Manufacture and Assembly Mechanism of Dougong

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Manufacture and Assembly Mechanism of Dougong

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Abstract. Dougong [斗栱] is a bracket between column, beam, and rafter in traditional timber structure building in China. It has several bearing blocks, named dou [斗], and some bracket arms, named gong [栱]. All components are connected by sunmao [榫卯]. It was born from the capital and later developed into a bracket that does not have to be related to the column. During the last 3000 years, its status in traditional architecture has been rising. In the Qing Dynasty, the architectural design work started it as the core. The chief aim of this research is to explore the possibility and key issues of using dougong for the prefabricated buildings. This research documents a folk building project in China from three aspects: the construction organization, the dougong component manufacture and assembly. After that, we study the mechanism and analyze the traditional technology. Finally, the study provides some suggestions for the prefabricated building. The first aspect is the construction organization. The component manufacture team needs more specialized skills than the assembly team. The two teams exchange information through the code on components and simple language. The proportion of dougong manufacture workload on the standard floor is 40%. The second aspect is the dougong component manufacture. A master carpenter, a chief engineer, is in charge of three tasks: architectural design, material requirements planning, and templates making. After that, he directed 4 carpenters to make components accorded with the templates. The dougong components are universal. Besides, carpenters assemble and code the completed gong components in layers in the carpentry yard. Each layer of gong uses 1 English capital letter to code. The other components are unassembled and uncoded. The third aspect is the dougong component assembly. The assembly team's workers need only simple skills to complete their work. Limited by the low precision of the hand-made method, they need to fine-tune the size of the gong at the joint between the gong and the column. In this project, the lowest component of dougong is gong, so, the workers assemble 5 layers of gongs into the columns from bottom to top first, and then assemble several dous between the gongs. The completed sunmaos at this stage are not tightly fitted, which leaves room for adjustment of the upper components of the dougong. The research we have done indicates that compared with the assembly stage, the manufacturing stage is a concentrated section of the technology and workload. So, the key to modernizing traditional buildings is the modernization of this stage, especially the dougong manufacture. If it is realized, we can save at least 40% hand-made workload of the standard floor. At the same time, the components will achieve higher accuracy, which is beneficial to improve the assembly speed and quality. Also, in the future, BIM can be utilized based on the

traditional design method, which is significant to the inheritance and improvement of dougong technology.

1. Introduction

1.1. Background

Dougong [斗栱] is a bracket between column, beam, and rafter in traditional timber structure building in China [1]. It consists of several bearing blocks, which named dou, and some bracket arms, which named gong [2]. All components are connected by sunmao [榫卯]. It was born from the capital and later developed into a bracket that does not have to be related to the column. During the last 3000 years, its status in traditional architecture has been rising. In the Qing Dynasty, the architectural design work started it as the core [3-5].

1.2. Research method

The project, located in Anhui Province, China, is a five-story building with a wooden structure (Figure 1, 2). It is an Anhui traditional dwelling, which is a faction of ancient Chinese dwellings. The case is a typical folk building. The project team is composed of people from non-scientific classes. This is one of the typical models of ancient architecture construction in Anhui Province. The article studies the manufacturing and assembly mechanism of Dougong by analyzing the engineering records and 3D modeling.

Figure 1. Architectural photo

Figure 2. Dougong

2. Engineering records

2.1 Engineering organizations

From the perspective of project organization, in this kind of construction organization, the boss and component production group, assembly group formed a vertical management structure. At the same time, a horizontal structure was formed between the two teams. There are component-based material transfers and information transfer in the main form of concise language and component code between

teams. The component manufacture team needs more specialized skills than the assembly team. The master carpenter is the core technical staff. The importance of the division of labor is polarized. This forms a technical core-edge structure relationship. In the personnel organization structure, the master carpenter is irreplaceable, and temporary changes of other personnel have less impact on the progress of the project. Therefore, the key to maintaining the stable structure of the engineering team is the stability of the master carpenter. The proportion of dougong manufacture workload on the standard floor is 40%. It is a typical component group with low material consumption and high labor consumption in a building.

2.1.1 Division of labor. The overall responsible department consists of three parts: the boss, the component manufacture team, and the assembly team (Figure 3). The project formed a construction organization structure with the master carpenter as the core technical leader.

The boss's job is to undertake projects, manage finances and materials. There are 5 members in the component manufacture team, responsible for the design and production of all components. Among them, the master carpenter, Mei Qiushan, age 63, working for more than 40 years, is generally responsible for architectural design, material planning, component design, making templates, and checking quality (Figure 4). He also enlarged the dimension lines and identified key sunmao. He manages four carpenters to make components and sometimes participates in the production himself.

There are 7 workers in the assembly team responsible for civil construction and assembly. A leader is in charge of arranging material distribution at the construction site, construction machinery, assembly technical guidance, and personnel arrangements. He manages 6 ordinary employees.

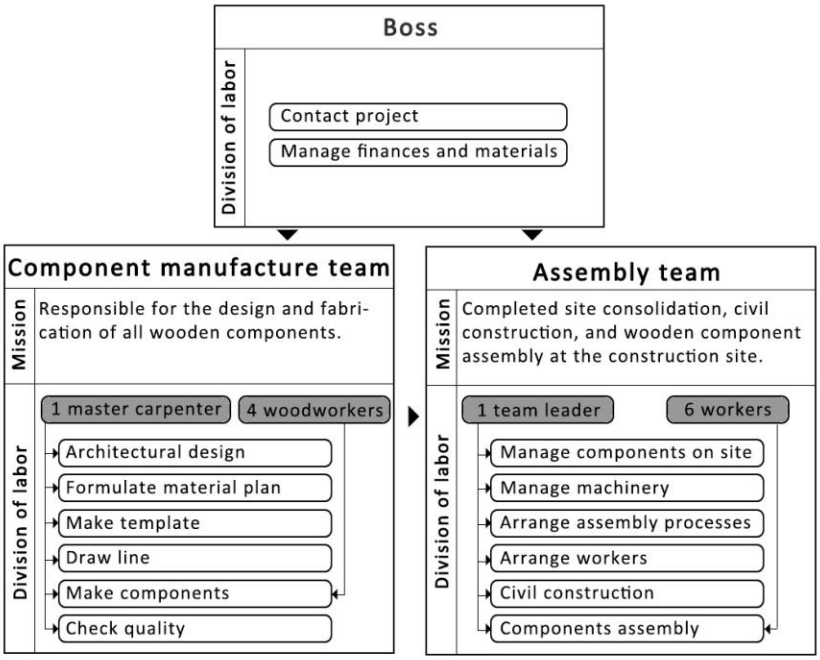

Figure 3. Construction organization structure

The carpentry yard and the construction site are arranged adjacent to each other, with a distance of about 50 meters. This facilitates component transportation. Component manufacturing and small component assembly are completed at the workshop (Figure 5, 6).

Figure 4. The master carpenter

Figure 5. The carpentry yard

Figure 6. The construction site

2.1.2 Construction sequence. After determining the architectural design plan, the component manufacture team started the components production work, but the assembly team started to work about two months later. The total construction period is about 3 months. In the first two months, the component manufacture team mainly produced components of 1-3 floors and some components of 4-5 floors, and in the third month, mainly made components of 4-5 floors and roofs. In the third month, the assembly team started the foundation consolidation, and then alternated the assembly of components and the pouring of the floor. It takes about 66% longer to make wooden components than to assemble those. The overlapping working time of the two teams is about 1/3 (Table 1).

Table 1. Construction sequence and progress

Team	Task	First month	2nd month	3rd month
Component manufacture team	Component manufacture	———	———	———
Assembly team	Assembly			— — —
	Civil construction			— — —

2.1.3 workload statistics. The dougong takes a huge amount of work in making and assembling. According to the statistics of the standard floor, the work volume of dougongs in component manufacturing accounts for about 40%, and the work volume of it in assembly accounts for about 22% (Table 2).

Table 2. Comparison of the workload

Stage	Timber frame in the standard floor	Dougongs in the standard floor
Component manufacture	60 working hours	40 working hours
Assembly	5 hours (7 workers)	5 hours (2 workers)

2.2 Design and manufacture of the dougong components

Dougong components are manufactured by hand based on traditional techniques. The master carpenter is responsible for the design and production of the components.

2.2.1 Design. The master carpenter will design the style of the dougong, determine the size of the dougong's internal components, make a template, and formulate a material preparation plan. In this case, the dougong has five layers of gongs, and there are oblique gongs (Figure 7). One dougong consists of 89 components (Figure 8). After assembly work in the carpentry yard, the number of components became 71. Among them, the gongs were changed from 21 to 9, and the pins were all assembled on the gongs, and the number of other components remained unchanged (Table 3). The

reason why the dous are not assembled may be that they are unstable during transportation and fall easily.

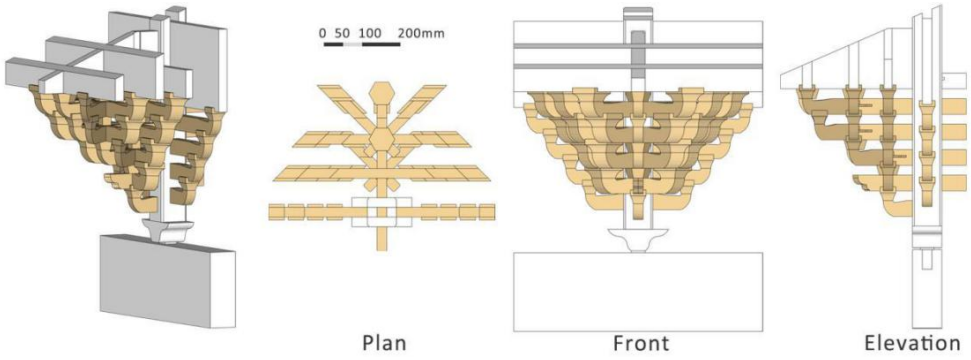

Figure 7. The dougong model in this case

Table 3. Components statistics in one dougong

Component statistics before the first assembly		Component statistics after the first assembly		
Code	Quantity（pcs）	Code	Quantity（pcs）	Note
d1	1	**d1**	1	
d2	9	**d2**	9	
d3	4	**d3**	4	
d4	9	**d4**	9	
d5	9	**d5**	9	
d6	2	**d6**	2	
g1	1	**E**	1	**E**=g1
g2	1	**D**	1	**D**=g2+g3
g3	1			
g4	1	**g4**	1	
g5	1	**C**	1	**C**=g5+g6+g7+g8+2x
g6	1			
g7	1			
g8	1			
g9	1	**g9**	1	
g10	1	**B**	1	**B**=g10+g11+g12+g13+ g14+2x
g11	1			
g12	1			
g13	1			
g14	1			
g15	1	**g15**	1	
g16	1	**A**	1	**A**=g16+g17+g18+g19+ g20+2x
g17	1			
g18	1			
g19	1			
g20	1			
g21	1	**g21**	1	
x	6			
Bamboo nails	28	**Bamboo nails**	28	
Total	**89**	**Total**	**71**	

Note: The codes of gong A, B, C, D, E are the actual codes in the project, and the rest are the codes of the author.

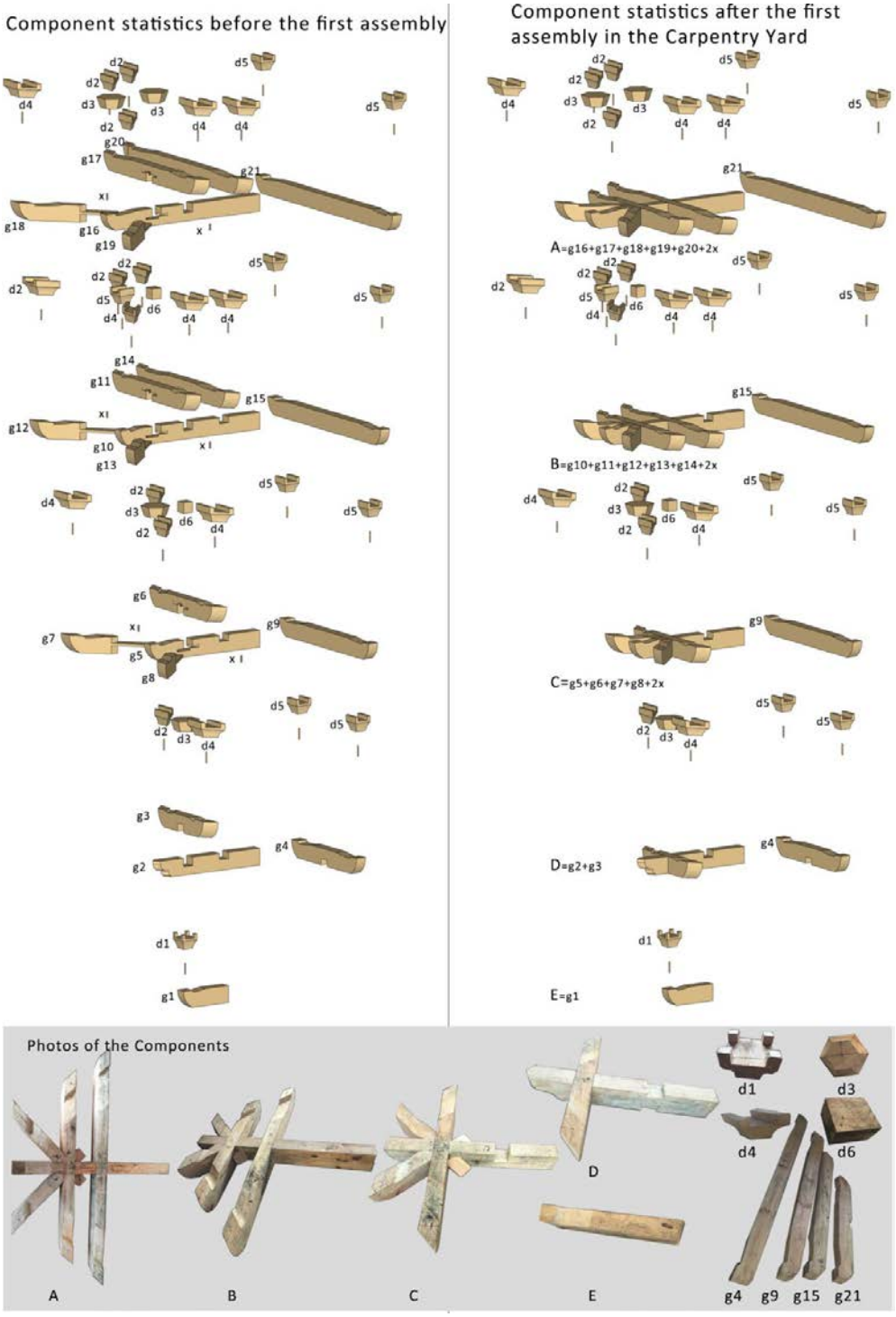

Figure 8. Components statistics in one dougong

2.2.2 Manufacture (1) Templates. The master carpenter made templates, which reduced the amount of repeated work and improved the accuracy of the work (Figure 9). The carpenter makes the components according to the template.

Figure 9. Templates

(2) Tools

The production tools have evolved from traditional tools to electric equipment (Figure 10).

Figure 10. Tools

2.2.3 Features of finished products. Among all the components of the building, the dougong components are the most universal components. Some components are pre-assembled and coded by 4 woodworkers in the carpentry yard to form 4 pieces of gong members (Figure 9). Each layer of 拱 uses 1 English capital letter for encoding. The other components are fragmented and uncoded. All components are sorted and stacked in the carpentry yard. (Figure 11)

Figure 11. Storage of components

2.3 Assembly of the dougong components

The assembly team's workers need only a simple experience to complete the work. Complex sunmaos are pre-assembled in the carpentry yard. Simple ones are completed in the assembly process.

2.3.1 Positioning. There are no drawings to assist. However, workers can find the position of the component based on experience only by looking at the surface mark on it. Various sunmaos convey accurate positioning information, and no tools or instruments are needed for positioning.

2.3.2 Assembly (1) Connection technology. Dougong components are pure wood components, which are connected by sunmaos. In this project, the most complex sunmaos form is inside the A, B, and C gongs assembled in the carpentry yard. The number of sunmao assembled at the construction site is large but simple (Figure 12).

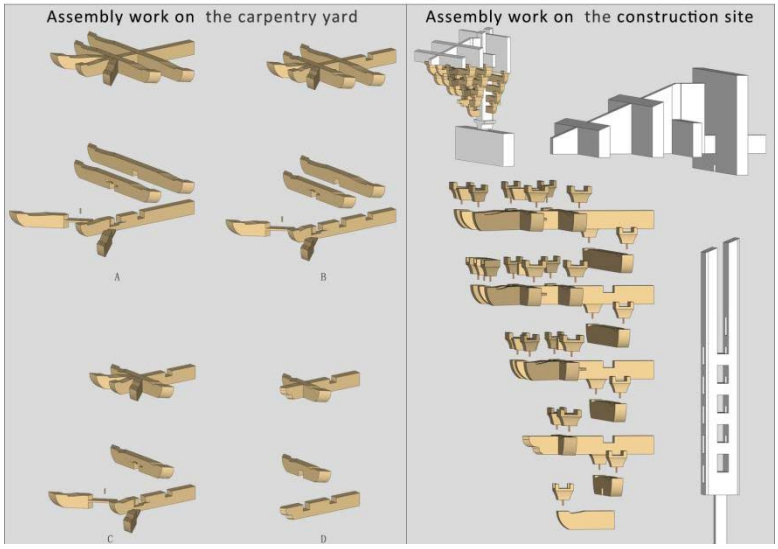

Figure 12. Sunmao

(2) Assembly technology

The two-stage assembly technology reduces the frequency of using the tools at the construction site, and also improves assembly accuracy and worker safety. In the assembly, the movable scaffolding is used to complete the work on the second floor. If the workers reach out to work, it will be inconvenient, unsafe, and it will easily affect the assembled components.

Stage 1: Some components are assembled into larger components A, B, C, and D in the carpentry yard.

Stage 2: components A, B, C, D and other components are assembled at the construction site.

In the assembly, the dougongs are assembled after the columns and beams of the building. After that, other components of the eaves are assembled. The sequence is a total of 10 steps (Figure 13, 14):

1) Assemble the horizontal gong between the gong D and E.
2) Combine the gong D, E and one dou, and then assembles them.
3) Assemble the gong C.
4) Assemble gong B.
5) Assemble gong A.
6) Assemble the dous between A, B, C, and D. The reason for the dous to be assembled after the 5-layer gongs are assembled is that there is a space for vertical movement between the components.
7) Assemble horizontal gongs and dous between the gong A, B, C, and D. All gongs are fixed firmly.

8) Assemble the dous on the A piece. The dougong has been assembled. The sunmaos completed at this stage are not tightly fitted, which leaves room for adjustment of the assembly of the upper part of the dougong.
9) Assemble the eave component.
10) Assemble the eave component. Eaves components connected with the dougongs are assembled.

This is the normal sequence within this project. There are also other sequences to complete the assembly, such as adding dous and gongs one by one during the assembly of gong A, B, and C.

The tools used are a mallet, hammer and saw. The worker knocks the gong into the column with a mallet or hammer, and adjusts the size of tail on the gong E with a saw.

Figure 13. The assembled dougong

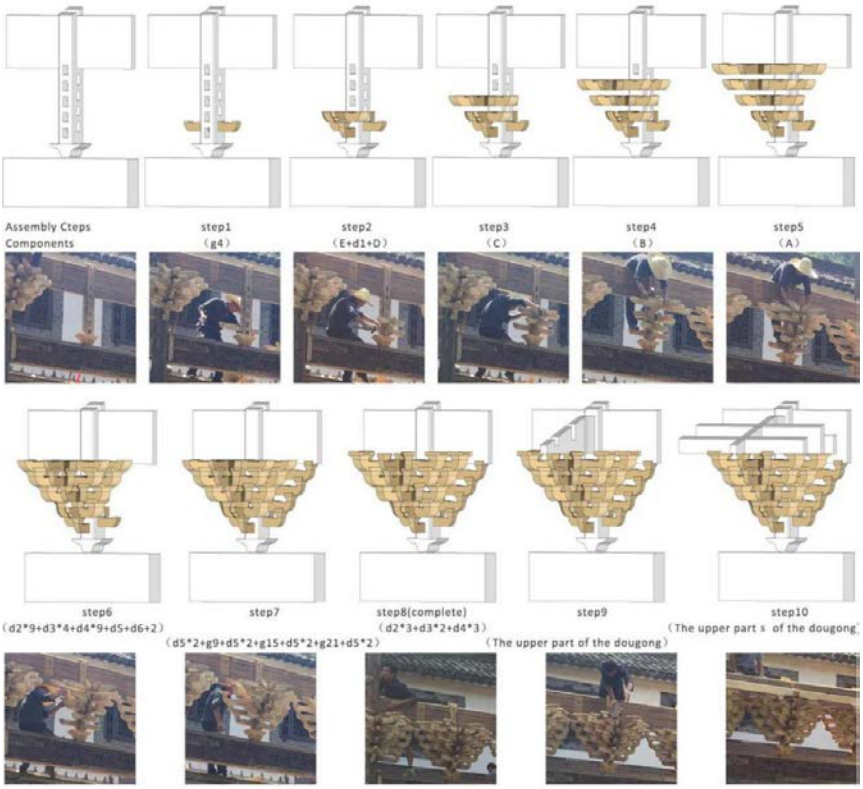

Figure 14. Assembly flowchart

3. Results and discussions

From the perspective of the project organization, the boss and the two teams form a vertical management structure. At the same time, a horizontal structure was formed between the two teams. There are component-based material transfers and information transfer in the main form of concise language and component code between teams. The component manufacture team needs more specialized skills than the assembly team. The master carpenter is the core technical staff. The importance of the division of labor is polarized. This forms a technical core-edge structure. In manufacturing technology, dougong design is the core technology (Table 4). The template facilitates the sunmao joint in manufacture. Recognizable components can be simply coded or uncoded. The two-stage assembly technology brings benefits such as construction safety and convenience. Sunmao technology is not only a key connection technology, but also conveys the main positioning information.

Table 4. Manufacture and assembly mechanism of dougong

Key aspects	Mechanism
project organization	The boss and the two teams form a vertical management structure.
Core Technology	The component manufacture team needs more specialized skills than the assembly team.
	The master carpenter is the core technical staff.
	The sunmao technology is the most critical technique for him.
Design technology	The sunmao design is at the core of design technology.
Manufacture technology	Workers use templates to control dimensions.
Coding technology	Only the key components are coded.
	The appearance of all components is strong enough to be assembled and used.
The two-stage assembly technology	The components of the first-stage assembly are determined according to the connection characteristics of the components.
	After the primary assembly, the weight and shape, meet the needs of one person to complete the second-stage assembly.
	The first-stage of assembly is to complete the complex sunmao as far as possible. The second-stage assembly completes simple sunmao.
Positioning Technology	The assembly does not require equipment or instrument positioning.
	The three-dimensional shape of the sunmao conveys positioning information.
Connection technology	The components are connected by sunmao.

4. Conclusions

The research we have done suggests that compared with the assembly stage, the manufacturing stage is a concentrated section of the technology and the workload of the traditional timber structure building. So, the key to modernizing traditional buildings is the modernization of this stage. If it is realized, we can save about 40 % of the production workload of standard layer components. At the same time, the components will achieve higher accuracy, which is beneficial to improve the assembly speed and the quality. Also, in the future, BIM can be utilized based on the design principles of dougong, which is meaningful to the inheritance and improvement of dougong technology.

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References

[1] L. Yunhe, Cathay's idea: design theory of Chinese classical architecture [M]. Tianjin: Tianjin University Press, 2005.236-242 (in Chinese).
[2] P. Dehua. Dou-Gong, Nanjing: Southeast University Publishing House, 2004 pp. 11 (in Chinese).
[3] M. Bingjian, Building techniques of Chinese ancient timber works[M]. Beijing: Science Press, 1991 (in Chinese).
[4] H. Youbin, A pictorial explanation of the history of ancient Chinese architecture[M]. Beijing: China Architecture & Building Press, 2002 (in Chinese)
[5] J. Yan, Manual of Ancient Architecture Engineering [M]. Beijing: Chemical Industry Press, 2014.