Chapter 10

Traditional Wooden Buildings in China

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/66145

Abstract

Chinese ancient architecture, with its long history, unique systematic features and wide-spread employment as well as its abundant heritages, is a valuable legacy of the whole world. Due to the particularity of the material and structure of Chinese ancient architecture, relatively research results are mostly published in Chinese, which limits international communication. On account of the studies carried out in Nanjing Forestry University and many other universities and teams, this chapter emphatically introduces the development, structural evolution and preservation of traditional Chinese wooden structure; research status focuses on material properties, decay pattern, anti-seismic performance and corresponding conservation and reinforcement technologies of the main load-bearing members in traditional Chinese wooden structure.

Keywords: traditional Chinese wooden structure, materials and properties, anti-seismic performance, reinforcement techniques

1. Introduction

Being one of the world's three major architecture systems, Chinese ancient architecture plays an important role in the global history of architecture. With its long history, unique systematic features and wide-spread employment as well as its abundant heritages, Chinese ancient architecture keeps growing and developing. Emerging from a system using earth and wood to one using bricks and wood, it held on its tradition of taking wooden structure as the main structure and carpentry as the main technology. After over 2000 years of progression and evolution, it has formed a complete system of structure and construction, which includes regulations and standards inherited both from Song Dynasty (1103 AD) and from Qing Dynasty (1734 AD). Compared to Western ancient buildings constructed with stones, bricks and natural concrete, Chinese traditional wooden buildings lack durability and need frequent maintenance and renovation, and properties of the wood in use have a fairly big influence on the joints and the performance of the whole structure. However, under the influence of traditional Chinese philosophy, buildings have been more of an exhibition of social status and the materials and structures involved have not been taken seriously as a technology for a long time.

The study with significance to the modern world in the field of Chinese traditional wooden buildings started in the 1920s and 1930s. Historic and artistic fields of the architecture attracted most attention and were often selected as main research directions over a long period of time. Up to now, limited number of fundamental studies on the structural behaviour of Chinese traditional timber structure and its typical joint connections can be found; hence there is an urgency to study and evaluate the seismic performance and structural behaviour of the existing historical timber buildings so as to prevent as much earthquake-inflicted damages as possible from occurring in the near future.

Taking Dou-gong brackets and mortise and tenon joints of Chinese traditional timber structure as objects, the ongoing research project of our team includes structure performance and anti-seismic mechanism of different joint connections between columns and beams, reinforcement technology of the weak parts, along with the utilization and analysis of modern engineering wood products as alternative materials in the repair and new construction of Chinese traditional timber constructions.

Material performance and structure behaviour researches of Chinese traditional wooden buildings are often based on specific emergency repairment and strengthening projects of historical buildings, which somewhat limits the systematicness and universality of the researches. On the other hand, taking convenience of cultural awareness and characteristic of oriental structural system into consideration, the results of relevant studies tend to be published domestically, which also increases the difficulty of international academic exchange and interaction. In consequence, the intention of this chapter is to collect and introduce relevant research status as well as phased achievements of my team systemically. And the publication of this book will be certain to generate a trend to study traditional wooden structure and encourage worldwide academic exchange and cooperation.

2. The structure and preservation of traditional Chinese wooden architecture

Represented by traditional Chinese wooden architecture, oriental wooden structure stands out in the architecture world, and after a long course of development and accretion, it has reached a high level of standard theoretically and practically. Take the example of the Yingxian Wooden Pagoda, the highest wooden tower existing worldwide. Besides the fact of being 67.1-m high, it has also survived several major earthquakes and therefore embodied the perfect combination of techniques and aesthetics of wooden structures as well as the intelligence of ancient Chinese people. Consulting two significant building standards from Song Dynasty and Qing Dynasty, this chapter introduces the development and structural

http://dx.doi.org/10.5772/66145

evolution of traditional Chinese wooden structure, focusing on three classic structures and via the examples of well-known wooden structures such as the Yingxian Wooden Pagoda, and presents the condition of study and preservation of historic buildings in modern China.

2.1. A brief guide to the evolution of traditional oriental wooden structures

Due to different cultural backgrounds, ancient architecture used to have seven independent systems, of which some are extinct or never widely spread and thus had limited achievements and influences. That left Chinese architecture, European architecture and Islamic architecture to be considered the world's three main architectural systems. And among them, Chinese architecture and European architecture are the most long-lasting, widely spread and successful ones. Ancient Chinese architecture had undergone primitive society, slave society and feudal society, among which the last one was the time when Chinese classic architecture developed the most.

1. **Primitive society (7000 years ago to twenty-first century BC)**. The building types vary due to different climates, geographical features and materials. Among them, there are two typical types: wooden frame and mud wall buildings that emerged from cave houses in the Yellow River basin and the Ganlan-style buildings (wooden buildings that built on stilts) from nest houses in the Yangtze River basin. In the late stage of the primitive society, building sites already had trace of privatization and the walls and roofs of buildings were mostly interwoven branches or twigs with mud coating (see Ref. [1]).

2. **Slave society (2070–476 BC)**. In the twenty-first century BC, the wooden frame and rammed earth construction and regular enclosed courtyard building groups came along, which showed great improvement in timber frame technology. The sixteenth century BC was the prime time for the development of the Chinese slave society and a time when documentary trace began. Based on the size of the rammed earth foundation of the palaces and temples, buildings at this point of the history had larger scale and stricter hierarchy and scale of cities, height of city walls, width of streets and other buildings of significance were required to be built according to their rank. In the Spring and Autumn periods (770–476 BC), the popularization of tiles and appearance of high-platform buildings for imperial and ducal palaces were the most important improvements. High-platform building means building a platform of tamped earth underneath the palace. As the leuds sought more magnificent palaces, the decoration and painting of ancient architecture were taken a step further (see Ref. [1]).

3. **Feudal society (475 BC to 1911 AD)**. With the collapse of slavery, agriculture and handicraft rapidly grew and the utilization of ironware accelerated the improvement of structure technology and wooden structure's construction quality. Fireplaces, heated brick beds and cellars can be seen at this period of time. The Han Dynasty was a thriving time for classic Chinese architecture when the nowadays commonly seen beam-lifted frame and through-type frame wooden structures were formed. And at the same time, the traditional roof of Chinese buildings also flourished. Since then, the introduction of Buddhism greatly boosted the development of Buddhist architecture, one of the most

important types of classic Chinese architecture. The Tang Dynasty was a time when the techniques and artistic qualities of classic architect were developing the fastest. Tang-style architecture demonstrates the extremity of size and regulations, extremity in architectural complex layout and features of large expansion and large volume. And the construction form and material requirements of wooden structures especially Dou-gong brackets were standardized. Tang-style architecture also produced a far-reaching influence on countries such as Japan. Later in the Song Dynasty, modular system was adopted and the book building standards were officially published which set standard rule for buildings' measurements and basic moduli so that the size of wooden components could be properly defined.

In the late stage of feudal society, building forms were becoming more and more simplified and the entirety of the beam-column frame was enhanced. The buildings presented a serious and rigorous image with more ingrained decoration and painting. In Qing Dynasty, the ethnic diversity contributed to the blossoming of various residential building types. And the monomer building form of official architecture was set and therefore improved the standard of architectural complex design. The promulgated book construction practices enumerated 27 practices of monomer building and formulated new construction moduli, which contributed much to accelerate the design and construction process and controlling material consumption (see Ref. [2]).

2.2. The structural system and characteristics of traditional Chinese wooden structure

Based on different construction frames and geographic features, the traditional Chinese wooden structure frame system can be divided into three types: through-type frame, beam-lifted frame and log-cabin-type frame (see Refs. [3, 4]), as seen in **Figure 1**.

1. **Through-type frame**. The through-type frame is constructed of vertical connection with separated frame and mostly used in rural housing. There is no reference to this type in the official building standards. The common practice of this type is to connect the columns with square crossbeams along the length of the house, forming a truss and then use square crossbeams to connect every two trusses, forming the frame of the house. The characteristics of this type include using materials with small cross section that are easy to obtain, using multiple square crossbeams along the length of the house that can be assembled beforehand, enhancing the entirety and stability of the structure and ren-

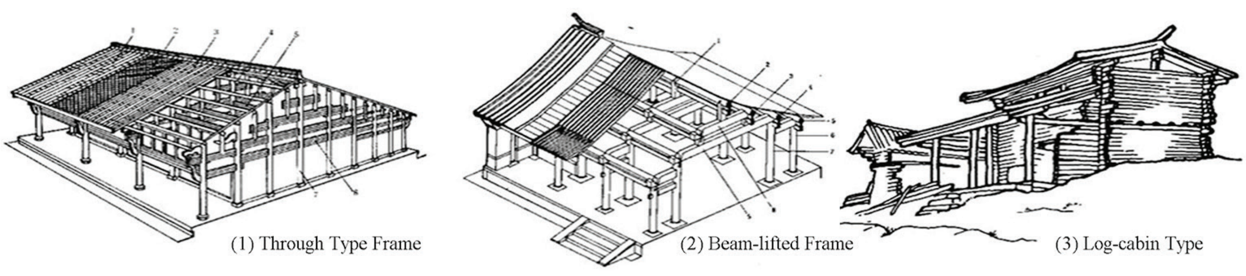

Figure 1. Three types of traditional Chinese wooden structure.

dering the installation of walls convenient and saving manpower and materials with its simple practice, direct force transmission and ever-evolving and adaptable nature.

2. **Beam-lifted frame**. This frame type formed in the Spring and Autumn period kept evolving and then became a settled practice. This frame type varies in material size and frame combination according to different social ranks, which was strictly set in regulations such as building standards in Song Dynasty and construction practices in Qing Dynasty. Beam-lifted frame is usually composed of the frame layer, the Dou-gong brackets layer and the roof layer. Usually, it is constructed by placing a beam head on top of a column and then on top of that, using a shorter column to hold a shorter beam and another beam head and another column and so forth. And eventually, the short column on the short beam holds the weight of the purlin. This type was widely used in large-scale buildings such as palaces and temples in northern China. The characteristics of beam-lifted frame are long distance between columns along the length of the house, enclosing larger interior space and aesthetically pleasing structural features.

3. **Log-cabin type**. Log-cabin type is an ancient structural type that dates back to the primitive society. In China, it was found to be used in building the outer coffin in Shang Dynasty tombs from over 3000 years ago and in the caved patterns on Han Dynasty relics found in Yunnan province in south-western China. It is referred as 'Mukeden' in north-eastern China, meaning to pile up caved logs (often cut into semi-cylinders) to build houses. This type of structures is often seen in areas such as Inner Mongolia, forests in north-eastern China and mountain areas in Sichuan province and Yunnan province in south-western China. Its characteristics are as follows: it can regulate the room temperature to fit the fickle climate in mountain areas and can withstand earthquakes to some extent; it requires only simple materials and minimum manpower but possesses great diversity and mobility; however, to build this type of houses, a great amount of wood is required and the size and location of doors and windows are greatly limited so it is not as widely spread as the other two types.

2.3. The preservation and research status of two typical remaining historic wooden buildings in China

(1) Yingxian Wooden Pagoda. Yingxian Wooden Pagoda, originally known as the Yingxian Wooden Pagoda of Fogong Temple, was built in 1056 AD, Liao Dynasty, and is the largest and oldest high-rise wooden building in existence in the world (as seen in **Figure 2**). It is a 67.31-m tall pagoda of a multi-storied pavilion type with an octagonal cross section and nine floors that disguised as five. It has a diameter of 30.27 m, weighs 7400 tons and altogether consumed 3700 m^3 of timber. With 54 types of Dou-gong brackets of different functions, shapes and sizes installed, it is often referred as a museum of Dou-gong bracket. However, as a consequence of multiple earthquakes during the recent thousand years, wars and unfit repair in modern times, the pagoda suffers from all kinds of problems such as a severe tilt of the main body and the twist of the column frame of the second and third floors. Based on the observation data of 2010, the overall slope was 1.25% and counting, especially of the second floor which accounted for 60–70% of the slope.

Figure 2. Yingxian wooden pagoda.

Since 1933, Liang et al. began to conduct detailed researches and measurement on Yingxian Wooden Pagoda. In 1966, the book Yingxian Wooden Pagoda was published, and in 1973 (see Ref. [5]), architectural experts such as Yang Tingbao began their 10 years of restoration of this architectural treasure after discussing the issue of its partial tilt and setting basic rules and solutions regarding the repair and reinforcement of the pagoda. The Committee of Yingxian Wooden Pagoda Restoration and Preservation Construction Management was found in the 1990s, and after the early-stage study, it started monitoring the structural soundness of the pagoda in 2008 and continued till this day. Since the 1990s, many scholars and their teams have studied the structural state (e.g. Ref. [6]), damage dispersion, seismic reaction analysis (e.g. Ref. [7]) and material deformation (e.g. Ref. [8]) features under external forces. Refined finite element (FE) models were established, respectively, based on the Dou-gong bracket joints and the whole structural system and load-bearing quality analyses were conducted under lateral load (e.g. Ref. [9]). And the ideal restoration model of the pagoda was established through computer-aided design (CAD) drawings and three-dimensional (3D) models (see Ref. [10]). Yet, there are still issues to address in terms of repair and preservation. In recent years, scholars came up with plans such as major repair of the framework, total support of the pagoda and raised support of the upper section. But because of the significance, structural complexity and uniqueness of the pagoda, the present plan is to reinforce and repair the tilted parts and damaged components on the second and third floors (see Ref. [11]).

(2) East palace of Foguang Temple. The palace is located in Wutai county, Shanxi province, in northern China and originally built in Northern Wei Dynasty (386–534 AD, one of the

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Northern Dynasties), as seen in **Figure 3**. With the remaining main hall rebuilt in 857 AD, Tang Dynasty, the palace is one of the remaining oldest Tong Dynasty wooden structures and acclaimed as 'the primary national treasure of China'. With a building width of seven rooms and length of four, the roof, column frame and Dou-gong brackets all belong to the top rank and exhibit classic structural features of Tong Dynasty. The Dou-gong components have cross-sectional size of 210 × 300 cm, 10 times the size of the same type of components in Qing Dynasty. The eaves are 3.69 m long, and the triangle Y-shape support system in the beam frame is the first of its kind in China. In the palace, there are 61 m^2 of Tang Dynasty wall paintings preserved and other treasures such as inscriptions from Tong Dynasty and painted sculptures.

As a classic example of the structural frame and construction technology of Tang Dynasty architecture, multi-dimensional studies were carried out on the East Palace of Foguang Temple regarding spatial form, structural bearing capacity, anti-seismic reinforcement and artistic characteristics (e.g. [12, 13]). As to the protection of the palace, surrounding residents were moved out in 1954 and repair and reinforcement began. In 1985, local government built dams around it to protect it from mountain torrents and stone walls, flashing and gutters to reduce humidity.

Figure 3. East palace of Foguang temple.

3. Properties study on traditional Chinese wooden structure

3.1. Study of physical properties on wood materials from historic buildings

In order to protect all the wooden buildings with hundreds of years of history across China, a research team was formed to carry out field study on the structure materials of historic buildings in 11 provinces, municipalities and autonomous regions. Experiments were carried out on the worn components after replacement and thus conclusions were drawn concerning the species and physical properties. Furthermore, a national mandatory standard *Technical code for maintenance and strengthening of ancient timber buildings*, see Ref. [14], was established.

3.1.1. Researches of the species of wooden materials used in historic buildings

According to the field researches and some microstructure identifications, the main components in historic buildings such as beam, fang (a square pillar), column, purlin and rafter are mainly made of nanmu (*Phoebe zhennan S. Lee*), cypress (*Cupressus funebris Endl.*), China fir (*Cunninghamia lanceolata (Lamb.) Hook.*) and pinus (*Pinus massoniana Lamb.*) in southern China. In northern China, Chinese pine (*P. tabulaeformis Carr.*), larch (*Larix gmelinii (Rupr.) Kuzen.*) and pinus armandi (*P. armandii Franch.*) are widely used. And in common housing, poplar (*PopulusL.*) and elm (*Ulmus pumila L.*) are used while in large-scale historic buildings of great importance, there are wood materials such as nanmu from the south involved, which indicates that these buildings are mostly constructed with local materials except for important ones with higher standards. Buildings in Sichuan province in southwest China and Hubei province in the middle south are constructed of nanmu and cypress for there was a large reserve at the time. However, the value of this wood goes up as the reserve goes down nowadays.

3.1.2. Studies on the physical properties of the components in historic buildings

The first concern of all the people working in the field of ancient architecture is the change pattern of the properties of load-bearing components. But studies concerning this topic or relevant ones have been hard to find. The leading difficulty lies in that the environmental conditions that the components are in play an important role in how their properties change and different species react largely differently to the environmental conditions. In addition, it is also difficult to manufacture viable specimens using modern materials as a control group due to the massive variation of wood materials.

In 1977, Chen G.Y carried out physical properties experiments on a worn component from the Yingxian Wooden Pagoda, see Ref. [15]. It was a column on the horizontal slot of the two-raftered roof beam on the second floor that was 900 years old according to C14 dating. The column was 2.7-m high, 33 × 23 cm in section size and made of north China larch (*L. principis-rupprechtii Mayr*). Being hidden inside the pagoda, the column was spared from erosion by wind and rain and thus showed no obvious erosional furrows and darkening but demonstrated some split (being hit by artillery shells). The experiment results are seen in **Table 1**. In 1982, Chen experimented on the middle column from the Jing Qing Gate in Jinci Temple, see Ref. [15]. The column was about 600 years old, 6-m high, 40 × 40 cm in section size, and made of poplar (*Populus L.*). The column was not eroded by rain and demonstrated darkening and different levels of split. It showed trace of weathering and was eroded into powder at approximately 1 m above the root, rendering the root conical and leaving the upper half relatively intact. The results are seen in **Table 2**.

Both experiments proved that after 600–900 years of load bearing, the tensile strength and compressive strength perpendicular to the grain of the material were weakened the most:

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the former by 50% and the latter by 80% in pinus and poplar, respectively. At the same time, the stiffness and shear strength were enhanced: the former by 11–16% and the latter by 15%. This indicates that old wood material has denser cell structure and therefore higher level of stiffness than new material. And due to the ageing of its internal structure, the material suffered from different level of degeneration concerning other physical properties. Properties relying on late-wood resistance such as compression strength parallel to the grain and bending strength degenerated less heavily and maintained good uniformity while properties relying on early-wood resistance such as tensile strength paralleled to grain degenerated more and maintained good uniformity as well. On the other hand, properties relying on both late wood and early wood such as splitting strength and impact hardness had much poorer uniformity. This points out that the timing takes a great toll on physical properties of wood material.

Parameters	Old wood in Yingxian Wooden Pagoda	New wood	Old/new (%)
Compress strength parallel to the grain (kgf/cm^2)	467.7	576	81
Chordwise compress strength perpendicular to the grain (kgf/cm^2)	15.8	84	19
Radial compress strength perpendicular to the grain (kgf/cm^2)	20.6	46	45
Tensile strength parallel to the grain (kgf/cm^2)	651.7	1299	50
Bending strength perpendicular to the grain (kgf/cm^2)	964.7	1133	85
Chordwise shear strength parallel to the grain (kgf/cm^2)#	96.2	68	110
Radial shear strength parallel to the grain (kgf/cm^2)	89.13	85	105
Radial splitting strength (kgf/cm^2)	7.4	10.1	73
Chordwise impact hardness (kgf)	127.7	425.7	30
Radial impact hardness (kgf)	113.9	227.8	50
End-face impact hardness (kgf/cm^2)	433	377	115

Table 1. Comparison between old wood in Yingxian Wooden Pagoda and new wood in Ref. [15].

In 1994, Ni et al. ran chemical component analysis on the replaced columns from the main hall of Bei Yue Temple and Da Bei Lou building in Chang Ling, Hebei province, in northern China during renovation, see Ref. [16]. The two columns were, respectively, 900 and 200 years old and made of Chinese spruce (*Picea asperata*) and cypress (*C. funebris Endl*.). Samples in the experiments were taken from the intact part of the column. Results are seen in **Table 3**.

Parameters	Old wood in Jingqing Gate	New wood	Old/new (%)
Compress strength parallel to the grain (kgf/cm^2)	539	427	126
Chordwise compress strength perpendicular to the grain (kgf/cm^2)	42.6	49	87
Radial compress strength perpendicular to the grain (kgf/cm^2)	57.3	65	88
Tensile strength parallel to the grain (kgf/cm^2)	450	1070	42
Bending strength perpendicular to the grain (kgf/cm^2)	267	796	34
Chordwise shear strength parallel to the grain (kgf/cm^2)	108	73	148
Radial shear strength parallel to the grain (kgf/cm^2)	105	95	110
Radial splitting strength (kgf/cm^2)	12.1	12.2	99
Chordwise splitting strength (kgf/cm^2)	13.6	15.8	86
Chord plane hardness (kgf)	372	242	154
Radial plane hardness (kgf)	399	227	130
End-face impact hardness (kgf)	509	306	166

Table 2. Comparison between old wood in Jingqing Gate and new wood in Ref. [15].

It can be inferred from the data that various extract amounts from old wood showed different levels of increase while the amount of holocellulose and α-cellulose decreased, which showed that the main components of cell walls in old wood had degraded and had looser structure than newly lumbered ones. Cellulose is the main cause of high tensile strength parallel to the grain, and hemicellulose and lignin give the material elasticity and compression strength so the decrease of these three components microscopically explains the macrolevel mechanical properties degeneration.

3.2. Study on the decay pattern of physical properties, residual strength and longevity of wood material

Due to the special fact that ancient buildings are being reserved, old materials in studies are mostly the small components being replaced during renovation, which severely restrained the study on the strength of wooden structures. And the fact that the strength alters differently under different load conditions makes it even more difficult to study the decay of physical properties of old wood structures.

In 2006, Liu et al. did a study on the relevance between chemical components and bending strength and degree of decay on the old materials from the Wu Ying Palace in the Forbidden City, see Ref. [17]. The experiment samples were from the beam and made of larch. And the

Component	Tree species					
	Spruce			Cypress		
	Old	New	Old/new (%)	Old	New	Old/new (%)
Moisture content (%)	6.65	6.02	110.4	6.19	7.57	81.8
Ash content (%)	0.42	0.78	53.8	0.58	0.41	141.4
Cold water extract (%)	5.53	1.42	389.4	6.69	3.42	195.6
Hot water extract (%)	7.27	2.68	271.2	7.98	4.56	175.0
Phenethyl alcohol extract (%)	6.60	1.63	404.9	6.35	6.90	92.0
1% NaOH extract (%)	25.1	12.4	202.4	23.5	17.1	137.4
Pentosane (%)	11.5	11.6	99.1	16.6	10.7	155.1
Lignin (%)	30.0	28.4	106	33.1	32.4	102.1
Holocellulose (%)	58.6	66.2	88.5	56.6	64.9	87.2
α-Cellulose (%)	36.2	41.5	87.2	34.9	39.1	89.2

Table 3. Comparison of chemical composition between old wood and new wood in Ref. [16].

decay degrees were determined according to *GB/T 13942.2-92*, see Ref. [18]. The relationship between decay degree and cellulose and the content of 1% NaOH extracts can be seen in **Figure 4**. Due to the limited amount of old wood materials, chemical components analysis was carried out on healthy wood with a bending strength of 90, 100 and 110 MPa. The results of the relevance between bending strength and cellulose and the content of 1% NaOH extracts are shown in **Figure 5**. As the results showed, as the decay degree elevates, 1% NaOH extracts content evidently rises. Positive proportional relation can also be observed between 1% NaOH extracts and bending strength. The study showed that not only can the alkali extracts be used to determine the preliminary decay degree but they can also be used to determine visually healthy materials' physical properties.

To address the issue that in physical property experiments on ancient buildings, old materials are rare and the material qualities of new materials are different from those of the old ones, Xu et al. came up with the solution of accelerating the decay process via inoculation of fungus, see Ref. [19]. The process is to infect the wood with single fungus under suitable environment to accelerate the decay. This study provides the physical properties of wood from different decay degrees and the decay patterns of physical properties of wood from different decay degrees. And it offers a new way of thinking about the quantification of wood decay degree.

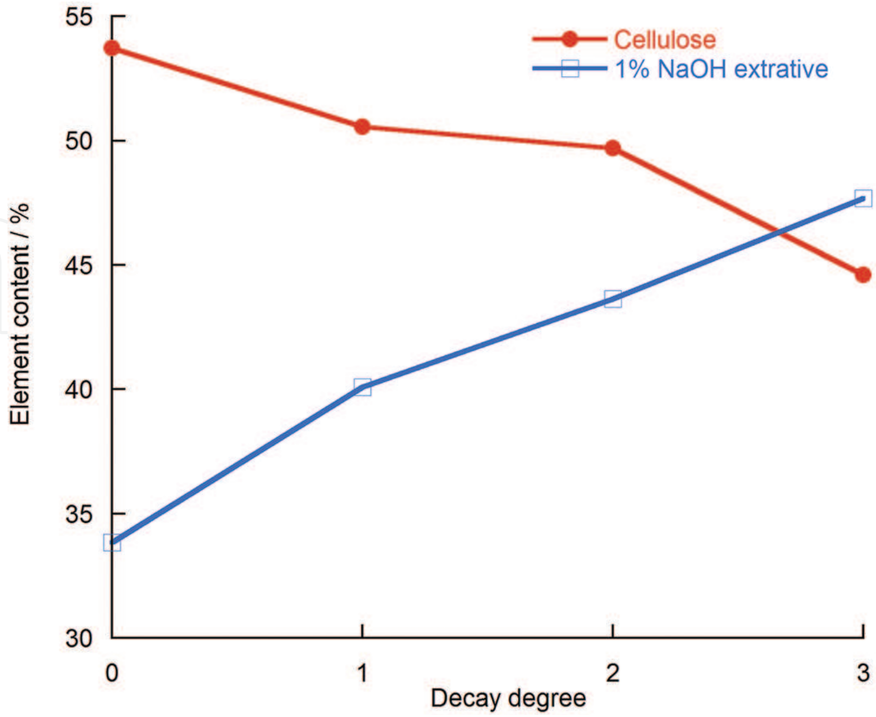

Figure 4. Variation in cellulose and 1% NaOH extract along decay of larch wood in Ref. [17].

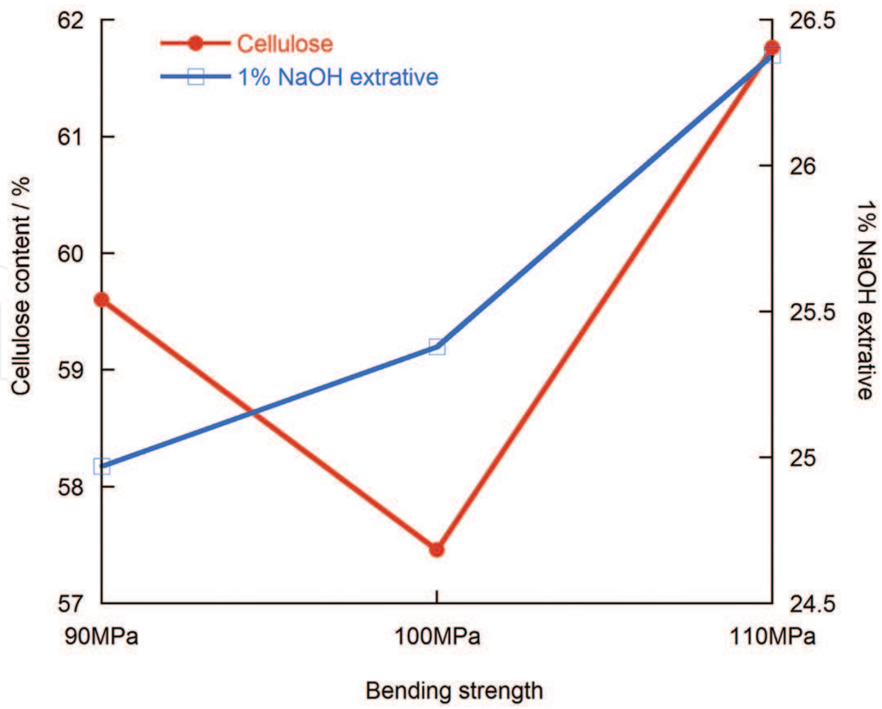

Figure 5. Variation in cellulose and 1% NaOH extract along bending strength of larch wood in Ref. [17].

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3.3. Study on modern engineering materials' application in traditional wooden structure

In modern China, all the constructions of new palaces and temples involve reconstruction of pre-existing historic buildings or reference to classic elements. This requires similar construction method as well as high-quality materials. Among the new engineering wood materials, glued-laminated timber (glulam) shows all kinds of advantages such as natural wood texture, high quality of anti-corrosion, high usage and stable physical properties. In addition, glulam also has great plasticity and special expressive ability that can rival steel structure. Being well liked both worldwide and here in China, glulam has been applied to the construction of traditional structures, see Ref. [20].

(a) Main hall of Xiangji Temple in Hangzhou (b) Main hall of the White Lotus Lore Temple in Shanghai

Figure 6. Typical applications of glulam used in Chinese traditional structure.

Xiangji Temple is a historically famous temple in Hangzhou, Zhejiang province, in south-eastern China. First built in 1016 AD, the original building was destroyed in a fire and was rebuilt in 2010 AD. The major structures of the temple's bell tower, drum tower and the Kinnara hall were built in steel while the monastery, the guest house and the dorm rooms were in log structure and the rest were in glulam structure. Glulam combined with traditional roof made a column-free room possible. With the traditional multi-overhanging eaves, the main hall demonstrates a splendid momentum as well as openness and brightness, as seen in **Figure 6(a)**.

In the White Lotus Lore Temple in Shanghai, the Buddha hall has a glulam body. Different from the traditional temples, this temple represents its own era (as seen in **Figure 6(b)**). Built up high, with large overhanging eaves and mild-slope roof, it was totally built according to the proportion of buildings in Tang Dynasty. It is completely made of glulam and structured with grid structure to make a column-free indoor space.

The Yu Xi Temple Tower in Chao Mountain in Hangzhou, Zhejiang province, in south-eastern China is a pavilion-style tower with an octagonal section and a pillar in the centre. The tower has five floors with four additional floors hidden inside. It was made of glulam and the hidden floors were of structural reinforcing purpose just like those in the Yingxian Wooden

Pagoda. The Laojun tower in Qingcheng Mountain, Sichuan province, in south-western China is another wooden structure bu`ilding built on top of a mountain. After reconstruction, it is 28.05-m high, with a reinforced concrete base. The first and second floors are made of concrete and glulam and from the third through ninth floors are made of glulam, with Douglas fir.

Thanks to the variety of materials and connection types, traditional wooden structures are more frequently combined in modern construction. On the one hand, wood is combined with glass, concrete and steel, resulting in more flexibility in wooden structure design. On the other hand, wooden structure borrowed the steel system such as the grid structure in the White Lotus Lore Temple and the truss system in Kai Yuan Temple which extend the building scale. What's more, traditional mortise and tenon joints are combined with metal joints and adhesives. Through structural innovation and optimization, with advanced construction techniques, contemporary traditional wooden structures will be perfect in structural logic, creativity and details.

4. Anti-seismic performance study on traditional Chinese wooden structure

Wooden structures have an outstanding advantage over other forms of structures when it comes to anti-seismic performance. Traditional Chinese wooden buildings have a unique form of structure that allows them to withstand earthquakes with remarkable stability, hence the saying 'The building stands even though all its walls collapse'. One of the most significant features of traditional Chinese wooden structure is that it 'emphasizes structural members rather than joints', so the mechanical properties of joints take a huge toll on the performance of the whole building. This chapter shows studies on anti-seismic performance of key joints and whole buildings.

4.1. The anti-seismic structure and mechanics of ancient Chinese wooden structures

After analysing the damage that past earthquakes did on existing ancient wooden structures, experts found that ancient Chinese wooden structures have their unique features in design concepts, structural layout and building techniques. Special building techniques such as the floated joint between a column and the stylobate, the semi-rigid mortise and tenon joint between a beam and a column and the tilt columns and raised columns of the column frame along with the Queti, a kind of trimming joists at the end of a beam, the Dou-gong bracket and the 'grand roof', make classic wooden buildings distinct from modern reinforced concrete structures regarding anti-seismic performance.

With relatively high ratio of strength to weight, wooden material can maintain a certain level of resilience and ability to recover from deformation when external forces are applied. The mostly used joint formation between wooden components is semi-rigid mortise and tenon joint which not only improves the resilience of the whole structure but also effectively cancels the horizontal thrust and consumes a notable share of energy generated by the friction and rotation of mortises and tenons. Besides, classic Chinese wooden structure can also consume and absorb seismic energy through the auto-deformation of its load-bearing frame system.

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Looking at the small components of the structure, it can be found that the connection between the column and the floor is often smooth and horizontal with no embedment or adhesion, which allows the upper section of the building to slide independently and stably as a whole during an earthquake without collapsing. A tilt column means to make the bottom of a column into a gentle slope, resulting in the top of it tilting slightly inward, the mortises and tenons above pressed together and the deadweight of the mortises and tenons providing the original bending moment of the joint. It can also act as an effective limitation on the movement of the upper beam frame. As the transitional layer between the column frame layer and the beam frame layer, the Dou-gong bracket layer is constructed of many small components interlaced, forming an upside-down triangle by using less and less components from top to bottom. It functions as a spring cushion and reduces the earthquake effect. And because of the transition and separation of the Dou-gong bracket layer, the roof and the beam frame as a whole can be analysed as a rigid entirety with slopes, as seen in **Figure 7**.

Before the 1990s, out of the purpose of reserving cultural heritage, studies on ancient buildings mostly highlighted their historical and artistic qualities rather than scientifically analysing their structures. In 1991, Wang T's analysis (see Ref. [21]) of the static load performance of the critical components, joints and the whole structure of ancient buildings marked the beginning of structural studies on ancient buildings. And studies on ancient Chinese structures have thrived so far. Focusing on the outstanding anti-seismic quality of classic wooden structures, Fan from the Harbin Institute of Technology, Yu and Xue from the Xi'an Jiaotong University, Zhao and Zhang from the Xi`an University of Architecture and Technology and Fang from the Tsinghua University conducted a large amount of experiments and theoretical analyses on the dynamic features, anti-seismic behaviours, destruction assessment and joint reinforcement. Li from the Taiyuan University of Technology and Zhou from the Peking University, respectively, conducted years of anti-seismic and reinforcing restoration experiments and studies on the Yingxian Wooden Pagoda and ancient buildings in the Forbidden City, as seen in Refs. [22–25], for example. Currently, the most commonly used methods of analysing the anti-seismic behaviours of classic wooden structures are static procedure, response spectrum analysis, dynamic-timing analysis and nonlinear static procedure. After years of studying, scholars at home and abroad have come up with methods of building analytical modules such as the semi-rigid calculation module of mortise and tenon joints, the combination module of beam units, the single degree of freedom (SDOF) system module and the mechanics module.

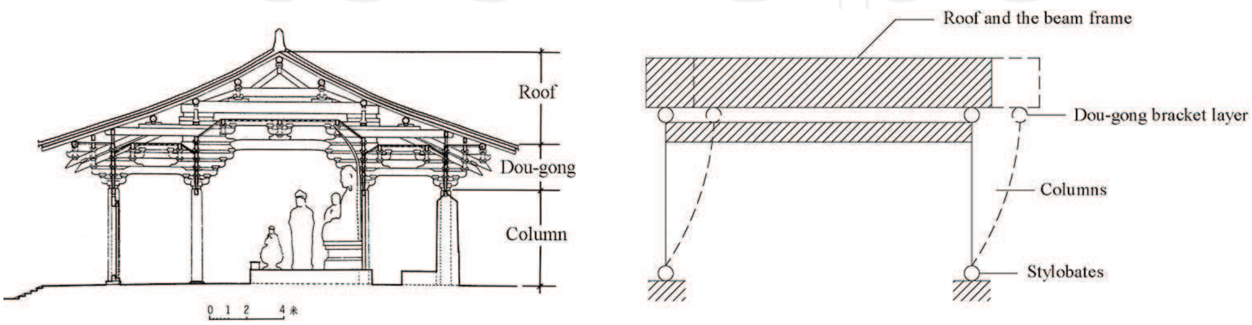

Figure 7. Typical structural vibration model of traditional Chinese wooden buildings.

4.2. The anti-seismic performance study on mortise and tenon joints and Dou-gong brackets

4.2.1. Mortise and tenon joints

Mortise and tenon joints are often used in classic buildings to join beams and columns. These joints can bear some lateral load and joint-bending moment and allow some rotation and relative slide between the beam and the column. These are all 'semi-rigid' features that this type of joints demonstrates, which can consume part of the energy and reduce structural reaction to earthquakes.

As to experiments, Gao et al., see Ref. [26], conducted lateral low-cyclic reversed-loading tests on three wooden structure models with Queti of the watchtower in Xi'an, Shaanxi province, in north-western China. They analysed the deformation features and destruction pattern of joints and found after calculation that the ductility coefficient changes within the range of 1.58–3.99. Xie et al., see Ref. [27], conducted the same experiments on dovetail joint models and discussed the effect on the anti-seismic performance of joints of vertical load, Queti, Pupai-fang components and the module size effect. As to calculation module, Wang simplified mortise and tenon joints as hinges and Queti as cantilevers with load focused on the tips in static calculation of wooden structures and double-checked the load-bearing capacity of components, as seen in Ref. [19]. Fang and Yu et al. built an FE model fit for ancient wooden buildings by defining 3D variable semi-rigid joints that reflect features of the Dou-gong bracket and mortise and tenon, based on studies on structural features of ancient wooden buildings, as seen in Ref. [28] and **Figure 8**. The module was first used in the calculation of the unequal settlement of the base of the watchtower in Xi'an and then used in the mechanics performance analysis of ancient buildings such as the drum tower in Xi'an, the Baoguo Temple in Ningbo and Zhejiang province, and performed quite a good job. Feng and Zhang et al. (see Ref. [29]) combined the shaking table test on the column frame unit model formed by four columns in the palace hall structure in building standards of Song Dynasty and low-cyclic reversed-loading tests on the model and numerical simulation, conducted lateral vibration analysis and random destruction theoretical analysis on the Dou-gong brackets and studied the features of semi-rigid mortise and tenon joints. And came up with the rigidity formula for mortise and tenon joints and the equivalent viscous damping coefficient.

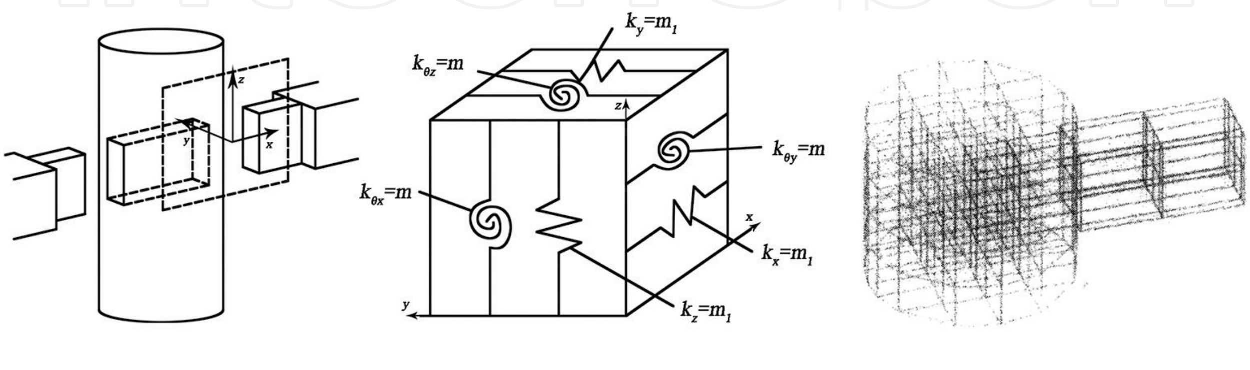

Figure 8. Semi-rigid joint model and finite element modelling of mortise and tenon joint in Ref. [29].

4.2.2. Dou-gong brackets

Dou-gong bracket, a special connection component between the column and the beam, plays a pivotal role in both structural force transmission and decorative function. Composed by many cantilever joists (named as Gong) staked one on top of another on crossed direction and

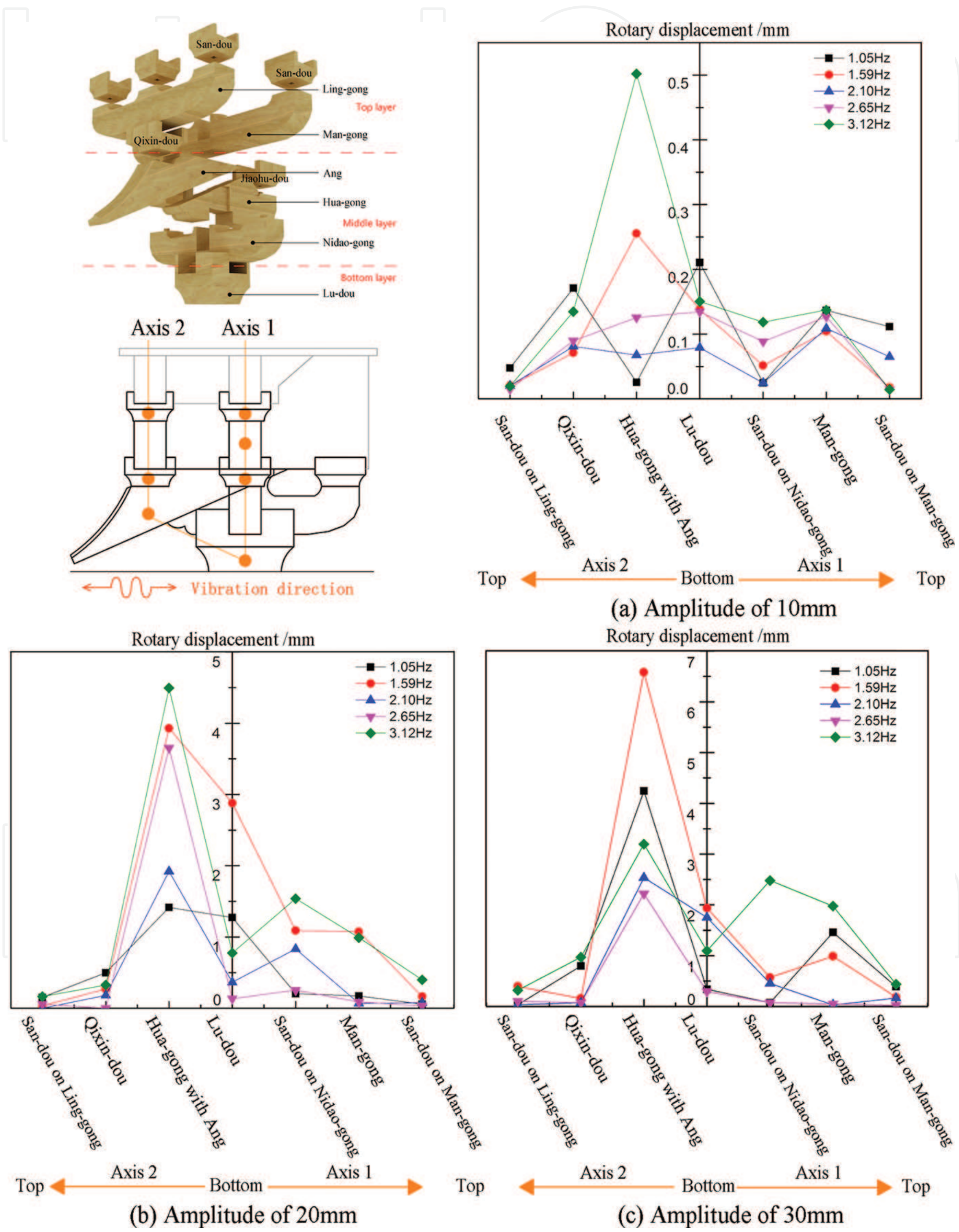

Figure 9. The rotary displacement of the Dou-gong components in shaking table tests along two axes in Ref. [33].

connected by Dou members, Dou-gong bracket as a whole could just be regarded as a beam pad. This special structure forms as an inverted fixed-hinged support which has compression deflection and rotary movement on vertical plan as well as slip movement on horizontal plan. In respect of structural performance, because of the overhanging on two directions, Dou-gong bracket shortens the span and enhances the load-carrying capacity of upper beams; meanwhile, it helps to adjust the depth of eaves, making it more graceful and harmonious. On the other hand, instead of sticking together, all the Dou and Gong elements are connected by mortise and tenon joints. With the addition of its unique shape with overlapping cantilevers, Dou-gong bracket becomes a ductile connection to dissipate energy between column and beam, especially under lateral forces such as earthquakes.

Chinese scholars mainly conducted studies on two types of Dou-gong brackets: the Song style and the Qing style. During the restoration project of the tower of the east city gate in Xi'an in 1996, with the help of the repair team, Yu et al. conducted and performed static and dynamic experiments on the two types of Dou-gong brackets, see Ref. [30]. Gao et al. performed six 1:3.52 models of the bottom two pieces of Song style 8 layers Dou-gong brackets with second-class material according to the regulations in building standards and came up with load-displacement calculation module, mass-spring-damper model and lateral force-displacement-restoring force model under vertical load via vertical monotonic-loading tests and lateral low-cyclic reversed-loading tests. They also calculated the vertical seismic transmission coefficient and the lateral energy consumption, which showed great two directional anti-seismic performance of the Dou-gong brackets, see Ref. [31]. Sui et al. drew the conclusion of a restoring force model that reflected the restoring features and stiffness variation regulation of Dou-gong through low-cyclic reversed-loading tests on singular-layer, double-layer and quadruple-layer Dou-gong models, see Ref. [32]. As to other transitional types of Dou-gong brackets in the transition periods, our team of the Nanjing Forestry University conducted shaking table tests on full-scale models made of Douglas fir and China fir based on the Dou-gong brackets in the Ming Dynasty Tian Wang Palace of Bao Sheng Temple in Luzhi and analysed factors such as the between-layer displacement reaction features, the contribution ratio of the rotation and slide deformation of the components and the structurally weak-part assessment as seen in Ref. [33] and **Figure 9**.

As to numerical simulation, Wei, see Ref. [34], studied the non-linear variation patterns of the connection rigidity, calculated the ductility coefficient and the equivalent viscous-damping coefficient and compared results between the axial compression tests and the low-cyclic reversed-loading tests via ANSYS simulation based on the operating mechanism, destruction form and anti-seismic performance of Dou-gong. Du studied the Yingxian Wooden Pagoda, built the simplified models of the rigid connection and hinges in a Dou-gong bracket using the dynamic equivalent features method and calculated the range of the dynamic features though the two simplified models and then applied them to the calculation of the whole tower, see Ref. [35].

5. Conservation and reinforcement techniques of historic wooden buildings in China

5.1. The principles of historic architecture restoration

Since 1920s, China began to attach importance to the conservation of historic wooden buildings. In 1928, the *Central Commission for the Preservation of Antiquities* was established. In 1929, Zhu et al. founded the *Society of the Study of Chinese Architecture*. In 1930, the government issued the *Regulation of Antiquities Conservation*, which symbolized the start of legal management of antiquities. The *Law of the People's Republic of China on the Protection of Cultural Relics* was promulgated in 1982, including the protection of antiquities in the law, which symbolized the standardization and internationalization of historic wooden buildings protection. At present, the protection of historic wooden buildings in China mainly follows the *International Charter for the Conservation and Restoration of Monuments and Sites, Law of the People's Republic of China on the Protection of Cultural Relics* and the standard *GB 50165-92*. Maintenance and reinforcement construction comprises regular maintenance project, major project of historic preservation and maintenance, partial restoration project, relocation project and emergency project, and abides by the principle of maintaining the buildings' original state, including (1) original architectural form such as plane layout, modelling, construction characteristic, artistic style and so on, (2) original building structure, (3) original building materials and (4) processing technology (see Ref. [18]).

5.2. Traditional reinforcement techniques of historic wooden buildings

5.2.1. Common damages of historic wooden structures

The common damages of historic wooden structures include (1) component deformation under compression: column yielding such as splitting of column tips under compression, decay on the bottom of columns due to long-term exposure to humidity and splitting along the grain on the body of columns; bending and splitting of girders and square beams between column and Dou-gong brackets; breaking and splitting of subcomponents of Dou-gong brackets. (2) Components under tension: square beams through the columns on the top or the bottom usually get adrift or break off at the mortise and tenon joints. (3) Components under shear strength: the force analyses at the mortise and tenon joints are more complex and the joints tend to detach under long-term shearing action, as seen in Ref. [15].

5.2.2. Traditional reinforcement techniques of ancient wooden buildings

Regarding the whole-beam frame of wooden structures, reinforcement methods include major repair of the structure (disassembling the wooden frame completely of partially, repairing or replacing the damaged components and reassembling it while reinforcing the structure), restoration with external support (adding external support and restoring the tilted, twisted or detached components while reinforcing the structure without disassembling the frame) and overall reinforcement (direct reinforcement of the whole structure of projects with minimum structural deformation).

Reinforcement methods are as follows (**Figure 10**):

1. Partial or complete replacement: (a) patching and reinforcing. It can be patched up with wooden powder and waterproof adhesives when the splits or corrosion of beams and columns are slight. (b) Reattachment of columns: Replace the rotten part of the column with new materials when the rotten part takes up more than a quarter of the height. The spot where reattachment is conducted is often reinforced with a semi-tenon and an iron hoop. (c) When the damage depth of the beam at both sides takes up more than a third of the height, it is appropriate to use the clamp connection method but when the depth takes up more than three-fifths, a replacement of the beam head is necessary.

2. Mechanical reinforcement: (a) Ironware reinforcement: Using flat iron to reinforce beams and columns or to connect joints between beams and columns. This way, the flat iron can improve the mechanical properties of components by bearing part of the tensile, compressing, bending and shearing forces. (b) When the deflection of beams and square pillars transcends normal limitation or the load-bearing capacity is insufficient or splits are found, it is appropriate to use tensile bars to form now load-bearing components.

3. Chemical reinforcement: Since the 1970s, unsaturated polyester resin filling was widely used in historic building restoration. Via the filling, soaking, patching or painting of chemicals, not only can the strength of the damaged wood be improved but the stability and antirot capacity can also be enhanced. In the restoration of the main palace of Nanchan Temple in Wutai, Shanxi province, 782 AD in 1974, epoxy resin was filled in the splits of two main beams and iron hoops were fixed on the beams. In the 1975 restoration of the main palace of Baoguo Temple in Ningbo, Zhejiang province, 1013 AD, without disassembling the wooden frame, the termite-ridden columns were filled with chemicals and wrapped in fibre-reinforced plastic (FRP). According to calculation, despite the larger expenses of chemical fillings, at least 30% of the budget was saved because disassembling the whole frame was avoided, see Ref. [36].

There are some disadvantages while using the above traditional reinforcement techniques. The ironware is usually applied inside the components and easily corroded so the appearance of the structure may be affected. The antirot chemicals greatly harm the health of the management staff. When using the reattaching method or the tensile bars, the original appearance of the building is inevitably damaged.

(1) Reattachment of columns and Mechanical reinforcement (2) Chemical reinforcement (3) CFRP sheet reinforcement

Figure 10. Reinforcement techniques of ancient wooden buildings.

5.3. The study on and application of FRP reinforcement techniques in historic wooden structures

Fibre-reinforced polymers (FRP) have advantages such as large tensile capacity and are light weight. It can also endure erosion, heat and freezing. Besides, it is highly plastic, easy to apply and inexpensive. As a result, it is widely used in the restoration of reinforced concrete and brick structures. The study on FRP started in the 1990s and has matured in the theory of reinforced

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concrete restoration. In the field of wooden structure reinforcement, FRP utilization especially carbon fibre-reinforced polymers (CFRP) and glass fibre-reinforced polymers (GFRP) utilization are becoming a heated study topic. Based on relevant studies and projects, FRP reinforcement can reduce several variation coefficients and strength indices of mechanical properties of wooden components. Variation coefficients after reinforcement are limited by 15%. FRP reinforcement can also improve the bearing capacity and reduce the long-term creep of wooden components, optimize the cross-section size and enhance the fire-resisting and antirot capacity.

FRP reinforcement can improve the anti-seismic capacity of mortise-tenon joints. Zhou et al. from The Palace Museum made a special frame model with four beams and four columns at the ratio of 1:8 using the Korean Pine and tenon-mortise connections based on the actual size of the partial frame of the Hall of Great Harmony in the Imperial Palace and conducted exploratory experiments using CFRP fabric. Through low-cyclic reversed-loading tests, load-displacement hysteretic curves were drawn and skeleton curves, energy dissipation capability and stiffness degradation of the structure were analysed. Results show that although the structural energy dissipation capacity decreased slightly after the model is strengthened by CFRP sheets on tenon-mortise location, the cross-section size of the tenon that will pull out of the joint reduces. Its lateral stiffness and load-bearing capacity both improve and with slight stiffness degradation, the frame still has good deformation capacity. Besides, the team also considered to conduct performance comparison among mortise-tenon joint models using nails, iron hoops and CFRP reinforcement. The results showed good deformation capacity preservation in all three scenarios. CFRP fabric excels in joint-bearing capacity and energy dissipation capability but showed the most stiffness degradation. So, it is recommended to use CFRP in reinforcement of medium to small wooden structures (see Ref. [37]).

Huang deducted the calculation of FRP anti-sheering reinforcement using basic materials mechanics formulas. Yang analysed the influence of CFRP and GFRP on the bend-resistant capacity and came up with the formula of ultimate bearing capacity for the analysing method based on failure strain. A team from the Xi'an University of Architecture and Technology did much work on the analysis of and tests on RFP reinforcement in historic building component units and structural joints. Case in point, Xie (see Ref. [38]) tested the bend-resistant capacity of square beams with CFRP reinforcement and compressive strength of cylinder columns and established the calculation of shear strength of beams and compressive strength of columns in different damage forms. Besides, he built scale models of the column frame according to the classic ancient architecture rules in Song Dynasty, 960–1270 AD and conducted low-cyclic reversed-loading tests on the original structure, CFRP sheets-reinforced structure and flat steel-reinforced structure, based on which the restoring force model of wooden structure was established. Hang et al. (see Ref. [39]) analysed the load-bearing performance of damaged joints reinforced with CFRP based on the above-mentioned-reinforcing approach and damage form of the joints, and came up with the calculation of the bend-resistant strength of the joints based on relevant experiments and calculation presumptions.

In the field of construction application, CFRP wrap combined with traditional wooden structure reinforcement methods has already been used on historic buildings such as the Tiananmen Gate tower and explored in a practical manner. In the emergency restoration of Yingxian Wooden Pagoda, in Fogong Temple, Shanxi province, 1056 AD, experts recommended FRP materials to maintain its original appearance. Combined with the characteristics of Chinese wooden structures, FRP reinforcement's performance in fire-resistant capacity and structural assessment under long-term load awaits further study.

6. Conclusions

Chinese traditional wooden architecture, well known as a unique and independent system of the architecture world, has formed its typical structural styles and construction technology after over 7000 years' development. Besides the research on and conservation and reinforcement status of many precious historical architectural heritages, this chapter is also focused on the analysis of structural features, anti-seismic behaviour and utilization of new materials in traditional wooden architecture based on a large number of studies in recent years.

To better protect ancient wooden structure, many researchers have carried out a large amount of physical properties experiments on wood materials from historic buildings, and a method for predicting the degeneration pattern of physical properties, residual strength and longevity of wood material through studying wood decay has been proposed. In addition to traditional reinforcement techniques such as mechanical reinforcement and partial or complete replacement, new reinforcement materials and techniques have already been explored, among which FRP is becoming a heated academic topic.

The superior seismic performance of Chinese traditional wooden architecture, owing to many unique characteristics of the structural design and constructional technique, has generated a great deal of interest at home and abroad. The objects and models of anti-seismic behaviour study also show characteristics of miniaturization and diversification. In addition to researches on historical wooden buildings, attempts of using new engineering wood products in the modern wooden architectures of traditional style are becoming a great upsurge nowadays.

At present, researches of Chinese traditional wooden structures have made some headway, yet there are also some remaining issues. First, material performance and structural behaviour study of historical wooden buildings are often based on specific emergent repairment and strengthening projects of historical buildings, which somewhat limits the systematization and universality of the researches. Second, attentions have been focused on historic and artistic aspects for a long time, and limited number of fundamental studies on the structural performance of Chinese traditional wooden structure and its typical connections types can be found. What's more, combine the excellent features of traditional construction technologies with modern materials, techniques, and then inherit and improve them, there is still much work for us to do.

Acknowledgements

This work was supported by the Special Fund of Top-Notch Academic Programs Project of Jiangsu Higher Education Institutions (TAPP) and National 'Twelfth Five-Year' Plan for Science & Technology Support (2015BAD14B0503).

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