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Construction Forms and Seismic Performance of the Ancient Chinese Buildings Joined by Tenon–Mortise Joints

Linglong Pan [1], Man Zhou [2,*], Haiyan Zhuang [2] and Juan Wang [3]

1 School of Civil Engineering, Jiangsu Yangzhou Technician College, Yangzhou 225000, China; xiaopan10091117@163.com
2 School of Civil Engineering, Wuhan University, Wuhan 430072, China; 15251867705@139.com
3 School of Civil Engineering, North Carolina State University, Raleigh, NC 27207, USA; 00033574@whu.edu.cn
* Correspondence: civilzm1988@163.com; Tel.: +86-152-5186-7705

Abstract: Zijincheng, also known as the Forbidden City, is the largest and best-preserved ancient palace-type wooden building in China, built without using a single nail. Since it was built in 1420, it has served as a palace where the emperor lives and works. Almost 600 years old, it has gone through two dynasties (i.e., the Ming and Qing dynasties (AD 1368–AD 1912)) and 24 emperors. It has survived more than 200 devastating earthquakes throughout its history, and it is still standing strong. In this paper, the authors introduce the construction technology of the ancient Chinese wooden structure as well as the greatest secret of the well seismic performance of the Forbidden City. The study found that the secret to the Forbidden City's ability to withstand many powerful earthquakes lies in the flexibility of its timber structure, which is mainly reflected in the application of the tenon-mortise joints, energy-dissipation capacity of Dougong brackets and shallow-buried columns. The seismic responses of a 1:5 reduced-scale model of Shoukang Palace of the Forbidden City under different earthquake magnitudes are studied through a series of shaking table tests.

Keywords: tenon–mortise joint; wood structure; seismic resistance performance

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1. Introduction

In human architectural history, the West represents stone culture, while the East, represented by China, belongs to the earth-wood culture of the tenon–mortise joint. The tenon–mortise joint is the origin of Chinese wood culture, and its history extends farther back than that of Chinese characters; it is an essential part of ancient Chinese building wisdom [1].

With the innovation of material science and construction technology, modern wooden structure building nodes almost no longer use the traditional mortise and tenon joint connection, and are now more inclined to use modern metal components for obtaining a better joint performance [2]. In ancient China, whether for architecture or furniture-making, nails were not necessary. Nails not only have high production costs and poor corrosion resistance, but are also less convenient than the tenon–mortise joint. Tenon–mortise joints are environmentally friendly due to metal fittings not being used [3]. Thus, in ancient Chinese buildings, no nails or rivets were used; instead, tenon–mortise joints were adopted [4]. Tenon–mortise joints mean that traditional Chinese wooden structures offer a unique flexible framework that outperforms various contemporary architectural structures, such as bent structures, framework, and rigid frame structures. They not only can bear a greater load but also allow a certain amount of deformation, which effectively means that they are earthquake-tolerant [5]. Under the action of the earthquake, the destruction of the intact ancient building wood structure is mainly caused. It takes place at the tenon–mortisen joints and bracket sets [6,7]. Through an experimental study, Chen et al. found that the bearing bracket can improve the pulling-out resistance capacity of mortise–tenon joints, and the dovetail mortise–tenon joints are one of the best connection forms for pulling-out resistance and bending capacity [8]. The seismic characteristics of several typical mortise–tenon joints of Chinese southern traditional timber frame buildings were experimentally studied by Chun et al., which can provide a theoretical basis for seismic design and maintenance of mortise–tenon structures [9]. Ancient buildings made with tenon–mortise joints have survived weathering and natural disasters, and they have witnessed history; among these, the legendary Forbidden City in Beijing is an outstanding representative, as shown in Figure 1. Shaka Pagoda, built in Liao Dynasty, is located in the Buddhist Palace Temple in the northwest of Yingxian County, Shuozhou City, Shanxi Province. It is the tallest wooden pavilion-type pagoda with an existing structure, as shown in Figure 2. It is known as one of the “three strange towers in the world” along with the inclined Tower of Pisa in Italy and the Eiffel Tower in Paris. The whole tower uses 54 kinds of dougong, which has the reputation of “dougong Museum of Chinese Ancient Architecture”. It is considered to be the most typical example in the history of wood structure construction in the world today. Haka Pagoda has been hit by many strong earthquakes, in more than five degrees of more than a dozen earthquakes, but the key to not falling for a thousand years lies in the wooden tower structure having the combination of mortise and tenon [10].

Figure 1. The Forbidden City building and its periphery.

Figure 2. The Shaka Pagoda.

This paper first introduces the concept and the development process of tenon–mortise joints, as well as their structural forms. Furthermore, the seismic performance of mortise–tenon structure has been verified through existing experiments of a scale model of the Forbidden City. The analysis results are presented showing that the tenon–mortise joint, the Dougong bracket and the columns with special erection are the reasons why this all-wooden structure still stands after experiencing more than 200 earthquakes.

2. Materials and Methods

2.1. The Concept of the Tenon-Mortise Joint and Its Development

The tenon–mortise joint is a structure that allows wooden components to be connected without the need for other fasteners. This type of joint has been widely used in Chinese traditional architecture, decoration and furniture, and it is the core of traditional wooden structures. In a tenon–mortise joint, the protruding portion is called the tenon and the recessed portion, the mortise. The interspersion and joining of tenons and mortises can effectively limit the ability of these wooden parts to twist in various directions, and thus they serve to bind and fix [11]. As the wooden parts to be joined will have different shapes, a variety of combinations of tenons and mortises have been derived, which have enabled wooden buildings to achieve a perfect unity of function and structure.

The development of the tenon–mortise joint is closely associated with the ancient Chinese economy and metal smelting technology, and it has roughly undergone three stages. Nearly one hundred wooden parts with tenons and mortises were unearthed during the first stage of excavations on the remains of the bole fence buildings of the Hemudu culture site, which is a national relic protection unit that dates back 6500–6900 years. These tenon–mortise joints are the earliest examples ever discovered [12], and they represent the initial stage of the development of the tenon–mortise joint. In this stage, metal tools had not yet emerged, so the tenon–mortise joint was rather rudimentary. The second stage was the development stage, which occurred from the Spring and Autumn Period of the Northern and Southern Dynasties (770 BC–AD 589). During this period, wooden structure technology experienced breakthroughs due to the emergence of metal tools. In the Warring States Period (520 BC–221 BC), carpenters noted the relationship between the inclination and the shearing force of the tenon. Documents from the Eastern Han Dynasty to the Northern and Southern Dynasties (AD 25–AD 589) indicated that at that time, the traditional building wood frame system, especially the Dougong bracket (a typical Chinese architectural component transferring the weight of the roof and eaves to the lower columns) had essentially been established and that the ancient Chinese builders had already acquired a good understanding of the reasonable loads transferring path. The third stage was the peak stage, which spanned from the Tang and Song Dynasties to the Ming and Qing Dynasties (AD 618–AD 1800) and represented the last stage in the development of ancient Chinese architecture. In the Song Dynasty (AD 960–AD 1279), "Ying Zao Fa Shi", also known as Building Codes at that time, the most complete ancient Chinese architectural book about operating rules, technical specifications and quality standards promulgated by officials were compiled and printed, indicating that the technical norm of the tenon–mortise joint in wooden architecture had been established and, as such, this represents the peak in popularity of the tenon–mortise joint technique [13].

2.2. Classification of Tenon-Mortise Joints

The tenon–mortise joints applied in ancient wooden buildings are introduced in this paper. These buildings include vertical and horizontal structural components with different intersection locations and methods, requiring different types of tenon–mortise joints. In terms of function, tenon–mortise joints can roughly be divided into five categories [14]. A 3D model with different views of an ancient Chinese palace wooden structure with the associated annotations is shown in Figure 3.

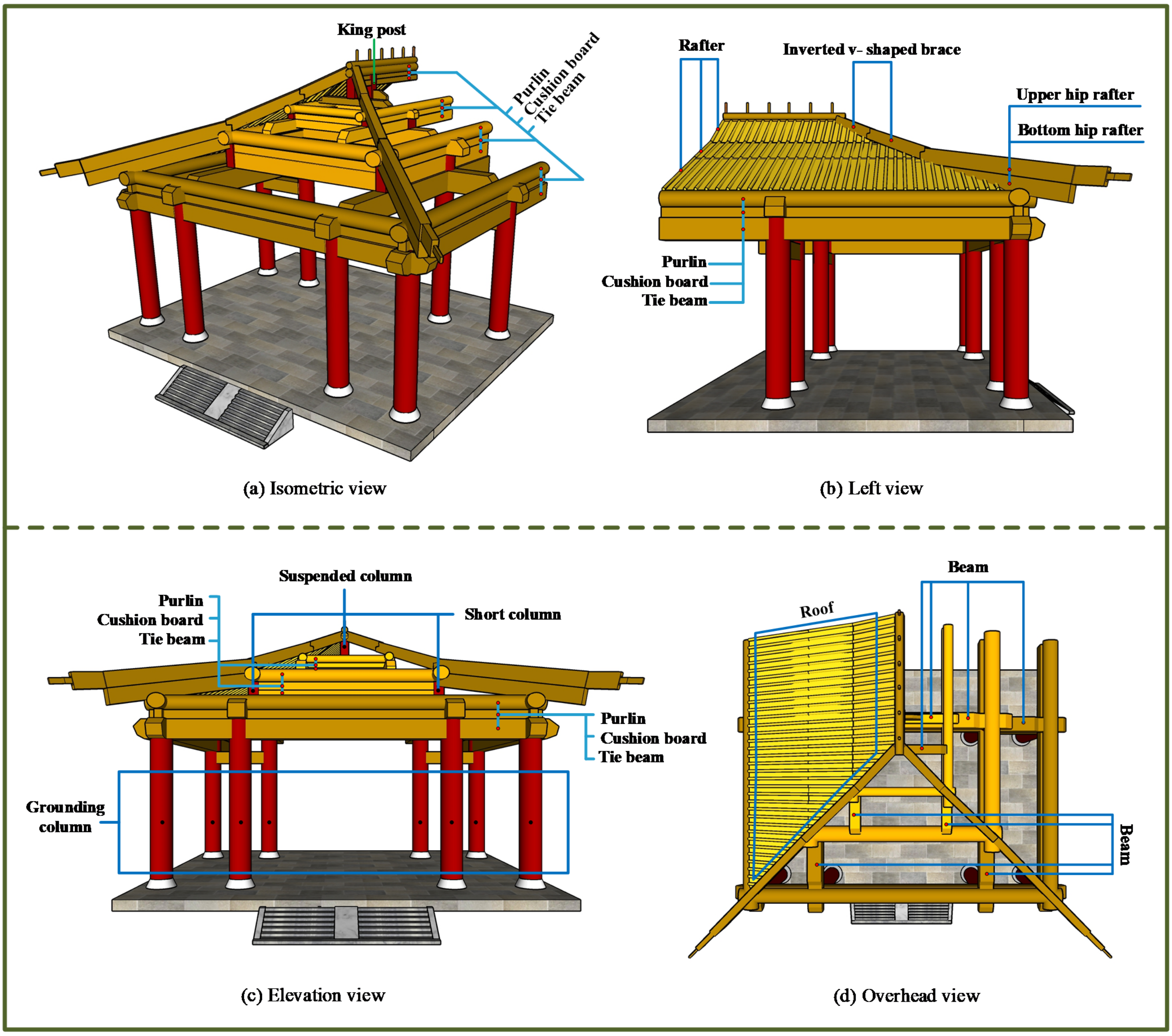


Figure 3. The model of a part of ancient Chinese palace wooden structure.

2.2.1. Tenon–Mortise Joints for Fixing Vertical Structural Components

The vertical structural components in ancient buildings are primarily columns. There are many types of columns according to different classification standards, but two major types of columns are particularly well-known. One is the grounding column, also known as the load-bearing column, including four types of columns depending on their location—the eaves column, hypostyle column, center column and middle column. The other type of column is placed on beams columns, which transfer the weight of the roof to the load-bearing column, including the short column, king post, and suspended column, as shown in Figure 3c. All columns need to be fixed with tenon–mortise joints, regardless of their position. The types of tenon–mortise joints for vertical structural components are listed as follows:

(1) Base tenon: fixation for the base of various grounding columns, as shown in Figure 4a.
(2) Top tenon: a column used to secure a promenade, as shown in Figure 4b.
(3) Half tenon at the base of a short column: designed for short columns perpendicular to the beam, as shown in Figure 4c.

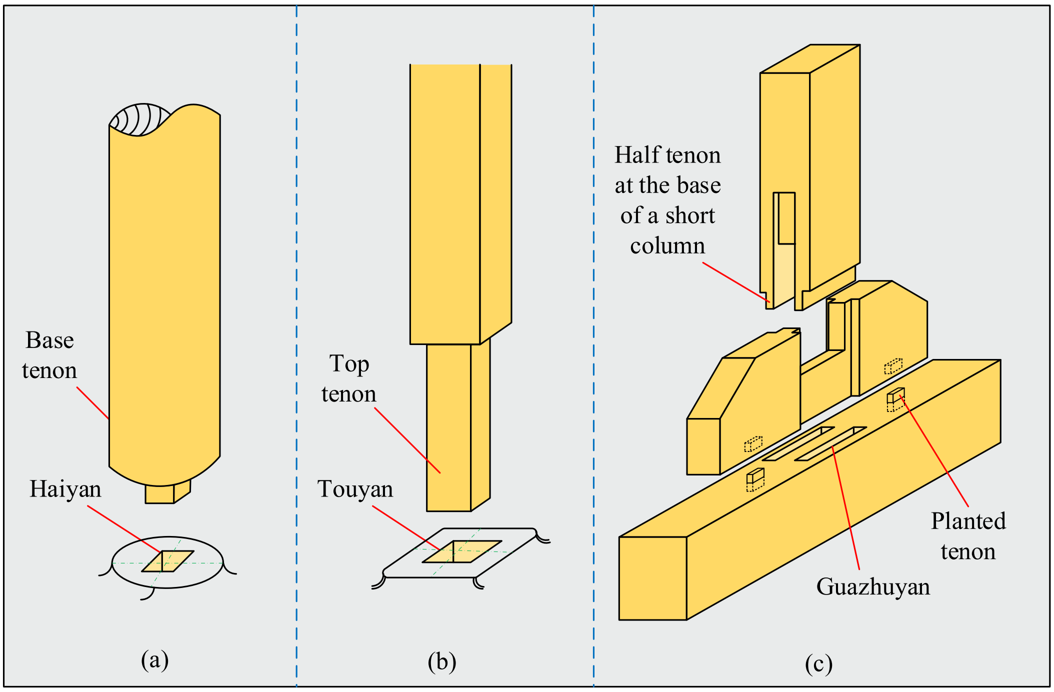


Figure 4. Tenon–mortise joints for fixing vertical structural components. (**a**) Base tenon; (**b**) Top tenon; (**c**) Half tenon at the base of a short column.

2.2.2. Tenon–Mortise Joints for Joining Horizontal and Vertical Structural Components

Common horizontal tenon–mortise structures include three typical components: beams, tie beams and purlins, as shown in Figure 3. The beam is placed on the column along the depth, bearing the weight of the components and roof in the upper structure, as well as its own weight. Tie beams, which assist beams to enhance the whole stability of the structure, are placed perpendicular to the beams. Furthermore, the purlin is an important component to fix the rafter and support the roof, which is laid on the tie beam or the cushion board. The three of them are often connected to vertical structural components via the following types of tenon–mortise joints:

(1) Steamed-bread tenon: a tenon used to perpendicularly join the top end of a column to one end of a beam, its function lies in preventing the horizontal displacement of the beam, as shown in Figure 5a.
(2) Dovetail tenon: a tenon commonly used for joining the other horizontal structural components, except the beams to the top end of a column, such as the eave tie beam connecting the eave columns (the outmost column), and the purlin tie beam connecting the hypostyle columns (within the eave column, all the other columns except the ones in the axis of the building), as shown in Figure 5b.
(3) Beam end-locking tenon: a special tenon that joins two tie-beams and a column at an end or a corner, and is supposed to lock the column tightly. The use of such tenons brings a strong tying force to the corner column and protects the column at the same time, as shown in Figure 5c.
(4) Through tenon: a tenon often made in the form of a "big tongue to enter and small tongue to protrude" at the end of a penetrating tie beam, which connects two columns in a row, as shown in Figure 5d.
(5) Half tenon: as its applicable part is similar to a through tenon, it is only used when a through tenon is not suitable, such as when joining the center column and the beam, as shown in Figure 5e.

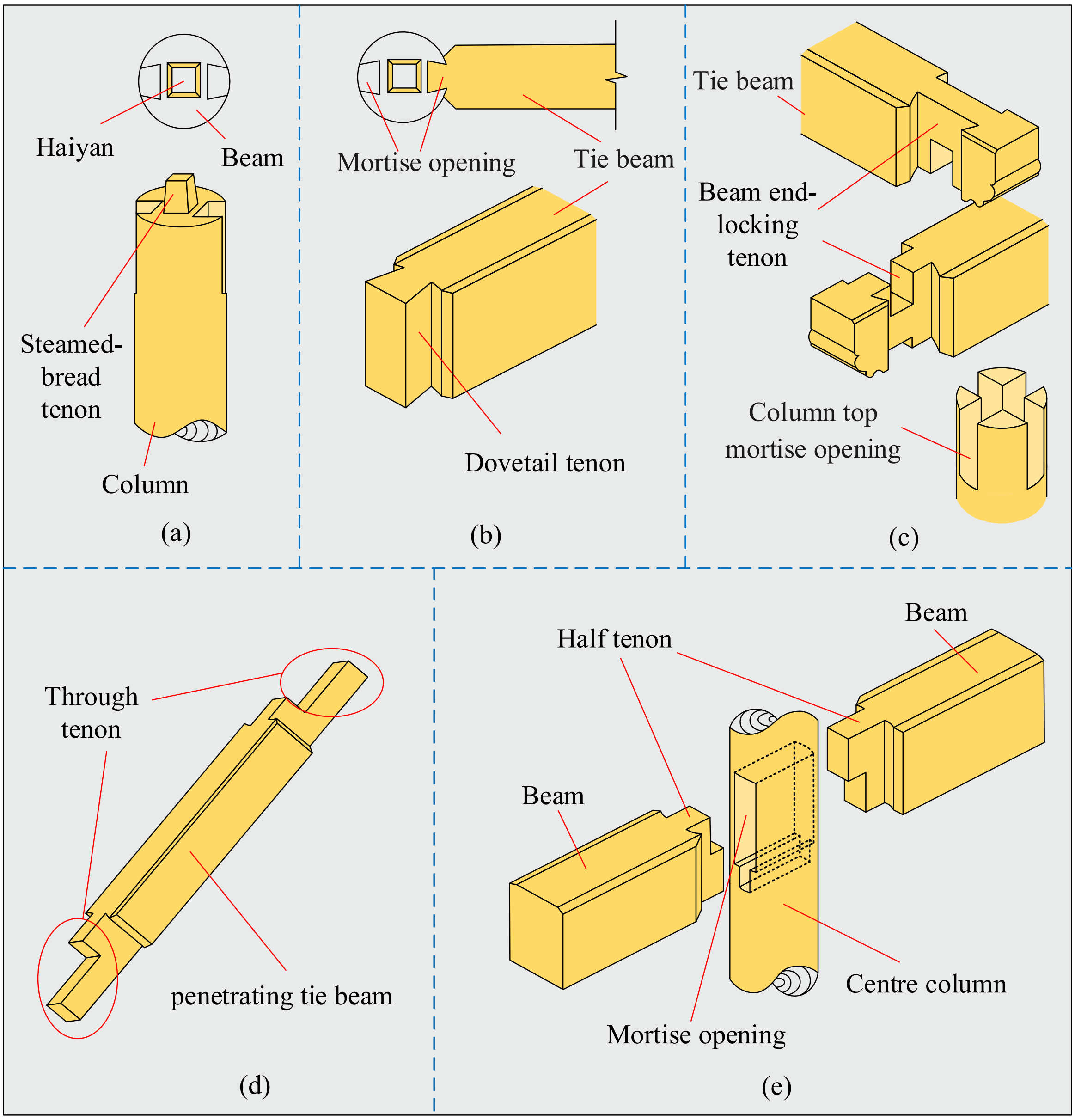


Figure 5. Tenon–mortise joints for joining horizontal and vertical structural components. (**a**) Steamed-bread tenon; (**b**) Dovetail tenon; (**c**) Beam end-locking tenon; (**d**) Through tenon; (**e**) Half tenon.

2.2.3. Tenon–Mortise Joints for Joining Intersecting Horizontal Structural Components

In ancient buildings, horizontal structural components often intersect (e.g., between tie-beams, between purlins, and between a tie-beam and a purlin), and they are often joined with the following types of tenon–mortise joints:

(1) Cross-shaped notched round tenon: a tenon mainly used to join cross-intersecting round-shaped or linear structural components, as shown in Figure 6a.

(2) Cross-shaped notched square tenon: a tenon mainly used to join cross-intersecting square-shaped structural components, mainly used for planar tie beams (specially created to support the Dougong bracket), as shown in Figure 6b.

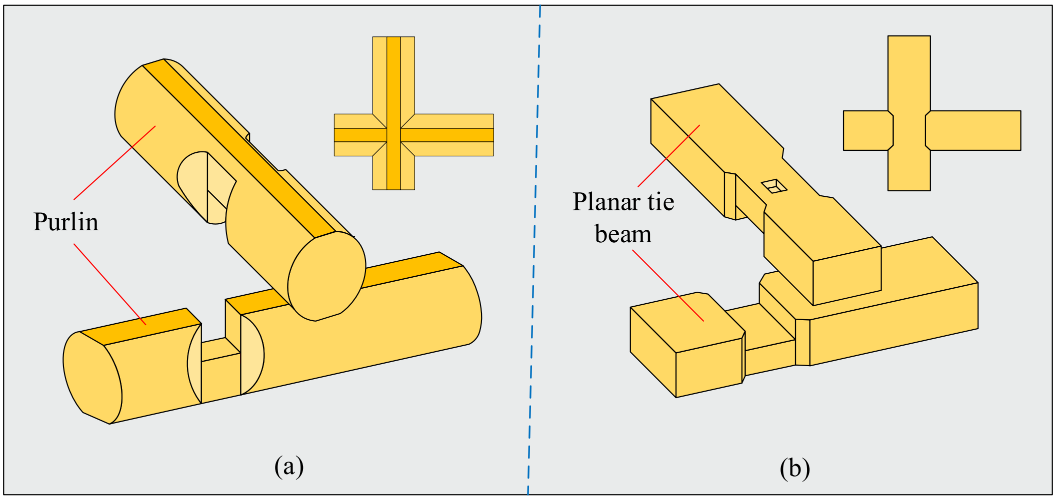


Figure 6. Tenon–mortise joints for joining intersecting horizontal structural components. (**a**) Cross-shaped notched round tenon; (**b**) Cross-shaped notched square tenon.

2.2.4. Tenon–Mortise Joints for Overlapping or Semi-Overlapping Horizontal or Inclined Structural Components

When two or more horizontal (or inclined) structural components overlap perpendicularly or semi-overlap at a certain angle, the following three types of tenon–mortise joints are used:

(1) Bowl for purlin: the joint for placing a purlin, located on top of the king post or beams, as shown in Figure 7a.
(2) Tenon at the beam end: a tenon mostly used in the extended joining of a hip rafter with an inverted v-shaped brace. The combination of them supports the wing angle, a special form of ancient Chinese architecture to prevent rain from dampening the walls, as shown in Figure 7b.
(3) Stepped tenon on the beam: a tenon mostly used for joining a short lying beam and a long lying beam. The lying beam is a type of beam lying on another beam, acting as a tie-beam, as shown in Figure 7c.

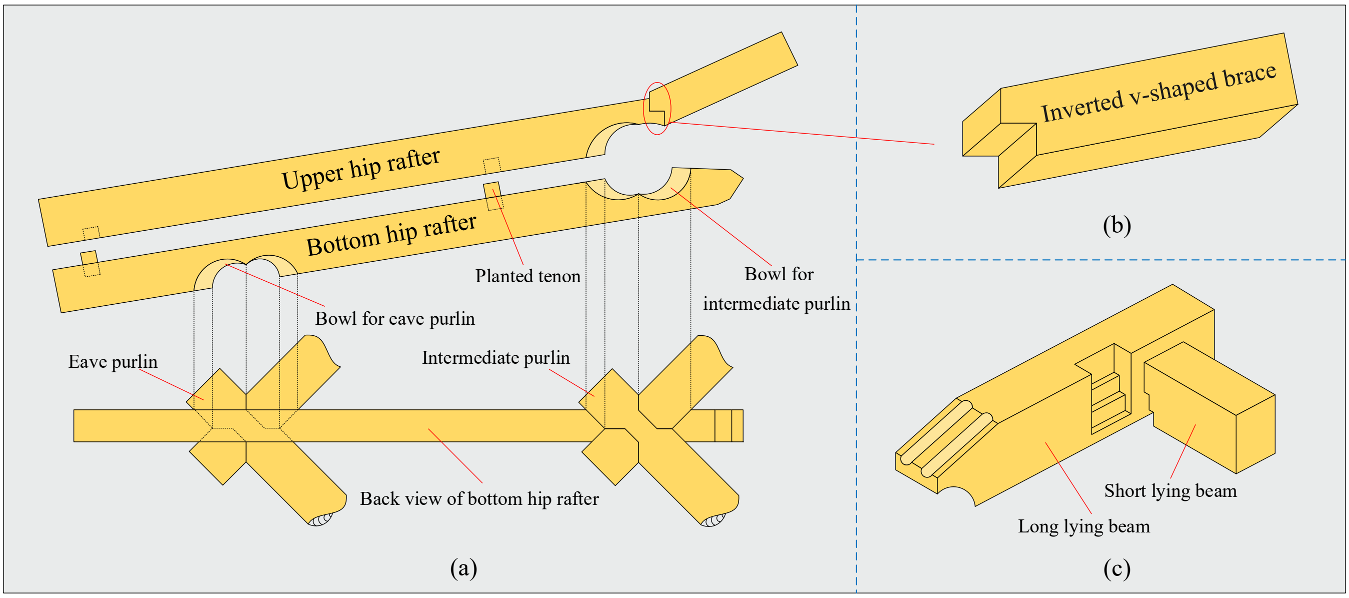


Figure 7. Tenon–mortise joints for overlapping or semi-overlapping horizontal or inclined structural components. (**a**) Bowl for purlin; (**b**) Tenon at the beam end; (**c**) Stepped tenon on the beam.

2.2.5. Tenon–Mortise Joints for Joining Boards

In the building of ancient structures and in the fabrication of some decorative structural components, wide boards, such as bargeboards (sealing the eaves board) and thick-boarded doors, are often used. To connect and fasten these boards, tenon–mortise joints are also needed in addition to adhesives.

(1) Silver-ingot opening: also known as the silver-ingot tenon, this is wide at both ends but slender in the center and so named for its shape, which resembles a silver ingot. It is most often used for joining solid boards, as shown in Figure 8a.
(2) Chuandai (belting through) tenon: this tenon runs through the dovetail tongue made on the back of glued boards and can prevent the unevenness of the board surface caused by deformation, as shown in Figure 8b.
(3) Dragon and phoenix tenon: a slot is made along one joining side of the board, and a groove is made along another joining side. Then, the two boards are joined together, as shown in Figure 8c.
(4) Rabbeted joint: the edges of the board are rabbeted and then joined. This joint is often used in gable boards, as shown in Figure 8d.
(5) Chaoshoudai: this tenon is one form of Chuandai, in which a hole is made through the width of the board. It is mainly used on thick wooden doors, as shown in Figure 8e.

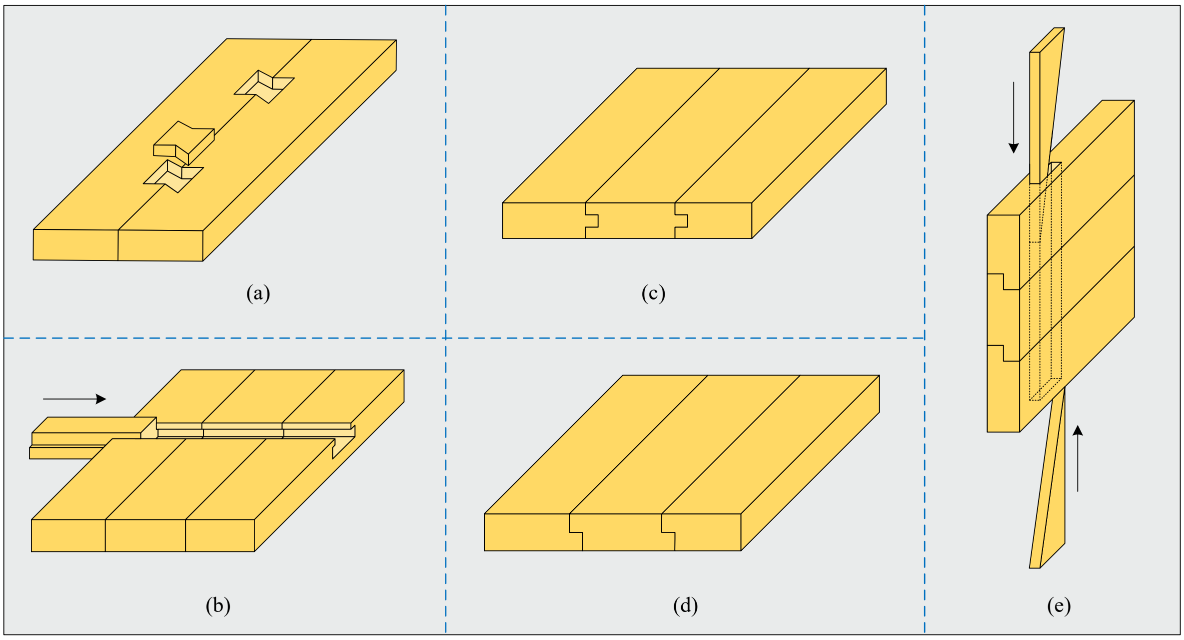


Figure 8. Tenon and mortise for joining boards. (**a**) Silver-ingot opening; (**b**) Chuandai (belting through) tenon; (**c**) Dragon and phoenix tenon; (**d**) Rabbeted joint; (**e**) Chaoshoudai.

2.3. Dougong Bracket

The Dougong bracket is a structural element of interlocking wooden brackets. As a load-bearing component for supporting the overhanging roofs, the Dougong bracket is commonly found in ancient Chinese wood architecture. According to the located positions under the roof, the Dougong bracket can be divided into three categories: the Dougong brackets above a corner column; the Dougong brackets above an intermediate column, and the Dougong brackets above the beam, as shown in Figure 9.

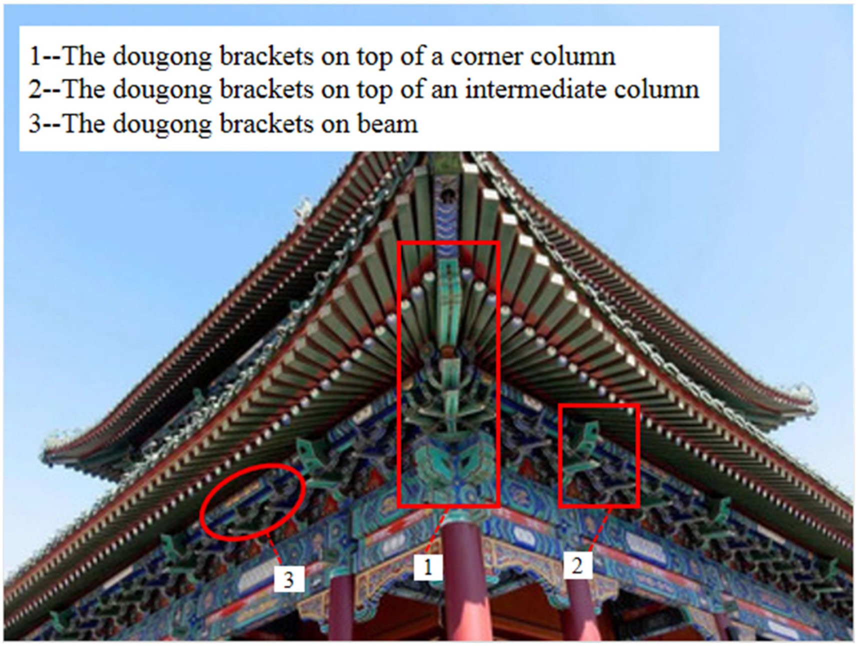


Figure 9. Types of Dougong bracket.

The Dougong bracket is a system of wooden brackets cantilevered out from the top of a column, which can carry the rafters and the overhanging roofs. It is formed by placing a large wooden block on a column to provide a solid base for the above bow-shaped brackets. The pieces are fitted together by joinery alone, without glue or fasteners, due to the precision and quality of the carpentry. Figure 10 shows a typical assembly process of a Dougong bracket popular in the Song dynasty.

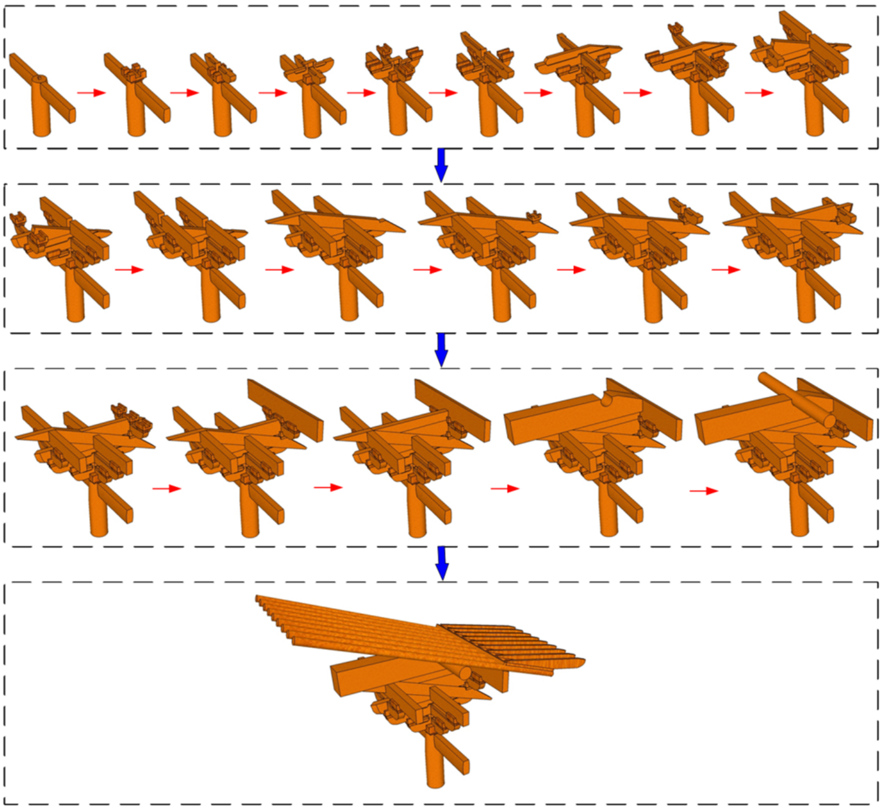


Figure 10. Typical assembly process of a Dougong bracket in Song dynasty.

3. Results and Discussion

Over the past 600 years, the Forbidden City has withstood more than 200 devastating earthquakes. For example, the 7.8 magnitude Tangshan Earthquake in 1976 basically wiped out Tangshan City in 15 s and caused approximately 250,000 fatalities, while the Forbidden City, only 153 km away from the epicenter, stood firm [15].

3.1. Scale Model Test

To investigate the mystery of the Forbidden City's favorable seismic performance, a scale model of Shoukang Palace, which was commonly the bedchamber of the emperor dowager, was made at a 1:5 ratio to conduct a series of earthquake simulation tests by Zhou et al. [16–19], as shown in Figure 11 and Table 1. The El-Centro wave was selected in consideration of the site type (Class II) of the Forbidden City, which acts on the model in both x and y directions. The ratio of peak accelerations in x and y directions is 0.85 [16]. The shaking table reproduces the energy of quakes in an increasing order of magnitude, and the earthquake duration at each tremor lasted 30 s. The initial test earthquake magnitude is 4.0, and the magnitude rose in increments of 0.5, a magnitude of 5.0 has thirty-two times the energy of a magnitude of 4.0. At a 4.5 magnitude, the model showed mild shaking. At a 5.0 magnitude, the model started shaking, the columns slightly tilted, the Dougong bracket was strained and one side the masonry collapsed. At a 7.5 magnitude, the shaking of the model intensified, the columns were significantly tilted, and the remaining side of the masonry collapsed, but the traditional wood frame was still standing strong. At a 9.0 magnitude, the stone bases shifted around, the model shook violently, the columns tilted more significantly, and a tugging noise between wood elements was heard. At a 9.5 magnitude, which is the largest magnitude that has ever been recorded for the Beijing area and is equivalent to 2 billion tons of TNT, the model shook more violently, the columns tended to collapse, and the tugging noise increased. Ultimately, at a 10.1 magnitude, the model shook drastically, and the tendency of the columns to collapse increased, but the wooden structure still stood firmly. At the end of the test, it was found that both sides of the masonry had collapsed, while the superstructure showed no noticeable damage, and nor did the column.

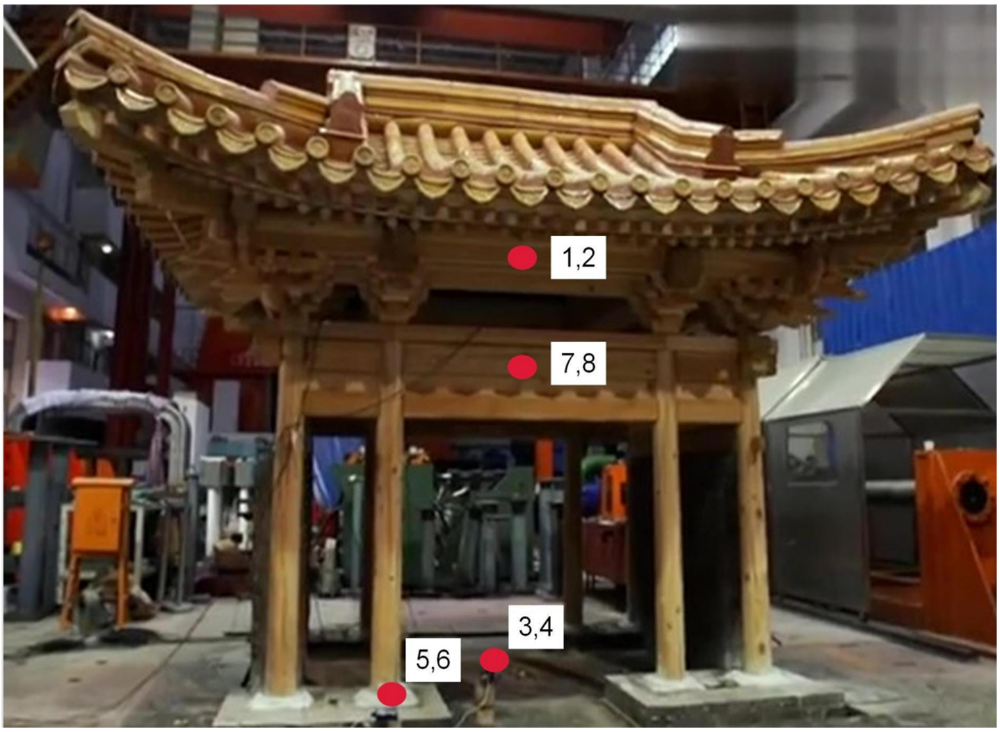


Figure 11. A 1:5 scale model of Shoukang Palace earthquake test map.

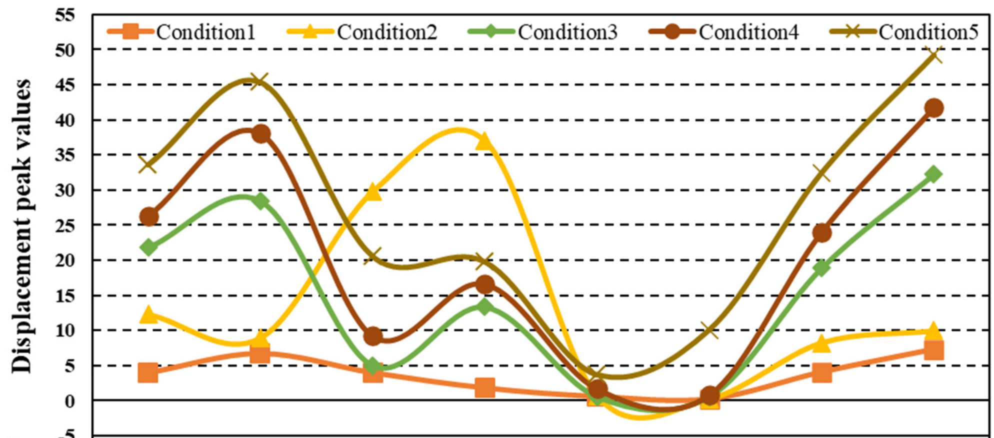
Table 1. Loading condition of the seismic waves.

Condition	Type of Seismic Wave	Load Direction	X toward the Peak Loading Speed/g
1	EI-Centro	x, y	0.10
2	EI-Centro	x, y	0.15
3	EI-Centro	x, y	0.20
4	EI-Centro	x, y	0.25
5	EI-Centro	x, y	0.30

Note: x is east-west, and y is north-south.

The experimental results show that the physical properties of wood, the application of tenon–mortise joints and the shallow-buried columns are the main factors of excellent seismic performance of ancient Chinese wooden buildings.

Wood is a kind of building material with light weight and good mechanical properties. It is easy to deform when the external force acts, while it also has enough displacement restoring capacity, which reduces the structural damage caused by an earthquake. Tenon–mortise joints are commonly used in ancient buildings, which make the whole wooden building more flexible, as shown in Figures 12 and 13 [16]. Tenon–mortise joints have a semi-rigid connection [20]. These semi-rigid joints (tenon–mortise joints) have high ductility, which enables the redistribution of internal forces within the structure. High ductility in joints is very important for dynamically, cyclically loaded structures (dissipation of energy). Although the tenon–mortise joint weakens the effective bearing area of the wood structural component, which leads to reduced bearing capacity at the joint site, the remainder of the load-bearing capacity of the wood structure is still strong [21]. Thus, the weakened wooden sections can still withstand heavy loads. Moreover, the tenon–mortise joints bind wooden components firmly while leaving space for them to loosen, and allow them to work both as individual units and together. During earthquakes, the components rub against each other and rotate, which easily creates severe deformations, offsets the strong impacts of the earthquakes and reduces the seismic response of the structure and the load of the key part [22–24]. Thus, the structure is extremely strong and flexible, making full use of the flexibility of these semi-rigid joints.



(mm)	point 1	point 2	point 3	point 4	point 5	point 6	point 7	point 8
Condition1	3.92	6.67	3.98	1.81	0.64	0.28	4.09	7.31
Condition2	12.33	8.95	29.76	37.01	0.7	0.3	8.27	9.99
Condition3	21.83	28.48	5.03	13.35	0.56	0.61	18.92	32.26
Condition4	26.3	38.09	9.24	16.65	1.71	0.87	24.05	41.75
Condition5	33.62	45.35	20.48	19.75	3.69	10.08	32.48	49.23

Figure 12. Displacement peak values of the points.

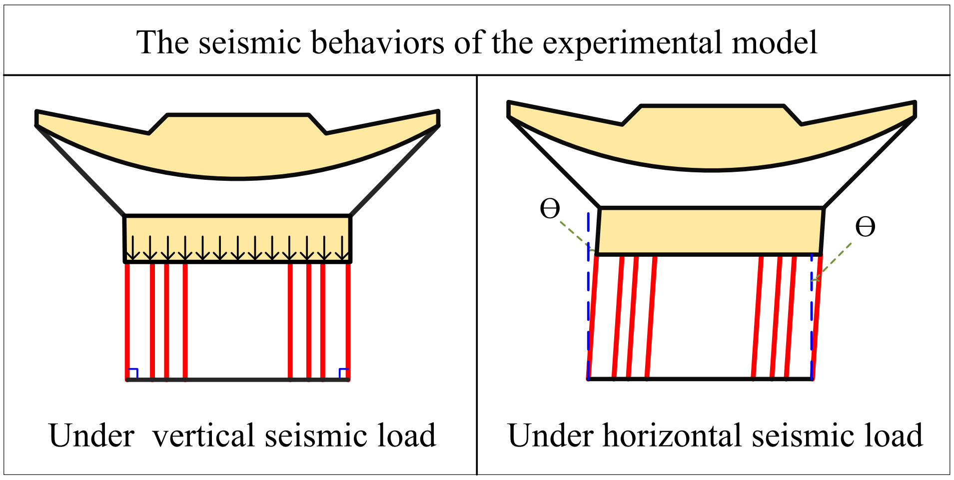


Figure 13. Flexibility of the wooden structure.

3.2. Analysis of Seismic Principle

Another important reason for the favorable seismic performance of ancient Chinese buildings is the application of a Dougong bracket, as shown in Figure 14. As a special combination of tenon–mortise joints, the Dougong bracket supports the roof as it stands on columns and undergoes compressional deformation under the action of the vertical seismic load, while the components shift against each other under the action of the transverse seismic load. When an earthquake occurs, there is both friction and rotation that absorbs a large amount of energy in a manner equivalent to that of a car's shock absorber. Although the Dougong bracket becomes loose due to compression and shifting, its structural components do not separate. Acting together, multiple Dougong brackets connect all structures within the entire building to create a "rigid body" and pass the force to columns capable of offsetting the seismic impact in accordance with the principle of "the abler shoulders bear more labour", which is the key to the anti-earthquake nature of the structure. Structures similar to mortise joints have a good ability to withstand earthquake action [25]. Tenon–mortise joints have strong seismic capacity and can respond to earthquakes rapidly [26].

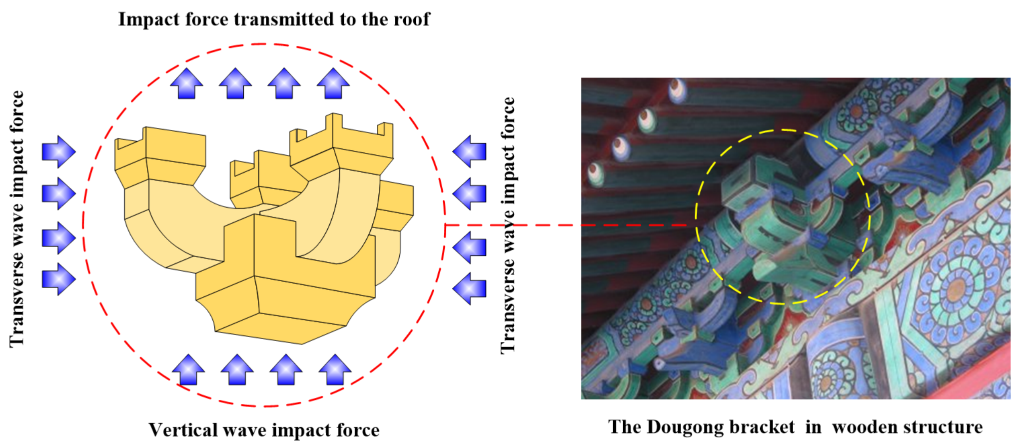


Figure 14. Anti-shock diagram of a Dougong bracket in an earthquake.

The special erection of the column also has an impact on the seismic performance of the wooden structure building, as shown in Figure 15. In Figure 15d, the displacement peak value of the point is 3.69 mm [16]. When a column is set deep into its foundation, it is easy for it to break during a strong earthquake, especially in the case of the wood material of the columns in ancient Chinese buildings, which are more fragile than concrete [27]. The columns of the structures in the Forbidden City are not deeply embedded underground, which allows them a certain degree of movement and can thus prevent structural collapse due to broken columns. In addition, the heavy roof acts as a counterweight, pushing down the substructure, so the flexible parts can move with the quake [28,29].

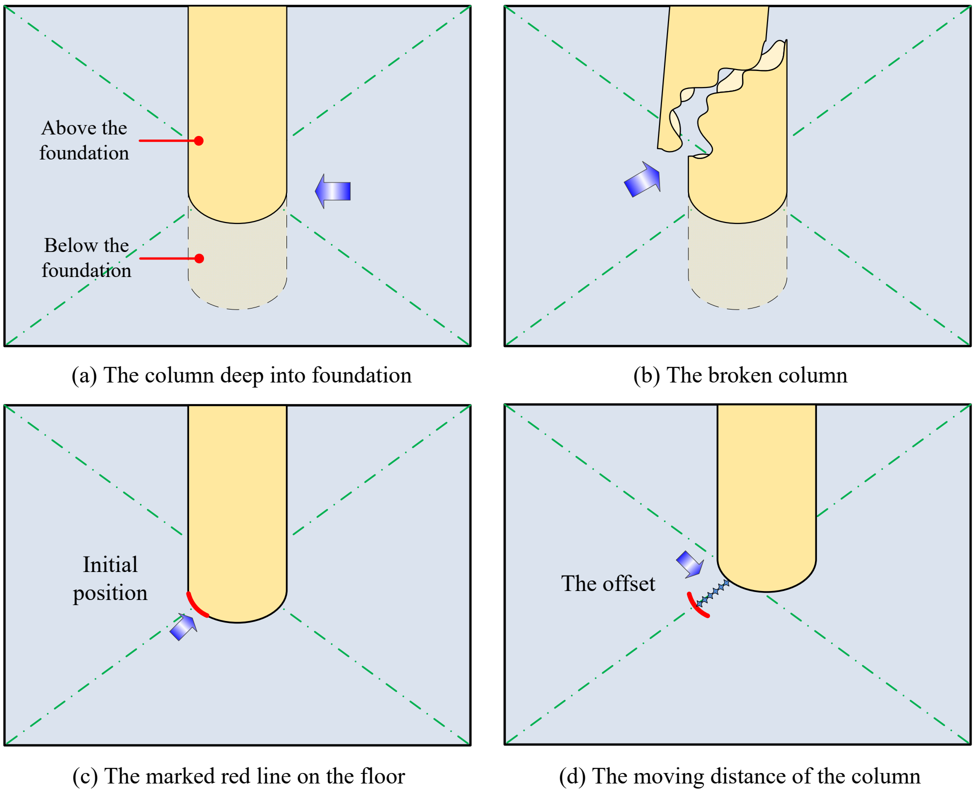


Figure 15. An earthquake resistance diagram of the columns of a scale model of the Forbidden City's Shoukang Palace.

4. Conclusions

Ancient Chinese buildings are commonly wooden structures joined by tenon–mortise joints, which conveniently enable wooden structural components to be bound to each other without any carrier and also makes these structures elegant. Tenon–mortise joints can connect components stably and firmly, and they withstand great loads while allowing the components to undergo deformation and movement. A wooden building then becomes a unique flexible structure that outperforms a contemporary bent frame, framework, and rigid frame structures. Ancient buildings bound through tenon–mortise joints are both strong and flexible, and this feature has made the 600-year miracle of the Forbidden City's earthquake resilience possible. Its wooden structure allowed the Forbidden City to survive a great force of nature.

Compared with the existing research results, the seismic performance of the tenon structure is verified by the existing Forbidden City scale model experiment. Under the action of earthquake, mortise and tenon joints are easy to damage, which leads to structural tilt or even collapse. The seismic performance of mortise and tenon joints is of great significance to the protection of ancient wooden structures. Under the action of seismic waves in different working conditions, the displacement curve of the model is almost uniform and stable, which reflects that the structure is in a stable vibration state and shows good seismic performance. Due to limited space, analysis of seismic performance of different tenon–mortise joints will be covered in a further study.

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