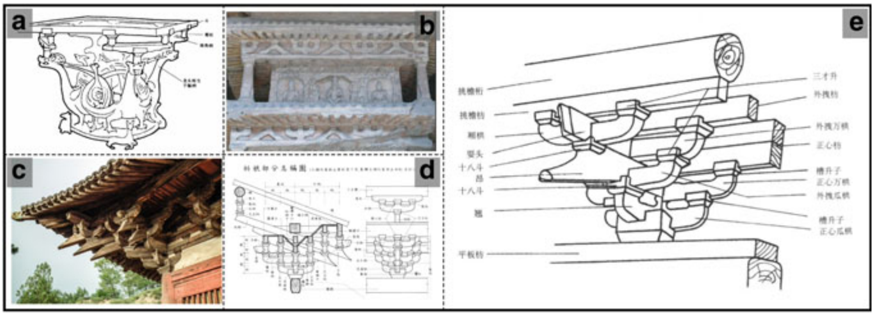

Fig. 2. The evolution of the bracket sets

The mechanical prototype of the bracket set is essentially a short cantilever beam, whose main structural function is to support the load of eaves. For the same amount of force on a cantilever beam, the larger the deformation of the cantilever end, the smaller the deformation of the support end. Therefore, it is necessary to increase the beam height from outside to inside to ensure the overall strength and stability. So, the bracket set adopts double eaves to hold the arch, and through the mortise-tenon joint, several beams become a whole, which increases the bending and shearing resistance of the bracket set. As supporting the eaves, the beam is too long, so the distance between the end of the bearing beam and the bearing support on the roof is too big, it causes the force arm becomes larger, and the bearing capacity of the beam becomes weaker, which is easier to break. Therefore, from the end to the starting point of the overhanging part, the bracket set adopts the way of layer-by-layer superposition and layered force transmission to ensure the overall stability.

The key mechanical components of bracket sets can be dissembled into buckets (Dou), arches (Gong) and levers (Ang). Specifically, the Dou is a square wooden block used to support the Gong and the Ang. The Gong is a bow-like part; the flower arm is vertical to the building facade, responsible for overhanging, while the horizontal arm is parallel to the building facade, which plays a balancing role. The Ang, an oblique cantilever beam structure and drooping frame, acts as a lever. The components of the bracket set are interlaced and stacked, full of rhythm changes.

4 Topology Optimization of the Bracket Set

In this experiment, the bi-directional evolutionary structural optimization (BESO) method has been applied to the design. The scale and position of the traditional bracket set are inherited. Also, the structural prototype of layer-by-layer force transmission is reserved. Through the digital form-finding and finite element analysis model, a new bracket set is designed on the premise of material efficiency and ensuring definite force transmission routes and a reasonable structure (Fig. 3).

Fig. 3. Topological optimized contemporary bracket set

4.1 Design Methodology

The authors used the Ameba plug-in to carry out topology optimization and BESO algorithm based on the Rhino and Grasshopper platforms. In the application of topology optimization, the rational distribution of bracket set materials is realized by deciding the removal, reservation or supplement of materials through finite element analysis (Fig. 4).

The design transforms the bracket set in the Ming and Qing Dynasties. In that period, the Ang (lever) is the fake lever, which doesn't have the structural character of lower Ang in the Song Dynasty. The force transmission of this bracket set is neater and better aligned with the property of layer-by-layer force transmission from top to bottom. In topology optimization, it is also the most effective structural morphology to transmit the upper load with specific boundary support, material consumption, and material type. To keep to the layer-by-layer force bearing and transmission mode of each bracket set part, this study adopts the "zoning optimization" as the core logic of bracket set optimization. Specifically, the bracket set is divided into Dou, Dong, Ang, Qiao and other parts, and then they are respectively optimized by BESO /Ameba; later all optimized parts are reconstructed and assembled.

4.2 Topology Optimization Form-Finding of the 2D Bracket Set

The 2D topology optimization and planar force analysis are conducive to the subsequent 3D structure form-finding of the bracket set. In addition, the 2D optimized results can be compared with the 3D optimized ones to decide the rationality of the results and provide a reference for adding supplements, resetting boundary conditions, and optimizing parameters. In the zoning optimization of the 2D bracket set, the primary parts, including cap block, small block, oval arch, regular arch and flower arch, are extracted. The axial bucket oval arch is selected as representative of component composition simulation analysis.

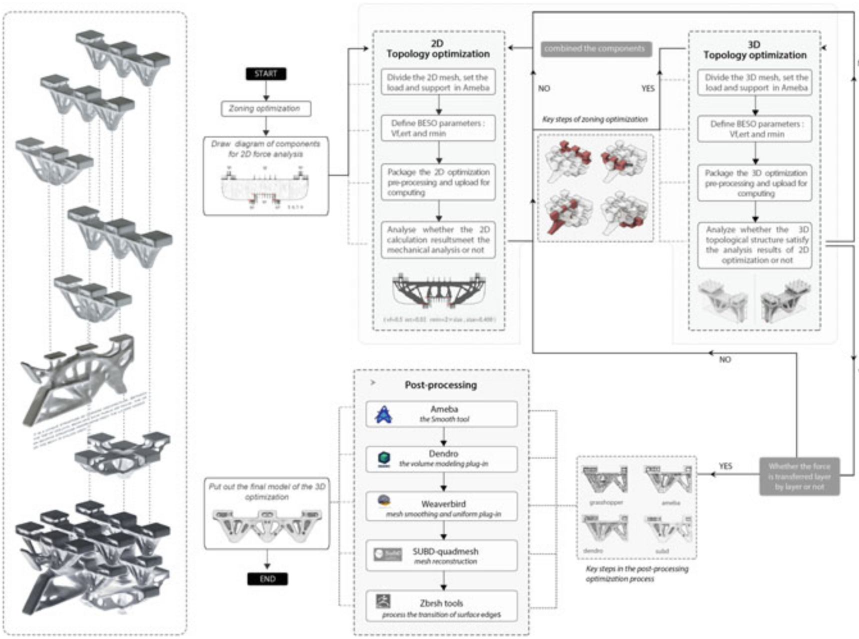

Fig. 4. Workflow of the bracket set optimization & exploded diagram of the optimized bracket set

First, the planar angle of each component is selected, and the ratio scale of each element is determined according to the Dou-Kou module system in the Qing Dynasty. Taking "Dou-Kou" as the modulus unit, an accurate 2D model of each component is constructed. Then according to the descriptions of force bearing of each part of the structure and the connection mode between Dou and Gong in Ying Zao Fa Shi and Engineering Practice Rules and Examples from Qing Dynasty, the force diagram of components is drawn for 2D force analysis. Next, the load and support are set as boundary conditions after generating the mesh element in Rhino/Ameba, and parameters for preprocessing are set to run the BESO algorithm for seeking optimal 2D topology structural forms (Fig. 5).

The 2D topology optimization results and force analysis obviously show that the entasis part's material deletions outnumber that of other parts. The corner in the traditional bracket set is a non-force bearing part or a part with less bearing load. The ancients artificially omitted the corner material based on their construction experience, thereby developing the practice of entasis. This is an experimental result of artificially saving materials and efficiently expressing structural force transmission. In the 3D topology optimization, the bracket set prototype is simplified into a more fundamental geometrical morphology without entasis, aiming to observe whether the original model without entasis will produce similar morphology such as entasis and chamfer after topology optimization. Finally, the critical sections are determined; in the subsequent zoning optimization process of 3D components, some parts are further resolved as a whole.

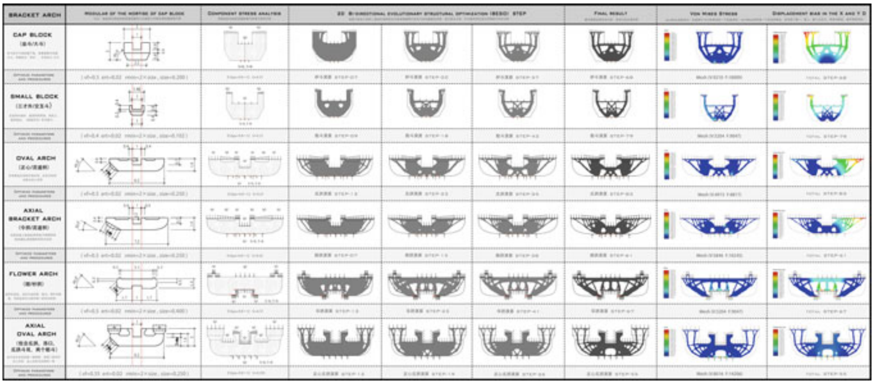

Fig. 5. 2D topological optimised bracket set components

4.3 Topology Optimization Form-Finding of the 3D Bracket Set

After previous 2D component decomposition optimization and considering the different shapes and low strength of the bracket wall after optimization, the small blocks were combined with the arch body in the 3D, prototype and a typical combination of overlapping arched and bucket-shaped blocks (one bracket set with three small blocks) were formed (Fig. 6). During the 2D optimization, the dangerous critical cross-section. The rabbets of the cap block, the first layer oval arch and the first layer flower arch complement each other with overlapped dangerous sections with hidden safety hazards. Therefore, we combined the three components with the central part as the integrated component to further supplement the strength of the critical section.

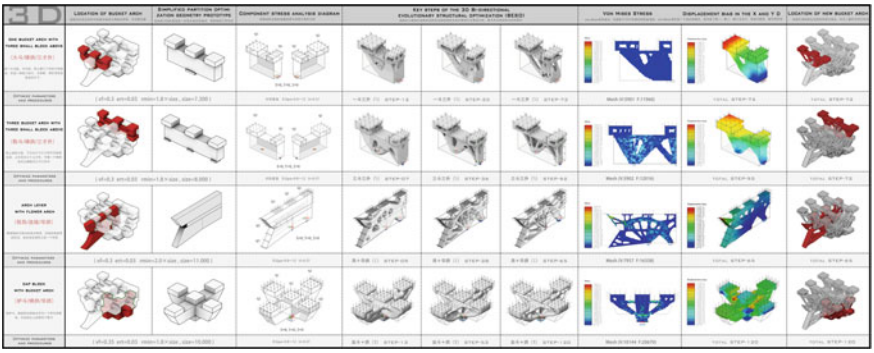

Fig. 6. 3D topological optimized bracket set components

During the optimization, the geometric prototype of the bracket set was simplified, and the entasis chamfer was cancelled to form a simplified, integrated cube. The purpose is to determine whether material deletion and chamfer would reappear at the original entasis position in the optimized structure. At last, four combinations were formed: one bucket arch with three small blocks, three buckets with three small blocks, the combination of Ang and lower arch, and the combination of cap and block flower arch. Then 3D optimization was performed and comparatively analyzed with the 2D optimization results. Parameters were adjusted to achieve the optimal solution for bracket set design (Fig. 7).

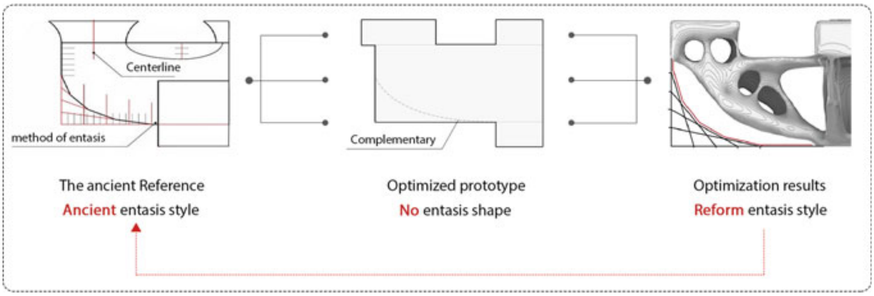

Fig. 7. 3D topological optimized bracket set components

According to the results of the 3D optimization, several bracket set combinations have presented a structural shape of oblique fractal bifurcation from the support to the load end. This mechanical structure is similar to the structural prototype of the tree-like column and the fractal structure of tree branches in nature, proving the high correlation and similarity between bracket sets and tree branches in the mechanical prototype. The upper and lower surfaces have complete materials for the structure of small blocks, while the middle part is a porous structure. Massive materials were cut for the original entasis position or even "entasis style" was formed. The chamfering amplitude of these designs was more obvious than in traditional bucket arches (Fig. 8). The topology optimization results also reflected the wisdom of ancient craftsmen and the excellent craftsmanship of the bucket arch, which is absolutely an architectural gem that integrated form and force (Fig. 9).

4.4 A Case Study and Topological Optimization Experiment of the Hall of Prayer for Good Harvests

Architrave is also an important part of the Chinese timber frame. Usually, an architrave is installed on the top of a column to link the bracket sets between columns with the load-bearing horizontal member. In some architectures, large and small architraves were stacked and juxtaposed with the middle connected by a clamp pad. These architraves were simplified as a complete geometric graph and were used as the optimized prototype together with the eave column. During the architrave topology optimization of the Hall of Prayer for Good Harvests, the combined member of a ring of architrave and eave column can be disassembled into six same units according to the symmetry. Then the 1/12 minimum optimization unit can be obtained based on the mirror-symmetric properties of the units (Fig. 10).

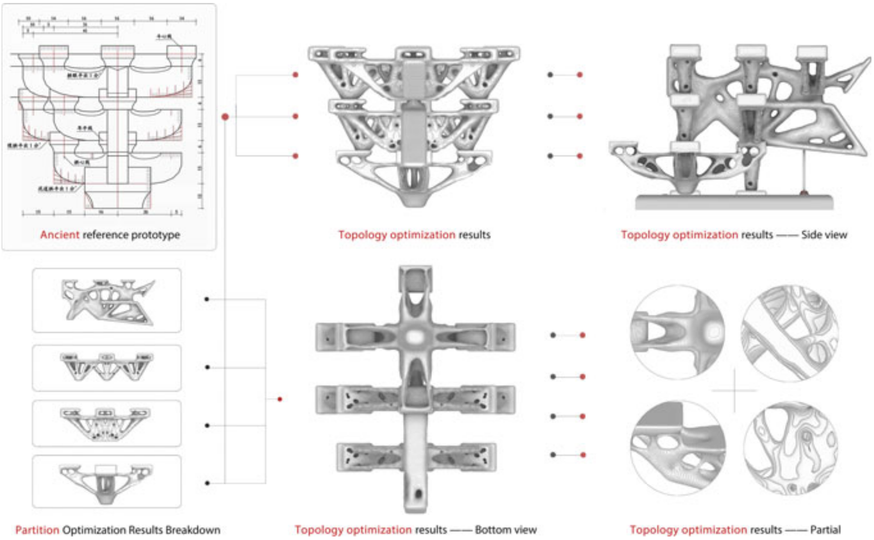

Fig. 8. Topology optimization results of the entasis part of the bracket set

Fig. 9. 3D topological optimization

For the load arrangement, the downward uniform load can be set on the upper critical plane connecting the architrave and bracket set, and a side thrust can be imposed on the sparrow brace, which ensures that all the units are closely connected in the partition optimization. The base was installed at the position of the symmetrically optimized vertical cross-section and column bottom. The overall effect after optimization was shown in Fig. 11.

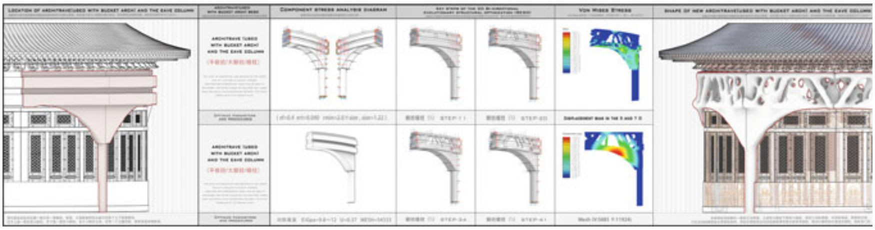

Fig. 10. 3D topological optimised architrave bracket set components

Fig. 11. 3D topological optimized architrave bracket set components

After the optimization of the architrave, we combined the results with the previous optimization results of the bucket arch. We replaced the corresponding original structure of the Hall of Prayer for Good Harvests while retaining the traditional paintings, doors, windows, tiles and other decorative components. The overlap of new and old elements formed a stark contrast in appearance (Fig. 12) while maintaining the same mechanical essence. This kind of hidden link ensures a more rigorous connection between culture and structure on the basis of the unity of aesthetic form and force in contemporary structure.

5 Conclusion and Future Work

Bi-directional Evolutionary Structural Optimization (BESO) was performed on the bracket set in this study. 2D and 3D comparison and partitioned optimization were applied to the design. The new bracket set was designed based on high and reasonable structural performance, material efficiency, traditional tectonic rule, with the features of aesthetic form and force-form united.

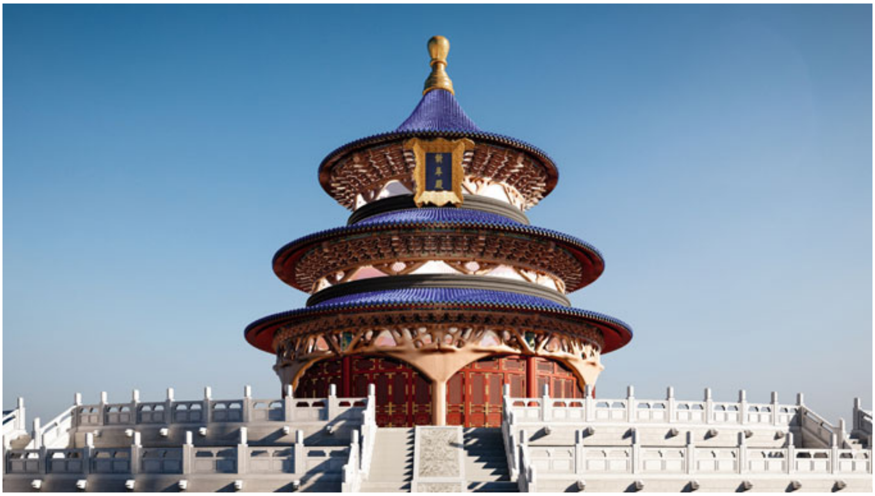

Fig. 12. Topological optimised Hall of Prayer for Good Harvests

The attempt of the new bracket set design can trigger the thinking about the new value of bracket set as a symbol of architectural culture in contemporary times. Meanwhile, we also applied the complete workflow to the architrave-eave column combination. The results also turned out to be enlightening. Through the attempts, we aim to encourage more scholars to explore the possibilities of inheritance and derivation of traditional architectural components from the structural perspectives.

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