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REVERSE RAFTER

Structural performance simulation based on wood tectonics

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Abstract. With the rapid development of the digital fabrication technology, structural performance based design shows broad application prospects. Based on the research project "Reverse rafter", this paper aims to explore the possibility of simulating and re-applying Chinese traditional wood tectonics with structure performance based computational technology. Taking "eaves rafter" as research prototype, this project employed topology optimization as research method and “Millipede” as analysis tool. Through the comparison between the analysis results of traditional structure calculation and topology optimization method, this project revealed the underlying structural principles of "eaves rafter", based on which a modern reciprocal structure installation was generated through digital design method. CNC cutting technology was employed to ensure the fabrication accuracy in digital fabrication processes.

Keywords. Structural Performance, Wood Tectonics, Simulation, Topology Optimization, Digital Fabrication

1. Introduction

Structural performance-based design methodology is a design process to find the reasonable relationship between spatial form and structure through simulation, calculation and optimization of structural behaviour. Not like the structural design methods of Graphic Statics Era(late 1800s-mid 1900s) and Structural Tectonic Era(mid 1900s-late1900s), structure performance-based architectural design in Digital Morphologies Era(1990s-) focus on the dynamic interaction between structure analysis and design, enabling the multiobjective and multi-dimensional morphological analysis and optimization based on structural behaviour (Philip F.Yuan, Yongheng Hu,2014).

Culture provides the context for the development of technologies. As a traditional architectural culture carrier, wood tectonics plays an important role in contemporary practices and researches of Chinese building culture. Development of structural performance-based technology provides a solution for architects to deal with traditional tectonics scientifically, integrating technology with culture.

2. Research

The advent of the digital technology in the 1990s brings about many structural performance-based computing methods and analysis tools, which provided powerful support for the structural performance-based design in Digital Morphologies Era. Through the analysis of traditional structural prototype, this article aimed to explore the possibility of digital simulation and optimization for Chinese traditional wood tectonic system.

2.1. ANALYSIS METHODS AND TOOLS

Based on the finite element analysis method, topology optimization, the emerging structure analysis method, determines the dismissal or retention of the structural material by dividing the structural volume into finite discrete units according to a specific algorithm, and showing a huge advantage in finding the optimal topological shape and size of structure under certain constraints. Topology optimization provides reasonable forces basis and structural reference for form finding, gradually being recognized by architects and engineers. With the rapid development of computational technology, many algorithms or programs based on topology optimization have emerged such as ESO (Evolutionary Structural Optimization) and BESO (Bi-directional ESO), which have provided an important foundation for the practical application of topology optimization (Y.M. Xie et al, 2011).

Among the topology optimization tools, Rhino based plug-in “Millipede” developed by Panagiotis Michalatos has become a new representative structure optimization tool due to its efficiency. This software comprises of a library of fast structural analysis algorithms based on topology optimization for linear elastic systems. It allows for very fast linear elastic analysis of frame in plane forces, having their results extracted and visualized in a variety of ways (Panagiotis Michalatos, 2014).

The topology sizing optimization function of “Millipede” provides a chance and foundation for structural simulation and optimization of Chinese traditional wood tectonics which is mainly composed of linear rods.

"Reverse rafter" is a structural installation from “DigitalFUTURE Shanghai 2014” [2]. Taking “Millipede” as a simulation tool, this project produced a possibility of computational simulation and optimization in Chinese traditional wood tectonics through design and fabrication practice.

2.2. PROTOTYPE RESEARCH

Pitched roof with deep overhangs is the most prominent feature of traditional Chinese architecture, which presents both elegant aesthetic expression and reasonable force flow. The project took “eaves rafter” as prototype, which plays the most important role in supporting the overhanging structure.

Traditional roofs mainly bear loads like self-weight and snow loads by rafters with two ends laid on purlins. The overhangs at the eaves put forward a higher structural performance requirement. Supported by eaves purlin, purlin on hypostyle and eaves tiebeam, eaves rafter cantilevers out obliquely to support the overhanging part of the roof or flying eaves (figure 1).

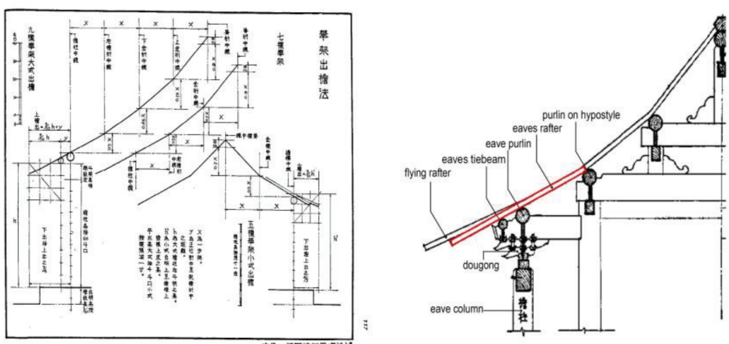

Figure 1. Diagram of eaves overhanging, “Qingshi Yingzao Zeli”.(left); Eaves rafter location relationship with other components(right).

The book “Qingshi Yingzao Zeli”, which is comprised of the design principles, manufacturing standards of Qing Dynasty extracted from “Qing Gongbu Gongcheng Zuofa Zeli”[3], provides the overhanging size of eaves rafter, the horizontal distance from eaves tiebeam to the eaves edge as 14doukou[4] (Liang Sicheng, 1981). The horizontal distance from eaves tiebeam to eaves purlin is defined as 6 doukou, while that between eaves purlin and purlin on hypostyle is 24doukou (table 1, 2). As the book does not give a clear explanation, it is not sure whether the overhanging size was dictated out of structural consideration. Chinese scholars (Jiang Yan et al, 2011) have given the overhanging size a structural interpretation through structural calculation and bending moment diagram. By simplifying the eaves rafter into a statically indeterminate oblique beam and balancing the positive and negative peak moments, the research come out with a result consistent with the description of " Qingshi Yingzao Zeli " (figure 2).

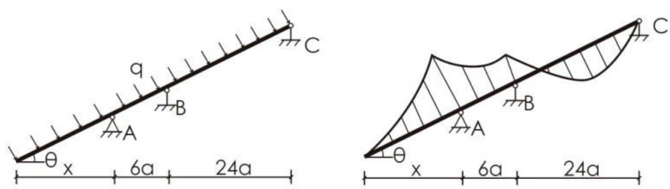

Figure 2. Simplified rafter model for calculation(left)；Bending moment diagram (right).

Table 1. Size relationship between Eaves rafter and Flying rafter.

	Wooden frame with dougong	
	Height or length	Cross-section
Flying rafter	3/10*(column height+dougong height)	1.5doukou
Eaves rafter	3/5*flying rafter length	1.5doukou

Table 2. Relevant data about eaves rafter.

Column	Wooden frame with dougong	
	Height	Cross-section
Eave column	60doukou	6doukou(1/1000contracture)

$$L = 3/5 * 3/10 * (60D + H) \quad (1)$$

L——eaves rafter overhanging size;
D——doukou, mortise of cap block ;
H——the height of dougong;

Structure calculations verified the rationality in the force distribution of eaves rafter, but did not really reveal the underlying structural principles. In contrast digital analysis software allows for more dynamic and interactive analysis and optimization. In this project, the physical environment for eaves rafter was simulated in “Millipede”. At the beginning, a rafter model with material information, load condition, and external constraints was created. During the simulation, shape changes were carefully observed with the adjustment of the overhanging ratio. Simulations showed that, with the same slope of rod, the reduce of the overhanging ratio would cause the deformation between support points B, C to increase; When raising the overhanging ratio, the cross-section near point A need to be strengthen to resist bending moment action. Therefore, the appropriate overhanging ratio should be the balancing result between the deformation of BC and section size of point A. After several attempts, we found out that when the length proportion of AD and AC was within the 0.46-0.48 range, the appropriate overhanging ratio could be obtained (figure 3).

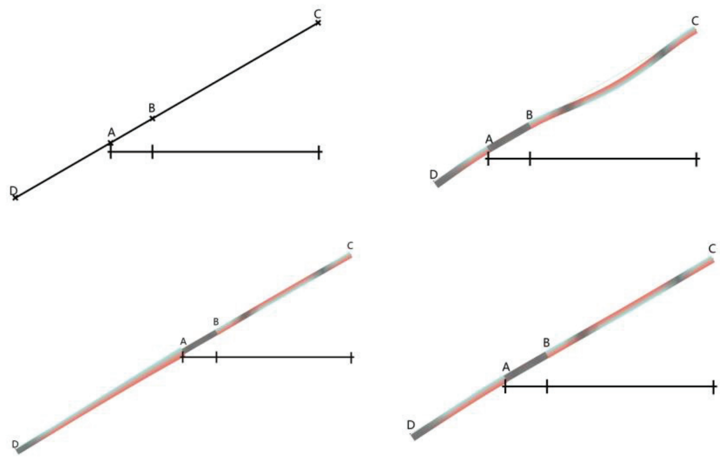

Figure 3. Simplified rafter model for simulation (up left); Equilibrium state when AD/AC equals 0.2(up right); Equilibrium state when AD/AC equals 0.8(down left); Equilibrium state when AD/AC equals 0.47(down right).

Further studies showed that, when the position of support point B was changed, the balanced proportion between AC and AD was almost unaffected, maintaining at 0.46-0.48 range (figure 4). This results are basically consistent with the description in "Qingshi Yingzao Zeli". It can be concluded that a most reasonable value exists in the overhanging size of multi-span continuous beam. In the practice, the overhanging size of multi-span continuous beam should be determined according to the specific conditions, thus saving material, reducing project cost. Compared with the traditional structure calculation method, the advantages of "Millipede" lies in its dynamic and interactive interface, however, as diagrams, the analysis result of "Millipede" requires further explanations to be reasonable for applications.

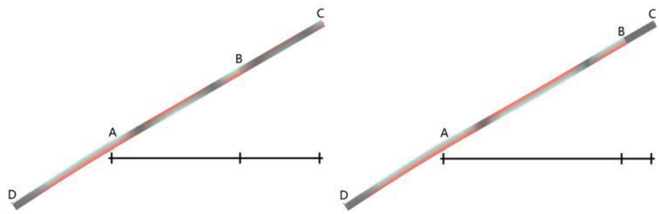

Figure 4. Equilibrium state when AB/AC equals 0.56(left); Equilibrium state when AB/AC equals 0.8(right).

Analysis above has fully proved that traditional tectonics accumulated through thousands of years contain a wealth of structural information. Structural analysis nowadays can help to extract the underlying principles. At the same time, the consistency between analysis results and traditional standards also demonstrates the effectiveness and potential of digital structural tools.

2.3. STRUCTURAL PERFORMANCE SIMULATION AND OPTIMIZATION

On the basis of the prototype analysis, the project further studied the role and significance of structural performance-based tools in structural design.

For further research, this project first accomplished a structural installation design based on structural principles analyzed above. Taking advantages of topological optimization function of "Millipede" in shape optimization and material size optimization, this project then simulated and optimized the form and cross-section of the structural installation.

Reciprocal structure[5] was introduced in design phase. In reciprocal structure, each rod overlaps with two adjacent rods, forming overhangs at both ends. Similar to the force condition of eaves rafters, rods bear mainly bending moment action. Reciprocal structure often served as supporting structure of bridges or pavilions in ancient China. As horizontal extension is the major feature, reciprocal structure is conventionally used to build a planar continuum. In contrast, reciprocal structure developed vertically in this project.

Structure with excellent performance can be obtained by combining the structural principles with certain algorithms. The basic unit was derived from the reciprocal unit with three rods overlapping each other with reasonable overhanging proportion (figure 5). While the upper unit was generated based on the lower one in vertical development, the unfolding degree of units increases layer by layer, rendering the overall structure an umbrella form. Only a few parameters such as the radius of the first layer were needed to generate the overall form and ensure each individual element to behave adequately.

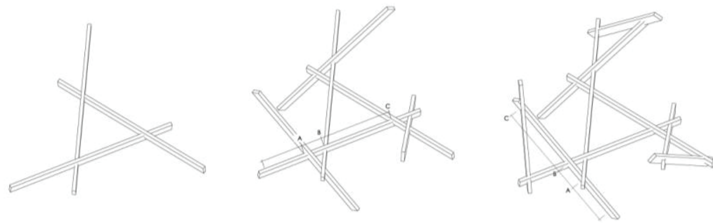

Figure 5. Generate process of a basic unit based on appropriate proportion.

Since each unit undertook the weight of all the upper ones, the deformation degree varies with height. Therefore cross-sections vary to respond to different force conditions of different layers. “Millipede” FE analysis assumes totally fixed connections between elements, which show completely different performance with overlapping connections. Therefore, the simulation model was built with each rod simplified into its central axis with auxiliary line connecting the axis at the joints. In this way, the force flow in simulation model was made closer to real situation (figure 6). After building the simulation model, the project simulated the structural performance—axial force， shear force, bending force, and resistance to deformation with “Millipede” (figure 7). The built-in topology optimization function of “Millipede” showed the appropriate cross-sections after optimization, which provided references for design adjustment. Sectional sizes after optimization varied nonlinearly following changes of stress state. Taking into account the accessibility and economy of materials, the project observed the optimization results and classified cross-sections into several types, which were then feed back to simulation. After repeating the analysis loop several times, the cross-sections of the rods were finally divided into four categories: 90mm*40mm, 70mm*30mm, 55mm*20mm, 40mm*20mm, which set an end to the optimization process. At this stage, the topology optimization function of “Millipede” effectively ensured the design and optimization of wood tectonics.

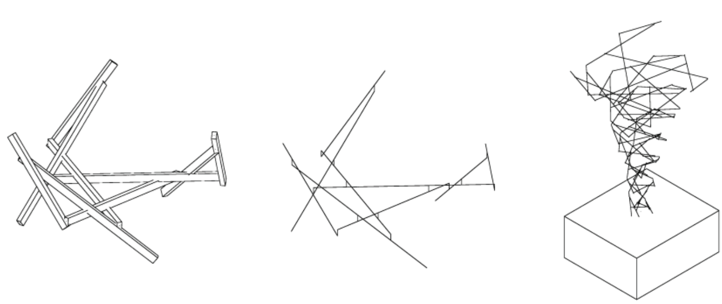

Figure 6. Simplify process of a basic unit (left& middle); simulation model (right).

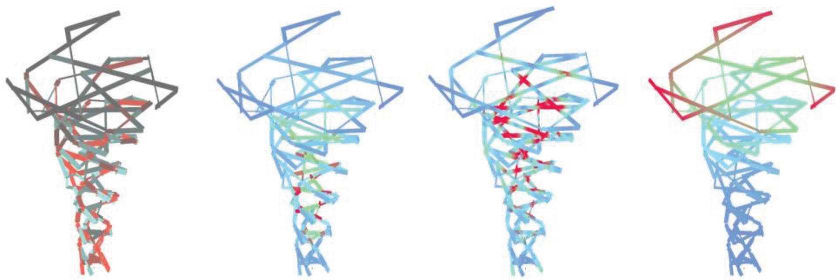

Figure 7. Axial force simulation(1st);shear force simulation(2nd);bending force simulation (3rd); resistance to deformation capability simulation(4th).

2.4. DIGITAL FABRICATION

Form Complexity in Digital Morphologies Era calls for highly accurate fabrication technology. Beyond the capacity of traditional techniques, the rapid development of digital fabrication technology provides critical support for the realization of the comprehensive structural performance-based design.

In this project, although the structural unit of each layer followed the same logic, the rod length, cross-sectional shape, overlapping position and inclination angle varies from each rod, resulting in extremely complex junctions. Deviations accumulation resulted from traditional manual fabrication process would inevitably lead to the loss of control of the overall form. The accurate fabricating capacity of 5 axis CNC's provides suitable response to this demand, preserving the intention of design initiatives (figure 8).

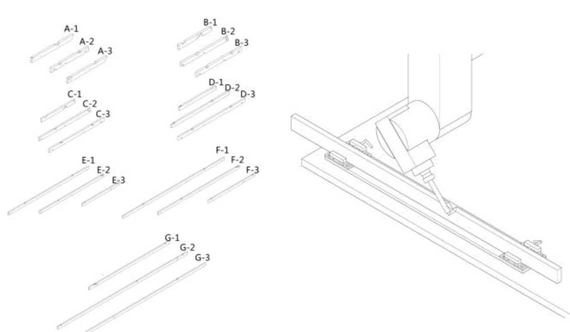

Figure 8. Rods classification and numeration(left); CNC processing diagram(right).

This structure comprises of 63 rods in 21 types of cross-sections, with lengths varying from 1m to 3m. Before fabrication processes, each rod was labeled in sequence in both digital and physical platforms. As each piece was unique, this was essential for assembling. The localization and milling process of junctions was mainly performed by the 5 axis CNC, while construction on site was achieved manually. Similar to Chinese traditional mortise-tenon structure, the entire structure was fabricated without any connecting members or reinforcement components (figure 9).

Figure 9. Rods milling with CNC (left); Junctions detail (middle); Connection between different layers (right).

The final structure presents an umbrella form of 6m high with seven layers, force flow passing spirally from top to bottom along the rods. The bottom radius of the structure is 0.5 meters, while the top radius extends up to 3 meters. The triangle bench placed at the bottom not only serves as resting space, but also acts as structural components to counter weight and resist the overturning force to maintain the overall stability(figure 10).

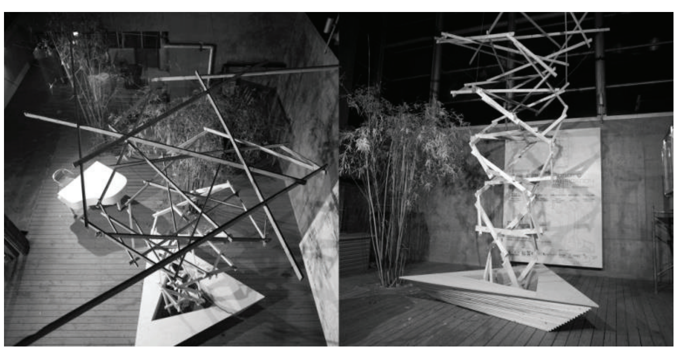

Figure 10. Site photos.

3 Conclusions and further research

With the rapid development of the digital fabrication technology, structural performance-based design shows broad application prospects. This project combined structural performance-based design with traditional wood tectonics, endowing the structural installation with both cultural significance and structural aesthetics. From this research, a new way for traditional structure interpretation has become clear, while a new impetus and direction has been pointed out for structural performance-based design development.

Sufficient researches on traditional wooden structures would inevitably point to an ultimate goal, the research on the intrinsic material characteristics and behavior of wood. With the development of new wood material such as composite wood, the characteristics and behavior of wood are constantly changing, which require us to constantly evolve with material to take advantages of its physical potential through performative design.

Endnotes

1. "Yingzao Fashi" is a technical treatise on architecture and craftsmanship written by the Chinese author Li Jie, the directorate of buildings and construction during the mid Song Dynasty of China.
2. DigitalFUTURE Shanghai is a series of academic events starts from 2011. Every year it will have a topic. "Robotic Fabrication Based on Structural Performance" is the topic of DigitalFUTURE 2014.
3. "Qing Gongbu Gongcheng Zuofa Zeli" is the technical treatise in Qing Dynasty of China, similar to "Yingzao Fashi" of Song Dynasty.
4. Doukou, modular system in Qing Dynasty.
5. Reciprocal structure is a three-dimensional self-supporting system with rods supported mutually in a circle.

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