Research on Mechanical Properties of Typical Bracket Set in Traditional Timber Buildings of Song and Yuan Dynasties in Jiangnan Region

Jia Xiaohu¹, Chun Qing¹*
¹School of architecture, Southeast University, Nanjing, Jiangsu, 210096, China
*Corresponding author’s e-mail: 101011418@seu.edu.cn

Abstract. The bracket set of traditional Chinese timber buildings in Jiangnan region plays a structural and decorative role. The research of it is of great significance for cognitive the characteristics of local traditional timber buildings. In order to further understanding the mechanical properties of typical bracket set in traditional timber buildings of Song and Yuan dynasties in Jiangnan region, the methods of field investigation and numerical simulation were used. The typical bracket set of traditional timber buildings of Song and Yuan dynasties were extracted. The construction practices, mechanical properties and importance of components were studied. The results provide a basis for conservation of bracket set effectively and scientifically.

1. Introduction
Traditional Chinese timber buildings have a long history and various forms. In the Song dynasty, the construction techniques of traditional Chinese timber buildings were clearly stipulated and systematically recorded in Yingzaofashi compiled by Li Jie, which focused on the summary of northern official buildings’ practices. In the late Qing dynasty, Yingzaofayuan written by Yao Chengzu mainly recorded construction practices in Jiangnan region. Construction methods are different in various regions, but there is an inalienable correlation among them. Research of traditional timber buildings in Jiangnan region is of great significance for clarifying the origins and pedigree of traditional Chinese timber buildings. It is more urgent and necessary to study and protect this special kind of components.

Bracket sets of traditional timber buildings have structural and decorative functions. They not only play the role of connecting the roof and columns, but also determine the hierarchy of buildings. Bracket set developed to maturity from Tang to Yuan dynasty. It is considered as a kind of component with much historic, scientific and artistic value. Since bracket set connects the roof, beam, column and other components, it plays an important role in stability and safety of whole building. Therefore, the research on the structure and mechanical performance of typical bracket set in traditional timber buildings of Song and Yuan dynasties in Jiangnan region is helpful to protect bracket set more effectively and scientifically.

In related domestic and foreign researches, historical researches are mostly based on the construction age to discuss the evolution of bracket set and its pedigree development. Pu Xiaofang[1] carried out studies on some existing bracket sets taking Yingzaofashi as the reference, and discussed the development process of bracket set from its heyday to decline. Chen Tong[2] made an detailed discussion on the description in Yingzaofashi in terms of the form and structure of bracket set. Based
on the archaeological typology of architecture, Xu Yitao[3] investigated the similarities and differences of bracket set of the form of northern official buildings in Yuan dynasty, buildings in Jiangsu and Zhejiang of Yuan dynasty, and Beijing official buildings in Ming dynasty. To review the research on the structure of bracket set, Xie Linlin[4] conducted an experimental analysis on the hysteresis energy dissipation characteristic of typical bracket set in the Song dynasty and put forward their simplified hysteresis model. Pan Yi[5] took bracket set in the Grand Buddha Hall of Raoyi temple as research object, and used finite element method (FEM) and experimental method to analyze the mechanical properties of this kind of bracket set under vertical and horizontal cyclic load. Zhou Qian[6] respectively conducted horizontal and vertical seismic performance tests of bracket set on the first and second eave of the Taihe Palace in the Forbidden City, and studied the horizontal seismic performance of bracket set in the Ming and Qing dynasties. Tsuwa[7] carried out micro-vibration and free vibration tests on bracket set models to study the differences of dynamic characteristic among bracket set of different sizes. Kyuke[8] simulated the earthquake through the shaking table test with full-scale model of bracket set, showing that the stiffness of bracket set under dynamic load is consistent with that under static load test. Akihisa[9] assumed that bracket set are elastic-plastic bodies to simplify the calculation of bracket set.

To sum up, previous studies mostly stay in bracket set form comparison, mechanical tests and numerical simulation, and pay more attention to the northern official buildings. Few studies have been conducted on the styles and mechanical properties of typical bracket set in traditional timber buildings of Song and Yuan dynasties in Jiangnan region. Therefore, this paper selected bracket set in traditional timber buildings of Song and Yuan dynasties as research object. Numerical analysis of bracket set was carried out to study their mechanical properties, so as to provide the basis for scientific protection and conservation of this kind of components.

2. Materials and Methods

2.1. Literature research and field investigation

Literature review and field investigation on traditional timber buildings and their bracket sets of Song and Yuan dynasties in Jiangnan region were conducted. Four cases, Baoguo Temple (Ningbo), Yanfu Temple (Wuyi), Tianning Temple (Jinhua) and Shisi Temple (Lishui) were chosen for field investigation (Figure 1). For the construction time, vertical comparison is made through four cases covering different historical periods from Song to Yuan dynasties. Particularly, Yanfu Temple and Tianning Temple can be used for horizontal comparison, because the construction time gap of their main halls is only one year. For the geographical location, four cases are mainly concentrated in the area of Jiangsu and Zhejiang provinces. For the type of buildings, the main hall of Shisi Temple belongs to palatial-style structure, and the others belong to hall-style structure, covering the two major types of traditional timber buildings in Jiangnan region. The styles of bracket sets of these four cases are summarized to form a typical bracket set style and provide example to the subsequent numerical simulation.

The field investigation is equipped with digital camera, drawing board, grid paper, pens, drones, and laser rangefinder. The investigation took place between January 4, 2020 to January 11, 2020. The main methods of recording the type of bracket sets are: (1) Photographing with digital camera and drone, recording the locations and numbering the photos; (2) Drawing the appearance of bracket sets on site; (3) Using laser rangefinder to measure the specific components.
2.2. Three-dimensional modeling and numerical simulation

After summarizing the style of typical bracket set and its construction practices of traditional timber buildings in the Song and Yuan dynasties in Jiangnan region. The typical bracket set was modeled and numerically simulated by using finite element analysis software ANSYS. Bracket set is usually subjected to vertical load from roof, which is the most important form of force during normal service of bracket set. Therefore, the force properties of a typical bracket set under vertical load were simulated to clarify the force transmission path and mechanical properties.

In order to improve the calculation efficiency and meshing scheme, the typical bracket set model was simplified to some extent through reducing the number of flaps at the end of the second bracket-arm and leaving out the chenfengtou. Since the bracket set was in elastic deformation, so the material type was set as linear elasticity. Chinese fir is the most widely used building material at that time in Jiangnan region. Its elastic modulus is 9000MPa and Poisson ratio is 0.3. Tetrahedral element was used in meshing. The trial calculation showed that the range of von Mises stress distribution is basically the same when the minimum mesh size is 30mm, 40mm and 50mm respectively, which verified the convergence of the model mesh, and the minimum mesh size of 30mm was taken to make the results closer to real situation. The vertical dead load was applied at eaves joist and column-top joist according to the apportioned roof load. The specific constraint condition, names of components with their translations and load distribution are shown in Figure 2 and Figure 3.

In the process of numerical simulation, the contact problem between different planes was considered. Contact pairs were defined at the contact surfaces of members, and friction coefficient was
determined as 0.3. In this way, the force characteristics of a typical bracket set under vertical load condition were obtained.

Then, on the basis of this model, the component importance analysis of the typical bracket set was performed. By reducing the elastic modulus to 0.05% of the initial value one by one, and the influence degree of each on the deformation energy of the overall structure per unit volume was obtained, and the component importance was ranked. Components with reduced elastic modulus could transmit force and deformations. Their mechanical behavior are consistent with the real damaged conditions.

3. Results and Discussion

3.1. Construction analysis of typical bracket set
The results of field investigation were compiled (Figure 4). Combined with relevant literature, the mechanical properties of typical bracket sets in traditional timber buildings of Song and Yuan dynasties in Jiangnan region were summarized.

Figure 4. Photographs of bracket sets taken in the field investigation

Regarding the style, a bracket set is composed of 6th rank with one bracket-arm and two descending cantilevers was used. This exterior projection practice of a bracket set contrasts with common practice in the north area, which usually use two bracket-arms and one descending cantilever. The first bracket-arm use “stolen-heart”-style. For the arrangement of alternating brackets and joists piled up within the wall plane, usually use two layers of plaster channel bracket-arm and joist. The bracket-arms are replaced by a wedge which called xuexie to support the end of descending cantilever in the inner part.

With regards to detailed practices, considering common practices in Jiangnan region, carving petal shape at the front of the second bracket-arm which called huatouzi. The inner bracket-arms are replaced by a large wedge, which could simplifies the form of inner part (Figure 4(b)). Due to regional characteristics of actual practice, a slight adjustment was made on the basis of this style to form a typical bracket set style which is shown in Figure 5(c).

In the aspect of modular design and scale, based on the setting of modular design in the Yingzaofashi, the low-grade and high-grade three-bays hall-type structures usually use 4th or 5th grade of cai which represents a timber of standard width and height in Song-dynasty carpentry. For example, the value of each fen (an absolute unit of measurement in ancient Chinese chi-fen system of length) of the main hall of Baoguo Temple is about 1.43-1.45cm, which is closer to the requirement of the 5th grade of cai (1.40cm/fen) in the Yingzaofashi. Therefore, the 5th grade of cai is chosen as the standard of measurement for the timber scale of typical bracket set.

To sum up, the scale of basic bracket set in Yingzaofashi was used as a prototype (Figure 5(a)). In present study, a typical bracket set style of Song and Yuan dynasties in Jiangnan region was designed for the mechanical analysis by slightly adapting the regional practice in Jiangnan region (Figure 5(c)).
3.2. Mechanical properties of typical bracket set

Figure 6 illustrates the main stress direction of typical bracket set. The force flow is transmitted from eaves joist, column-top joist and lowest roof-purlin. The force flow at lowest roof-purlin is divided into two ways. One is from descending cantilever to plaster channel bracket-arm, and another is from wedge to cap-block. Width-direction members mainly bear compression, and length-direction members mainly take bend. The bracket-arms are similar to cantilevered bending members, only a small part of wedge is under compression.

As shown in Figure 7, the Mises stresses of members in each section along width-direction are generally small, mainly due to the relative displacement of members under load. While the stresses of each member in the length-direction are large due to bending. The stress values of wedge and bracket-arms in inner part are relatively small. The stress values are generally large in the outer part of bracket-arm and two descending cantilevers. The maximum Mises stress value of overall structure is 6.36MPa, which is found in the intersection of cap-block and the lower surface of the first bracket-arm of outer part.

The bending of the first bracket-arm of outer part is large. The maximum Mises stress value is 4.15MPa appearing at junction of its lower surface and cap-block (Figure 8). Outer part of the second bracket-arm is bent to a more obvious degree, and the maximum Mises stress value is 2.11MPa. While the inner part is less bent compared with the first bracket-arm. The main bending in the lower descending cantilever is concentrated in the middle. The maximum Mises stress value is 5.45MPa at junction of its upper surface and plaster channel bracket-arm (Figure 9). The stress value is smaller in the front part of the upper descending cantilever, while the stress values in the middle and rear sections are more consistent. The maximum Mises value is 2.10MPa at the intersection with the tenon of the second layer of column-top joist. The stresses in the wedge are mainly distributed along three sides, and the overall stress value is low. The maximum value of which is only 0.33MPa at the intersection of the upper surface and the lower surface of the lower descending cantilever.
Figure 8. Mises stress of the 1st bracket arm

Figure 9. Mises stress of descending cantilever

Figure 10 presents the component importance distribution of typical bracket. The names of the components were simplified and categorized to obtain the following rank: bracket-arm > upper descending cantilever > lower descending cantilever > plaster channel bracket-arm > cap-block > other block parts > other bracket-arm parts > wedge > decoratively-carved nose.

Figure 10. The importance distribution of typical bracket set components

To summary, on the one hand, the force transmission paths and stress distribution of typical bracket set were explored to better understand the mechanical properties. On the other hand, the importance ranking of typical bracket set members was obtained using the method of changing elastic modulus, which could assist in predicting the occurrence and development of mechanical residual damage such as cracking of members and provide a scientific basis for the arrangement of structural monitoring points.

4. Conclusions

This paper summarized styles of bracket sets in traditional timber buildings of Song and Yuan dynasties in Jiangnan region. The typical bracket set was modeled and analyzed numerically with FEM. Force transmission paths and stress distributions of typical bracket set were studied. The main conclusions are as follows.

Firstly, the style of bracket sets in traditional timber buildings of Song and Yuan dynasties in Jiangnan region is mainly from five to seven layers, while six-layer form is more widely used. The outer part is generally matched with bracket-arm and descending cantilever. The configuration of huatouzi, decoratively-carved nose, chenfangtou are flexible and without rules. The plaster channel bracket-arm part is mostly used overlap of bracket-arms and joists. The inner part is combined with bracket-arm and other components. The first jump of bracket set used “stolen-heart”-style.

Secondly, mechanical properties of typical bracket set under vertical load were obtained through FEM. The force transmission path is generally in three ways, the subdivisions of eaves joist, column-
top joist and lowest roof-purlin. Among them, the transfer of force flow at lowest roof-purlin is divided into two ways: directly along descending cantilever to plaster channel bracket-arm and along wedge to cap-block. The width-direction components are mainly compression bearing, and length-direction ones are mainly bend bearing. The maximum Mises stress value of whole components was 6.36MPa, which was found in the intersection of cap-block and the first bracket-arm of outer part.

Last but not least, the stress distribution of typical bracket set was initially derived. The importance ranking of typical bracket set components was also obtained by using method of changing elastic modulus. The specific sequencing is: bracket-arm > upper descending cantilever > lower descending cantilever > plaster channel bracket-arm > cap-block > other block parts > other bracket-arm parts > wedge > decoratively-carved nose.

Bracket sets of Song and Yuan dynasties in Jiangnan region were studied from the aspects of form, style, construction and structure. By the means of numerical simulation, the force transmission paths and mechanical properties were explored, and the importance ranking of typical bracket set components was obtained by using the method of changing elastic modulus. The research results could provide a scientific basis for the protection and conservation of such kind of bracket sets.

Acknowledgments
The research was supported by the National Natural Science Foundation of China under the project “Key early warning indicators, monitoring and evaluation techniques of important timber architectural heritage based on typical framing system in Jiangnan region” (Project No. 51778122).

References
[1] Pu, X.F. Li, L.P. (2018) Evolution and development of brackets system from the Tang Dynasty to the Qing Dynasty. Architecture & Culture, 09:215–217.
[2] Chen, T. (2017) Research on drawings of the Forbidden-City edition of Yingzaofashi. Journal of Chinese Architectural History, 01:63-139.
[3] Xu, Y.T. (2014) On the 13th-15th century timber frame structure of traditional Chinese official building in the north and Jiangsu-Zhejiang areas from the structural function of bracket sets (Dōugōng). Palace Museum Journal, 06:25-32+157.
[4] Xie, L.L. Yan, Z. Li, A.Q. Hou, M.L. Zeng, D.M. (2019) Research on hysteretic characteristics and simplified hysteretic model for typical Song style brackets sets. Journal of Building Structures, 40(08):170-180.
[5] Pan, Y. Yuan, S. Wang, H.Q. Wang, X.Y. Lin, Y.J. (2017) Numerical analysis of mechanical behavior of Tou-xin-zao and Ji-xin-zao tou-kung in Chinese ancient timber structures. Journal of Civil and Environmental Engineering, 39(05):9-15.
[6] Zhou, Q. Yang, N. Yan, W.M. Chun, Q. (2016) Experimental study on seismic performance of tou-kungs of 1st eave of Taihe Palace in the Forbidden City. China Civil Engineering Journal, 49(10):18-31+48
[7] Tsuwa, I. Koshihara, M. Fujita, K. et al. (2008) A study on the size effect of bracket complexes used in traditional timber structures on the vibration characteristic. In: 10th World Conference on Timber Engineering. Miyazaki. 1344-1351.
[8] Kyuke, H. Kusunoki, T. Yamaoto, M. et al. (2008) Shaking table tests of ‘MASUGUMI’ used in traditional wooden architectures. In: 10th World Conference on Timber Engineering. Miyazaki. 1315-1322.
[9] Akihisa, K. Kiho, J. Ivon, H. et al. (2010) Mechanical analysis of lateral loading behavior on Japanese traditional frame structure depending on the vertical load. WCTE, 1-9.