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Comparison of traditional Italian and Chinese timber roofs

Relatore:
Prof. Edoardo Piccoli

Correlatori:
Prof. Cesare Tocci
Prof.ssa. Tanja Marzi

Candidata:
Bingqi Liu

Abstract:

In construction history, timber has been one of the most essential materials for thousands of years. Both Italy and China have mature traditions of wood construction, especially in roof construction such as the Italian truss system (Capriata) and the Chinese bracket system (Dougong). This thesis summarises the existing studies of historic roof construction in the Mediterranean area (especially Italy) and in China. The thesis further aims to figure out what common design issues could be at play and how each country has solved them over time. Based on the previous research, it can be proved that the use of timber construction in Italy and China has both similarities and differences. The thesis explores in which way these two types of roof structure are similar or different, through the analysis and comparison of case studies, and considering history, structure, culture, etc.

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1. Introduction

The study of architecture is not only about culture and concepts, but also materials. When examining the history of architecture from the perspective of construction through the form of architecture, a certain process should be the development and advancement of tools and materials.

Wood is one of the earliest materials and has been the most fundamental construction material since before the record of mankind's history till the nineteenth century. The use of wood in building construction can be considered back to circa 5469 to 5098 B.C., the oldest known example could be the find of a wooden lining for a water well made out of oak discovered in eastern Germany (Tegel et al, 2012). In the Vernacular architecture, some materials could be very expensive and rare, therefore, timber had become the most common material since it could provide both economic and sustainable advantages during construction. Besides, timber has the advantage of its good compressive and tensile strength as well as its lightweight, which made it the only suitable material for beams and vaults at times.

It was Greece and Italy that gave rise to largely wood-built buildings throughout Europe. The majority of the notable ancient Greek temples were first built in wood and later reconstructed in stone after 650 B.C.. Many of these temples were rebuilt multiple times, with the most recent reconstructions often being done in response to damage from wars or natural disasters. In fact, "petrification" or "petrified carpentry" (Strickland and Handy, 2001) was the term used in ancient Greek to describe the process of replacing a wooden construction with stone. Later, the ancient Greek and Roman architects invented the timber truss which increased the roof span and enabled the development of public buildings, it thus became a great significant milestone in the history of timber construction. In Greek and Roman construction, wood was developed not only as a roofing material but also in furniture and ships. Although most of the medieval and earlier wooden structures could not be preserved until nowadays, carbonized beams and furniture found in the volcanic mud of Italy's Herculaneum and the shipwrecks which still existed in the Mediterranean sea could all prove the importance of wood in the Roman periods (Ulrich, 2017).

In ancient China, due to the climate and temperature, forests were easier to find. This made wood become easy to collect and the most used material. In particular, human society has made great progress in terms of tools from the Stone Age, through the Bronze Age, and then into the early Iron Age. The efficiency of people's logging of wood has improved and the precision of wood processing has also improved. Further, the wood frame composed of tenon and mortise joints along with the flexibility of the wood itself has a certain degree of mobility, so the whole wooden frame has great potential to reduce the damage of earthquake force. Because of the tenon and mortise joints which are detachable, it is easier to replace a certain component or dismantle and relocate the whole building. In addition, timber-framed structures do not require a long construction time. In ancient China, the monarchy was supreme and every emperor would build new imperial buildings. Therefore, the quest is for quicker construction instead of lasting eternity. While in Europe, theocracy is more respected than the monarchy, there is no need to replace religious buildings frequently. So that stone was often used to construct religious buildings such as churches and monasteries which could last for thousands of years. Timber was also used due to Chinese people's aesthetic and cultural characteristics. In China's popular Five Elements theory[1], wood symbolizes life and is also ranked at first in the five elements. Chinese architecture showed the flexibility of timber combined with Chinese culture. The stable structure, beautiful texture and harmony with the surrounding could reflect Chinese culture.

Both Italian and Chinese timber construction faced the problem of the span. On the one hand, medieval Italy was a highly religious based country and the need for large free-span space for believers evoked the design of timber trusses. On the other hand, public architecture like theatres and baths became popular during the Roman Empire, it also promoted the development of trusses. When considering the situation in China, timber roof construction has always been the huge focus in architectural design since it represents imperial power, while Dougong as the link of roof and building body had constantly developed during the dynasties.

[1] Five Elements Theory (*五行学说*): The Five Elements Theory is a Chinese philosophy used to describe interactions and relationships between things. Five Elements-Wood, Fire, Earth, Metal and Water each contain its energy and sensation and they are considered as the fundamental elements of everything (Ma et al, 2014). Five Element Theory had great influence on ancient Chinese architecture, for example the location, layout, selection of materials, use of colors and so on.

Although Italy and China both have a long history of timber roof construction, the logic and construction techniques were different. So far, there have been respectively many books and research on the topic of Italian and Chinese timber construction, some studies of the comparison between western and Chinese construction were also presented. However, not many resources on the comparison between Italian and Chinese timber roof construction and especially of the structure Truss and Dougong. This thesis primarily focuses on the similarity and differences between timber roof construction in Italy and China with the research on the roles of timber trusses and Dougong structure.

2. Timber roof construction in the Mediterranean area

Letarouilly, Paul-Marie. Basilica di San Paolo fuori le mura. 1849

Since the origins, roof construction had primarily the function of protecting humans from rain, snow and other natural phenomena, which is still the most basic function. With the development of architecture, roofs started to contain as well as an aesthetic function apart from their structural function. In architectural history, the appearance of the roof could be considered a sign of a genre of architecture and a concentrated expression of spiritual connotation. The appearance of the roof varies with the passage of time and has experienced multiple periods of stylistic evolution. From the ancient Greek construction, pitch roofs became the standard roof form for large scale public architecture such as theatres, temples and government halls. Further, as the ancient Romans developed from the ancient Greek roofing techniques, aesthetically, many ancient Roman temple roofs were modeled after this Greek style for example the pediment (see figure 1) could be one of the major characteristics of both Greek and Roman architecture. However, the Romans adapted with more sophisticated constructions and durable materials.

Figure 1: The pediment of the Pantheon (Barry, 2014)

The reason why pitched roofs are the most used form of architecture in the Mediterranean area is due to the climate reason, most of the buildings were designed with sloping roofs, which are naturally conducive to drainage so that problems such as water seepage, water leakage and cracking could be prevented. It could be noticed that the slopes of pitch roofs are not always the same. One of the influencing factors could be the time, the slope changed over time so steeper slopes appeared in the later periods. In Ulrich's book (2007) where he claimed the roof slopes based on previous archaeological surveys of ancient temples[2], which have more information recorded compared to other kinds of architecture. Temples in the ancient period (6th to 5th century B.C.) were usually with a slope of 12 to

15 degrees; while in the later Republic and Empire period (from the 2nd century B.C. onwards), the slope changed to between 18 to 23 degrees. In the meantime, Brunetti (2012) argued that another influencing factor of the degree to which roofs were pitched changes along with the climate temperature. For instance, it could be observed that the degree of slope is much greater in northern Europe compared to the Mediterranean area due to the cold climate (see figure 2: the comparison of the pitched roof of the Temple of Hephaestus in Greece and the Stave churches in Norway). The greater slope of the roof in northern Europe is also affected by snowfall. If the slope of the roof is not enough and the snow cannot fall in time, the accumulated snow will directly overwhelm the roof and cause collapse. Or after the snow melts, if the snow water cannot be discharged, the water would leak through the gaps in the roof.

Figure 2: Left: Temple of Hephaestus (Dinsmoor, 1975); Right: Heddal church of the Stave churches (Kjerulf, 1848)

The construction technique of the pitched roof changed and developed over time. In Greek construction, the roof structure was mainly supported by a timber skeleton or frame (see figure 3). As Klein's summary (1998) of Hodge's opinion:

> *"... the woodwork of Greek roofs generally consists of primary timbers (ridge beam and purlins) and secondary timbers (rafters, battens, sheathing), where the ridge beam and purlins run parallel to the long axis of the building and provide the underlying framework for some or all of the secondary timbers just listed…"*

[2] Ulrich's study was mainly on Roman Forum and ancient Etruscan rock-out tomb in Cerveteri, San Giuliano, Tuscania, and Blera.

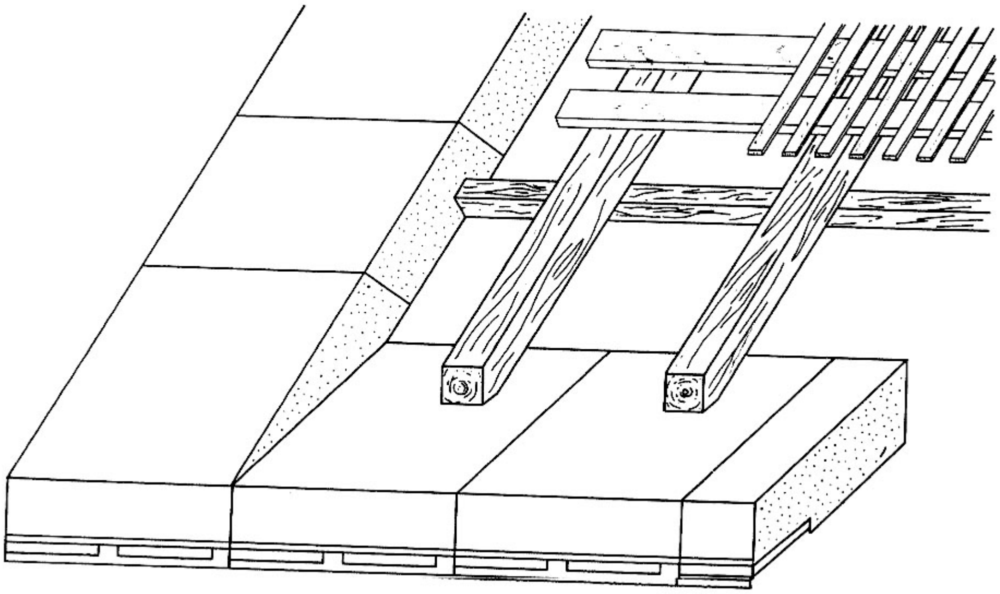


Figure 3: Greek roof framing (Klein, 1998)

For small-scale architecture, this kind of frame roof was directly supported by the columns or walls, however, for larger spans, some intermediate supports were needed for the ridge beam. The widely used method was called "Post and Lintel"[3] roof (see figure 4) where "post" is a vertical element supported by columns or walls and connected by the horizontal element "lintel" so that the ridge beam and rafter could be loaded on "Post and Lintel". As Hodge reported in his study of mainland Greek architecture (1960), the biggest advantage of the "Post and Lintel" structure is that it's easier and better in combination with the cantilever to support a deeper pediment on the front or back of a temple. The Post and Lintel roof has remained for a very long time as the most common structure of roof construction, in fact, it lasted even after the creation of the truss roof and can still be found in many houses nowadays. The Post and Lintel structure could only cover up to a limited span, which caused another obvious feature of Greek architecture: the grid of columns inside the temples and halls. A famous example of this type of roof could be the cella[4] of the Parthenon (see figure 5) in Athens is covered by a post and lintel roof for approximately 11 meters free span despite the help of internal colonnades (Hodge, 1960). However, due to the weight of the roof structure and under such a relevant free span, it could be risky that the beam tends to sag if it

[3] In some books this is also referred to as "Prop and Lintel" roof or "Trabeated system".

[4] Cella: a proliferation of golden rectangles in the inner chamber of the temple (Ripley and Bhushan, 2016).

fails to bear the tension or is under the extra weight. Thus, spans beyond this range can be covered more efficiently using tie beam trusses (Klein,1998).

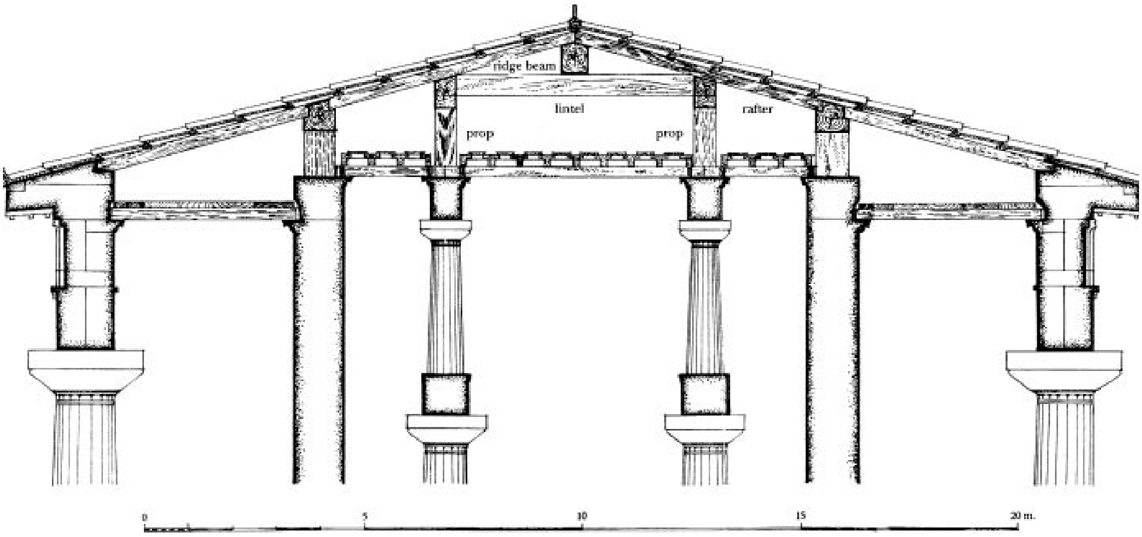


Figure 4: Post and Lintel roof (Klein, 1998)

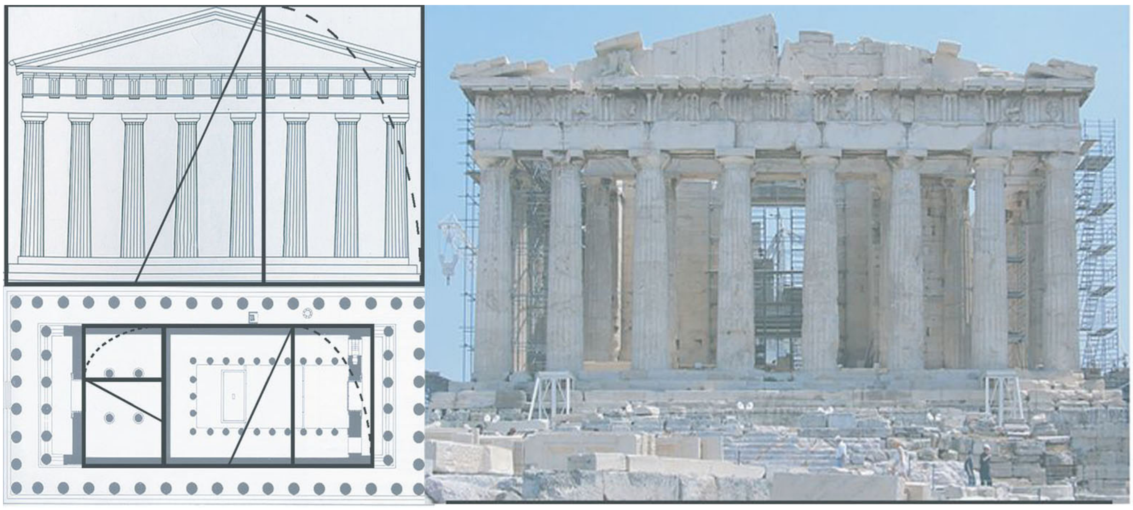


Figure 5: Cella of the Parthenon (Ripley and Bhushan, 2016)

However, with the development of architecture, the span limitation of the frame roof made it no longer suitable for construction. As Benvenuto wrote (1981)[5]:

> *"...le spinte orizzontali esigono robusti contrafforti che solo negli edifici ecclesiastici possono essere realizzati, in secondo luogo perche su grandi luci interviene la flessione delle travi. La forte pendenza del tetto che e*

[5] "..the horizontal rafters require robust buttresses that can only be built in ecclesiastical buildings, secondly because the bending of the beams intervenes on large spans. The steep slope of the roof that is required gives an unpleasant effect to the eye, as happens in many ancient roofs, for example in the Tuileries in Paris, whose slate roofs are so high as to seem a second construction superimposed on the masonry one..."

richiesta, da un effetto sgradevole agli occhi, come accade in molte antiche coperture, ad esempio nelle Tuileries di Parigi, i cui tetti di ardesia son cosi elevati da sembrare una seconda costruzione sovrapposta a quella in muratura…"

Structurally, the main problem of the frame roof was its lateral thrust to load-bearing walls or columns underneath while for the Post and Lintel roof another drawback could be the weight of the roof with the vertical and horizontal elements inside. In order to overcome the problem of a heavy roof and eliminate the lateral thrust, it is necessary to connect the rafters of both sides at their base level with a stretched element called the "*Catena*" (Tie beam) (Brunetti, 2012). This triangle structure is the basic form of "*Capriata*" (Truss).

With the need for a longer span of the Roman civic basilica and the public buildings, especially free large span architecture such as theatres and churches, the simple post and lintel structure no longer met the construction requirements. The main design goal for these kinds of public architecture was to optimize the availability of space. Thus, it was necessary to avoid structural barriers such as intermeddle walls or the grid of columns between the speaker and hearers. Truss has therefore become the leading structure of roofs. Different types of wooden trusses have been developed to guarantee the coverage of substantial spans and be able to support the roof weight at the same time. Compared to the post and lintel roof, smaller and lighter types of wood were used for the truss roof. The most obvious advantage of the truss roof is to better support the weight of the roof and provide larger space to be spanned. The simplest truss form consists of three pieces of wood which form an equilateral triangle: two rafters and a horizontal tie beam. The tie beams act in tension, counteracting the lateral thrust of the rafters. The simple truss which is called "Capriata semplice" (simple truss) could reach a roof span of 8 meters without intermediate support.

Each truss component is subjected to different stresses: in its minimal configuration, rafters are subjected to compression and bending, while the tie beam is subjected to tension. Essentially, the truss could be seen as a use of the concept "non-deformable triangle" that has the advantage of eliminating horizontal forces due to its triangular structure (Macchioni and Mannucci, 2018). Therefore, trusses have a fundamental difference from post and lintel structures, because trusses are usually structures without thrust.

However, the truss was not the only structure to solve the problem of large span roofs. Another method was to construct the posts close to the two ends of the beams in order to reduce the load and bending moments in the middle of the beams and prevent them from breaking or bending. For instance, the roof of the Castello di Valentino in Turin (see figure 6) was composed of a ridge beam, five series of purlins and three layers of beams and posts (Bertolini Cestari et al, 2015).

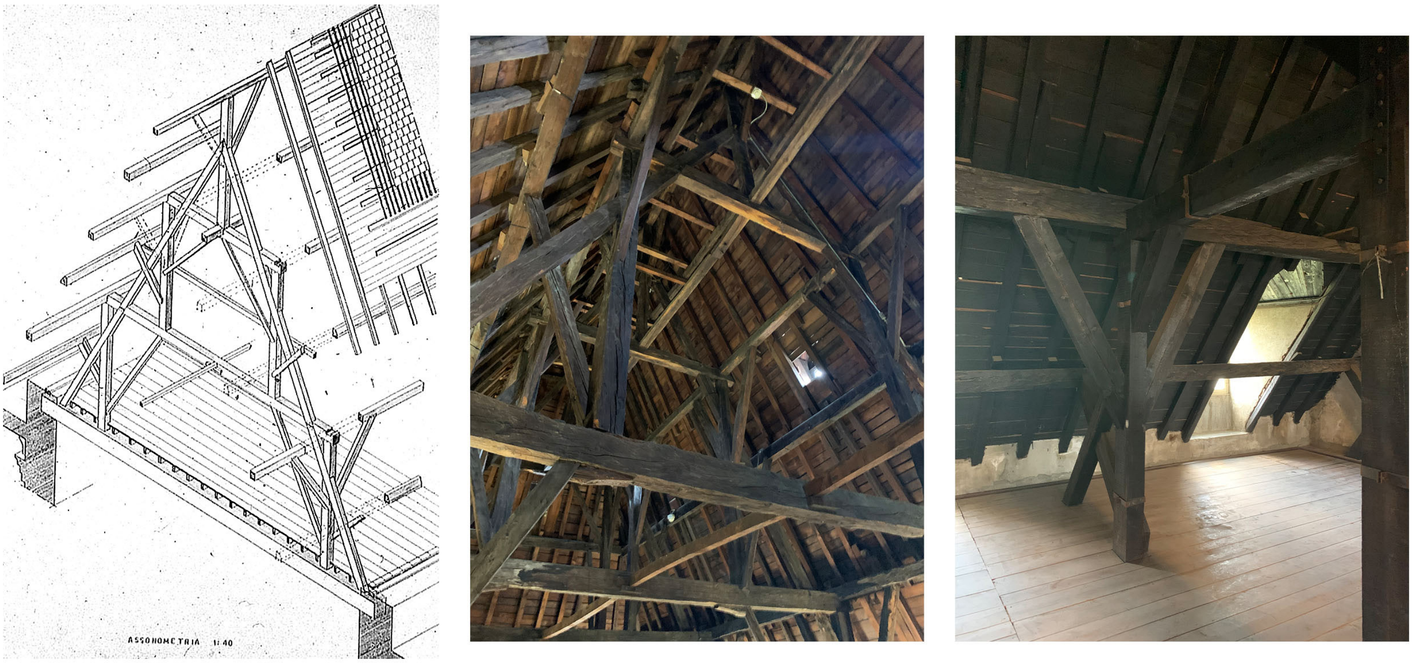


Figure 6: Left: detail of the timber frame roof of Castello di Valentino (drawing by Bertolini Cestari 1986); Right: photos of Castello di Valentino

2.1 The orientation of the timber frame

In the simplest form of post and lintel structure, the pitched wooden roof can be carried by a sequence of beams or joists and the direction of the main beams is fundamental. One of the arrangements is with a series of beams in the direction of the slope purlins supported by longitudinal beams and walls. Nowadays in Northern Italy, this type of arrangement is called "*L'orditura Piemontese*" (Piedmontese frame) (see figure 7 left). Another arrangement is that the beams are perpendicular to the slope rafters and resting on the gable walls, which is called "*L'orditura Lombarda/Romana*" (Lombard/ Roman frame) (see figure 7 right). In both cases, the spacing of beams or joists can vary widely, depending on the characteristics of the vertical load-bearing structure. These two kinds of frames without a transverse beam are typically used for a limited span which is typically no more than 5 m.

L'orditura Lombarda/Romana: The Lombard roof is a pitched roof characterized by a particular load-bearing system where the primary beams that support the roof, *terzere*, are parallel to the eaves and the load-bearing walls are transverse. In the Lombard arrangement, the rafters are placed at a distance of 3 to 3.5 meters in between each other while the secondary beams are placed with a spacing of 1 to 1.7 meters (Brunetti, 2012). Since the beams are parallel to the walls, there is no thrusting force from the roof structure.

L'orditura Piemontese: In the Piedmontese roof, the horizontal load-bearing elements "*terzere or arcarecci*" (secondary beam) rest on inclined beams "*puntoni*" (rafters) supported by longitudinal walls and the "*colmo*" (ridge). In the Piedmontese arrangement, the rafters are placed at a distance of 1.2 to 1.7 meters in between each other while the secondary beams are placed with a spacing of 0.6 to 1 meter. The spacing of the components is much closer compared to the Lombard roof arrangement. Another fundamental difference between these two arrangements is that the Piedmontese roof requires a central wall or ridge in order to support the rafters. With one end of inclined beams loaded on this central wall or ridge and the other end loaded on the walls at both sides, a force pushing to the side walls would be generated.

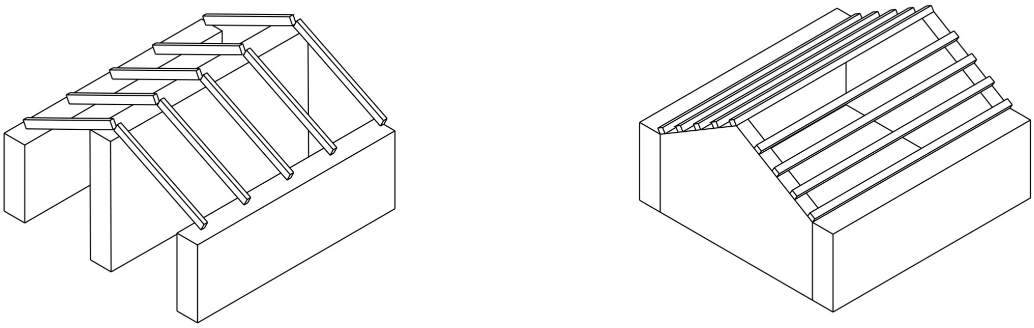


Figure 7: Left: Piedmont roof; Right: Lombard/Roman roof

Same as the post and lintel roof, the truss roof also follows the arrangement of Piedmont or Lombard/Roman framing. Figure 8 shows the modified scheme of the Piedmont and Lombard/Roman roofs with trusses.

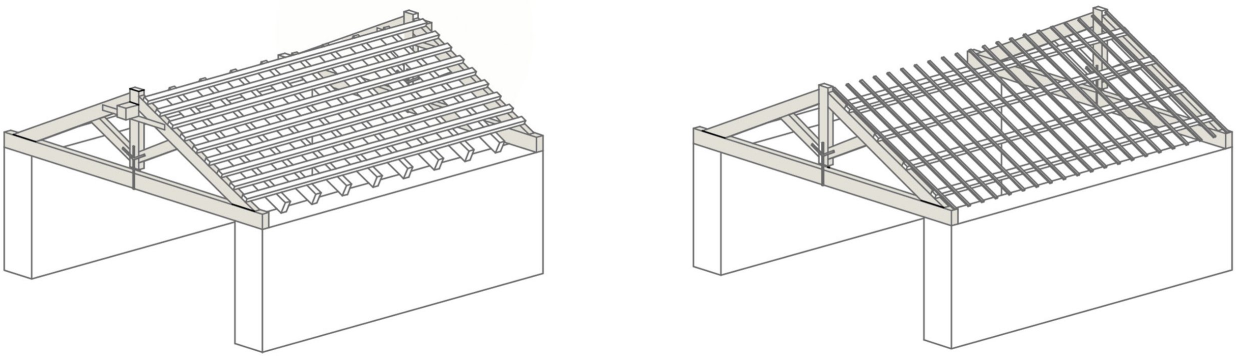


Figure 8: Left: Piedmont roof with truss structure;Right: Lombard/Roman roof with truss structure

3. Truss

3.1 History of truss

The question to identify a truss used in buildings has always been based on technical grounds and generally arises only when the width to be spanned without intermediate supports exceeds 11 meters (Klein,1998). Although there is no existing example of timber roofs from ancient Greek architecture, it could still be observed based on the archaeology activities and research about the roof construction of Greek temples. On the basis of indirect evidence that can be found in stone remains, some authors for example Hodge[6] (1960) and Klein[7] (1998) supposed that timber trusses had already been used in the Greek temples at Selinus (Sicily, Magna Graecia) in the 6th century B.C.. The Greeks used trusses extensively in roofing. Further, according to the need for more interior space in the later period, the use of trusses for expansion of span was also presented in Roman architecture and the construction of large halls became possible. According to the researchers[8], the oldest and still existing trusses are those of the church in the fortified monastery of St. Catherine on Mount Sinai (see figure 9), dating back to the mid-6th century A.D.. The trusses designed by the architect Stefano di Eilath already have all the characteristics of subsequent constructions except for the absence of the connecting strap between the king post and the tie beam (Tampone, 1996).

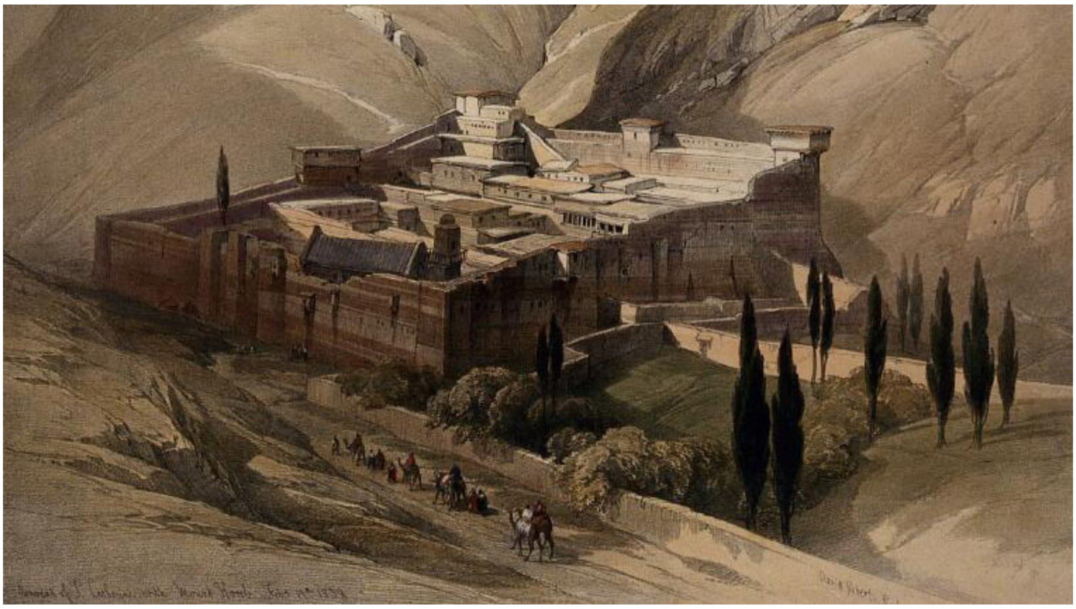


Figure 9: St. Catherine on Mount Sinai (Roberts, 1849)

[6] Hodge, Trevor. 1960. *The Woodwork of Greek Roofs.*

[7] Klein, Nancy L. 1998. "Evidence for West Greek Influence on Mainland Greek Roof Construction and the Creation of the Truss in the Archaic Period".

[8] Fielden and Bernard. 1994. *Conservation of historic buildings*.

In Roman architecture, the original trusses in bronze used to support the porch roof of the Pantheon that finished by 128 A.D. which were shown in Renaissance drawings could be considered as the earliest evidence of a Roman building which used a truss structure in Italy (Tampone, 1996). Therefore, it could be assumed that by that time the tie-beam truss roof had already been spread around Roman architecture. From the Medieval, the truss was mostly used for large-scale timber construction mainly in civil architecture and religious architecture. Compared with the Greek construction techniques, the Roman truss system provided more flexibility of the frame and a larger span distance between vertical load-bearing structures such as columns and walls (Ulrich, 2017). At the end of the 16 century, long-span structures were developed rapidly in Italy according to the need for new forms of architecture such as Counter-Reformation churches and larger space political buildings. These architectures have the main function of gathering that highly required free span spaces, thus, the solution of eliminating the supporting vertical elements in the middle of space by trusses had been developed as well. In addition, in terms of the choice of material, most of the large-span structures have good performance in tension and compression whereas timber becomes an appropriate material for large span structures due to its strength and stiffness. Timber trusses generally give a solution for spans over 25 to 30 meters. For larger spans, trusses are typically spaced 5 to 12 meters in between each other (Crocetti, 2016). In the development process of trusses, the constructions rely heavily on the material supplement, local culture and functional needs. Till the 19 century, apart from religious architecture, trusses have been used for residential buildings and bridge construction as well. The use of the truss continued in the 19 and 20 centuries, especially in the construction industry, alongside the traditional wooden material, metal trusses were started to be more used in order to obtain more resistance to traction.

The specific name of the truss structure has been changed since the medieval until now. In Italy, the word "*capriata*" was actually started to be used only after the 19 century (Guardigli, 2021), before that this roof structure was first indicated as "*armanmenti*", a necessary piece of equipment for the operation of ships. Besides, the words "*incavallatura*" or "*cavaletto*" have also been used starting from the 15th century till the 19 century. Finally, the word "*capriata*" which is widely used in the Italian language nowadays came from "*capra*" in Latin which indicates an ancient tripod that was later introduced to define a structure that would not transfer any horizontal loads to the walls.

3.2 Definition

Most types of traditional trusses consisted of the following components.

1. Rafters (*puntoni*): Inclined beams that are stressed by normal force and bending moment. The rafters exert on the tie-beam a thrusting action and tensile stress.
2. Tie beam (*catena*): A horizontal element that supports tensile stresses on the supporting point of rafters. Its function is to cancel the horizontal component of the thrust by joining the opposite ends of the rafters so that the weight of the entire structure could be transferred to the wall where it is located by vertical action.
3. Post (*monaco*): A vertical element in the middle of the capriata. It has the function of connecting and limiting the bending moment of the chain. With a metal bracket anchored on the "sides", it perfectly fulfills the task of restoring part of its weight to the key of the three-hinged arch, or to the head of the two rafters, as well as the bracket that surrounds the chain prevents twisting of the structure. For larger spans, a form of two vertical elements to replace the king post was generated and they were referred to as queen posts.
4. Braces/Struts (saette): The elements with an inclination opposite to that of the rafters that limit the deflection of the rafters themselves, discharging the compression force to which they are subjected onto the king post

Traditionally, the truss should contain at least three elements: rafters on both sides and a tie beam, in which the rafters are stressed under compression and the tie beam is subject to tension. This triangle form structure could be seen as the simplest appearance of a truss as called "*Capriata semplice*" (simple truss). A simple truss could cover a free span of up to 8 meters.

In the simple truss, the tie beam must be strong enough to resist traction, but in the meanwhile, it can not be so heavy that it could be bent in the middle. Therefore, it was very difficult to achieve a longer span with this type of truss. The appearance of a vertical support "*monaco*" (king post) that contrasts the inflexion of the tie beam was considered the beginning point of the truss evolution (Benvenuto, 1981). As mentioned above, the basic structural logic of the truss is the indeformable triangle. Therefore, it is possible to obtain a greater rigidity and resistance to bending by increasing the number of reticular meshes of the structure, which became a general rule to make it possible to cover longer spans. According to this rule, the simple truss with a vertical element in the middle (see figure 10) which divides the form into two triangles was generated and known later as "*Capriata semplice con monaco*" (King post truss). However, the theory of enhancing the truss by increasing indeformable triangles inside can only be adopted when the post is mortised to the tie beam. If the post and tie beam did not have a rigid connection (as an open-joint truss which will be discussed later), then the structural performance was not improved as much as the closed-joint truss.

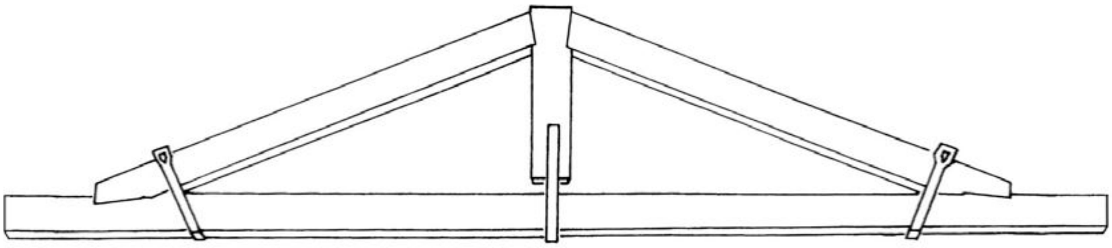


Figure 10: King post truss (*Capriata semplice con monaco*)

For short span roofs, the king-post truss is the most common truss form which could cover a span distance from 4 meters to 15 meters. In the classic scheme, the king post is detached from the tie beam and the two are connected by U-shaped metal straps. In such a way the vertical load is not transferred to the tie beam, which only has to resist the outward thrust from the principal rafters in addition to a load of its own weight.

A simple evolution of the king post truss is called "*Capriata semplice con saettoni*" (King post truss with struts), with the addition of diagonal struts (see figure 11), the king post, which serves as a tension member, receives the roof loads that are imparted to the top chord. Struts also contain the function of preventing rafters from inflecting in the middle.

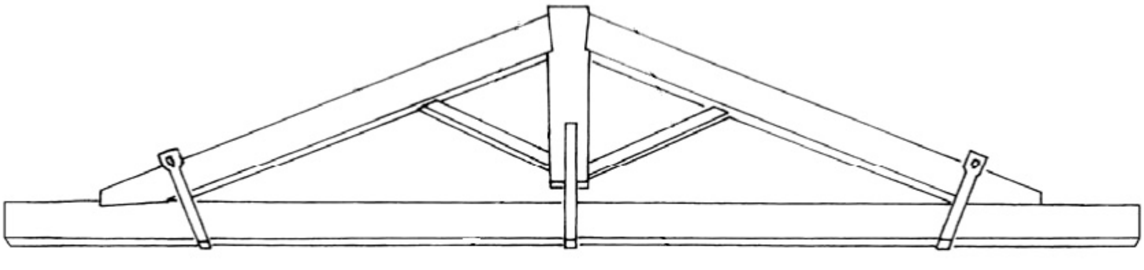


Figure 11: King post truss with braces (*Capriata semplice con saettoni*)

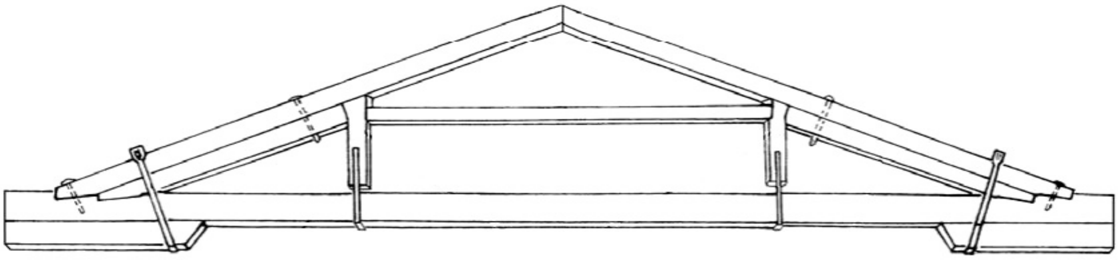


Figure 12: Queen post truss (*Capriata composta*)

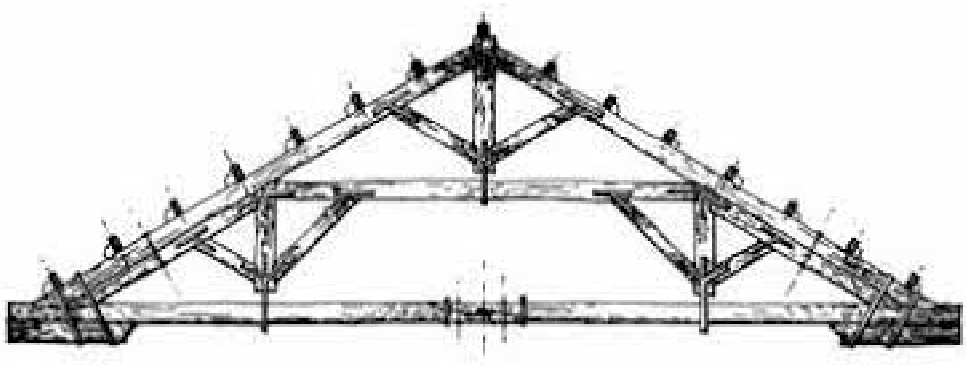
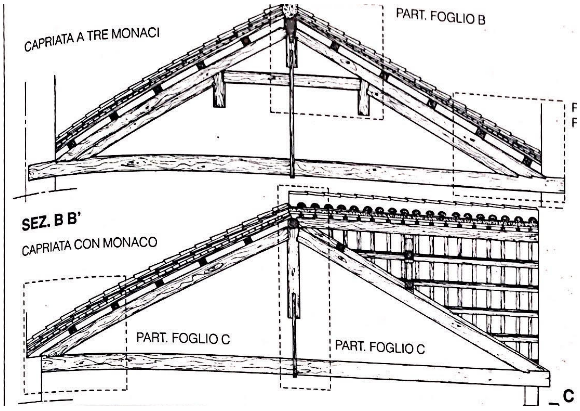


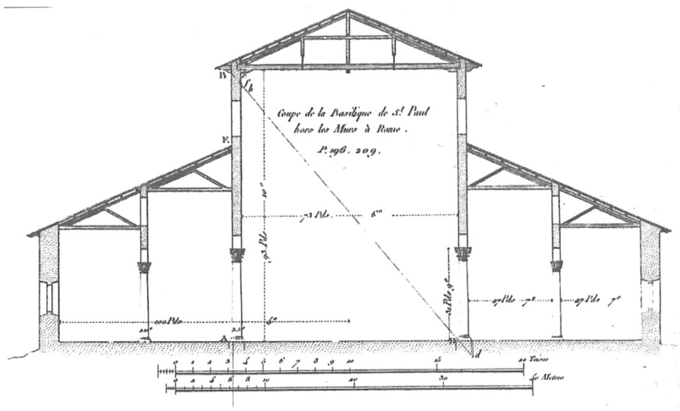
Figure 13: Queen post truss with braces (*Capriata composta alla Palladiana*)

Valeriani discussed (2005) that the word "*Palladiana*" was after the famous architect Andrea Palladio not only because he used plenty of queen trusses in his projects but this type of truss was also presented in his surveys and drawings of classical architecture. It could be therefore assumed that it has some connections with the ancient construction tradition. Actually, the term "*Palladiana*" is often used to describe the truss structure characterized by rafters, tie beam, straining beam, secondary rafters and posts which could be from one to three, mostly two on both sides but in some cases as the truss in Basilica di San Pietro in Vincoli[9] in Rome. As shown below (figure 14), the roof was supported by three post trusses and simple trusses. Another example could be the truss in Basilica San Paolo Fuori Le Mura[10] whose roof covered a span of circa 26 meters has

[9] Basilica di San Pietro in Vincoli was firstly built during 432 to 440 and had been rebuilt in 8 century, 15 century and 18 century. The architectural drawings here were from the survey during the 18 century.
[10] Here the case is based on Rondelet's drawing in 1814 which was before the great fire of Basilica San Paolo Fuori Le Mura in 1823.

been considered a magnificent example of simplicity and verve. In this case, there were three posts (see figure 15) and the rafters were reinforced by extra pieces of wood called "*sottopuntone*" (secondary rafter) placed under.





Left: Figure 14: Trusses of the Basilica di San Pietro in Vincoli (Giovanetti, 1997)
Right: Figure 15: Basilica San Paolo Fuori le Mura at Rome (Rondelet, 1814)

The queen post truss became popular at the end of the 18th century. The reasons could be first the queen post truss required shorter lengths of timber compared to the king post truss under the same span. In addition, queen-post trusses provided usable space inside the roof (Yeomans, 2015) and lowered the degree of pitch roof.

From the above evolution of trusses, the Italian truss could be further divided into two main types. The types differ from each other in the relationship between posts and tie-beams: they are called closed-joint and open-joint trusses (Barbisan and Laner, 2000), depending on whether the posts are connected with a carpentry joint to the tie-beams or not. In the closed-joint trusses, posts could be connected to tie beams with tenon-mortise joints or with dowels, as in the basilicas of St. Peter (figure 16 left) and St. Paul in Rome (figure 16 right). In open-joint trusses, the posts are physically detached from the tie beam such as in the trusses of St. Catherine on Mount Sinai but possibly linked with a metallic strap. In this case, the metal straps only play the structural role when the tie beam is bent. Furthermore, when the upper part is sinking or the joint of rafters and king post become cracked, extra compression directly to the tie beam could be prevented by separating the king post and tie beam. The open-joint truss was the classic type from the Renaissance period for example the trusses (see figure 17 left) of the Salone dei Cinquecento in Palazzo Vecchio in Florence built in the 16 century, it was also used as the construction example in many handbooks. In Baldi's sketch (1621) (see figure 17 right), the figure he used to explain the mechanism of the truss was an open-joint truss.

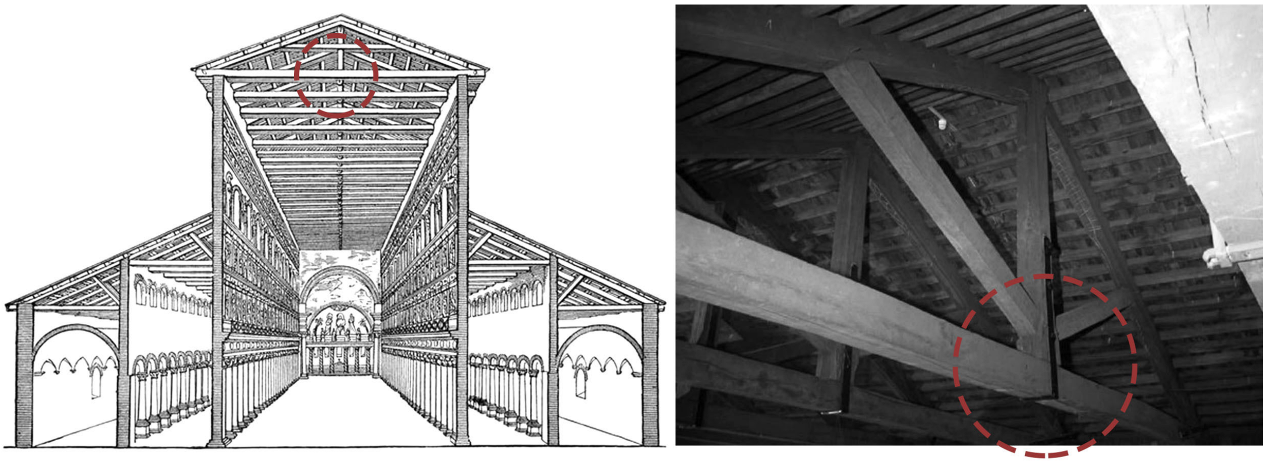


Figure 16: Left: Section of the Basilica of St. Peter (Spagnesi, 1995); Right: Detail of a closed joint truss of the Basilica St. Paul (Valeriani, 2012)

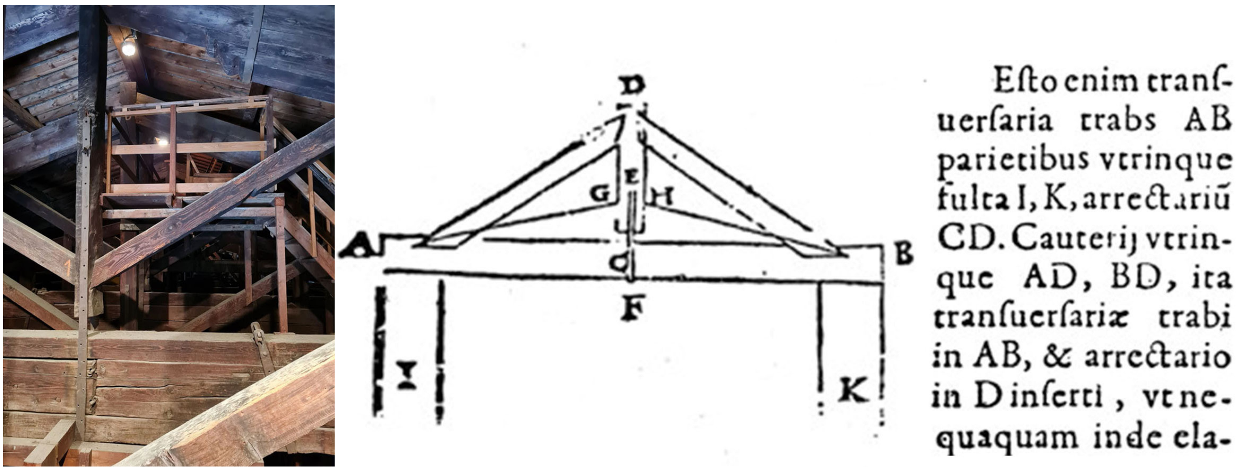


Figure 17: Left: Open-joint trusses in Palazzo Vecchio; Right: Bernardino Baldi’s sketch of king post truss with open-joint. (Nenci, 2011)

In Italy, the use of closed-joint trusses and open-joint trusses differs from regions (Valeriani, 2006). For instance, in the northern and central parts of Italy, closed-joint trusses had been used mostly. In both cases of having the king post or queen posts mortised to the tie beam (*Capriata con nodo chiuso*) or simply connected (*Capriata monaco appoggiato*). Taking the Veneto region as an example, in both Santi Giovanni e Paolo and Santa Maria dei Frari (figure 18) in Venice the closed-joint trusses had been used. While for the truss cases in Rome, the king post and tie beam were not connected but linked with metal straps (*Capriata con nodo aperto*). For a long time, closed-joint and open-joint trusses coexisted and had been developed in the work of carpenters in different regions of Italy. However, since the 16th century, the advantage of closed-joint trusses has gradually diminished, which will almost completely disappear by the end of

2019 (Barbisan and Laner, 2000). Although many researches of the existing examples showed during the 16th century most of the truss structures were applied with open-joint trusses. In a popular manual during that time, Seven Books of Architecture by Sebastiano Serlio of which first incomplete edition was published in 1537, the drawings of Capriata used closed-joint trusses. Guardigli (2021) argued that might be because at times the construction focused more on practice rather than books. Serlio's manual presented only the example and module of trusses, however, there was not any detail of joints or choice of beams described. From which it can be speculated that after the structural form was designed, most construction details were determined by the experience of the craftsmen.

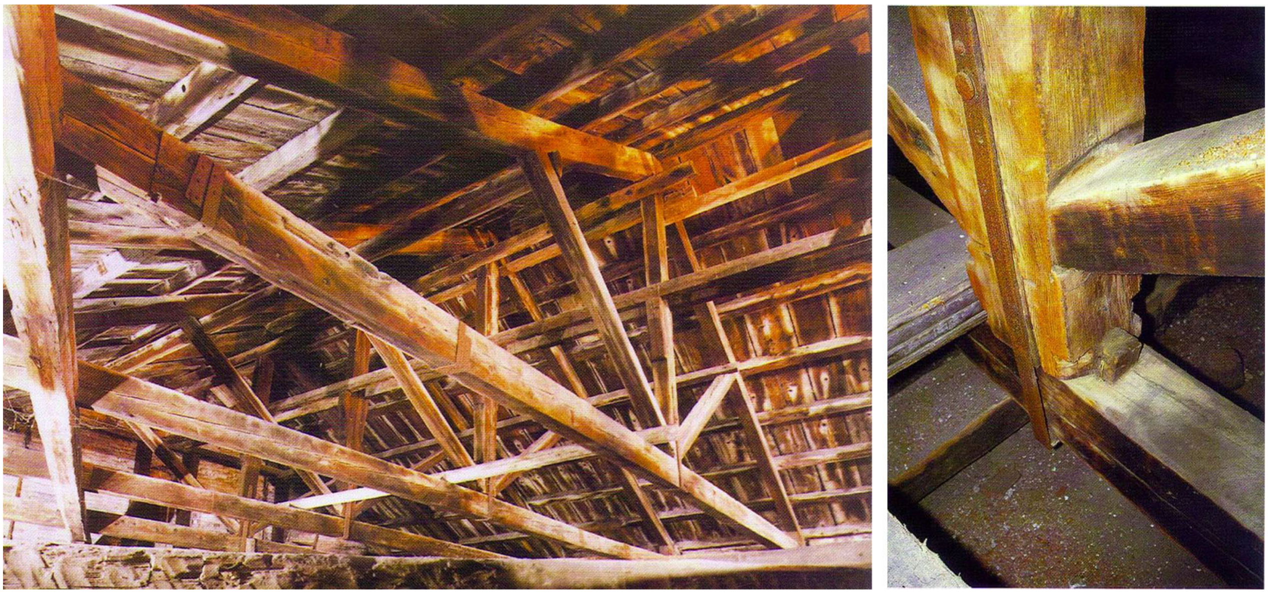


Figure 18: Closed joint trusses in Santi Giovanni e Paolo (left) and Santa Maria dei Frari (right) (Valcanover and Wolfgang, 2000)

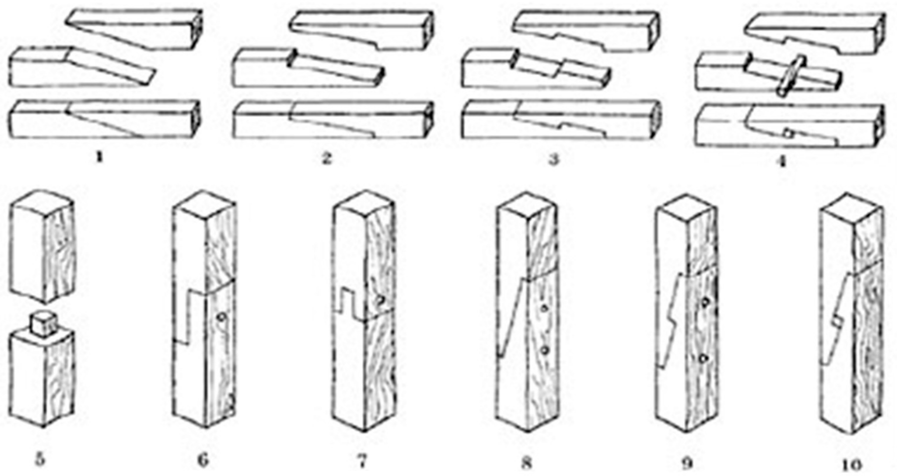
To better understand the reasons why open-joint trusses showed such good performance in structure compared with closed-joint trusses, it is necessary to analyze the construction details of both structures and to understand their static behavior. Taking into account the general technical background of the time in the meanwhile. According to Zamperini's analysis (2015), it shows that in the case of a closed joint truss if the joint of the rafter and tie beam progressively reduce its resistance, the tie beam would tend to support the post which would further cause the tie beam break in the middle point where contains most load. The structural degradation of the joint point could be caused due to extra weight on the roof structure or simply because of the decay phenomena of wood. While the open joint trusses indicate efficient functioning in accordance with the idea of a non-deformable triangle without having a rigid connection between the post and tie beam.

Besides, the open joint trusses suit better with the lower pitch and as discussed above, most Italian roofs contain low-pitch roofs compared to the average slope in Europe according to the Mediterranean climate.

3.3 Connection

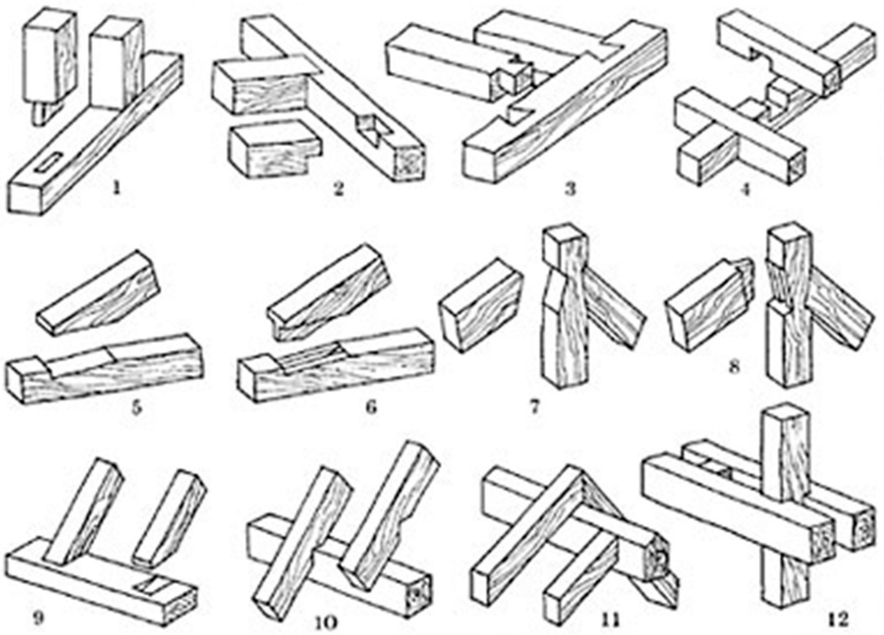
In the TFEC (Timber Frame Engineering Council) guide (2020), it said that ideally, each component of a truss meets at joints that are idealized as hinges or pins that are incapable of transmitting bending moments. The force would be applied at these joint nodes, which keeps the truss itself shear-free. However, in a real truss, the self-weights of each component should also be taken into consideration. So the truss responds to applied loads with a combination of axial stress, bending moments, and shear in their members. Since joints have such an important role in the structure, studying the joints could be one of the most important methods to analyze trusses.

The elements of the truss could be assembled together in various ways, including creating clamping slots in the wood and using dowels or connecting through hardware such as screws and nail plates. The earliest Greek method for connecting wood species included scarf-joint, tenon and mortise joint, lap-joint, dovetail joint and etc. (see figures 19 and 20). These different joints changed the connecting surfaces in order to resist tension, compression and flexion within the wood structure (Adam, 1999).The Romans continued to use these pure wood connection technique until the iron was used, it quickly became an essential material for the joints. The metal elements were added at various joints to reinforce wooden trusses especially the metal strap between the king post and tie beam. In Italian woodworking, it has been a tradition to combine wood and metal (Valeriani, 2006). The use of metal pins and nails in carpentry to connect pieces of wood could be dated back to the Roman period.



1. splayed scarf-joint
2. splayed joint with part abutments
3. splayed indent scarf or 'Jupiter's shaft'
4. splayed indent scarf with transverse keys
5. scarf-joint with tenon
6. halved scarf-joint
7. scarf-joint with slit (slot) mortice
8. splayed scarf-joint
9. scarf-joint with indentation
10. scarf-joint with indentation

Figure 19: Timber jointing (Adam, 1999)



1. mortice and tenon joint
2. square halved joint
3. dovetail joint
4. halved joint
5. lap-joint
6. lap-joint with mortice and tenon
7. lap-joint with abutments
8. lap-joint with mortice and tenon
9. lap-joint with abutments
10. overhanging base bearer of common rafter
11. heads of common rafters jointed at the roof-ridge
12. braced joint on a double tie beam holding a vertical piece

Figure 20: Timber jointing (Adam, 1999)

Apart from the general connection of wood pieces, the joints of various components also determine the structural performance of a truss. Firstly, the joints of the tie-beam to the rafter are for sure the most stressed within the whole truss (Barbisan and Laner, 2000). In this node, the force would divide into both horizontal and vertical directions. The vertical force becomes the compression through the intersection surface, while the horizontal force expresses the tension that is connected with the tie beam. A structurally good module would be that the three axes of the rafter, tie beam and wall all meet at one point as the conditions a,b,c in figure 21, otherwise the misalignment would generate bending moments as well as tangential tensions (see condition d in figure 21). From the historical manuals (figure 22), it could be seen that the original connection at this node used the tenon and mortise. On the types of joints, it is also possible to resort to more or less complex joints, riveting, bolting and stirring as some examples are shown in figure 23. The choice obviously depends on the preference for appearance or on the availability of the equipment. In the majority of the constructed examples, this junction was created using a single or double-tooth connection with the assistance of a few nails that are pushed perpendicular to the rafter (Barbisan and Laner, 2000). Almost always, metal U-plates and metal wedges are used to keep the joint in place. For fire protection, bolts and nails are preferred choices.

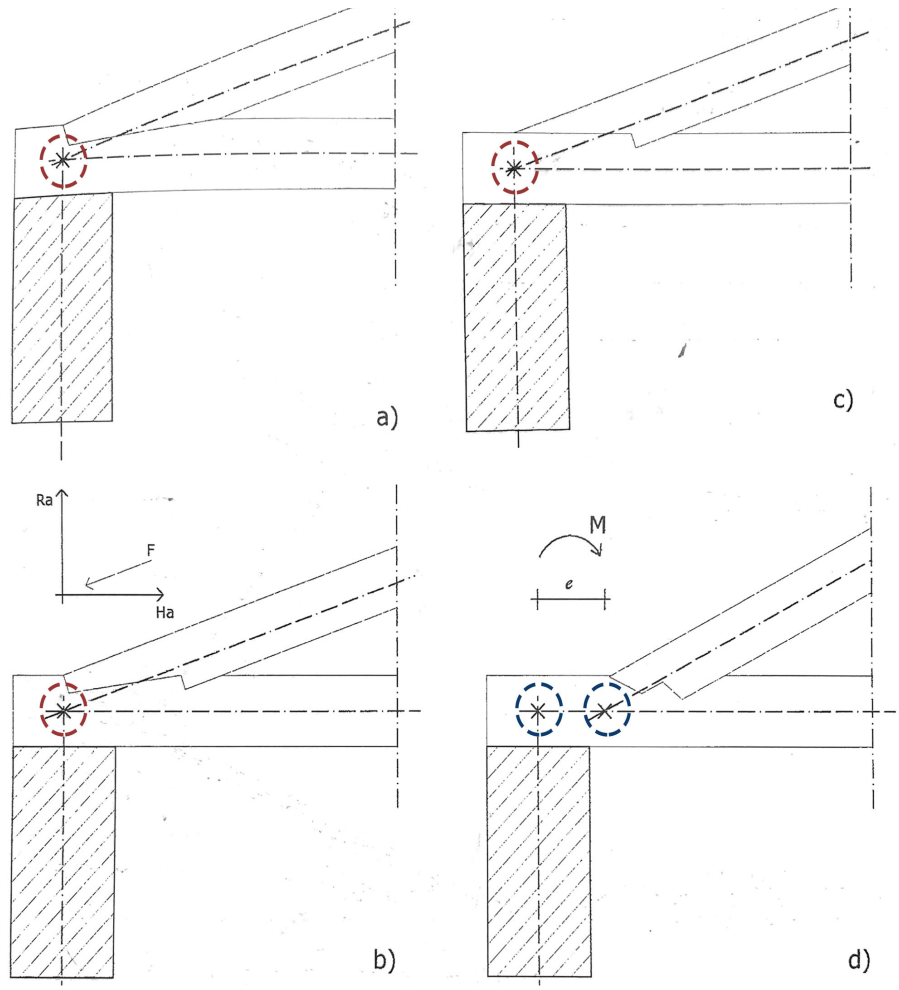


Figure 21: Connection of the axes of rafter and tie beam (Barbisan and Laner, 2000)

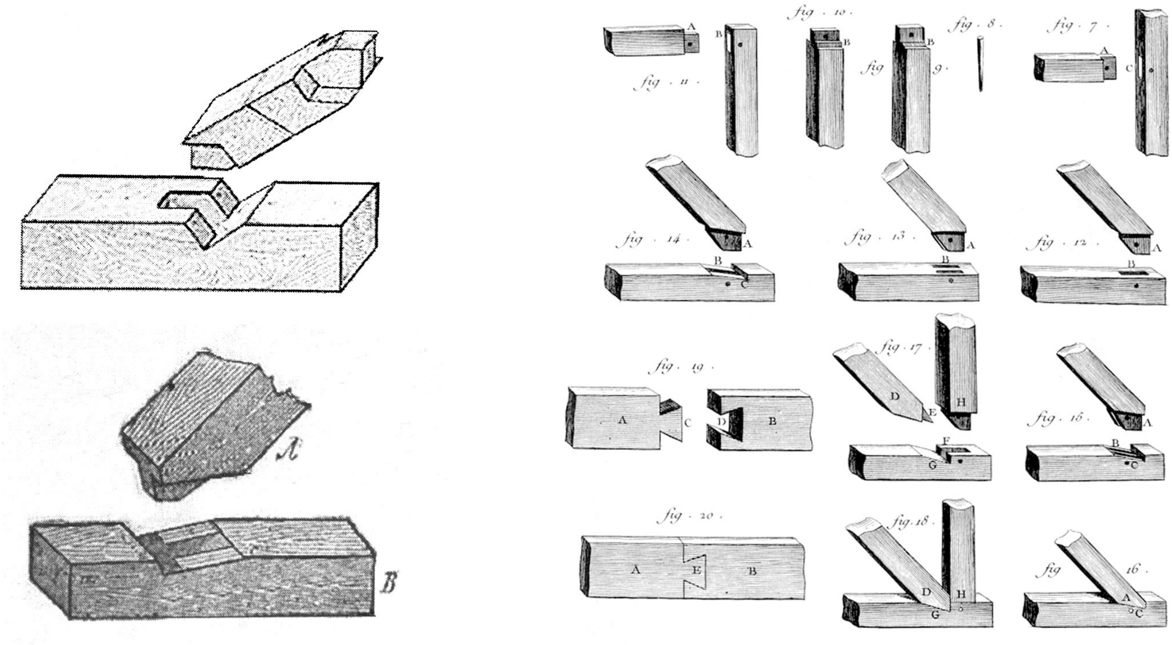


Figure 22: Tenon and mortise connection between rafter and tie beam (left above (Gandolfo, 1869); Left below (Breymann, 1985); Right: *Encyclopédie ou Dictionnaire raisonné des sciences, des arts et des métiers*, 1765)

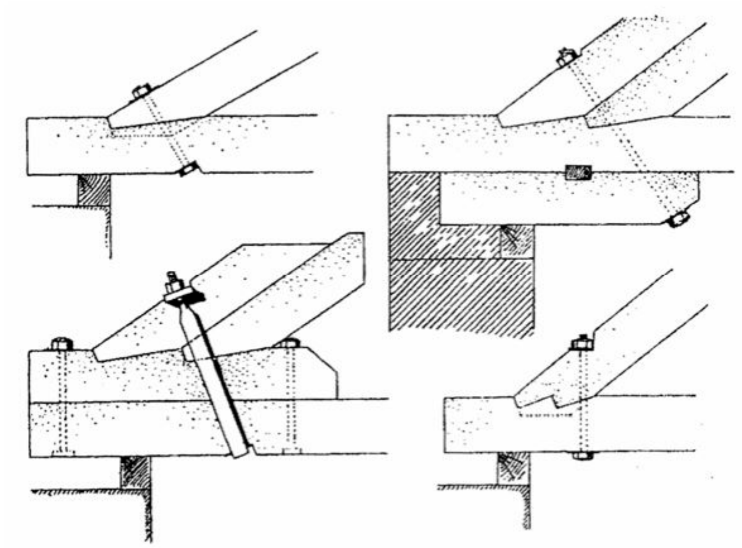


Figure 23: Examples of connection of rafter and tie beam by T. Krauth and F. Sales Meyer (Barbisan and Laner, 2000)

Another important node is the joint of rafters and posts. Due to the contrasting effect of rafters on both sides, the top part of the post tends to be compressed. In most common types of truss, the post has the main function of enhancing the resistance to bending moment and also the constructive function of facilitating the connection between rafters (Brunetti, 2014). If the rafters were connected directly to each other, the case would be that they meet at the corner of two rectangles that generate excessive stress concentrations in the head of the rafters. However, as shown in figure 24 there were still some architects such as Aluisetti and Pizzogalli (1827) that proposed solutions withing cutting the corner of rafters but connecting them with metal straps. The more common method on this nodo was to cut off the corner of rafters and insert them into the post with tenon and mortise joint as in Breymann's book (1985).

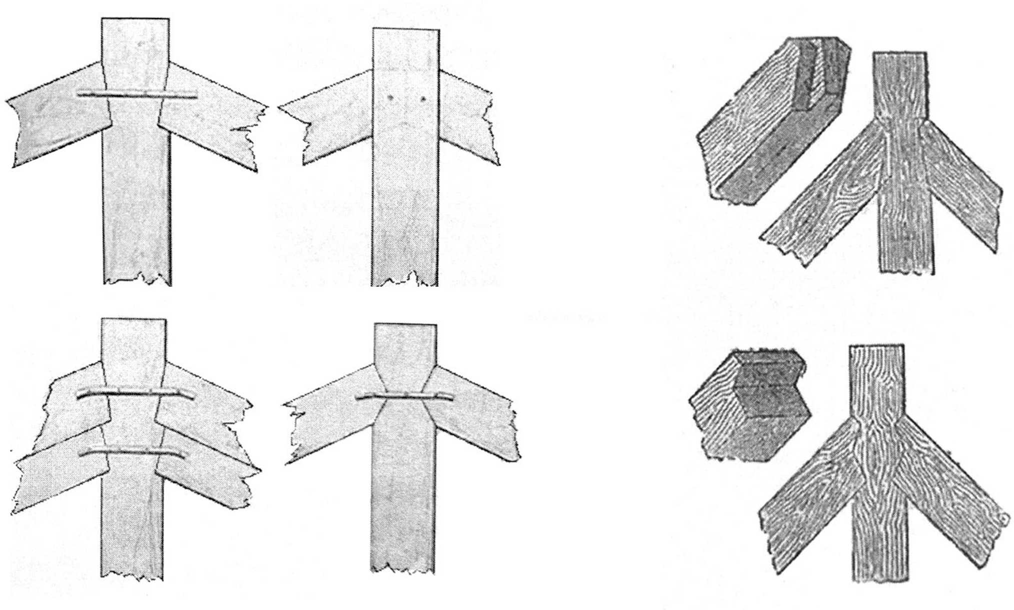


Figure 24: Left: connection with the corner of rafters remained (Aluisetti and Pizzogalli, 1827); Right: tenon and mortise connection between rafter and post (Breymann, 1985)

Finally, when considering a truss as a roof element, it would be necessary to analyze the connection between the truss and load-bearing walls. A good connection between the truss and wall could increase the stability and integrity of the roof and the whole building in order to against the cyclic forces under earthquakes and reduce the risk of collapse. The oldest connection between timber truss and masonry walls was to insert the rafters and tie beam directly inside the wall with a depth equal to half or more of the thickness of the wall. Normally small masonries or grouting materials were used around the ends of wood tie beam in order to fix the truss (Solarino et al, 2019). Later, considering the different characteristics of materials and especially to prevent the decay of wood species (Barbisan and Laner, 2000), an air gap was left between the tie beam and masonry (see figure 25). Similar as the connection of rafters to tie beam, the combined use of metal and wood quickly replaced the pure wood connection, the use of adding a metal strap inside the wall and connecting to the tie beam could enhance the mechanical properties. In some cases, the strap to fix truss to the wall is also connected to the metal U-plates between the rafters to tie beam so that the integrity of the truss itself and with the masonry would be further improved.

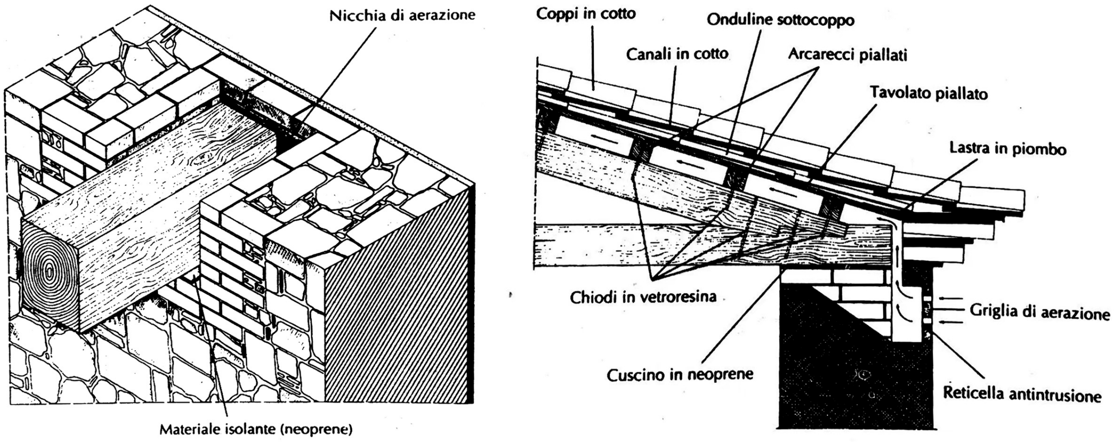


Figure 25: Air gap between tie beam and masonry wall. (Liotta, 1994)

3.4 Influence

With the "Grand Tour" started flourishing after the Renaissance and particularly in 18th century England, young scholars were traveling around Europe with Italy as a key destination. They focused on Greek and Roman history, art and architecture to study the cultural heritage from antiquity and Renaissance. Some researchers organized and published books and articles to spread Italian architectural knowledge, and some of the young architects from other countries in Europe also collaborated with local projects to achieve a comprehensive understanding of the construction techniques. Italian architecture had thus grown great influence through both indirect and direct ways of propagation among countries in Europe, especially in England.

From the map (see figure 26) of the route of the "Grand Tour" in Italy based on the book <Dictionary of British and Irish Travelers in Italy>, it could be seen that big cities like Rome, Florence, Venice and Naples were the focus of the visit. As the difference and area of influence of the Piedmont and Lombard/Roman framing have already been discussed above and based on the cities they visited during the Grand tour, a conjecture could be drawn that the Lombard/Roman roof frame might have a greater and wider influence in other countries. At the same time, the Piedmont roof frame was more of a local construction practice in the northwest part of Italy but also have some impact in the area of France and Switzerland which are at the borders with Italy.

Figure 26: Map of places visited by Grand Tourists (Ceserani et al, 2017)

While talking about the influence of Italian truss in other countries, the most well-known evidence could be the Wren and Jones's truss in England from 16 century to 18 century. Inigo Jones was one of the earliest groups of architects who brought Italian roof construction techniques to England and proposed a new way to build free-span architecture. Before that, most of the large span architecture in England still used post and lintel or arch structures, some examples of pitch roofs with truss structures were presented in south England but mostly used queen post truss. Jones learned from Palladio and Serlio's detailed drawings (Yeomans, 1986) and introduced the king post truss roof to achieve a large span distance with less heavy structure. Following the achievement of Jones, the king post truss was also the most used form in Christopher Wren's design. His works (see figure 27) were dedicated to further development and standardizing the king post truss structure but still used the Italian model (Campbell, 2002).

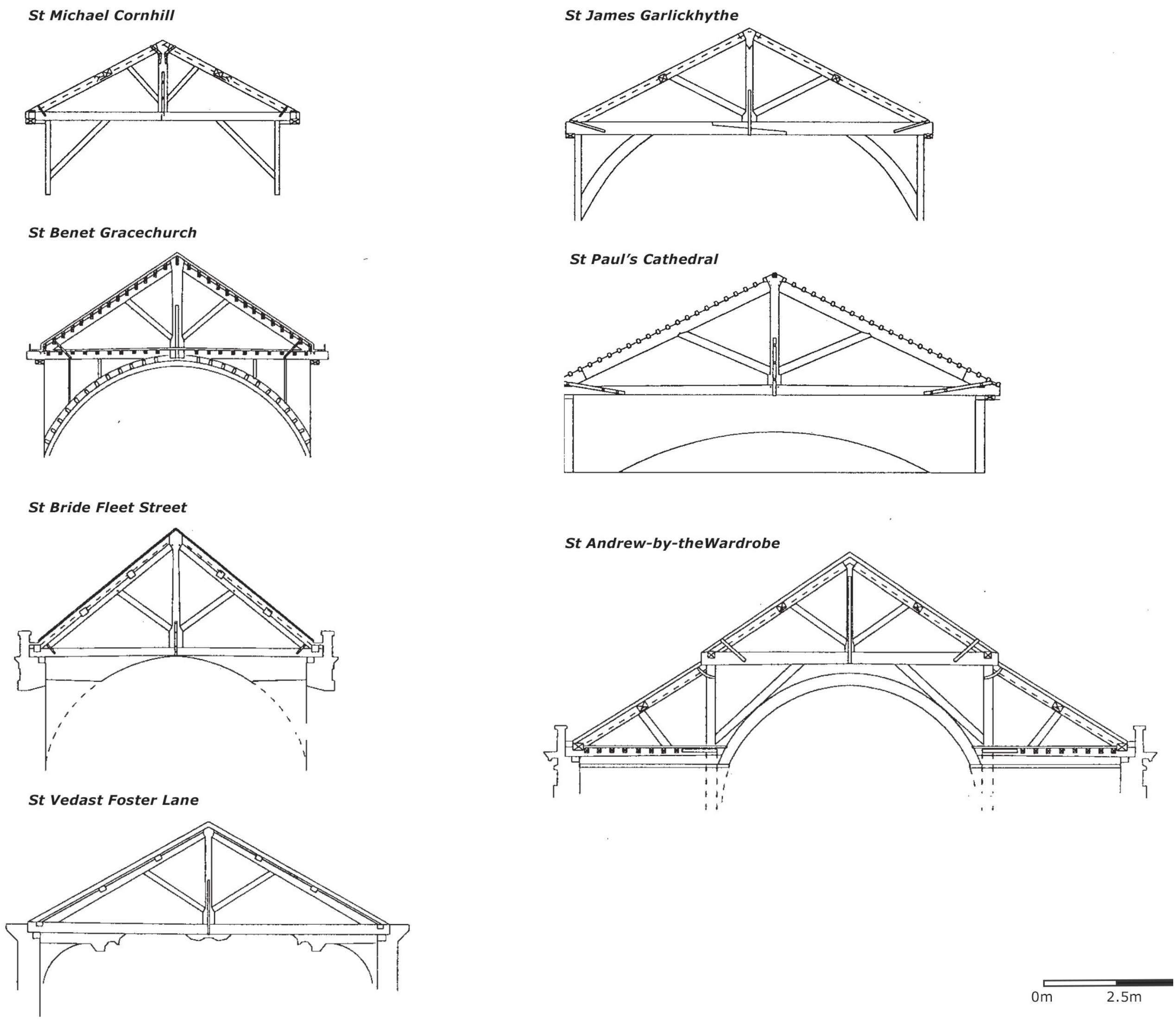


Figure 27: King post trusses in Christopher Wren's works (Campbell, 2002)

Another fact that could be observed from Jones and Wren's works is that the trusses used were mainly closed-joint trusses. As discussed before, the use of closed-joint trusses had already been reduced in Italy from the 16 century, whereas by the time when Jones and Wren traveled and studied the Italian truss structure there were still many closed-joint trusses presented, which led to both Jones and Wren's work used rigid connections between post and tie beam. Valeriani (2006) proposed that Jones's choice of closed-joint truss was based on his study of the bridge at Cismone from Palladio's book <*I Quattro Libri dell'architettura*>. From the detailed sketch (see figure 28) he left under Palladio's drawing it could be assumed that although in Palladio's original drawings he did not explain the joint detail between the king post and tie beam, Jones might have combined it with his own understanding of which the connection here was a closed-joint truss. Although here the case was a timber bridge, not a roof, it was still a meaningful analogy and showed Jones's interest in scrutinizing the connection between the post and tie beam (Valeriani, 2006).

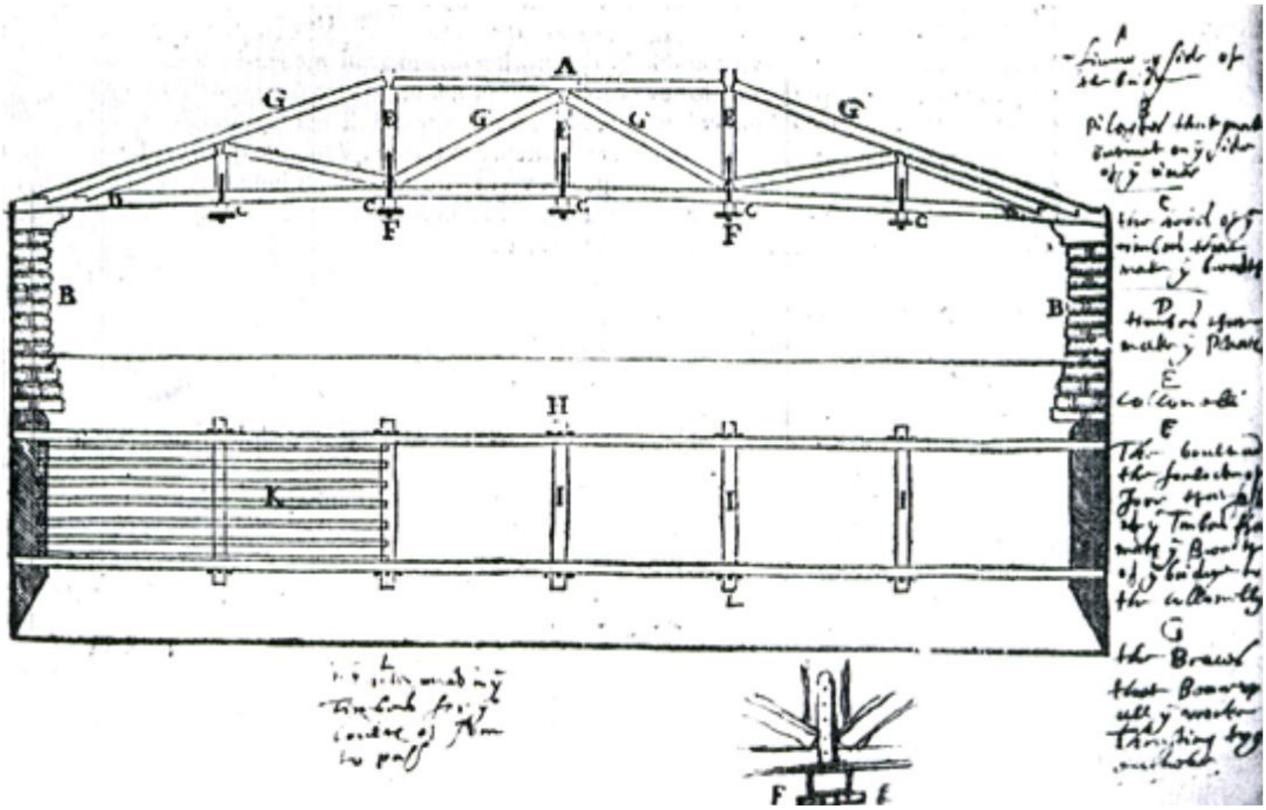


Figure 28: Inigo Jones's sketch (Jones [1573-1652] 1970, Book III, p.15) (Valeriani, 2006)

3.5 Case study

The Venice Arsenal built from 1104 was the largest industrial building group in Europe before the Industrial Revolution in which a large number of trading ships were produced. In 1258, it appeared the first document recorded that the Venice Arsenal become a state shipyard factory. Later in the 14 century, it was also used as a storage for timber materials (Dalla Costa et al, 1994). Until now, due to it large scale and historical value, the Venice Arsenal is still being used for exhibitions, museums and international events.

Since the building group had the initial function of constructing shipyards, lots of the buildings required long span roofs where the truss structure was more adaptable. Within the roofs in Venice Arsenal, different types of trusses were used according to the construction time from 1300 to 1900 (Menichelli et al, 2009) and the different spans needed; figure 29 shows the roof construction times and the identification of trusses.

Figure 29: Roof construction times and identification of trusses by G. Bettiol (Menichelli et al, 2009) (Bertolini Cestari and Marzi, 2018)

Thanks to the Venice government, over the last 30 years there have been lots of studies and conservation projects about the Venice Arsenal, especially the structure "*Tesa all'Isolotto*", the *squero* in which the shipyards were constructed. The "*Isolotto*" is composed of two connecting buildings, the main part was the northern extension of the New Arsenal (figure 30 in red) which is considered as the only existing evidence of the 14 century *squeri*. Menichelli wrote in the article (2009) that the roof of "*Isolotto*" was only built after the first half of the 14 century. The other part of the pitched roof of "*Isolotto*" was built by a series of trusses with struts that support a span of 18 meters while the other part (figure 30 in blue) presented both king post trusses and queen post trusses depending on the increasing spans. The trusses for this part of the roof ranged in size from 1 to 15 metres due to the triangle shape and they were made of materials left over from earlier constructions which was the most distinctive feature of this part of the building (Menichelli et al, 2009). It could be noticed that the "*Isolotto*" is the only building in the Venice Arsenal that used simple truss or king post truss, the rest buildings were constructed mostly with queen post trusses.

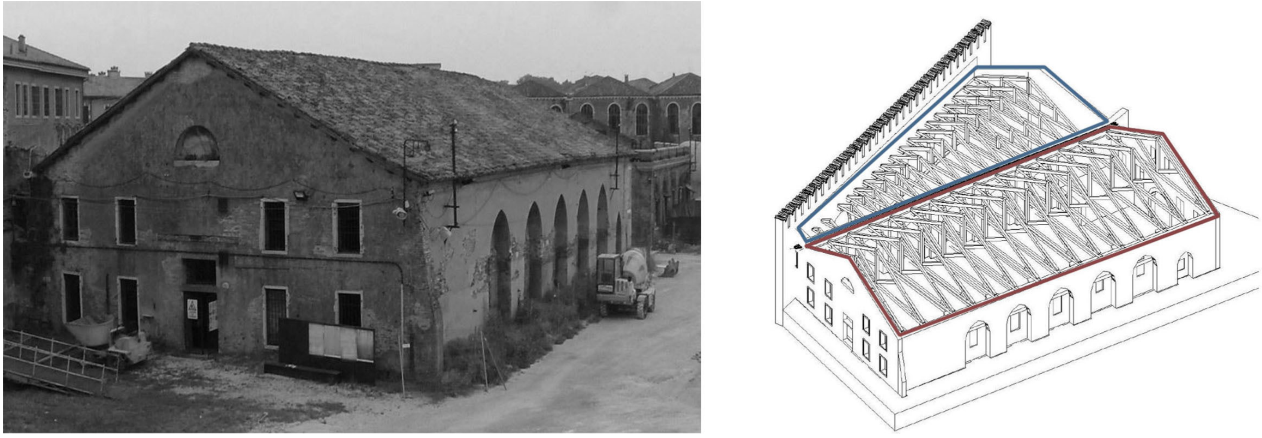


Figure 30: Photo(Menichelli et al, 2009) and axonometry diagram of "Isolotto" (original diagram from Soprintendenza Archeologia, belle arti e paesaggio per il Comune di Venezia e Laguna archive)

From the survey photos, it could be seen that the original trusses in "*Isolotto*" constructed during the 14 century were closed joints with tenon and mortise connection between the post and tie beam, which proved the previous discussion of the closed joint truss was widely used before the 16 century around the Veneto region. The "*Isolotto*" was not the only example that used closed joint trusses, they were used in most of the trusses used in the Venice Arsenal before the 19 century. In fact, during the 14 and 15 centuries, architects made the joints of the post and tie beam with both tenon and mortise connections and the U-shape stirrup, which could better hold the tie beam and prevent it from bending. In the 19 century, there were several interventions for the Arsenal and due to the high demand for construction in a short period, the tarusses were changed into open joint trusses as shown in figure 31 (Menichelli et al, 2009). This might further explain the reason why open joint trusses became more common than closed joint trusses in the 16 century, although the closed joint trusses have a good connection between the post and tie beam, with the node of tenon and mortise connection it required a lot of time and labours. With the rapid development of long span architecture in the 16 century, open joint trusses were easier and quicker to construct.

Figure 31: Survey photos (Menichelli et al, 2009) show the original connection of the post and tie beam (left) and the intervention of an open joint truss in the 19 century (right)

As Ferretti et al discussed in their article (2022), another building "*Gaggiandre*" which was initially built in the 16 century and further intervented during the 19 century also presented evidence of the change of truss from closed joint to open joint. "*Gaggiandre*", as described by Piana (1994), was one of the most important parts of the extension of Venice Arsenal during the 16 century. The original roof of "*Gaggiandre*" was constructed by queen post trusses with closed joint and covered a span of around 25 meters (Ferretti et al, 2022). Same as the case of "*Isolotto*", the intervention project of "*Gaggiandre*" during the 19 century also changed the queen post trusses here into open joint. Additionally, the intervention also added braces on the trusses (see figure 32) to reinforce the structure but with smaller (cross-section: 26cm x 20cm) elements compared to the original rafters (cross-section: 26cm x 35cm), posts and tie beams. Martini (1877) explained in his book that apart from the quicker construction, another reason for the intervention was that the bending of the tie beam was one of the major problems of the existing trusses. Especially due to the lack of protection technique for the wood species, tenons of the post to tie beam nodes were found decayed which further caused the failure of a rigid connection. Thus, the intervention cut the posts from tie beams, besides, after changing the truss from closed joint to open joint, the existing two posts could no longer support the rafters, so the secondary rafters and braces needed to be added.

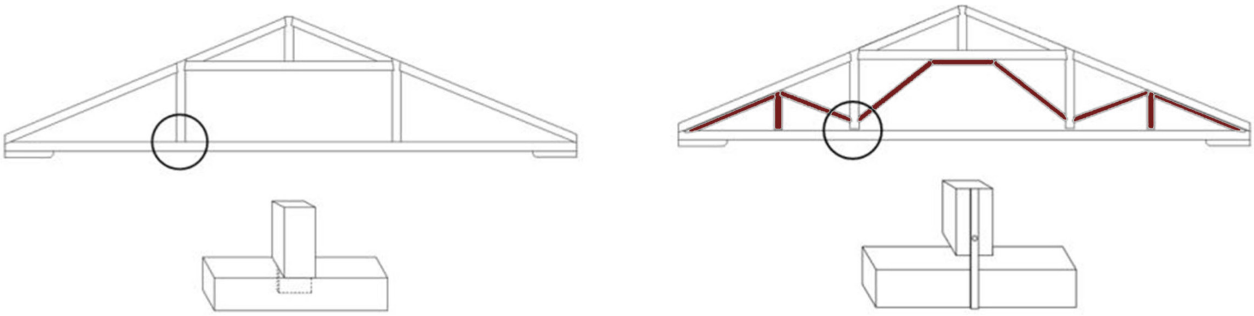


Figure 32: Left: original closed joint truss; Right: intervented open joint truss, the new elements highlighted in red (original drawing by Ferretti et al, 2022)

Another case within the Venice Arsenal could be the "*Corderie*" (see figure 33) which was first built in 1303 and rebuilt during the end of the 16 century, this architecture was used to construct anchor lines and their ancillary facilities for the shipyards. Two main architectural features of the "*Corderie*" are the huge masonry columns and the queen post trusses that cover a span of 21 meters.

According to Bettiolt et al's experimental test (2008), although the size and wood species of the tie beam in "*Corderie*" was the same as "*Isolotto*" (cross section: 32cm x 28cm, made by larch) it did cover a long span and had less risk of bending in middle due to the masonry columns as intermediate supports.

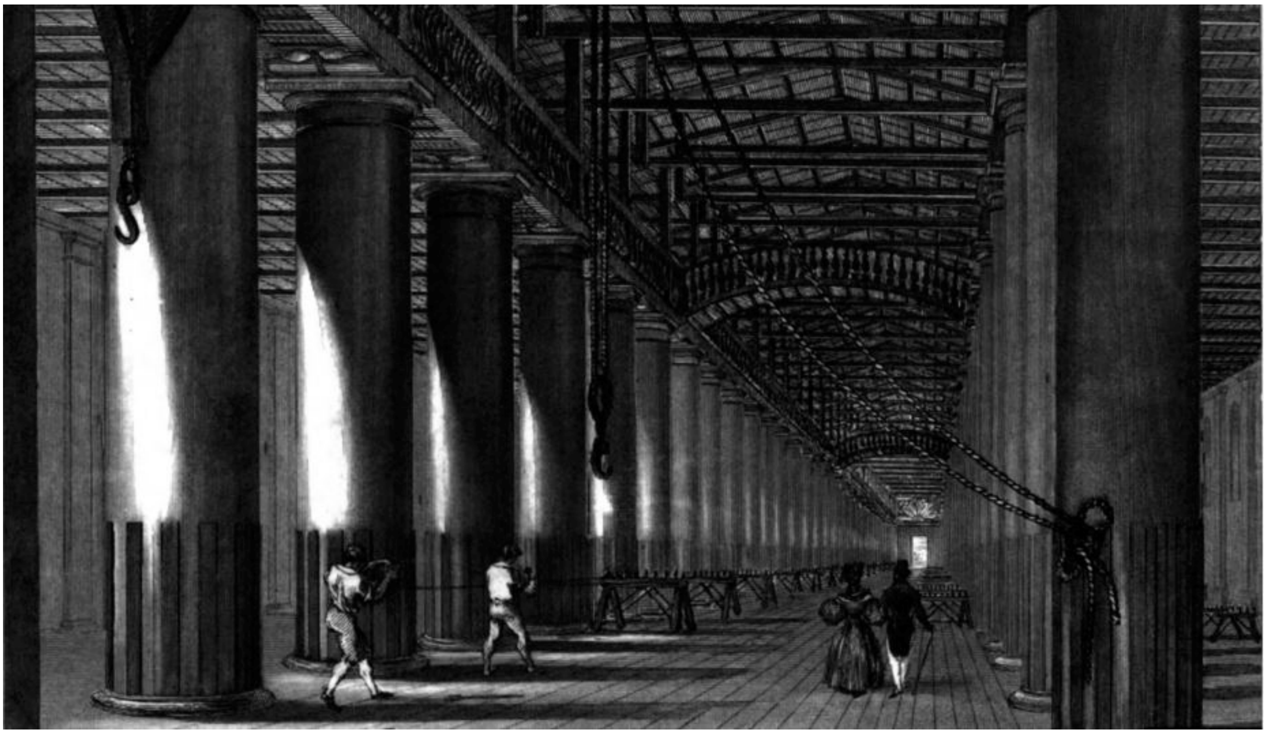


Figure 33: Perspective view of "Corderie" by Andrea Tosini and Antonio Lazzari in 1829 in Museo Civico Correr (Dalla Costa et al, 1994)

It is worth the mentioned the intervention and reconstruction of the trusses in "*Corderie*" during the second half of the 19 century. Apart from the basic form of the queen post truss, some evolution types were intervented in "*Corderie*" and other buildings, including the queen post truss with braces and the version discussed above in the "*Gaggiandre*". Further, following the industrial revolution, iron became a common material for construction. From the previous diagram, it could be seen that wooden trusses were mainly distributed in the northern part of the Venice Arsenal while the southern part contained more wood-iron trusses or fully metal trusses. Combined with the timing of the construction of the individual buildings, the reason for this division is due to the increase in span and the development of industry and technology. In the "*Corderie*" the mixed use of iron and timber was introduced from the late period of the 19 century, considering the different mechanical performances, iron was used for the elements that resist traction such as the tie beam; while timber was used for those that resist mostly compression. A modern type of truss - Polonceau (figure 34 left) which was constructed during the 19 century had only the rafters made of wood and all the rest parts were composed of iron (Menichelli et al, 2009). The Polonceau truss first designed by Camille Polonceau in 1839 was considered as one of the most successful roof structures of the 19 century (Putzolu and Bosch, 2018), a main feature within the Polonceau truss is the flexible connection between the iron ties and nuts to prevent trusses from sagging (Holzer, 2010). Right following the appearance of the poloncеau truss, the material changed from mixed-use to all metal which almost eliminated the sagging problem. Especially in some interventions during the late 19 century and early 20 century, the english trusses (*capriata all'inglese*) that consist of multiple posts and struts worked in compression and tension (see figure 34 right) (Menichelli et al, 2009). Apart from ensuring the function of supporting large spans, these new trusses were visually lighter than traditional wooden trusses which further made the roof space appear larger. Another feature might be the degree of the roof slopes which were made by english trusses was smaller, it is probably because the activities of shipyard production require more on the larger span so that the steep slope roofs were no longer necessary.

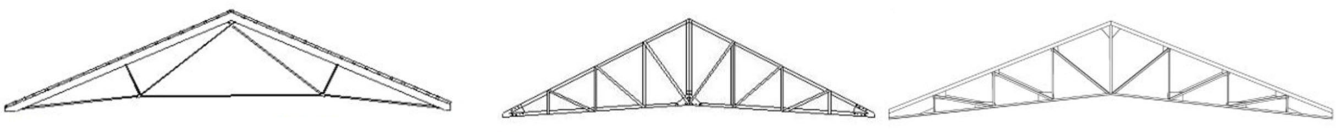


Figure 34: Left: Polonceau truss; Right: English trusses (Menichelli et al, 2009)

4. Timber roof in China

Wang, Mengxi. 千里江山图 *[Thousands miles of mountains and rivers]*. Northern Song dynasty.

Normally ancient Chinese architecture contains a platform, column-beam, dougong story and pitch roof. The platform base which is made of masonry and supports the whole house is located under the building; above is the main body, which is mostly built with wooden frames as the skeletons, with doors and windows and partitions installed in the middle; finally, the roof appears with the shape of elegant curves, covered with grey tiles or glazed tiles.

From the division of ancient Chinese architecture (see figure 35), roofs occupied a mass proportion of the architecture from visual and sensory points of view. Roofs have the leading role not only from the visual perspective, but the spatial design of ancient Chinese architecture also mainly depends on roofs. The design logic follows the order of first determining the form and size of the roof and then designing the beams and columns according to the roof, which means the roof has a restrictive effect on the overall space of the building. Besides, during dynasties the types of roofs refer to the classes of architecture directly, for example, the Hip roofs were mainly used for imperial palaces, so the Chinese roofs are also reflections of the culture and politics.

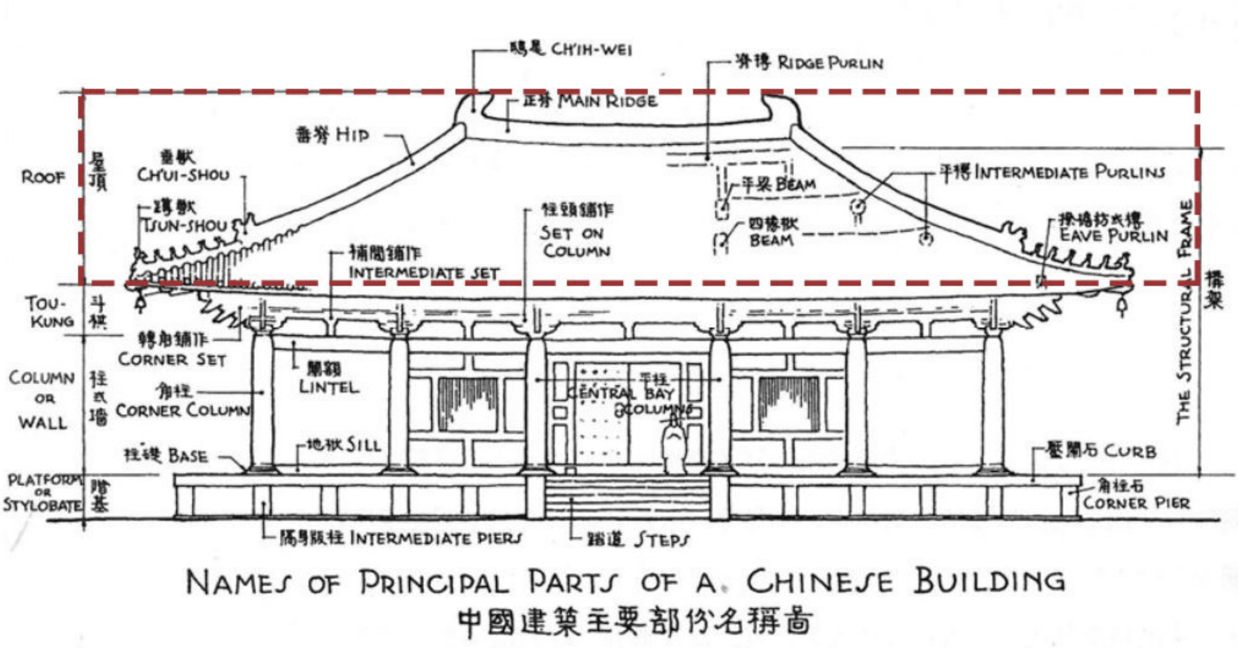


Figure 35: The construction system of traditional Chinese architecture (Liang[11], 1984)

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[11] Liang Sicheng (1901-1972), a Chinese architect and architectural historian. Liang had a great achievement on the surveys of ancient Chinese architecture and he also completed a series of book of the history of Chinese architecture using the modern architectural methods. In the meanwhile, he also had tremendous contributions in architectural education.

From the functional aspects, firstly, the mass roofs had the function as basic insulation for heat to maintain a suitable interior living environment. Overhanging is one of the main characteristics of ancient Chinese roofs. Apart from its function of beautifying the overall appearance, the shape was made also from the consideration of thermal insulation and sunlight shading. After the curved roof became the standard design, sunlight could be introduced inside at a maximum level (Figure 36 left).

The design of the overhanging roof was related to the altitudes of the sun. Taking the palace of the Forbidden City in Beijing as an example, the design goal was to keep direct sunlight outside to avoid the heat, especially at noon in the summer and to invite the sunlight in to gain maximum solar heat in winter (Hao, 2014). As figure 36 right shows the sun orientations at midday in the case of summer and winter, according to the changes in sun orientation, the direct sunlight reached only the outside columns on summer days so that the heat could be kept outside the hall; while in winter, the interior gradually receives light as the sun rises, the sunlight entered the inner wall of the room at noon to maintain the indoor temperature.

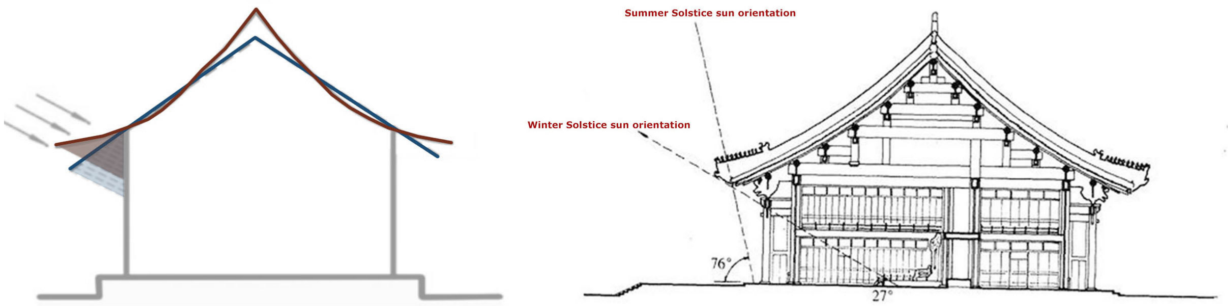


Figure 36: Left: Summer Solstice and Winter Solstice sun orientations; Right: Shadow area with different slopes of the roof

Another main function of ancient Chinese roofs was the drainage of rain. In "*YingZao-FaShi*" the logic of folded roof shape was called "*JuZhe*" (*举折*) (Lift fold) (see figure 37 left). Most ancient roofs had a folded shape which went from a larger angle to a narrow angle to use the steep slope to make the rainwater flow down rapidly and then use the inertia to let the rainwater rush out of the eaves. Throwing rainwater far away could effectively prevent rainwater from splashing on the wooden columns as well, which was conducive to the anti-corrosion of wooden structures (Li and Liu, 2017). Through the theory of the "Brachistochrone" curve in mechanics, for displacement between two points caused by gravity, the fastest path is not a straight line connecting the two points but a curve line. Although with the "*JuZhe*" method, the roof shape is formed with polylines, after tiling, the roof is very close to the curved surface. From figure 37 right, it could be seen that the curved shape of the ancient Chinese roof is very close to the "shortest speed line" which had better rain drainage rather than a straight pitch roof. The main aim of the "*JuZhe*" design is to have the shortest time of rainwater leaving the roof instead of having rainwater reach the farthest point from the cornice. Reducing roof rain load helps prevent rainwater from leaking or damaging the roof surface (Tang, 1996). Besides, most of the roofs of ancient buildings use glazed tiles. One reason for using glazed tiles is to prevent the roof from absorbing rainwater and increasing the load on the building, while another reason might be to reduce friction to let the rainwater fall faster.

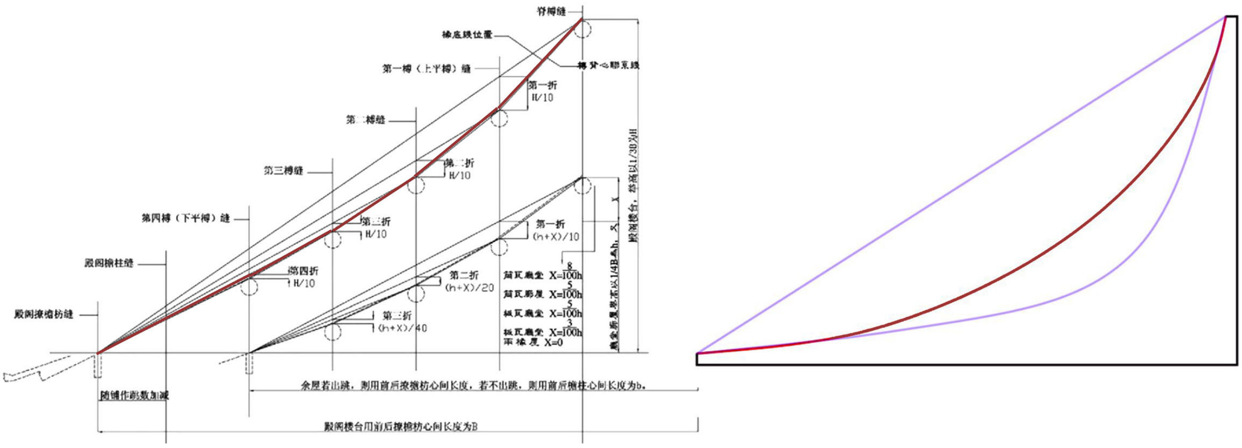


Figure 37: "*JuZhe*" system in <*YingZaoFaShi*> and "Brachistochrone" curve

For the function of roofs in the decorative aspect, the construction of ancient Chinese roofs had strict requirements of hierarchy, for instance, certain types could only be used for the royal family. The use of tile materials and decoration elements on roofs also had its own regulations. Therefore, the forms and structures of ancient roofs strongly reflected the order and hierarchy of the architecture. The roofs had schematized and standardized features. The roof types and their uses were divided by hierarchy grade as follows.

1. Double Eaved Hip roof (*重檐庑殿顶*): Main hall of important temples, Main all of palace.
2. Double Eaved Gable-and-Hip roof (*重檐歇山顶*): Palaces, Gardens, Temples.
3. Hip roof (*庑殿顶*): Other important buildings.
4. Gable-and-Hip roof (*歇山顶*): Other important buildings.
5. Overhanging Gable roof (*悬山顶*): Nongovernmental buildings.
6. Flush Gable roof (*硬山顶*): Nongovernmental buildings.
7. Curved Gable-and-Hip roof (*卷棚顶*): Nongovernmental buildings.

And finally the Pyramidal roof (攒尖顶)which is not graded: Pavilion.

Various types of roofs (figure 38) enrich the shape and outline of the building, hence the roof is also known as the fifth façade of ancient Chinese architecture (Liu, 1984).

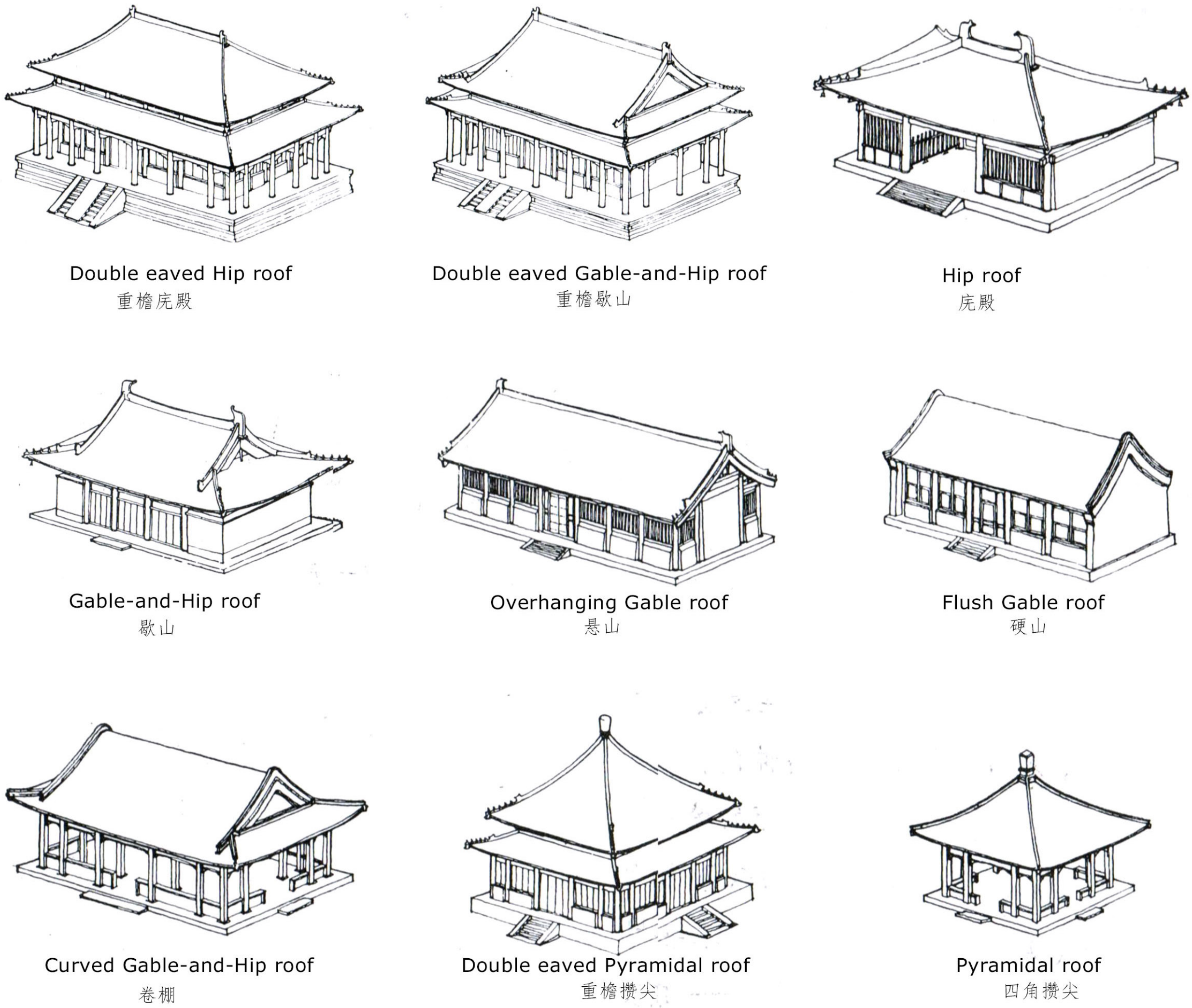


Figure 38: Traditional Chinese roof types

Structurally, a typical ancient Chinese roof transmits the force from top to bottom (see figure 39), and gradually disperses the force downward from the highest point of the roof in a triangle shape "Purlin-Dougong (if exists)-Beam-Column" from layer to layer.

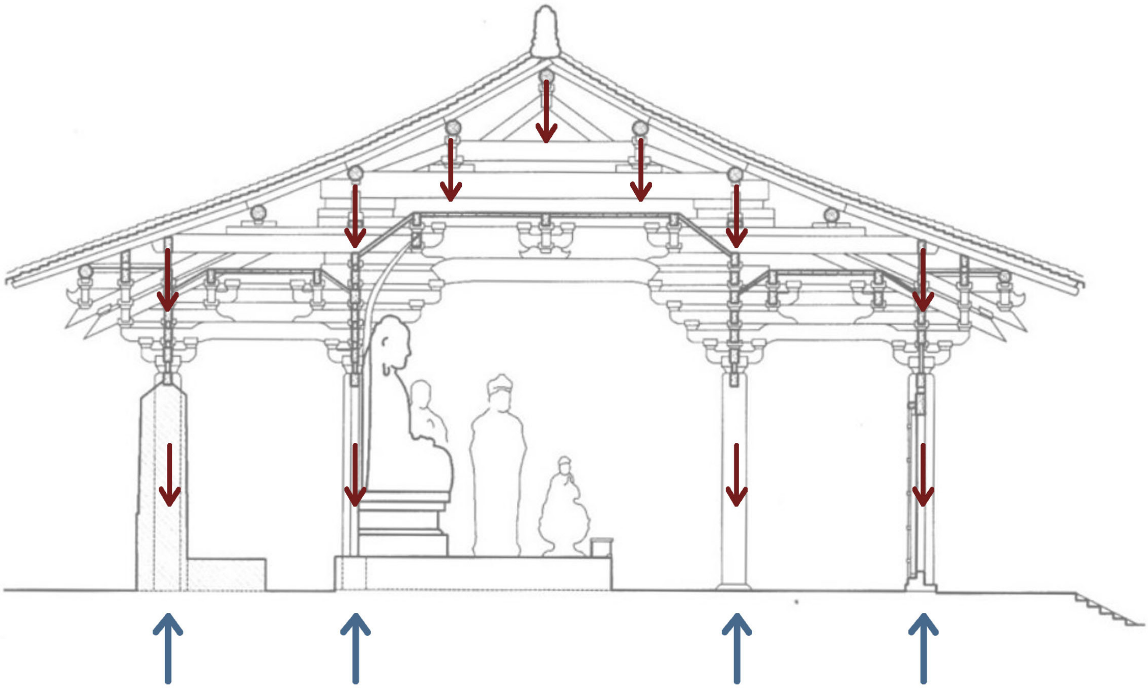


Figure 39: Transmission of forces within Chinese architecture, example of the main hall of Foguang temple

There are two main categories of the timber frame for Chinese roof construction. Firstly, the "*Chuandou*" (穿斗) system (see figure 40 left): In the *Chuandou* structural system, several layers of tie beams are tenoned through the pillars to join them together and the pillars support the purlins directly without the use of a bracketing layer.

> *"...Chuandou has a verbal connotation, referring to a particular procedure of construction. First, pillars of the truss-like framework perpendicular to the roof ridge are connected by the tenoning work of Chuan, and then multiple frames of different bays are interlocked parallel to the roof ridge by the work of Dou to form the whole timber-frame structure…" (Liu, 1980)*

In construction, the *Chuandou* system has the advantage of reducing the use of material, strong integrity and better resistance under earthquakes. But since its grid layout, this system was mostly used for houses. For larger scale architecture such as palaces and temples, the columns would block the interior space.

Another roof frame is the "*Tailiang*" (抬梁) system (see figure 40 right): A system in which beams are as structurally important as pillars and posts in supporting purlins. Literally[12], "*Tailiang*" means fitting beams on top of the pillars, and fitting posts on top

[12] In Chines, "*Tai*" (抬) means to raise and "*Liang*" (梁) means the beams.

the beams. Consequently, in this system, there are less pillars in the building interior which allows more free-space design. To further distinguish it from *Chuandou*, *Tailiang* is interpreted as a framing system in which beams are supported on top of the pillars, and purlins are extended across the beams. The *Tailiang* system was used more in palace and temple architecture to solve the problem of large spans. However, the *Tailiang* system required more materials. Compared with Italian roof construction, *Tailiang* is more similar to a truss system which reduced the use of columns and expanded the interior space.

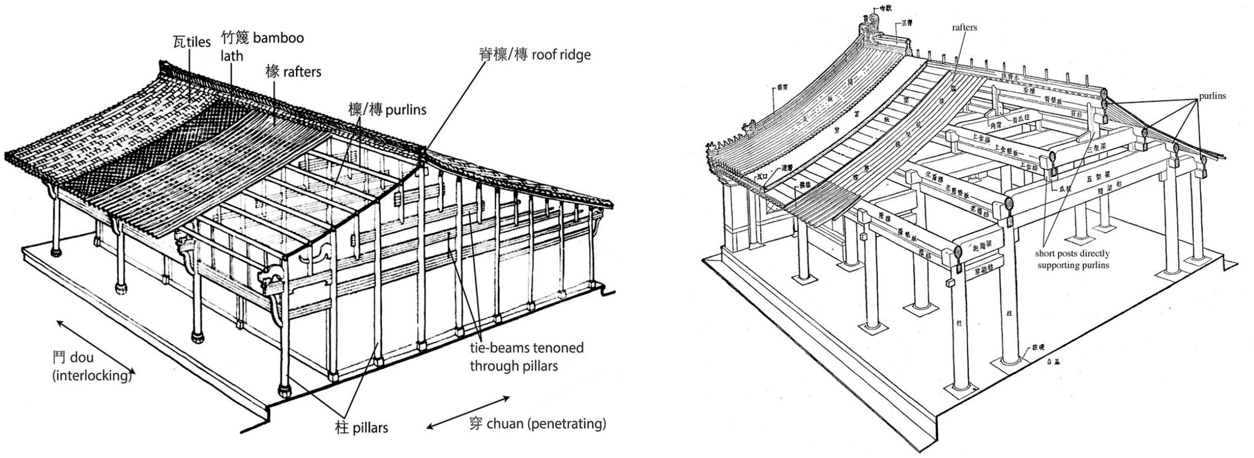


Figure 40: Left: *Chuandou* system; Right: *Tailiang* system (Liang, 2005)

5. Dougong

Dougong is the transition part between the roof and column-beam structure, where the load-bearing structures which extend above the column were called "*Gong*" (Arm) and the connection elements between Gong were called "*Dou*" (Bucket) (Figure 41). This structure has been considered both a forced structure and a decorative element. Structurally, Dougong has function as a joint between the roof and beam-column, the load from the upper part is transmitted to the lower parts of the architecture through Dougong. Aesthetically, with a well-organized shape like flower baskets, Dougong is a unique component of ancient Chinese architecture.

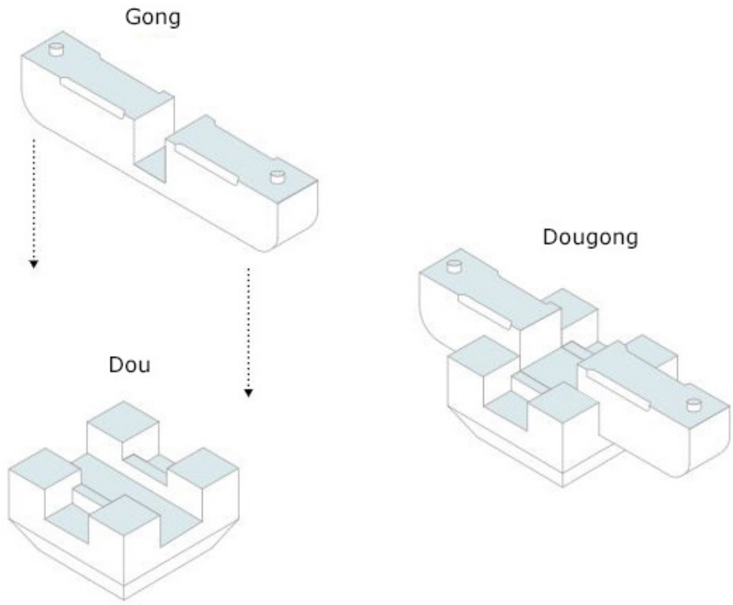


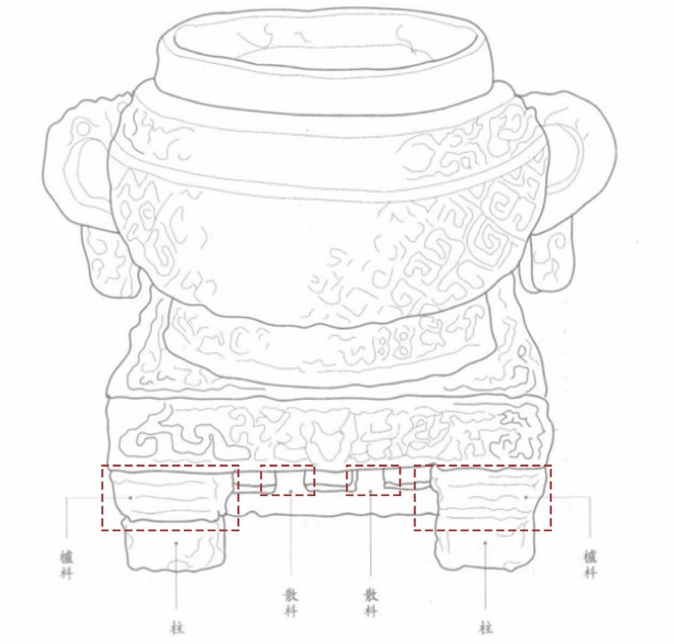
Figure 41: Components of Dougong

5.1 History of DouGong:

The Dougong structure has different names in different periods. For example, as recorded in the <*YingZaoFaShi*> it was called *Puzuo* (*铺作*) in the Song Dynasty. And it was not until the Qing Dynasty that this wooden structure was called "Dougong"[13].

Dougong structure was first realized during the end of the Shang Dynasty (circa 1046 B.C.) and the beginning of the Western Zhou Dynasty (1046 B.C. to 771 B.C.), the era when bronze wares flourished. Archaeological discoveries showed that the bronze wares of the Western Zhou Dynasty already had the shape of the component "*Dou*". A significant example is the Ce-Ling-Gui(*夨令簋*) (Figure 42). Since many architects and researchers (Pan, 2017) claimed that the partial appearance of the building could be reflected in the bronze ware of the same period. The foundation part of Ce-Ling-Gui

[13] In this thesis, hereinafter is collectively called "Dougong" as it is the most used name.

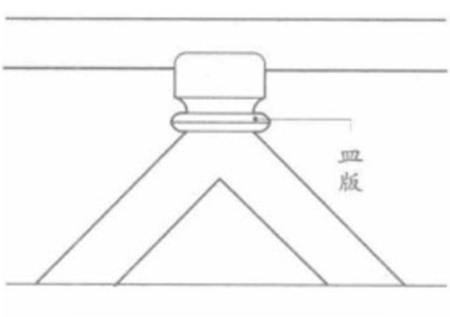


contains the same elements as Dou provided the proof that the use of "*Dou*" was dated back to the Shang and Zhou Dynasties.

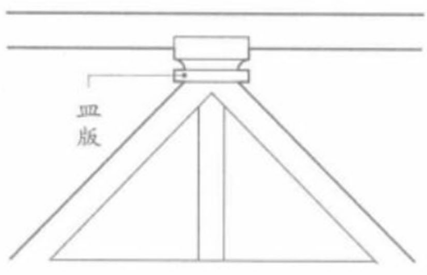
Figure 42: Components like "Dou" on bronze ware (Pan, 2017)

There are also a large number of elements of bucket arches on stone towers, bright utensils, portrait stones and portrait bricks from the Han dynasty (206 B.C. to 220 A.D.). In Han architecture construction, Dougong was mostly used on the top of columns or on the end of cantilever beams. During the Northern and Southern Dynasties to Sui Dynasty (420 A.D. to 618 A.D.), a great development of the Dougong structure was the "*Renzi Gong*"[14] (人字拱) (see figure 43) between columns. Seeing the cases of cave 9 in Yungang Grottoes (453 A.D. to 495 A.D.) in DaTong, ShanXi and cave 5 in Maiji Mountain Grottoes (around 600 A.D.) in Tianshui, Gansu, a development of "*Renzi Gong*" could be found as the diagonal elements changed to a curved form. Moreover, in Guyang cave in Longmen Grottoes (built from 493) in Luoyang, Henan, a column (like the "post" in truss) had been added in the middle of "*Renzi Gong*" to better support the bucket located on the top. There are also cases proving that "*Renzi Gong*" could be combined with another layer, for instance in cave 275 in Mogao Grottoes (401 to 439) in Dunhuang, Gansu. In this case, the "*Renzi Gong*" supported first an arm and then the upper structure.

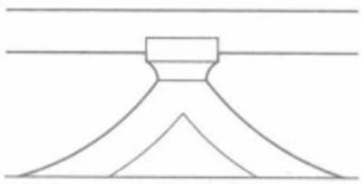
[14] *Renzi Gong* (人字拱): In Chinese characters, "人" means human. The *Renzi Gong* is a structure consisting of two diagonal elements and its appearance looks like the character "人" so that it was named after the character.



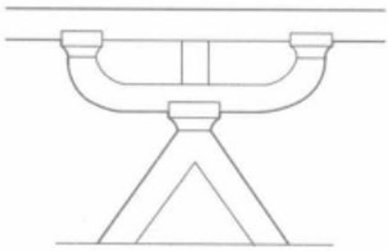
Straight *Renzi Gong* in Yungang Grottoes



Renzi Gong with “post” in Longmen Grottoes



Curved *Renzi Gong* in Maiji Mountain Grottoes



Renzi Gong combined with another layer in Mogao Grottoes

Figure 43: Evidence of “Renzi” Gong in Grottoes (Pan, 2017)

From the Tang Dynasty to the Song Dynasty (618 to 1279), the primary developments of the Dougong structure were increasing the eave's distance in order to construct larger roofs. Dougong had become part of the horizontal frame and maintained the integrity and stability of architectural frames. From the perspective of the proportion in the architecture, the Dougong built in the Tang Dynasty occupies the largest size of the architecture compared to the cases built in other dynasties. As the focus of development turned to structure and the production of Dougong began to produce a module system in this period, the size of Dougong had been increased while the complexity had been reduced, and some detail elements such as “*Renzi Gong*” were barely found after the Tang Dynasty.

The Song Dynasty had great development in the social economy, culture, handicrafts and commerce which made the architecture during the Song Dynasty reach a new level and made brilliant achievements. Since the Song Dynasty, with the improvement of wooden construction regulations and the publication of <*YingZaoFaShi*>, the production of Dougong then had strict regulations on system, grade, name, order and size. However, compared to the Tang Dynasty, Dougong was reduced in size but increased in number, which made the architecture contain a more aesthetic value. During the Northern Song Dynasty, the proportion of Dougong was reduced to only 2/7 of the column height.

Since the Song Dynasty, the real structural function of Dougong started to be reduced and the building techniques changed from simple to complex.

In the Yuan Dynasty, the Dougong bucket further shrunk in size and tended to become more of a decorative element so that the structural function was gradually weakened. During the Ming Dynasty and Qing Dynasty (1368 to 1911), the main function of Dougong has been transformed from structure to decoration and the use of the scale and form of Dougong has strict regulation according to the hierarchy (Pan, 2017). Over years of development, Dougong has been seen as one of the most obvious properties of Chinese architecture and an important element to identify ancient Chinese architecture.

In the developments of Dougong, Song style Dougong and Qing style Dougong are the two representative types (see figure 44) for contemporary research. Comparing these two types of Dougong, the primary difference is that Song style Dougong has more structural function while Qing style Dougong works more as a decorative element so both the size and complexity of Dougong were greatly reduced from Song style to Qing style, from figure 45 it can be seen the change of the proportion of Dougong and column. In this thesis, the following analysis will be based on Song style Dougong.

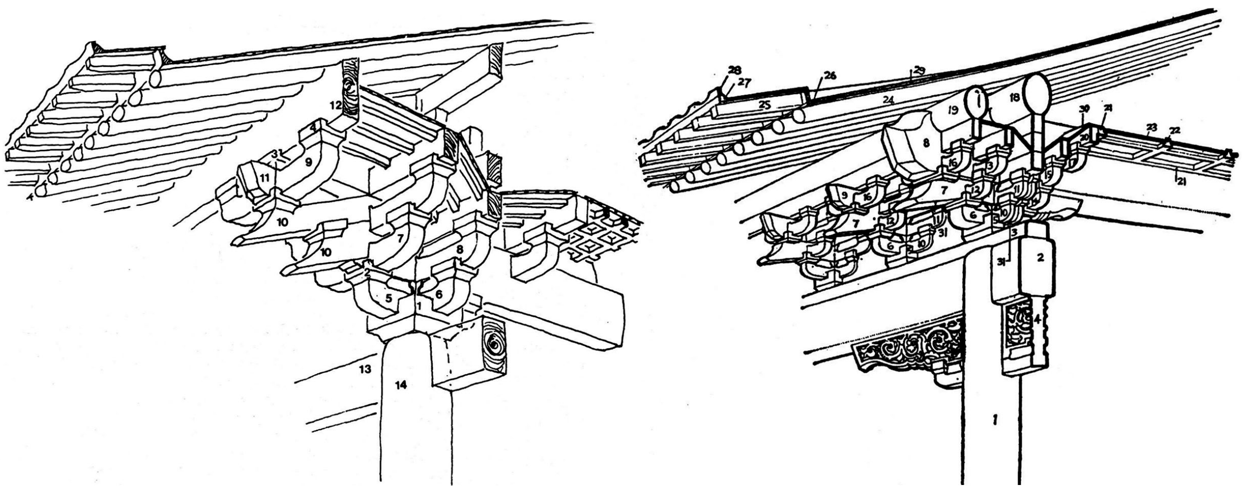


Figure 44: Comparison of Song style Dougong (left) and Qing style Dougong (right) (Liu. 1984)

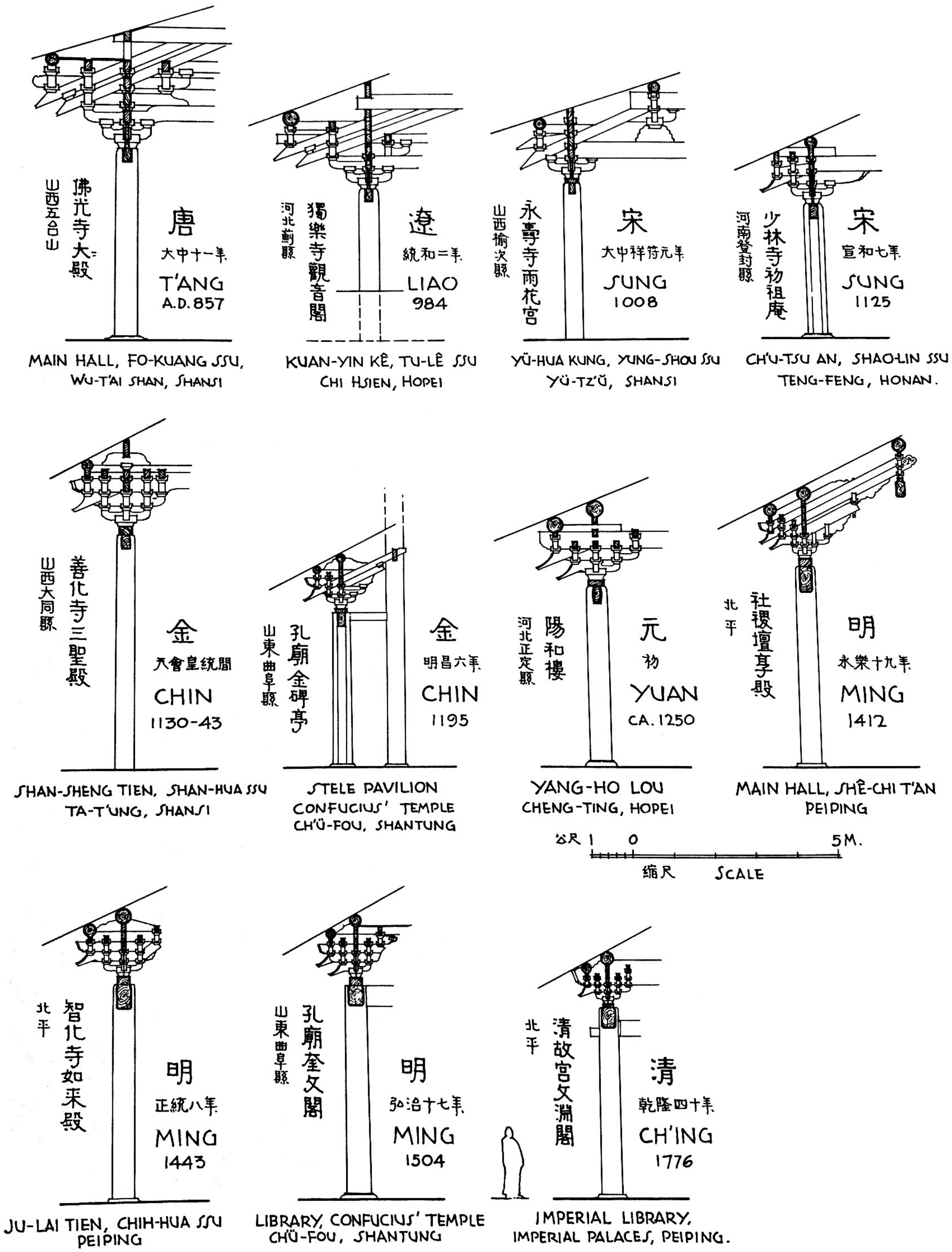


Figure 45: Change of proportion of Dougong over dynasties (Liang, 1984)

5.2 Classification of Dougong:

The classification of Dougong based on the part it presents in the architecture could be divided into two main categories: “Outer eaves Dougong” (外檐斗拱）)(eg: p1,p2 in figure 46 right) which present on the eaves of the building; “Inner eaves Dougong” (内檐斗拱) (eg: p3 in figure 46 right) which located in the inner eaves of the building, its main function is to support the ceiling or become the joint of beams (Pan, 2014).

Further, according to the position of Dougong and columns, the group of “Outer eaves Dougong” (figure 46 left) is classified as:

1. “Column Dougong” (柱头斗拱): Sit directly on the column (eg: p1). It is the main structure to support the weight of the eaves.
2. “Dougong between columns” (补间斗拱): The one on the forehead plate or slab in between two columns (eg: p2). which is an auxiliary support.
3. “Corner Dougong” (转角斗拱): On the corner column (eg: p4). It is also the main structural component that supports the corner beam.

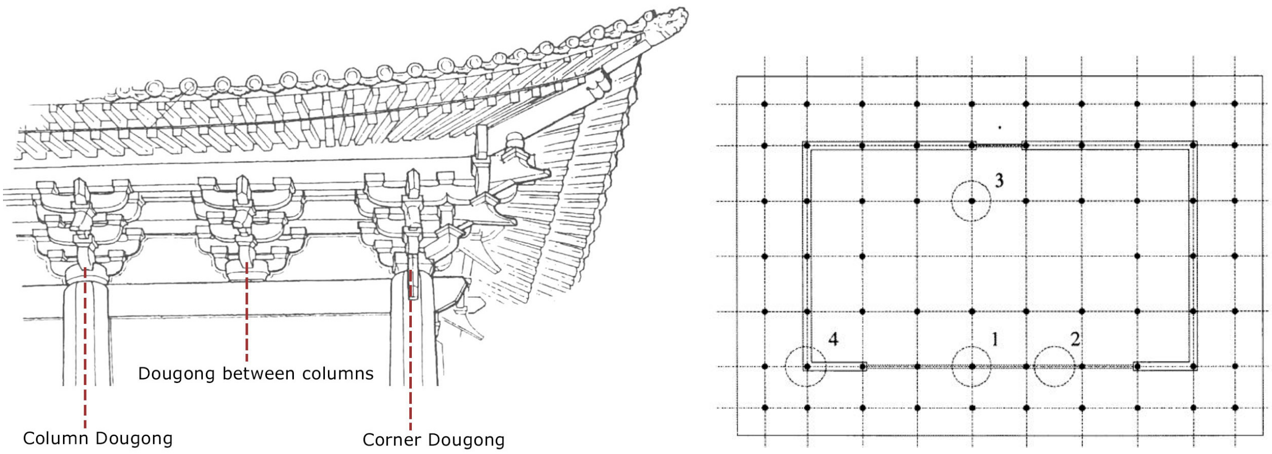


Figure 46: Classification of Dou Gong

To classify the Dougong, it is also important to know the scale. The basic unit is repeated many times along the horizontal lines. A long transverse Gong intersects the units and joins them in their entirety. The units may be used in successive tiers, each extending front and rear a certain distance beyond the tier below. Such a tier and extension is called a “Jump”. Generally, a set of dougong structures can have one to five jumps. In the <*YingZaoFaShi*>, Dougong is called “x Puzuo” in which x is a number, x=total jumps+3. So the rank of “Puzuo” ranks from four to eight.

5.3 Components of Dougong

The basic Dougong is consist of the following components by layers (see figure 47)

Dou(斗): Bucket.

1. Lu Dou (栌斗): the base of the bracket set, supporting the full weight of the set. Sitting on a column and connecting the bracket set with the main body of a building.
2. Jiaohu Dou (交互斗): The connection bucket sits on the end of the cantilever.
3. Qixin Dou (齐心斗): centre block sits on the centre of a longitudinal arm.
4. San Dou (散斗): small block sits on the ends of a longitudinal arm.

Gong(拱): Arm.

1. Hua Gong (华拱): the lowest longitudinal arm which sits on Lu Dou. Its length varies according to its position in the bracket because it may be used in successive bracket bays, each extending front and rear a certain distance beyond the tier below. It makes the cantilevered eaves possible.
2. Nidao Gong (泥道拱): the lowest longitudinal arm which sits on Lu Dou, perpendicular intersection to Hua Gong.
3. Guazi Gong (瓜子拱): A longitudinal arm sits at the end of the bucket of Hua Gong or an Ang but below the Ling Gong.
4. Ling Gong (令拱): The highest arm in the bracket set. It sits on the end of the bucket of Hua Gong or the Ang and supports the eaves purlin.
5. Man Gong (慢拱): all the other arms in the bracket set except the arms mentioned above.

Ang(昂): Cantilever.

Another transverse component in the brackets is "*Ang*". A long, slanting arm that the cantilevered eave is parallel to. The purlin of the eave is supported cantilever by the Ang. The weight of the next higher purlin on the cantilever's tail balances off the weight of the eaves.

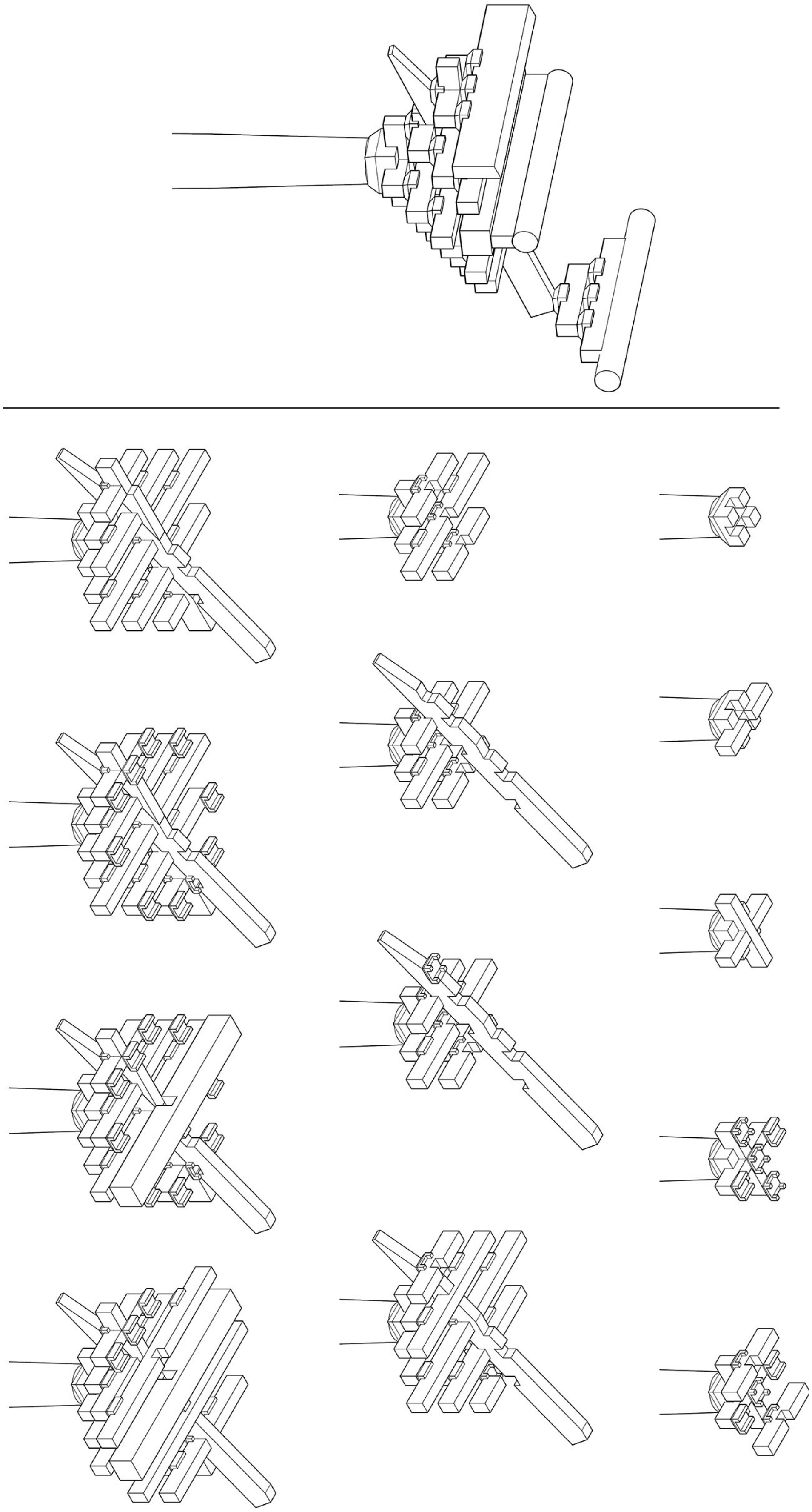


Figure 47: Consist of Dougong

5.4 Function of Dougong:

The Song style Dougong had more structural functions rather than aesthetic functions such as load transmission, increase eave distance and so on. There are five main functions of the Dougong structure:

1. Linking up the roof and beam-column by conducting the force.
Following the force path of "roof-dougong-beam-column-foundation", in which the weight of the roof compresses the Dougong and distributes the weight evenly throughout this structure till the foundation. The multiple brackets are interlocked which enhances the integrity of the whole structure and also prevents each element from cracking. A set of Dougong structures formed by several "*Gong*" cross stacking on each other and connected by different types of "*Dou*". "*Dou*" and "*Gong*" components are connected by "Sun-Mao" joints, which protect the Dougong structure from claps or shaking. The load transferred from the mass roof goes layer by layer through Dougong and absorbs part of the force during this process.

2. Increasing the eave distance.
In ancient China, roofs tended to be constructed larger to protect the lower structure like columns and the foundation from rain and snow. Dougong supports the overhanging roof by expanding in the horizontal direction, in which the component "*Ang*" plays a leverage role, utilizing the weight of the internal roof structure to balance the weight of the overhang part of the roof (Liang, 2005).

3. As a scale to measure the "size" of architecture (Feudal hierarchy).
In ancient China, apart from structural elements, dougong was also used as a measurement of hierarchy. During the Song Dynasty, the cross-section of "*Gong*" is considered the basic unit of measurement. Each type of building such as palaces, ritual architecture, temples etc. has strict regulations on which type and size of Dougong it should use which further determines the scale of architecture. Based on the modularization of the dimensions of each part of the building, the basic forms of components also have been finalized. Therefore, each component can be processed and assembled at the same time during construction, which greatly reduces the construction time (Pan, 2014).

4. Protecting architecture from calamities.
Dougong as the structure consists of both vertical and horizontal stacks that are inserted in between the roof and beam frame which increase the degree of elasticity of architecture. This type of structure has the ability to resist seismic waves from both vertical and horizontal directions and improve anti-seismic performance. The connection between the roof and column-beam layer is not a rigid connection since the Dougong bucket converts the kinetic energy in the horizontal direction into the gravitational potential energy in the vertical direction through squeezing, rubbing and friction, and then offsets it through friction.

5. Decoration
The decoration elements could be enriched by using different shapes, scales and colours of the buckets. In feudal Chinese society especially during the Ming and Qing dynasties, one of the important symbols of the feudal hierarchy is Dougong, the use of Dougong in buildings represents the level of the building.

5.5 <YingZaoFaShi>:

Due to the uniqueness of ancient Chinese construction techniques and the difference in language and measurement, it is important to study the rules before studying the history of Chinese architecture (Liang, 1984). There are 2 books which were considered the grammar books of Chinese architecture, *<YingZaoFaShi>* in the Song dynasty and *<GongChengZuoFaZeLi>*[15] in the Qing dynasty.

<YingZaoFaShi> (*营造法式*) was published by the Office of Construction in 1100 during the 3rd year of the North Song dynasty. With the rapid development of cities, the country has been carrying out major construction projects of palaces, government offices,

[15] *<GongChengZuoFaZeLi>* (*工程做法则例*), published in 1734. Contains the building construction examples and limitation of material quantity. It was the official architecture regulation book in the Qing dynasty.

temples, and gardens. In order to solve the issues of local officials misusing powers and the construction managers corrupting large amounts of money. This architectural and construction standard was formulated, which regulates the design scale of different types of architecture, the use of materials and the construction quota. <*YingZaoFaShi*> was the first building standard in Chinese history which also recorded the building techniques of the time. Although at time that <*YingZaoFaShi*> was published it was only a manual book for the construction, it has become the most important reference for the research and study of the history of Chinese architecture.

From the <*YingZaoFaShi*>, the architectural unit during the Song dynasty is called "*Cai*" (材) (see figure 48). The standard unit of "*Cai*" is a cross-section of "*Gong*" that is 15 "*Fen*"(份) and a full unit is 21"*Fen*". The Song dynasty carpentry module system was called "*Cai-Fen*" (材份制). However, the value of "*Cai*" was not fixed. Buildings were divided into 8 grades and each grade had its value of "*Cai*". According to the Song dynasty's construction regulation, the drawings listed only "*Cai-Fen*" numbers instead of actual sizes in order to be reused for other buildings in different grades. One important fact to be noticed is that the ratio of the height and width of "*Cai*" is always 15:10.

Although the <*YingZaoFaShi*> specified "*Cai-Fen*" as the basic unit of construction drawings, it was already first used in the Tang Dynasty. From the survey of the main hall of Nanchan temple (782) and main hall of Foguang temple (857), the "*Cai-Fen*" module had already been used. From this, it can be speculated that at the earliest in the early Tang Dynasty (early 7th century), the "*Cai-Fen*" module had been formed.

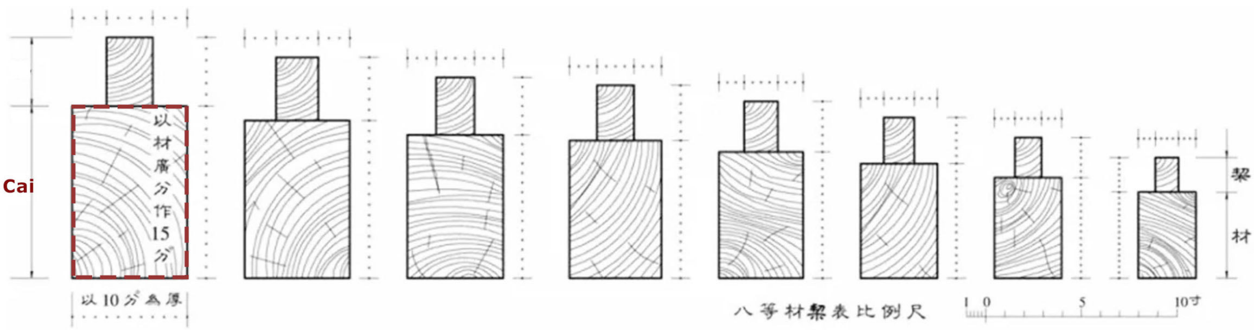


Figure 48: "*Cai Fen*" module system

Table 1 shows the calculation between Song scale to centimetres. The Song scale is the actual unit during construction (1 Song scale = 32 centimeters). "*Cai Fen*" system is the architectural unit, the number which is marked in "*Cai Fen*" has to be further calculated in the Song scale which is the actual unit for construction. The different units were used according to social position, and the number of units grows from officials to the emperor (Koolhaas et al, 2018).

Grade	Fen		Cai=15 Fen	
	In Song scale	In Centimeter	In Song scale	In Centimeter
1	0.060	1.920	0.900	28.800
2	0.055	1.760	0.825	26.400
3	0.050	1.600	0.750	24.000
4	0.048	1.536	0.720	23.040
5	0.044	1.408	0.660	21.120
6	0.040	1.280	0.600	19.200
7	0.035	1.120	0.525	16.800
8	0.030	0.960	0.450	14.400

Table 1: Calculation between Song scale to centimeter

The wooden frame is the skeleton of ancient Chinese architecture, it is also the primary factor to constitute the space and volume. Therefore, the study of the wooden frame could be seen as a key to understanding ancient Chinese architecture. Compared with other dynasties, the existing buildings from the Song dynasty and Liao dynasty havea big vacancy, so that the studying of the detailed description of timber construction in <*YingZaoFaShi*> has useful value for filling the gaps in existing buildings. However, due to political reasons, most of the examples in <*YingZaoFaShi*> were palace architecture or Buddhism and Taoism temple architecture which require the research to be combined with the built architecture of the period. Following are several architectures that were built around the same period of <*YingZaoFaShi*> which could help to understand this manual and the real timber construction at the time.

5.6 Case studies:

Foguang temple is an essential example of Chinese temple architecture, it is also a symbol of the inheritance and development of Chinese Buddhist culture. Its architectural structure, spatial design and decoration techniques are unique, which not only shows ancient Chinese aesthetics but also reflects the high level of construction techniques at the time. Especially the main hall (see figure 49) of Foguang temple (857), it is the oldest existing wooden structure in China. Foguang temple is also one of the most typical representations of ancient Chinese timber construction for the following research. Due to its construction period being very close to the publication of <*YingZaoFaShi*>, Foguang temple has been considered as a lively explanation of <*YingZaoFaShi*> together with the Dule temple[16] (984) and Yingxian Wooden Pagoda[17] (1056).

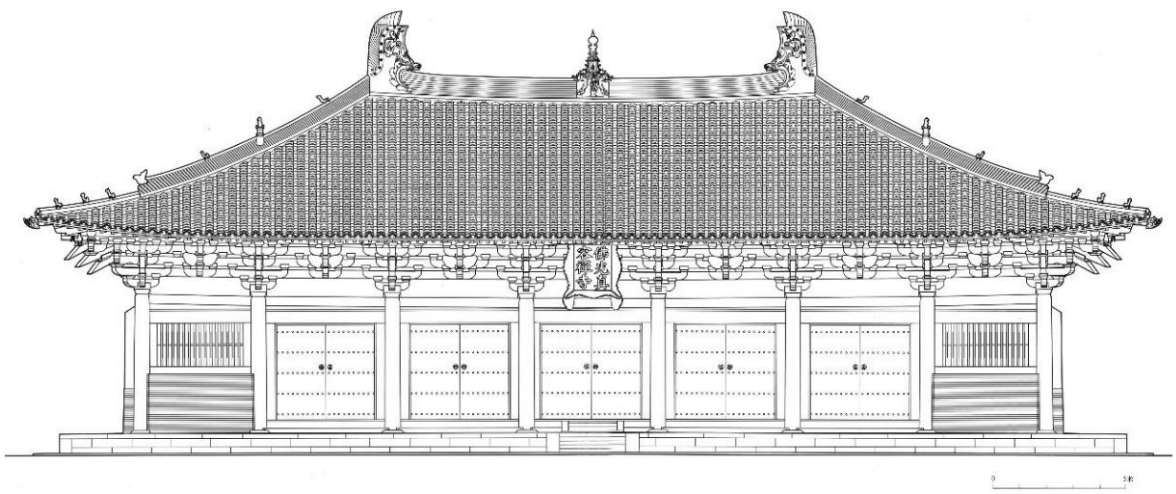


Figure 49: Elevation of the main hall of Foguang temple (Liang, 1984)

The main hall of Foguang temple was first built as seven bays (34.02 meters), three stories and 29 meters high hall, unfortunately, only one story has remained till now (Liang, 1984). Same as the Yingxian wooden pagoda, the primary wood species used for columns and beam were larch (Fu, 2012). The design and construction of the hall referred to the regulations of the official temple construction at that time and it is the representative work of the Tang Dynasty wooden architecture. From a structural point of view, the main hall has such an important value because of 3 parts: Dougong, Space

[16] Dule temple: one of the most important architectures during Liao dynasty, according to Liang's survery in 1933 for the Guanyin hall in Dule temple, it was discribed as a highly standardised design.
[17] Yingxian Wooden Pagoda: the oldest existing wood tower that contains 54 types of Dougong which made it seen as one of the best representations of ancient Chinese timber construction.

and Roof Structure. The combination of these three aspects also highlights the mature wood structure technology during the Tang dynasty.

Talking about the roof structure, the main hall of Foguang temple showed the only existing evidence of using “rafter”[18] without a “king post” to support purlin (see figure 50). In Liang’s surveys (1944), he recorded that seeing from lots of architecture from the Liao dynasty to the Qing dynasty, the use of “rafter” was always combined with “King post”. While at the main hall of Foguang temple, six pairs of “rafters” were found without “king post” during the survey. Liang named the hall as “rational architecture” in his note since it reflected structural rationalization.

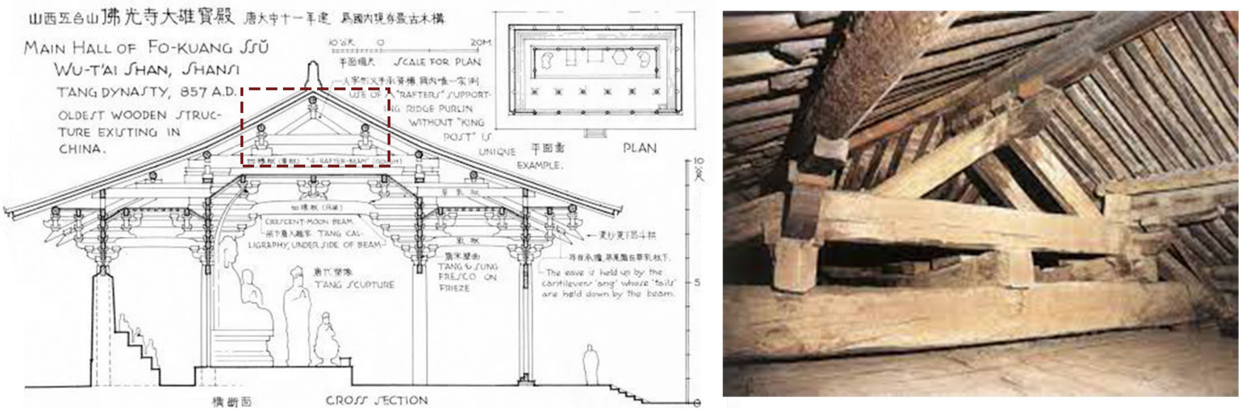


Figure 50: Section and photo of the “rafter” on the roof of the main hall of Foguang temple (Liang, 1984)

Another unique feature of the main hall is the use of the highest rank of Dougong. In <YingZaoFaShi>, Dougong was ranked from one jump to five jumps while till now there is no evidence to confirm the existence of the five jumps dougong. The column Dougong in the main hall of Foguang temple contains the four jumps Dougong thus reflecting its high value in Buddhist architecture at times. The four jumps Dougong on the inner columns have two Ang and two Hua gong (see figure 51) which double the height compared with other dougong used in the main hall. Observing the layout of ancient Chinese architecture, most of the halls, palaces and pagodas contained a main interior central space and an outer space[19] around it.

[18] Here the “rafter” is not the same as the rafter in a truss structure. Liang explained in his book (1984) that the triangle formed structure looks similar to a simple truss from the appearance, however, the method of load path was completely different. In fact, this particular structure is called “叉手” in Chinese (similar to “*Renzi Gong*” above), but since there is no exact translation in English, Liang wrote “rafter” as the English version in his book. Same for “king post” (“蜀柱” in Chinese).

[19] These two space is called “内槽” and “外槽” in Chinese.

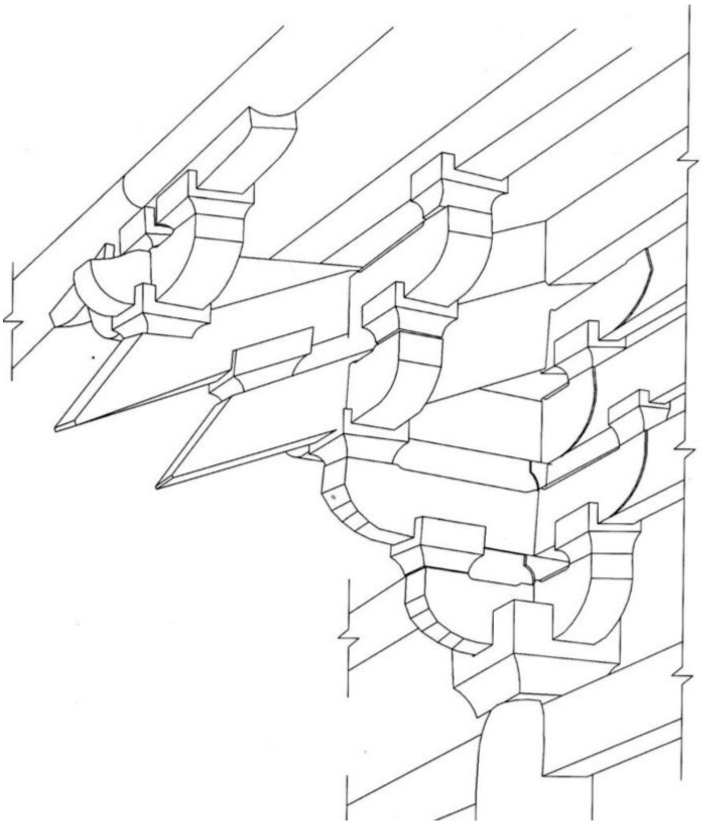


Figure 51: Four jumps Dougong on the inner columns with two Ang and two Hua gong (Pan, 2017)

Normally, the inner space was designed to place the Buddha statue while the outer space was for people's activities. The structural connection between these two spaces could strongly affect the integrity of the whole architecture. In Buddhist temples, normally the height of the inner space is greater than the outer corridor in order to highlight the Budda statue. The common design was to create this height difference by using columns with different heights, however, together with the Hualin temple, the Foguang temple was one of the only two existing examples which used columns of the same height for both inner and outer columns (figure 52) and meanwhile increased the number of jumps for the Dougong towards the inside on the inner column. It could be conjected that this different method to design the space on one hand followed strictly the palace structure order[20] to make sure the columns have the same height, on the other hand, by further increasing the size and rank of the Dougong it also shows the statement of the architecture.

[20] Palace order structure (殿堂) is a type of Tailiang system roof, in which all the columns have the same height and then adjust the different types of dougong to then form an inclined space as the roof. The other order is called hall order (厅堂), in which the columns have different heights and directly correspond to the roof. In ancient Chinese architecture, palace order can only be used for empire architecture or public architecture with high grades while hall order was commonly used for residential buildings.

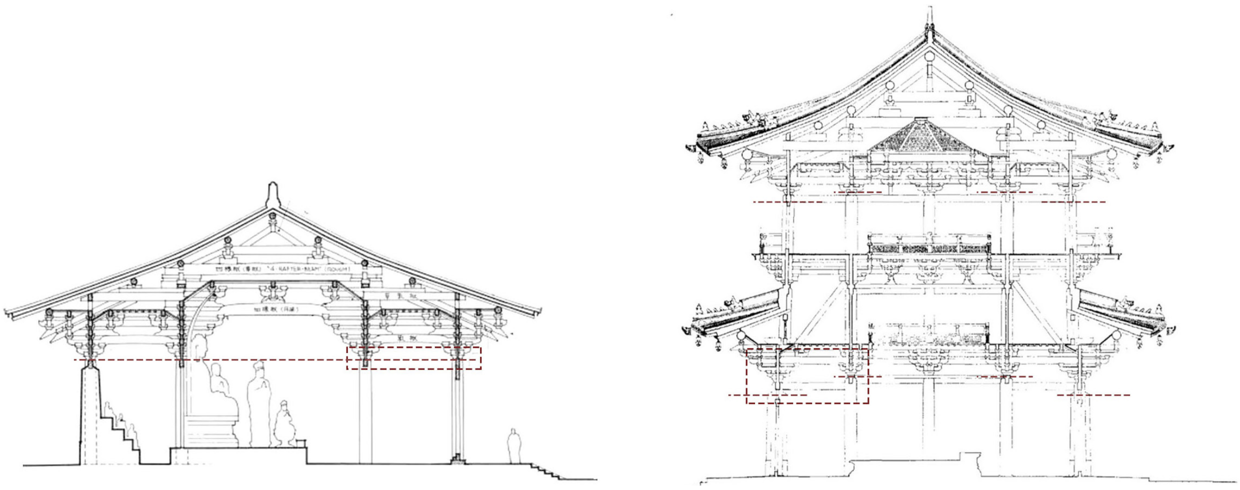


Figure 52: Comparison of the height of the outer column and inner column of the main hall of Foguang temple (left) and the Guanyin pavilion of Dule temple (right)

Foguang temple has also become a great example for researchers to study how to create a “perfect” interior space (Liang, 1944) using the combination of Dougong and columns. From the construction perspective, Foguang temple strictly followed the palace structure order in which the architecture could be horizontally divided into layers of column grid - dougong - roof. In the column layer, an ideal palace order would have both interior columns and exterior columns at the same height to create a horizontal surface for the dougong layer (see figure 53) which was just the same as the main hall of Foguang temple.

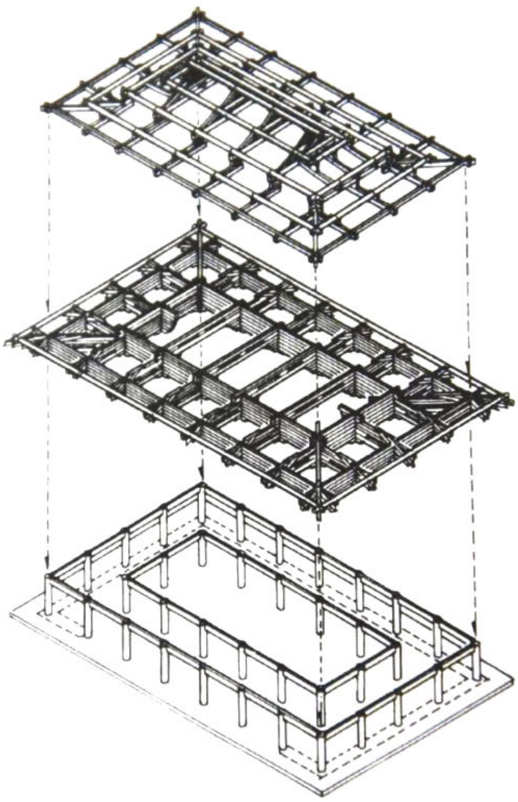


Figure 53: Axonometry diagram of a palace order architecture

Compared to the architecture that composed of inner columns and outer columns with different heights, the inner columns within the main hall of Foguang temple resist less compression from the roof. Furthermore, the Dougong on the inner columns and outer columns could be better connected. In ancient Chinese architecture, adjusting the heights of dougong and columns can be used to achieve a continuous interface. A continuous interface could be considered as a visual surface that consists of the same elements and it could also improve the structure performance if this interface is horizontal (Wen, 2014). For instance, as figure 54 shows the Linggong (in blue) of both the outer column dougong and inner column dougong could be linked at the same level and the beam (in red) above is also horizontal. This could greatly improve the integrity and stability of the structure.

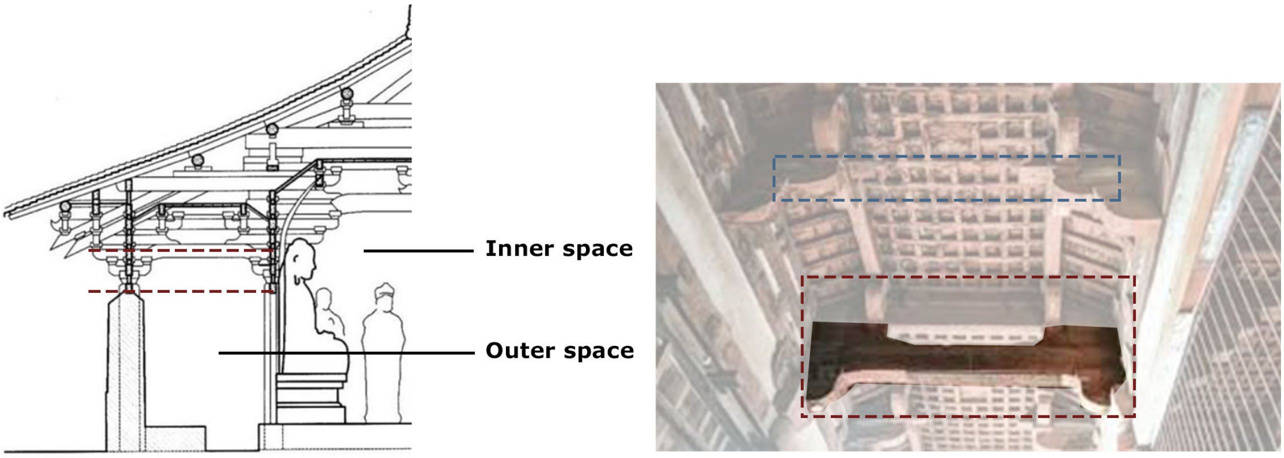
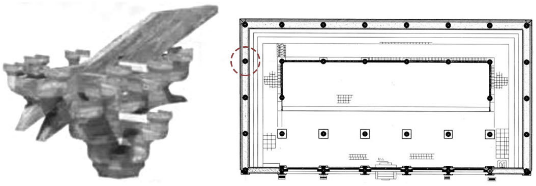


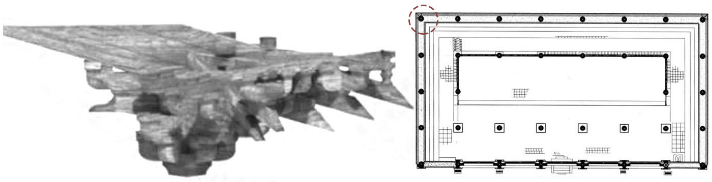
Figure 54: Continuous interface of the main hall of Foguang temple

As a comparison, the Tangshoti temple in Nara which was built during the same period as the Foguang temple could be studied. When repairing the Golden hall of Tangzhaoti Temple, it was found that its deformation was very serious and the interior columns were inwardly inclined. Actually, the Golden hall needed to be restored every few hundred years, which is much more frequent than the Foguang temple. The Golden hall that was built during the Nara period (710 to 794) was also constructed with the palace order but instead of the horizontal intersurface, the roof structure in Golden hall consisted also of inclined beams in between inner and outer space. Besides, the size of the dougong on the interior column in Golden hall was reduced which further shifted the centre of gravity inward. The inclined elements and the change of gravity centre increased the distance between the structural members above the exterior space and the interior space, so that the load of the roof was divided into vertical force and horizontal thrust which led the inner columns to turn inward and the Dougong above inclined outward.

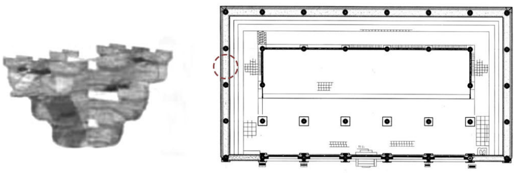
Table 2 shows the different types of Dougong used in the main hall. Another important Dougong to be discussed would be the outer eaves corner Dougong in the Foguang temple, it increased the eave distance up to 4 meters and became the furthest overhanging eaves among ancient Chinese buildings.



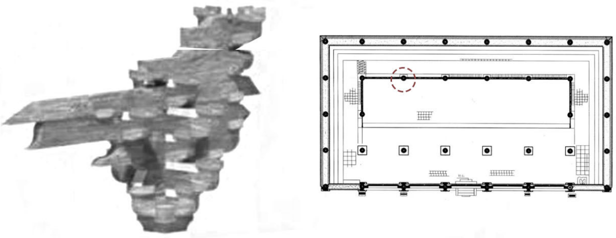
Outer eaves column Dougong
Seven *Puzuo*=four jumps+3



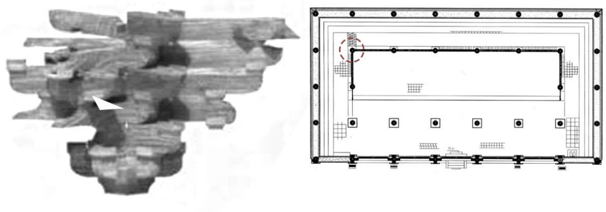
Outer eaves corner Dougong
Seven *Puzuo*=four jumps+3



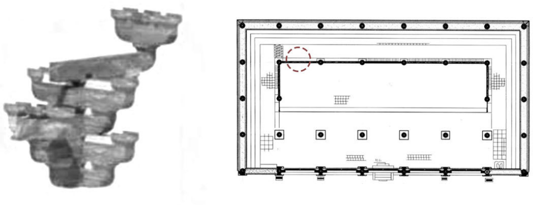
Outer eaves Dougong between columns
Five *Puzuo*=two jumps+3



Inner eaves column Dougong
Six *Puzuo*=tree jumps+3



Inner eaves corner Dougong
Seven *Puzuo*=four jumps+3



Inner eaves Dougong between columns
Five *Puzuo*=two jumps+3

Table 2: Types of Dougong in the main hall of Foguang temple

Another notable case is the Guanyin Pavilion in the Dule temple (see figure 55), the pavilion was built in 984 during the Liao dynasty and was the earliest timber-framed pavilion building. Since the construction was a few years before the publication of <*YingZaoFaShi*>, in Chen's research (2002) it was considered as a unique example that combined the architectural features of the Tang, Song and Liao dynasties. Moreover, from Liang's survey (1932) there were only six forms found for all the structural elements which indicated that by that time the standardization of components was already at an extreme.

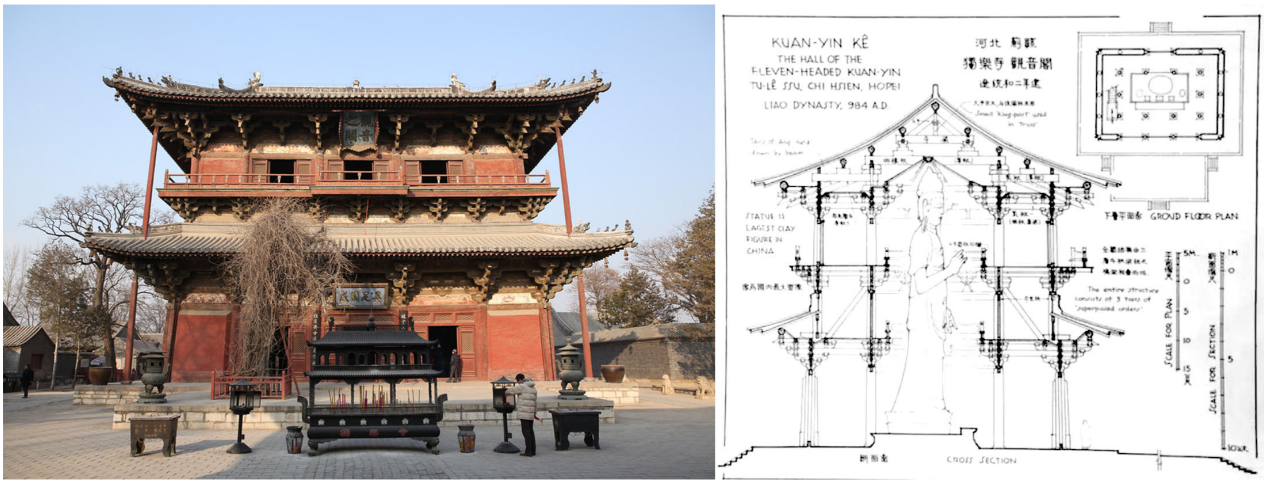


Figure 55: Photo and cross-section (Liang, 1984) of Guanyin pavilion in Dule temple

As introduced above, the change of the Dougong structure from the Song dynasty to the Qing dynasty was a process of transitioning from structural components to decoration components. The Dougong layer was still an essential part of the structure in the Guanyin pavilion. From the analysis of Liu and Yang (2007) the height of the columns under the roof was 406 cm while the height of Dougong was 258 cm which was approaching 2/3 of the column height, it could be seen the large proportion of the Dougong during that period. There were 24 types of Dougong presented in the Guanyin pavilion, Liang made comparisons of these Dougong and <*YingZaoFaShi*> in his article (1932) and found out the made of Dougong was highly consistent with the description in the book. Each type of Dougong is different from the others and performs different structural roles, which Liang gave a big compliment for their "organic" and "logical" combination.

From the photo of the Guanyin pavilion above, there were columns at the four corners to support the roof, they were added during the restoration in the 18th year of the Qianlong era (1753) (Liang, 1932). Both Liang(1932) and Chen(2002) criticized this restoration since it disrupted the balance of the original structure. Some guesses on the reason why this "negative" restoration was made could be due to the change of function of Dougong from the Song dynasty to the Qing dynasty. As mentioned above, one of the structural functions of Dougong is to increase the eave distance, however, since the Qing dynasty, Dougong became a complete decoration element the eave distance of the Qing dynasty architecture was also reduced. From the comparison in figure 56 it could be seen the difference in the eave distance during the Song and Qing dynasties, thus, the architects in the Qing dynasty might concerned about the heavy roof and its long eave distance and further added the columns at corners to support the roof. It might indicate that the development of architecture after the Song dynasty progressively turned the focus from structure to aesthetic aspect.

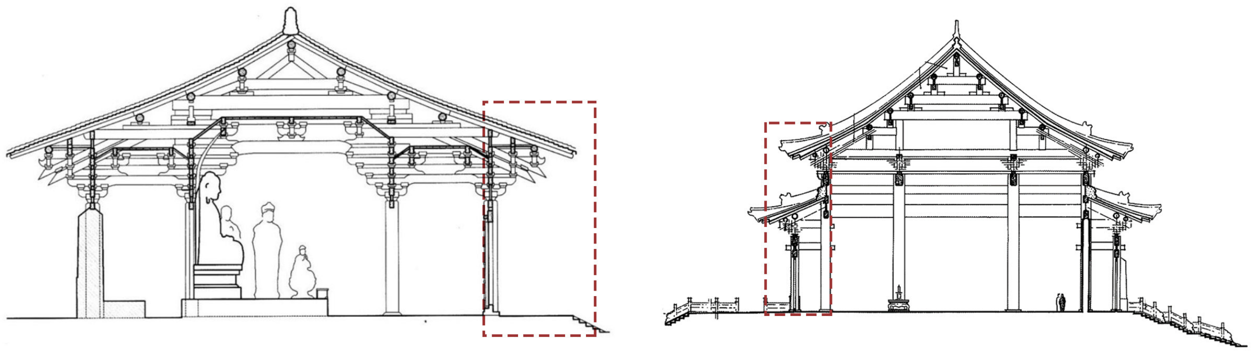


Figure 56: Left: Main hall of Foguang temple built in 857; Right: Sacrificial Hall in Tomb of Emperor Yong-Le built in 1424 (Liang, 1984)

6. Comparison

As the most complex part of a building, roof construction represents the carpentry technique. The appearance and structural performance of roofs have great influences on building integrity. The connection between roofs and vertical load-bearing elements (columns and walls) in construction determines the capability at a certain level. Especially when analyzing timber roofs, how the roof is constructed directly affects the span of interior space.

In China and Italy, different forms of roofs with their different construction techniques represent the culture, construction standards and woodworking technology of the time.

6.1 Connection:

Connection, which is the assembling of different parts or components of the building, could reinforce the architecture by on the one hand retaining the characteristics and capacities of each part and on the other hand creating the continuity between parts to fulfil new functions (Meijs and Knaack, 2009). The requirement for connections was not generated from the very beginning of the construction history (Martin, 1977), the progress from simply overlapping different parts to canonical and technical connections relied on the development of science, craftsmanship, construction technique and availability of new materials. In the early period, how to connect different pieces of wooden elements was the primary problem for Chinese and Italian carpentry. Before iron was invented, and even after due to the expensiveness of the iron, the joint between pieces of wood could be done exclusively in wood (Zwerger, 2012).

In China, from 6,000 to 7,000 years ago, the "Sun-Mao" (榫卯) (tenon and mortise joint) was started used in timber construction. The first Sun-Mao carpentry could be discovered as early as the Neolithic Age more than 7,000 years ago, the Hemudu people had already begun to use tenon and mortise (see figure 57). Many building wooden components unearthed from the middle part of the Hemudu site were chiseled with tenon and mortise, which were invented and used as early as that time. Dovetail tenons, tenons with dowel holes, and tongue and groove boards, the earliest tenon-and-mortise structures discovered so far, provided a remarkable achievement in woodworkingtechnology at the time. The technique of Sun-Mao was first used in the furniture field and then developed also in Architecture. The Sun-Mao connection required highly precise and form-fitting shapes at joints, when there is no machine for production, this requires a lot of labour force and manual skills.

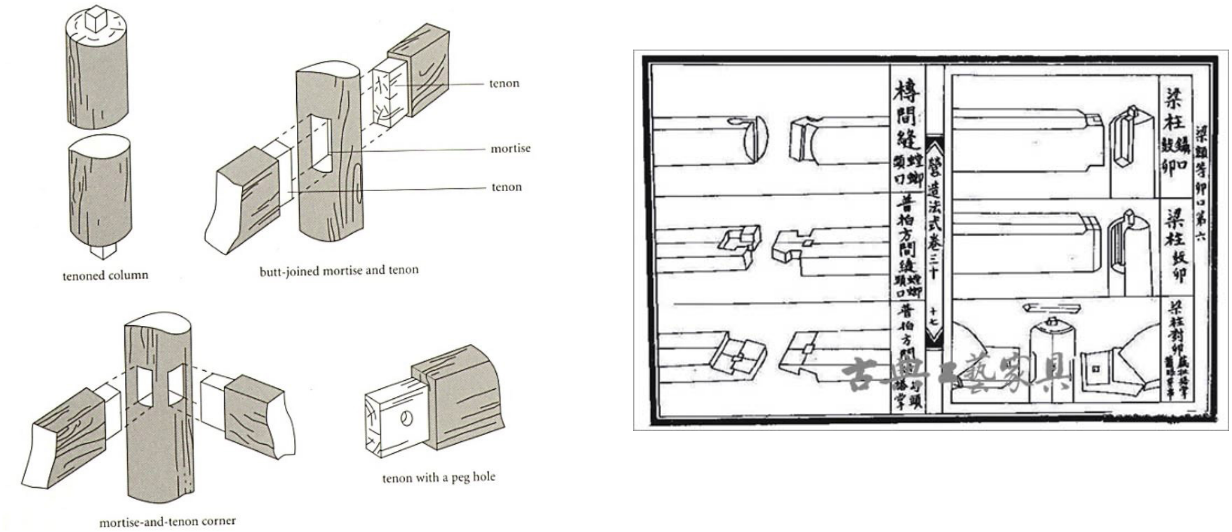


Figure 57: Sun-Mao joint in Hemudu site (Kim and Park, 2017) and in <*YingZaoFaShi*>

The main structural method of traditional Chinese architecture is the wooden frame structure which was composed of thousands of wooden pieces organized in a logical and geometric order and these pieces were assembled by Sun-Mao joint. Its basic building blocks are columns, beams, and purlins. Sun-Mao joints connect these diverse building blocks to create an elastic frame. The protruding part of the component is called "*Sun*", and the concave part is called "*Mao*". The most basic Sun-Mao structure consists of two components, one of the "*Sun*" which is inserted into the concave part of "*Mao*" to connect and fix the two components.

The tenon and mortise joint was also founded in about the same period in Europe at a timber framed well (figure 58) in Altscherbitz, Germany (Tegel et al, 2012). The age of

Figure 58: Timber well in Altscherbitz, Germany (Tegel et al, 2012)

the well is about 5469-5098 BC, which is about 7000 years away. According to analysis, the ancient well builders used mortise and tenon joints, a method that locks the parts in place with a fitting wedge. Further, the ancient Greeks and ancient Romans used mortise and tenon technology extensively in furniture and architecture.

In Italy, wooden nails and wedges were found to secure joints, which enhanced the stability of tenon and mortise joints. The wooden nails bear the force of the joint in the form of shear force, so the wood species selected for making the nails should often be the strongest, for instance, oak, laburnum and elm.

However, in the roof truss structure of large-scale architecture, in order to reduce the self-weight of the roof components, the cross-sectional dimensions of the columns and beams are often reduced to a minimum. If continued using tenon and mortise joints fully in wood the components will be further weakened at the nodes. Also, the wooden nails were not able to bear the enormous shearing force. It could be seen from Serlio's detailed drawings of truss design (1575) (see figure 59) in the late period of the Renaissance that metal plates became the solution for joints of large timber trusses. In the second part of the 18th century, along with the process of the industrial revolution, the use of iron components in roof trusses gradually spread throughout Europe, enhancing the performance of trusses and the development of larger-span architecture construction. As Nicholson purposed (1810) to solve the problem of tension within the wood itself,

> *"As wood is more apt to shrink sideways than in length, so the king post and side posts in consequence of the perpendicular position of the grain in the wood, and also in proportion to the quality of the wood, will be liable to shrink, the rafters of consequence will descend; this must be guarded against by the application of iron straps in proper positions.."*

By applying iron straps in specific positions, it is possible to keep the rafters in place and prevent damage.

In addition, from the outside appearance, the connection form of "Sun-Mao" joints is generally hidden inside to keep the end surface of the wood as little as possible exploded outside. While in Europe, the structure of the connection is shown on the surface.

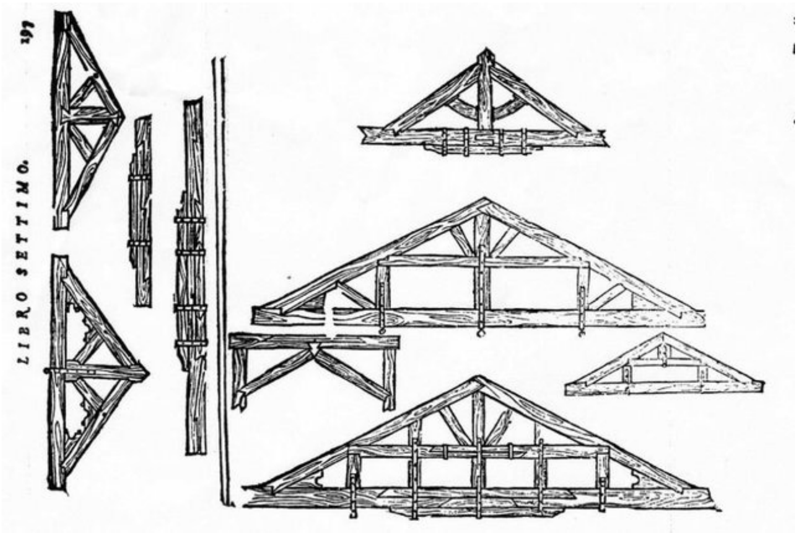


Figure 59: Timber truss with the metal plate.VII book of Sebastiano Serlio(1575)

6.2 Structural:

Both truss and dougong have the structural function to increase the roof span by solving the problem of the bending of the beams. In some cases, the force analysis of the roof system could be different, although there are both triangular wood frames. In a European truss roof, the load-bearing frame is a herringbone arch formed by inclined chords. In inclined chords, the pressure is transmitted diagonally down the axis to the bottom flat beam. Thus, the forces within an ideal truss should be all normal forces. In the Chinese roof, the load-bearing frame is the purlin and the column or beam supports the purlin through the dougong element as joints. Besides, the span of the beam has been reduced by the overhanging inverted triangular shape of dougong or by having the loads from the upper layer close to the columns. In summary, in Chinese roof structures, the transmission of force is only in the horizontal and vertical directions. This difference in construction also appears that usually in Italy, timber is widely used for roof construction while walls and columns are mostly constructed in brick or masonry. In China, traditional Chinese architecture is built in a pure wooden framework.

The rafters in Italian timber trusses are typically made of a single continuous squared log from the tie-beam joint to the ridge, and they are supported at an intermediate point by secondary members (braces); the purlins typically charge the rafters with the loads placed close together, so they should be better considered as a span load (Zamperini, 2012). Based on the case of an ideal truss (figure 60) with braces, the stress points should be distributed at the middle top of the truss and nodes where meet the braces; however, in a real truss, the load is a combination of axial stresses, bending moments and shear force. The rafters are stressed by the pressure-bending moment.

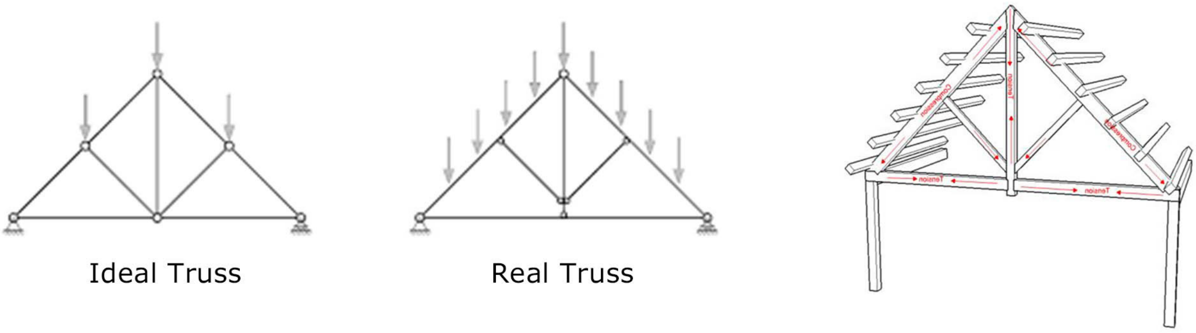


Figure 60: Design Guide for Timber Roof Trusses (2020)

From Liang Sicheng's survey and drawings of ancient Chinese architecture (see figure 61), it could be speculated that there existed some triangle-formed structures on the roof which seem very similar to the Italian truss.

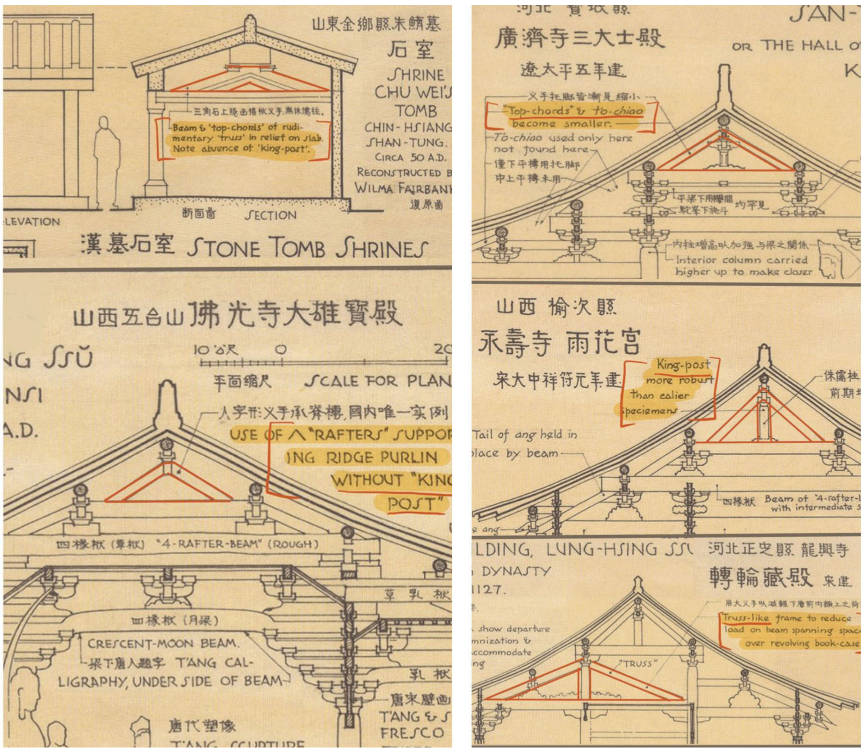


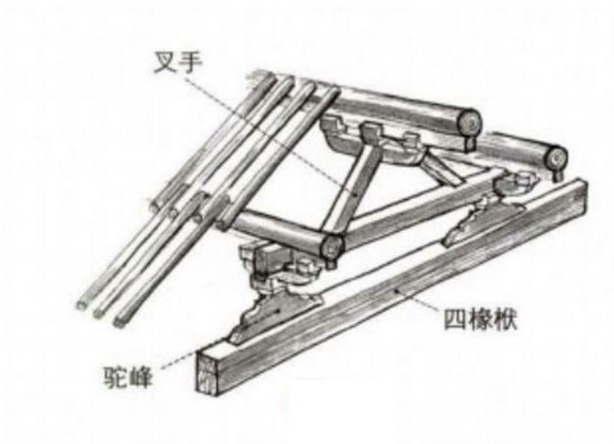
Figure 61: The "truss formed" structure in Liang's book (Liang, 1984)

However, even though the forms were very similar to trusses, the force paths were different. Besides, in Italy, the whole roof structure was supported by trusses while in the drawings of Chinese temples during the first period of the Tang dynasty (circa 780-850), the main structure was still the Tailiang system. This part of the structure for supporting the purlin first appeared with a triangle form and then improved by adding a "king post" to reduce the compression on rafters. In a later period, the rafters were completely replaced by "*Shuzhu*" (蜀柱).

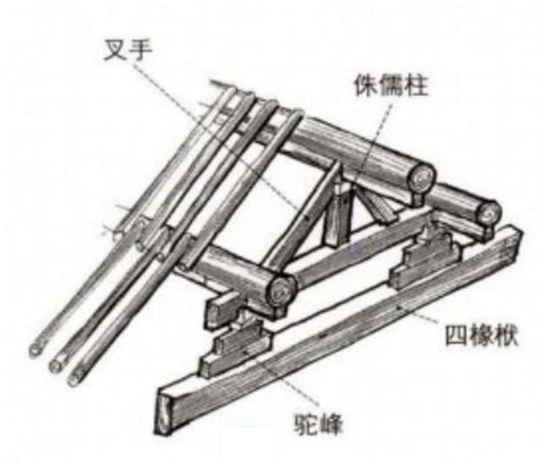
Figure 62: Left: "truss" in the Foguang temple; Middle; "truss" in the Nanchan temple; Right: "truss with *Shuzhu*" in the Longmen temple (Pan and Campbell, 2017)

From the following period of the Tang dynasty (circa 925), in the Longmen temple, a "king-post" is shown which reduces the structural function of the Chinese trusses and later the triangular structure became more decorative. The "truss" was not developed in China because of earthquake resistance, wood properties and environmental factors, also, Chinese architecture requires flexibility so it is best that the inclined beams not become the main force structure. The following figure 63 shows the change of this "truss" formed structure from Tang to Qing dynasties, which can be found since it was not a primary structural element, it become simplified and further turned to a decorative component.

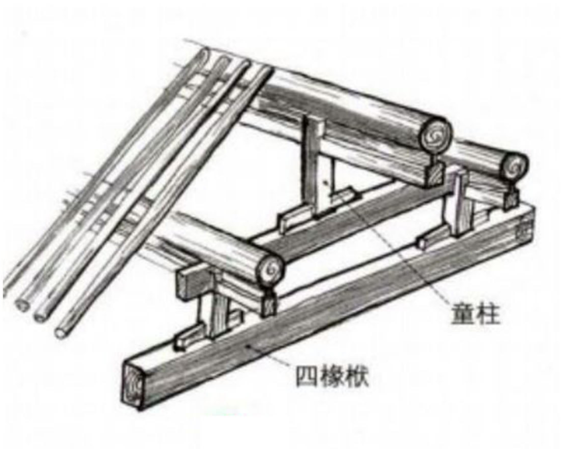
Apart from the structural aspect, Pan claimed in his book (2014) that in eastern culture, the concept of being impartial has a great influence on art and architecture. So that in ancient Chinese architecture it tended to not obviously use inclined components, it could be seen from the above examples that the triangle-formed structure is only a small part and is hidden in the roof structure.



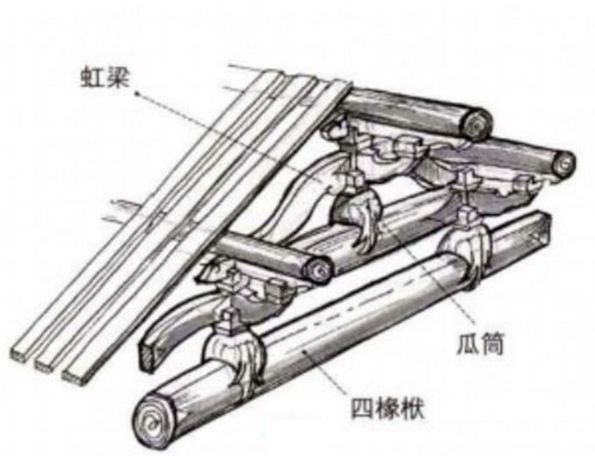
Main hall of Nanchan temple-Tang dynasty



Guanyin pavilion of Dule temple-Song dynasty



Lingen palace in the Imperial Tombs-Ming dynasty



Residential house in Fujian-Qing dynasty

Figure 63: Change of "truss" formed structure (*叉手*) in Chinese architecture (Li, 2009)

But had trusses been used in China in later decades? After the signing of the "Tianjin Treaty"[21] in 1858, the Chinese government opened up missionary freedom in China as well as the permission to build western churches. Thus, many churches were built by Western missionaries in China from the 1860s to the 1930s, the construction of which, of course, always was realized by the Chinese workers. Before 1900, most of the Churches were still using local materials and techniques, only adapting the western architectural form.

During the time of Christian inculturation, church architecture had been built in several cities in China. Although most of them have been demolished or rebuilt afterwards, trusses could be indicated from historic photos (figure 64). In the handbook <*Le*

[21] The treaties of Tianjin(*天津条约*), signed in June 1858, provided residence in Beijing for foreign envoys, the opening of several new ports to Western trade and residence, the right of foreign travel in the interior of China, and freedom of movement for Christian missionaries.

missionnaire constructeur> published by French Jesuit missionaries in 1926, recorded the transmission of Western techniques to Chinese workers. The workers had to design the trusses and determine the dimensions of the various components based on the span. In most rural areas and small provincial towns, church-building works were the first encounter between two completely different building traditions. Missionaries arrived with Western models, ceremonial requirements and theoretical knowledge about architecture and style, but had to adapt to local conditions, climate, and available materials, and communicate with craftsmen. However, in rural China, the techniques described in the manual are still difficult to implement. In many villages in northern China, building Gothic churches is an entirely different architectural expression, which can be called “foreign” or “imported” compared to local traditions. Missionaries needed workers to construct their churches and to train Chinese craftsmen with Western medieval techniques (Coomans, 2015).

Figure 64: Left: Chapel of the former Regional Seminary, 1935; Middle: Facade of the former church of St Louis, 1872; Right: “Truss” from demolition site of Church of St Louis (Coomans, 2015).

In some cases, it appeared a combination of Western and Chinese architectural characters. For instance, in a construction textbook published in 1934 (see figure 65) recorded a mix of king trusses and Chinese purlins manufacturing method.

One of the key obstacles during construction is the lack of knowledge of Chinese craftsmen for non-native construction traditions. Without the aid of models, drawings and on-site practice, Western architectural techniques can not be fully understood.

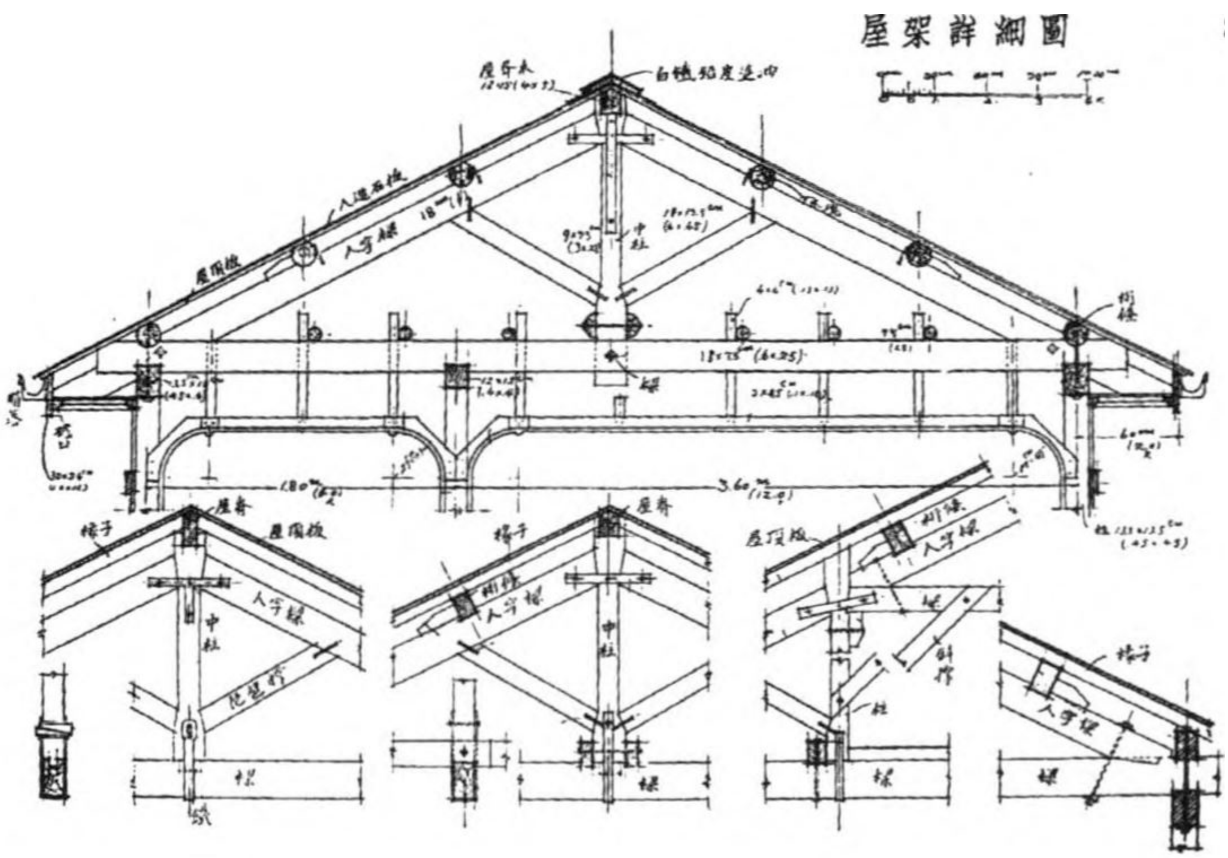


Figure 65: A combination of king trusses and Chinese purlins (Pan and Campbell, 2017)

6.3 Shape:

Ancient Chinese roofs are normally curved with the shape of bending from the middle and upward at the corners. Until today, this traditional roofing style is still used in many parts of China and is admired for its aesthetic value as well as its functionality. From a functional aspect, compared to the normal pitch roof, the upward curved roof could enhance natural light. Another function of curved roofs is to help with the drainage of rain. It can be found through observation that from the north to the south of China, the angle of the eaves is getting higher and higher since in south China there are more rain sessions. From an aesthetic aspect, it increases the upwardmovement of the building and presents the building vividly. In fact, the curved roof of ancient buildings is the product of thousands of years of architectural concepts and technological development. It solved the comprehensive needs of structure, function, culture and humanistic aesthetics. The use of Dougong in roof construction became a turning point in the roof shape trend. This flexible method of roof construction allowed for a more varied roof shape.

Compared with ancient Chinese roofs, a curving inclined roof could hardly be found in Western architecture. The pitched roofs in Europe are mostly with straight slope roofs or with multiple layers for example the stave churches. The reasons for this difference from the Chinese roof were mainly due to the structural aspect and lighting system. First, in the roof formed by the truss structure, the rafters are strained under compression, which should be straight for structural reasons. Furthermore, rather than increasing the eaves at the corners to let in more light, the western roof style has tiny apertures on the roof surface to promote natural lighting.

6.4 Material and quantity:

The understanding of materials is one of the most important factors in construction work, especially for the main building material - wood. Table 3 shows the distinction of traditional timbers according to their physical characteristics (Carbonara, 1996).

	Maximum	Average	Mediocre	Weak	Minimum
Resistance	Oak, Larch, Ash, Hornbeam, Elm, Beech, Scots Pine, Chestnut	Spruce, Alder, Walnut		Poplar, Lime, Willow	
Elasticity	Yew, Ash, Maplewood	Larch, Pine, Spruce, Elm, Young Oak	Beech, Maple	Lime, Willow	Pine, Poplar
Hardness	Boxwood, Cornelian cherry	Maple, Hornbeam, Wild Cherry, Yew, Ash, Robinia, Elm	White Maple, Beech, Walnut, Chestnut, Rowan, Oak	Red and white spruce, Horse chestnut, Alder, Birch, Larch, Pine, Cherry cluster	Lodgepole Pine, Poplar, Willow, Linden
Durability	Boxwood, Cedar, Cypress, Oak, Elm, Larch, Scots Pine, Robinia	Chestnut, Red and White Spruce, Ash	Beech, Hornbeam, Maple, Alder, Wild Cherry, Birch		Quaking Pine, Lime, Poplar, Willow

Table 3: Distinction of traditional timbers

In some cases, by identifying wood species used in the architecture, it could be helpful for determining the period of construction. In addition, the quantity of the wood materials and the way they were transported to the construction site could also become an interesting point for historical research. For example, under the same span distance, the Chinese Dougong structure requires more amounts of wood material compared to Italian truss systems due to the tediousness of the structure. Furthermore, apart from the type of truss, the span also depends on the selection of wood. For instance, the modest span trusses (5-10m) are mostly made of coniferous (fir, larch) or broad-leaved (oak, chestnut, poplar) timber while the larger span trusses (10-15m) are made exclusively from coniferous lumber.

The two main types of wood species used in Italy were conifers (*Pinophyta*) and broad-leaf (Macchioni et al, 2004). Conifers are suitable for constructing long straight components such as beams and rafters due to their feature of having less branches compared to other types of trees. While for broadleaf, tree species from oak (*Quercus*) and broad-leaved pine (*Pinus palustris*) are normally shorter in length and have higher densities, therefore, they also have good mechanical resistance. Macchioni et al (2004) also claimed that broad-leaved pine was mostly used in roof construction for church architecture during the 15-18 centuries. With these better and more durable materials, it showed the high value of the architectures at the time they were constructed or reconstructed. However, as mentioned above, in Italy carpenters from different regions might have made their different selections of wood species. Especially before the railway was developed, the logs and their heavyweights made it extremely difficult for timber transportation. The most often used structural timbers in northern Italy are the common alpine wood species like spruce (*Picea abies sp*.) and larch (*Larix decidua Mill*.). For instance, in the case of Venice Arsenal, both the trusses in "*Isolotto*" and "*Corderie*" were mainly constructed by larch and with few amount of other species such as spruce (Menichelli et al, 2009). While the chestnut (*Castanea sativa Mill*.), which grows swiftly and yields high-quality thin stems in the rich volcanic soils around the central and southern capitals of the former Italian kingdoms, Rome and Naples (Bertolini 2006). The chestnut is mostly used for beams and trusses (Carbonara, 1996).

Oak, a material favoured by medieval woodworkers, was valued because it is extremely durable, as its high content of tannins preserves it from biological attacks. In Coradeschi et al's book (2021), the advantages of oak have been described:

> *"Vitruvius and Pliny praised the qualities of this wood. Its use for the manufacture of structural elements has been well attested since prehistoric times, and oak forests cover large geographical areas included in the Mediterranean basin. Numerous studies have attested to the use of oak wood for building during Italian prehistory, as well as for the historical periods. The widespread use of deciduous and semi deciduous oak wood for the beams, rafters, columns and boards of many Roman buildings, as well as for the construction of naval frames, demonstrate the extent to which Romans appreciated this wood for construction purposes."*

However, oak can be very slow to grow and therefore the cost is also higher than other timbers (Carbonara, 1996).

In Chinese architecture, various materials were used depending on their availability, durability, and quality in the region (Zwerger, 2012). Changes in temperature and humidity in China are far more drastic than in Europe which means that wood is more likely to crack and rot from moisture. Therefore, in addition to choosing a wood with more stable wood properties and straight-grained wood, it is also necessary to paint on the outside of the wood for protection to reduce the range of changes in wood moisture content. Correctly selecting different kinds of wood along with the components that they were used for was an important aspect of Chinese carpentry. In fact, starting from the Song dynasty, trees from different areas needs to be made into wood species according to the specification before being sent to the carpenters (Fu, 2012). The specification classifies trees according to their sizes, weights, strength and toughness, and different trees would be used for different components of the architecture. For instance, for anti-seismic reason, the wood species used from roof to columns are getting heavier and denser.

The most common wood used in construction was Chinese fir (中国冷杉) (which is a kind of Spruce), it was widely used all around China. Chinese firs (*Cunninghamia*) have the advantages such as good anti-corrosion resistance and compression resistance, not often to be attacked by insects, the lightweight of the wood itself and it is not easy to deform, so it was considered an ideal building material in ancient Chinese construction. Chinese fir was mainly used for constructing columns, purlins and rafters. Instead, beech as a tough material was mainly used for beams. Apart from Chinese fir and beech, another suitable wood for columns and beams is Nanmu (*Phoebe*)(楠木). Nanmu has the strong advantages of a long shape and it is less likely to crack, which makes it a great choice for constructing columns and beams for large scale architecture. Besides, compared to other broadleaf trees, it has a shorter growing season thus it could be easier to collect (Li et al, 2004). However, Nanmu mostly grows in southwest and southeast parts of China while the capitals during most of the dynasties were in North or central China, which due to the difficulty in transportation Nanmu became a rare material in the North and it can only be used in extremely important architecture (eg: Taihe hall in Forbidden city).

The selection of trees for architectural components could also change due to their size and function. Taking the example of the Dougong structure, according to Yang's research (2008) before the Qin dynasty the most used tree according to the historic records was called “兰”, contemporary scholars believe that could be a kind of boxwood or Magnolia (Yang, 2008). These kinds of trees could have a long period for growing but they have the features of easy to fabrication and much denser and harder than other commonly used trees, such as fir and ginkgo; During the Tang and Song dynasties, with the structural function of Dougong kept enhancing, the wood species used changed to elmwood, poplar and juniper which are trees with good performance in hardness and durability (Chai, 2010); In the Qing dynasty, the most used wood species for Dougong was softwood pine since it had already become a decorative component so that there was less requirement on the hardness and density.

6.5 Spatial development:

When constructing a roof that required more than one truss, the trusses are arranged in lines which are formed in 2 dimensions and only in the horizontal direction. However, the Chinese roof structure is developed both in horizontal and vertical directions. Dougong itself as the joint is also interlocked with elements arranged in 3 dimensions.
In addition, in the roof system, Dougong could be considered a system of multi-joints; it could also be seen as a joint to connect the roof and beam-column frame. Within Dougong itself, the parts where the components meet are responsible for “connection” and force transmission and the intersections of the individual components prevent movement of the frame. When putting Dougong as a part of the whole architecture enhances the integrity between the roof and the main body of architecture. While the truss system itself could be seen as a structure even without the context of roofs, for instance, the truss is also a widely used structure for bridges.

6.6 Seismic resistance

From the global seismic hazard map (figure 66), it could been seem both Italy and large part of China were on the seismic zones.

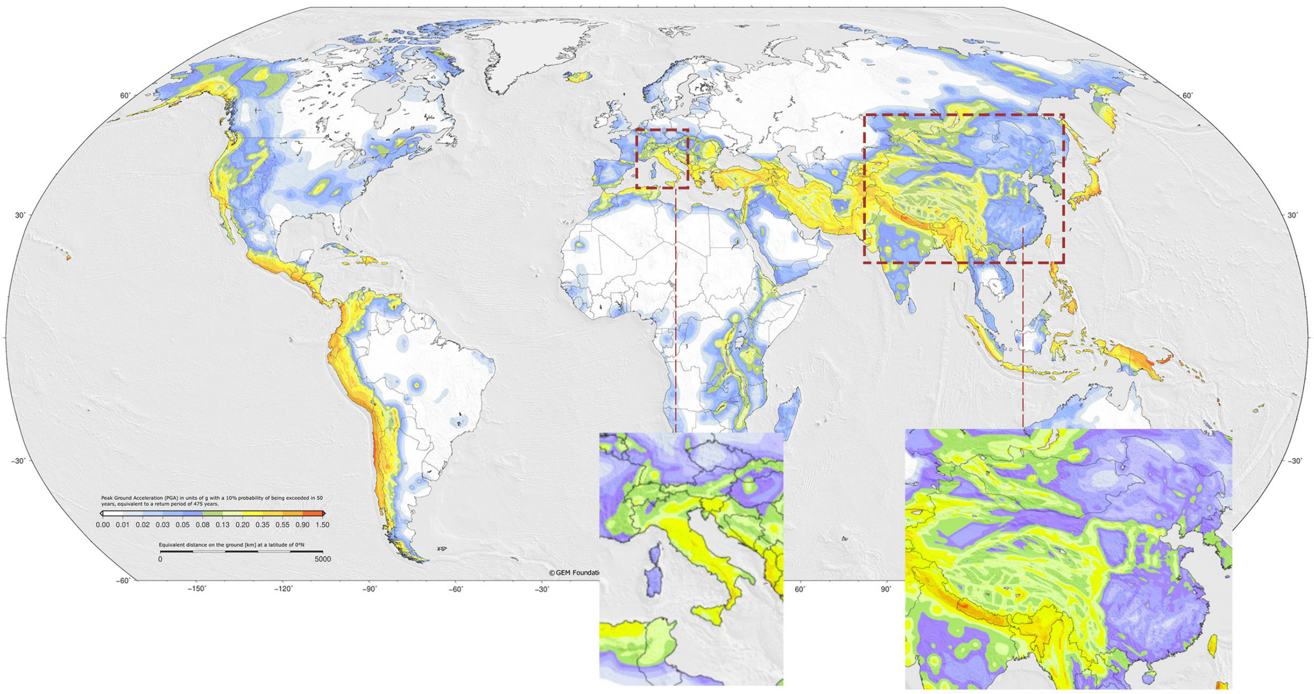


Figure 66: Global seismic hazard map (2018)

China has various seismic regions (especially in the southwest) due to the situation in both the Pacific seismic zone and the Eurasian seismic zone, but there are still buildings that stand for more than thousands of years after multiple earthquakes. According to historical records, the damage to wooden structures by major earthquakes in history was usually not destructive. Researchers[22] in the past have described the situation as "the walls collapse while the building does not collapse" or "the bottom of the column is displaced but the overall structure is intact".

How did ancient Chinese architecture perform during earthquakes? The way buildings are damaged by earthquakes is mainly affected by the way the seismic waves propagate and in most cases, there is a compound effect of vertical shakes, horizontal

[22] Gao, Dafeng; Zhao, Hongtie and Xue, Jianyang. "*木结构古建筑中斗栱与榫卯节点的抗震性能——试验研究* [Seismic performance of Dougong and mortise nodes in timber frame ancient buildings - an experimental study]". J*ournal of Natural Disasters*. Vol.17, No.2. (Beijing: Science Press, 2008); He, Junxiao; Wang, Juan and Yang, Qingshan. "*摇摆状态下古建筑木结构木柱受力性能分析及试验研究* [Analysis and experimental study of the stressing performance of wooden columns of ancient buildings under swaying conditions]". *Engineering Mechanics*. Vol.34, No.11. (Beijing: Journal of Engineering Mechanics, 2017)

swings and torsions. Under the vertical shake, a large dynamic load suddenly is given to columns and load-bearing walls on the ground floor. Superimposing the self-weight pressure of the upper parts, the columns and walls will collapse if the bearing capacity of the columns and walls on the ground floor is exceeded. After the collapse of the bottom layer, the weight of the buildings above will result in continuous collapse; Under the horizontal swing, a force that is repeated back and forth in the horizontal direction is applied to the building. If the strength or deformation capacity of the bottom columns and walls is not enough, the whole building will be skewed or toppled in the same direction; in other cases, the if the shape of the building is irregular it would generate torsion under the seismic waves. Buildings generally have poor torsion resistance and are easily broken and the collapse of the corner parts of buildings is mostly caused by horizontal torsion.

However, it could be observed that in the same area after the damage of the earthquake some buildings completely collapsed while some were only partially damaged. Buildings with different materials and structures have different seismic resistance. The main factors that affect buildings' seismic ability are the geometric shape, for example, some architecture with irregular shapes, especially those that have one side sinks and another side light up which is not able to balance themselves, have been greatly affected by earthquakes. Furthermore, the structure and construction quality also have a great influence.

The good seismic resistance and mechanical properties of Chinese timber structures are mainly reflected in their symmetry and integrity. Liang (1984) claimed that there is no other nation that used such an amount of symmetry axis in architectural design as China. From royal palaces, public offices, Buddhist and Taoist temples and residential houses, they are all distributed according to a strict central axis, both in single architecture and their overall layouts (see figure 67). A building that has a symmetry form and symmetrical arrangement of column grid could prevent itself from twisting during an earthquake. The plan of the ancient Chinese building is mainly rectangular with a ratio of 8:5 of length and width, or in a few cases, there are hexagons, octagons or circles but basically no complex planes. These regular shapes allow for uniform mass and stiffness of the plane.

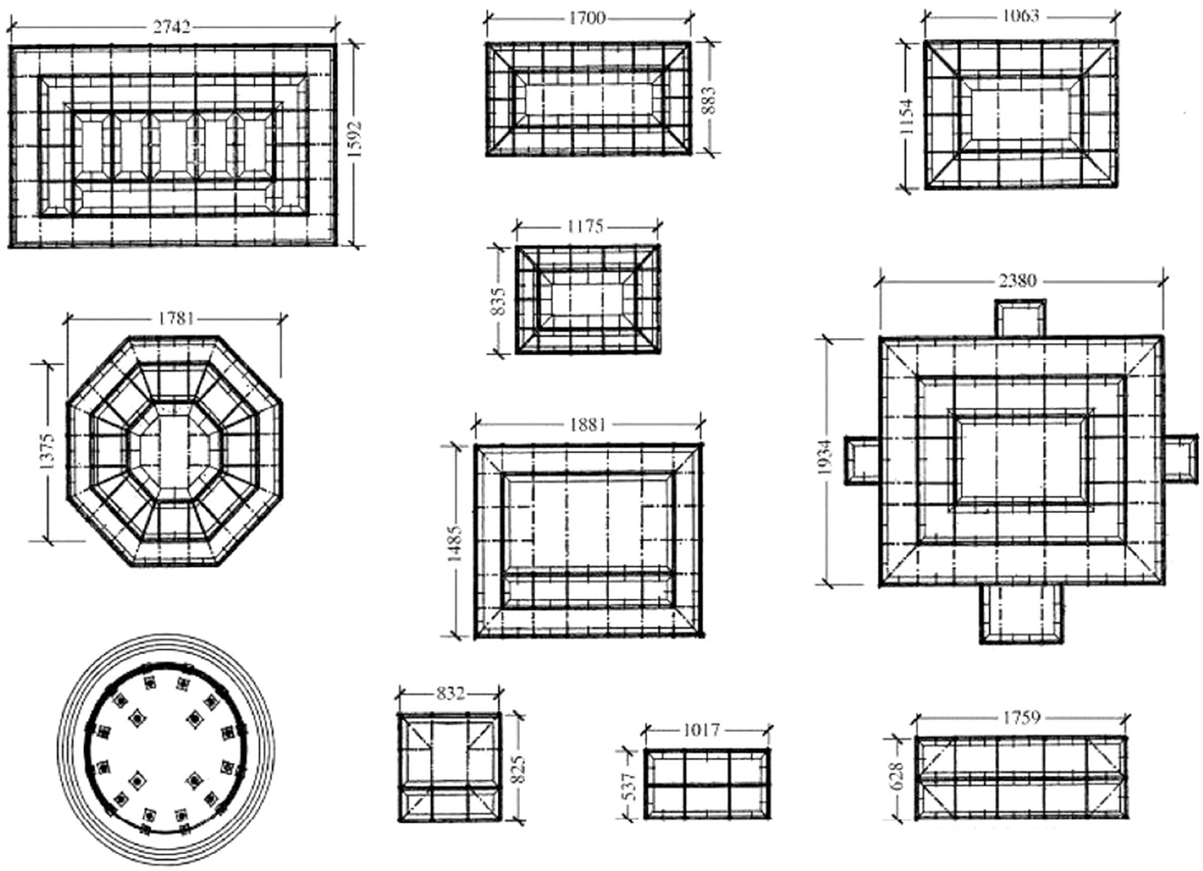


Figure 67: Plans of existing ancient Chinese timber architecture (Liu, 1984)

In addition, as mentioned before, the roof occupies a large proportion of ancient Chinese architecture. The heavy roof gives a large compression to the Dougong layer and to the frame of beams and columns, which could increase friction and damping between components in order to deplete the seismic energy.

One of the important anti-seismic approaches to Chinese timber buildings is the design of the column order. Ancient Chinese architecture is mainly load-bearing with wooden frames which can reduce the structural rigidity and reduce the earthquake effect. During the earthquake, the energy of a seismic wave first hits the foundation and plinths and then passes to columns. In ancient buildings, wooden columns often floated on a stone foundation (He et al, 2017) (see figure 68) which provides vertical support and part of horizontal friction to the bottom of the column. So that the friction slip or swing between plinths and columns could absorb part of the energy so that the seismic force passed to the upper structure is already reduced. The cross-section of the stone foundation is usually larger than the radius of the wooden column which prevents the column from falling and also gives enough space of movement for the column.

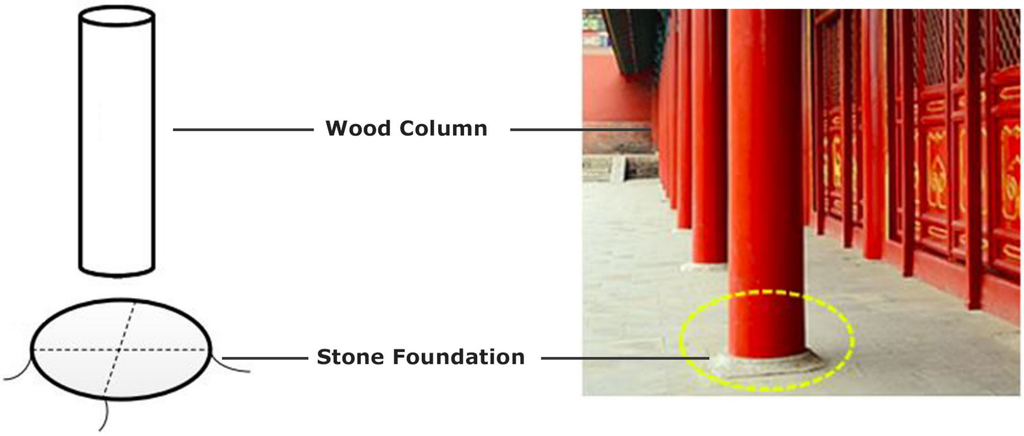


Figure 68: Wood column and stone foundation (He et al, 2017)

Apart from the connection between the column and the plinth, the placement of the column could also reduce the impact of earthquakes. It is specified in the <*YingZaoFaShi*>: "The head of the column is slightly retracted inward and the base of the column is slightly outward." This placement is called "*Ce Jiao*"(侧脚) (see figure 69) which means to side the bottom of columns. Depending on the facades of architecture: in the front, the column is inclined outward by 1/100 of the column height; at the side, it is inclined by 0.8/100; while the corner column is in both the front and side directions, it combines the inclination of both directions.

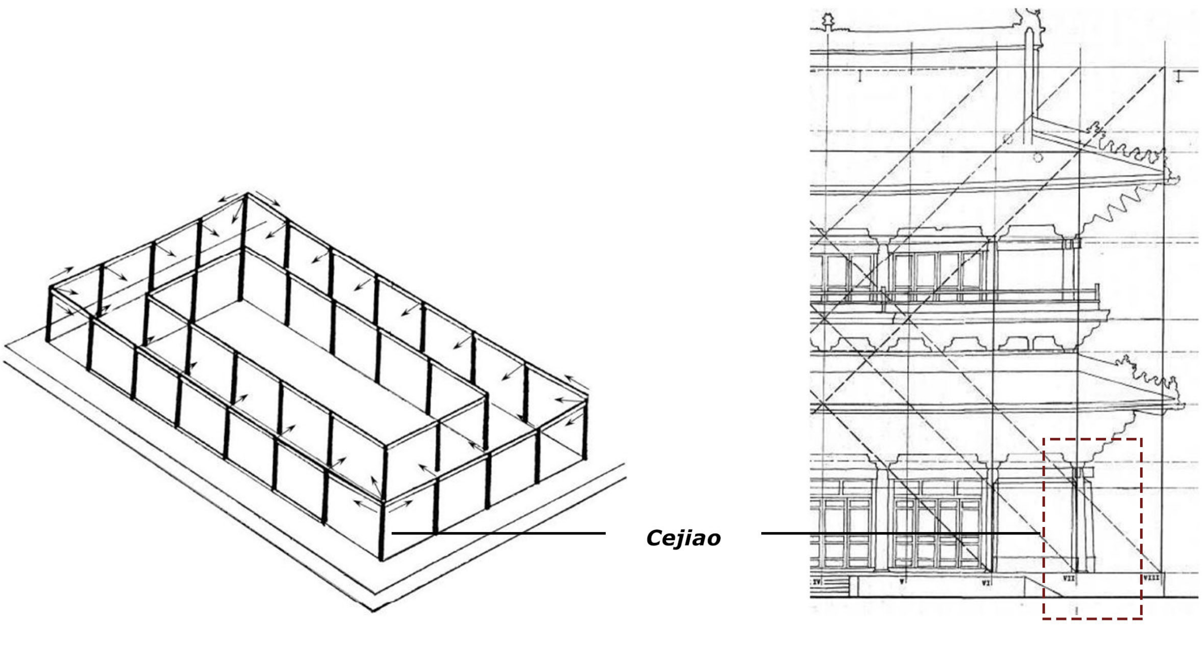


Figure 69: Left: diagram of "*Cejiao*"; Right present of "*Cejiao*" in Guanyin pavilion (Chen, 2002)

With this inclination of the column, its mortise and tenon joint with the beam is angled and tighter. The stiffness of the joint is enhanced and further improves the integrity and stability of the wooden frame. This "Ce Jiao" method can reduce the lateral deformation of the structure, in the meanwhile, it reduces the stress concentration in the components and improves the bearing capacity.

By inclining the column, it can convert the horizontal seismic force into the axial pressure of the column, so as to take a part of the seismic force and reduce the horizontal seismic action. Moreover, see figure 70 left if the columns are placed all vertically and parallel, the horizontal seismic force will cause rigid translational displacement of the roof and lead the structure to collapse; if applied with the "*Ce Jiao*" method (see figure 70 right), since the columns are not parallel and the angles of rotation of the columns after the horizontal displacement will also be different, the roof will have not only horizontally displacement but also rigidly rotation. After the roof is rotated, its weight will generate a component force $F=G\sin\theta$ along the slope, which is opposite to the horizontal movement force produced by an earthquake, so that the roof tends to return to its original position.

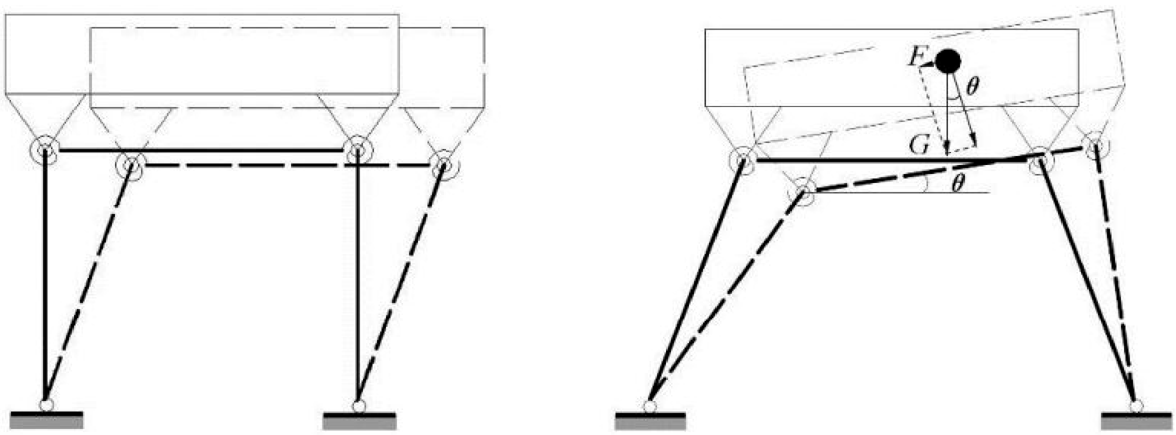


Figure 70: Left: parallel column; Right: column with "*Ce Jiao*"

Another construction method related to columns is the "*Shengqi*" (升起) of corner columns (see figure 71). The heights of the columns of the ancient wooden structures are different. From the central column to the corner columns, the column height increases to create a concave profile on the front façade. In the <*YingZaoFaShi*>, it was regulated that:

> "*...the height of the central columns do not change, the columns of the second bay and the end bay are raised by 0.06 meter relative to the central columns…*"

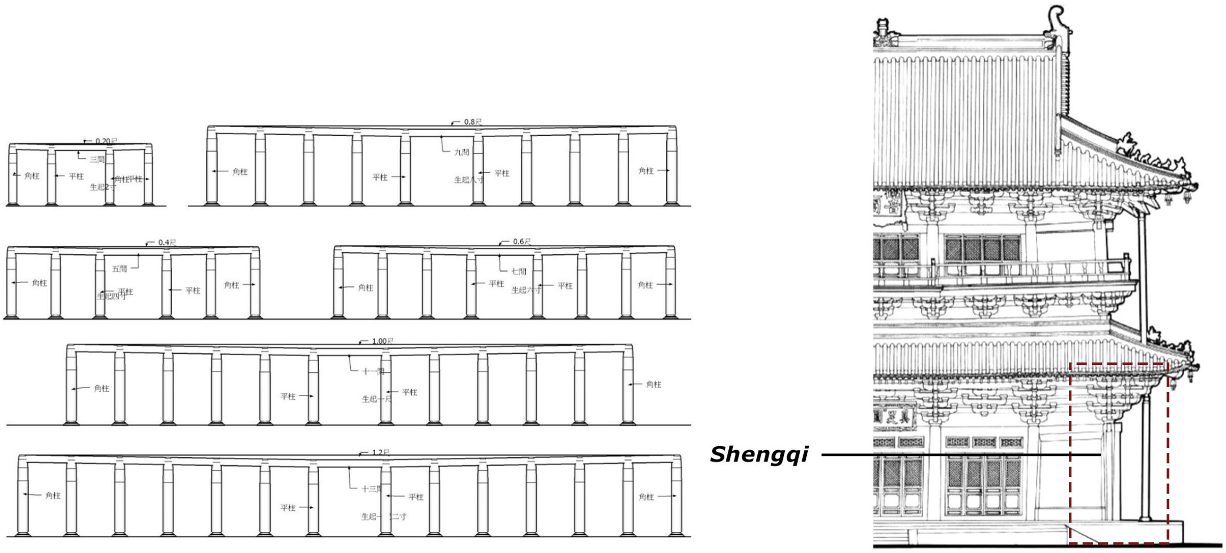


Figure 71: Left: diagram of "*Shengqi*" of the corner columns; Right: present of "*Shengqi*" in the Guanyin pavilion[23]

Apart from the column order, the connection of tenon and mortise could dissipate seismic energy by its deformation and displacement. The tenon-and-mortise connection is a semi-rigid connection, which can not only resist a certain bending moment but also bear partial pressure through deformation. Due to the compression between the tenons and mortises, a large plastic deformation is produced, which degrades the rigidity through the rotational deformation and highlights its connection characteristics of "flexibility". Further, the lateral displacement rigidity of the whole structure could be reduced thus effectively reducing the damage to the structure caused by the earthquake (Gao et al, 2008). According to Gao's experimental tests, the Dougong layer (see figure 72) has the strongest ability among all building layers to dissipate seismic energy and proved that the Dougong layer should be the main damping and vibration isolation layer of the ancient Chinese buildings. The design of the Dougong layer aims to reduce the stiffness both in the vertical and horizontal direction and make Dougong work as a buffer layer between the roof and beam-column layer.

[23] In some survey drawings of the Guanyin pavilion and other architecture that had been studied before 1933, the method "*Shengqi*" had not been recorded. Only after 1933, the scholars noticed this method by the comparison studying with the <*YingZaoFaShi*> (Liang, 1933). The drawing here was made by the architecture department of the Tianjin University in the 1990s.

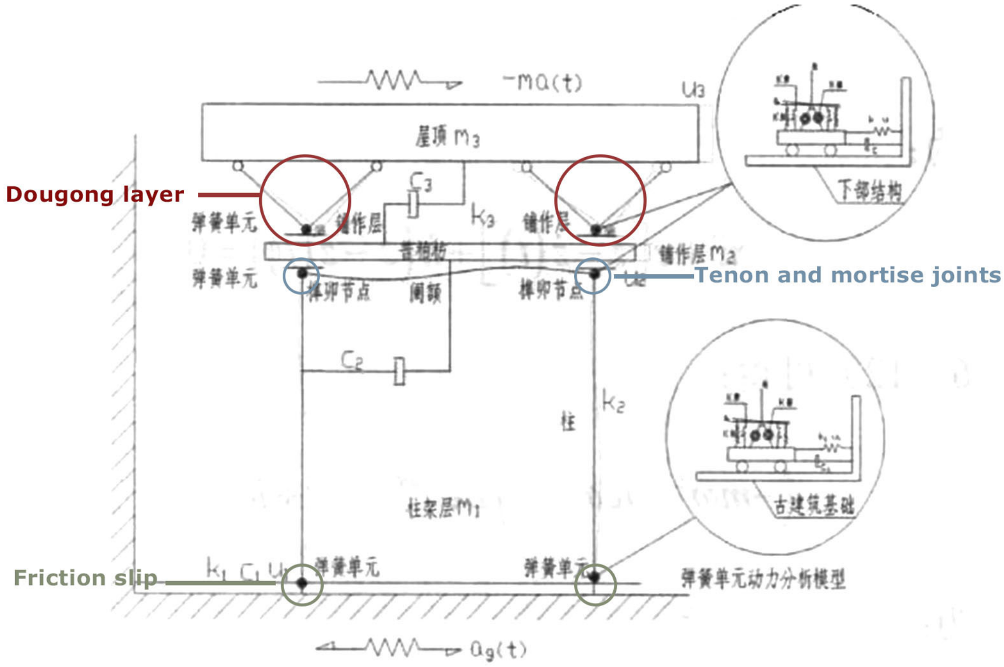


Figure 72: Dynamic analysis of ancient Chinese architecture (Gao et al, 2008)

On the other hand, Italy is also a country located in the earthquake zone, there have been many major earthquakes in history that have caused extreme damage to homes.

A major difference from ancient Chinese architecture is that in Italy stone masonry with timber roofs had been preferred instead of the fully wooden structure. However, with the continuous exploration of how to strengthen the anti-seismic structure, the Italian technicians figured that it is important to enhance the anti-seismic role of timber roofs by reducing their possible movement, which is to strengthen the connection of the timer roof and the load-bearing walls (Campisi and Scibilia, 2015). In addition, during the reconstruction of damaged buildings, some timber devices were widely used to reinforce the masonry since they are faster to construct.

Early examples of the use of wooden frames in masonry could be dated back to the Roman technique "*Opus craticium*", which used timber frames with diagonal elements to strengthen partitions. The House of Opus Craticum in Herculaneum (see figure 73 left) proved this technique was already used in 79 A.D. (Lavan et al, 2007). Although as Vitruvius pointed out its high flammability was an obvious drawback of the "*Opus craticium*", it continued being used since it was easier to apply in construction. In the 18 century, the "*Gaiola Pombalina*" system (see figure 73 right) was created after the earthquake (M = 8.5–9) in Lisbon in 1755. Based on the "*Opus craticium*" technique, the "*Gaiola Pombalina*" system further aimed at inserting an interior timber frame not only to enhance a single wall but created an additional timber structure connected with external walls to support the whole architecture (Carocci et al, 2021). Similar to the role of tenon and mortise joints in Chinese architecture, the "Gaiola Pombalina" system is also flexible as the columns and beams were connected to the walls through dowels and tenons (Campisi and Scibilia, 2015) which could absorb part of seismic force by deforming and displacing.

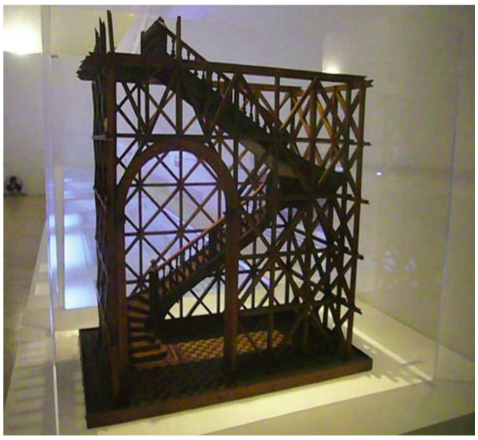


Figure 73: Left: House of Opus Craticum in Herculaneum (Archive, 2012); Right: "*Gaiola Pombalina*" system ((Instituto Superior Técnico de Lisboa)

With this combination of internal timber frame with external masonry, the building could still be support by timber frame even if the masonry got destroyed by the seismic force. Another similar system in Italy was the "*Baraccato*" system which was considered one of the most typical anti-seismic structures (Pagano et al, 2018). The system was born after the earthquake (M=6.9) in Calabria in 1783, according to analysis and assessments of damaged buildings after the earthquake, the low quality of masonry was considered the main cause of the collapsing of buildings. Giovanni Vivenzio noticed the good performance of the combination of timber frame and masonry and proposed his design Casa formata in legno (house made in wood) (see figure 74). Based on the aim of creating an inner secondary supporting frame, Vivenzio's design further shows the primary and secondary components. As Pagano et al discussed in the article (2018), the primary frame consists of vertical elements that continued from the foundation to the roof and then the horizontal and diagonal elements were inserted at the floor levels, and finally, the secondary layer of timber frames was placed around the openings. Different from the Portuguese technique, for large public architecture the "*Baraccato*" system used double timber frames both inside and outside the masonry while for small scale buildings the system was built inside the masonry.

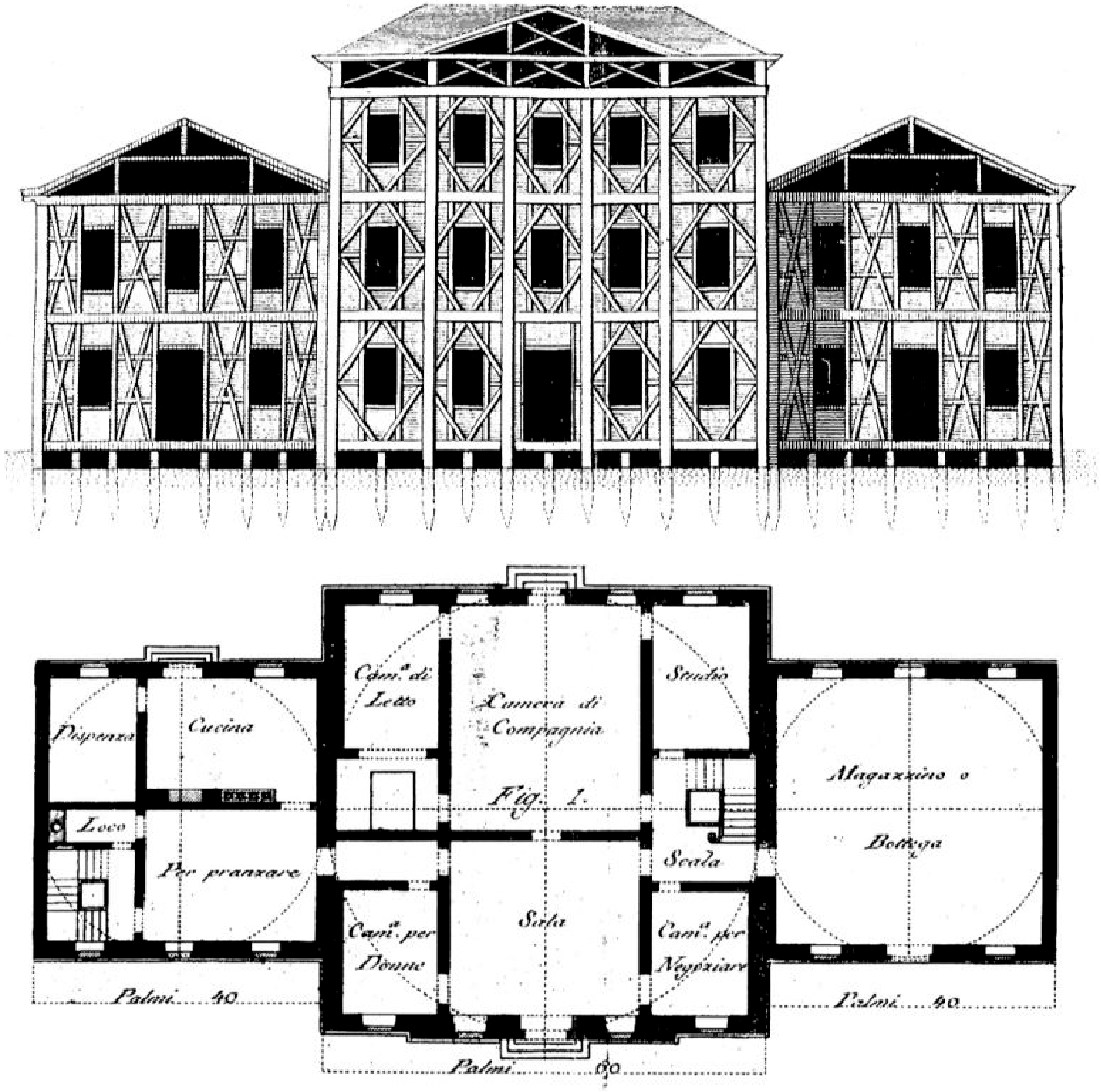


Figure 74: Casa formata in legno (Vivenzio, 1783)

The Bourbon government promulgated regulations specificity on the use of the "*Baraccato*" system and then it lasted for the 18 and 19 centuries as the well-known anti-seismic technique in Italy. Different from the Portuguese technique, for large public architecture the "*Baraccato*" system used double timber frames both inside and outside the masonry while for small-scale buildings the system was built inside the masonry. Moreover, similar to the role of tenon and mortise joints in Chinese architecture, the "*Gaiola Pombalina*" system is also flexible as the columns and beams were connected to the walls through dowels and tenons (Campisi and Scibilia, 2015) which could absorb part of seismic force by deforming and displacing.

Another technique is "*Radiciamenti*"[24] which is not just improving the quality of masonry but enhancing the connection among each part of the building. This technique was applied first after the L'Aquila earthquake (M=6.7) in 1703. The "*radiciamenti*" are the wooden elements that are inserted through masonry to hold the whole building (see figure 75), which normally were pure wooden structures, however, when considering large scale buildings or more significant buildings the use of "*radiciamenti*" was combined with metal anchors. Usually the "*radiciamenti*" were placed at the floor levels or near the openings which were seen as the weak point of the structure to ensure the continuity of the building. The technique "impalettature" appeared to aim to better connect the roof with the walls. It could be seen as an anchor system where the structural elements are interlocked, in the area of L'Aquila, the truss roofs combined with the "*impalettature*" technique were widely used (Carocci et al, 2021). The main aim of both "*radiciamenti*" and "*impalettature*" is to let the wooden elements work as tie rods to improve the integrity of the roof and the rest part of the building and solve the problem of thrust. However, since the truss itself already has the advantage of eliminating side thrusts by the tie beam connected to rafters, the "*impalettature*" might be seen as a further improvement of this advantage by strengthening the connection between the truss and walls.

Figure 75: Left:"*radiciamenti*" (Cangi, 2009); Middle: Pure wooden "*radiciamenti*" in Villa Sant'Angelo (Carocci et al, 2021); Right: The use of "*radiciamenti*" with metal anchors in Chiesa di San Flaviano (Carocci et al, 2021).

From above it could be seen that the anti-seismic approaches in ancient Chinese architecture focused mainly on strengthening the joint nodes especially introducing the Dougong components as semi-rigid connections. In addition, with the unique property of self-recovering after the deformation of the wood, part of the seismic force could be absorbed in the joints. While the Italian approaches aimed first at improving the quality

[24] The word "*radice*" means root. The name of this technique could probably come from its function of inserting wooden components into the walls like taking roots.

of the masonry and then also the connection between the timber roof and the walls. The "*Gaiola Pombalina*" and "*Baraccato*" systems tend to construct an internal wooden frame as the secondary support so that even though the masonry was destroyed by earthquakes, this internal frame could still support the roof structure. While the "*radiciamenti*" and "*impalettature*" are techniques that focus more on the connection of different parts of the building.

7. Conclusion

With the good performance of wood material, timber roofs have important roles in both Italian and Chinese architecture. In Italy, from the post and lintel roof to truss roof showed the relationship between the evolution construction and the development of geometry and mechanics. The development of trusses further becomes a fundamental condition for increasing the span. In China, timber roof constructions were various in different scales, functions and locations of architecture. Additionally, Dougong as the most important representation of ancient Chinese architecture, has changed during dynasties especially in the size and from a structural function to a decorative function.

In conclusion, the differences between traditional Italian and Chinese roof construction can be found in structures, shapes, materials etc. The reason that caused those differences could be mainly because of the difference in woodworking technique, selection of materials and traditional and local ideas.

In Italy, the development of the truss structure is a process of continuous exploration. In early periods, progress is summed up by the craftsmen from construction experience, however, the development of architecture is not only influenced by tools and craftsmanship, but also by the development of mathematics and geometry (Rinke and Kotnik, 2010). From the construction logic, after the 19 century the development of carpentry in Italy relied on science and mechanics.

The influence of a science-based perspective on structural characteristics shows the change from a construction that was theory-oriented to one that was craftsmanship-oriented, which was intended to be logical, methodical, and extremely effective. On the contrary, in China, it was mostly based on tradition over generations. Besides, under Chinese feudal ethics, innovation was not advocated. Taking roof construction as an example, Italian architects focus on structural stress and how to improve it by changing the geometric relationship between parts; In China, the overall structure and appearance did not change over the years, architects worked more on perfection in details.

From another aspect, Italian wood roofs were constantly increasing in span. From the beginning of large public and religious buildings and basilica in ancient Rome to the need for large scale churches in the Middle Ages, the invention and development of timber trusses were aimed to solve the problem of free span. Different from Italian religious architecture which represented theocracy in a single architecture, Chinese architecture focused more on the layout of building groups. For example, even the highest hierarchy level hall only needed to be outstanding in its building group. Therefore, there was no such requirement for a larger span in ancient China and the basic roof structure did not change, hence the overall structure (eg: the Tailiang system) did not change much over history.

However, there are also some similarities between traditional Italian and Chinese timber roofs. The tenon and mortise joint was found in both cases, which proved the knowledge of the good connection of wooden elements in both countries. It showed also the use of timber frames in anti-seismic approaches, both in the Chinese case of enhancing the joint nodes of the original timber frame and in the Italy case of combining the timber frame with the masonry. Furthermore, dating back to the post and lintel roof periods, the roof structure could be considered similar to the Chinese Tailiang system. Later, with the requirement of increasing span, the generation of trusses changed the roof construction in Italy. Although there is no proof of the use of truss structures in ancient Chinese architecture, it was still introduced in China during the Christian inculturation in the 19 century. It can be surmised that with the cultural communication and spreading of the concept of the architecture of both countries, the advantage of the material wood and its use in construction has been continuously enhanced and both the timber construction in Italy and China have developed their own identity.

Glossary

Capriata: Truss

Capriata semplice: Truss without post

Capriata semplice con monaco: King post truss

Capriata semplice con saette: King post truss with braces

Capriata composta alla Palladiana: Queen post truss with braces

Capriata composta: Queen post truss

Capriata con nodo chiuso: Closed joint truss

Capriata con nodo aperto: Open joint truss

Catena: Tie beam

Colmo: Ridge beam

Monaco: King post

Puntone: Rafter

Saette: Struts

Sottopuntone: Secondary rafter

材份制 (Cai-Fen): Carpentry module system in the Song dynasty

侧脚 (Ce Jiao): Inclinating the corner columns inward

叉手 (Chashou): A “truss” formed structure in Chinese roof

穿斗 (Chuandou): Chinese roof system of beam connecting column in middle

斗拱 (Dougong)/ 铺作 (Puzuo): Chinese brackets

举折 (JuZhe): Folded roof shape

人字拱 (Renzi Gong): A triangle formed Gong

升起 (Shengqi): Increasing the columns heights from central to corners

蜀柱 (Shuzhu): A “post” formed structure in Chinese roof, find together with Chashou

榫卯 (Sun-Mao): Tenon and mortise connection

抬梁 (Tailiang): Chinese roof system of beam support by column and connect to the purlins

营造法式 (YingZaoFaShi): Manuel book for building standard in the Song dynasty

Chronology: Chinese Dynasties and Periods

Xia (夏): 2100-1600 B.C.

Shang (商): 1600-1100 B.C.

Zhou (周): 1100-221 B.C.

Western Zhou (西周): 1100-771 B.C.

Spring and Autumn period (春秋): 770-476 B.C.

Warring states period (战国): 475-221 B.C.

Qin (秦): 221-207 B.C.

Han (汉): 206 B.C.- 220 A.D.

Three Kingdom (三国): 220-265

Jin (晋): 265-420

Northern and Southern Dynasties (南北朝): 420-589

Sui (隋): 581-618

Tang (唐): 618-907

Five Dynasties (五代): 907-960

Song (宋): 960-1279

Northern Song (北宋): 960-1127

Southern Song (南宋): 1127-1279

Liao (辽): 916-1125

JIn (金): 1115-1234

Yuan (元): 1271-1368

Ming (明): 1368-1644

Qing (清): 1644-1911

Bibliography

Adam, Jean-Pierre. *Roman Building, Materials and Techniques.* (London: Routledge, 1999)

Aluisetti, Giulio and Pizzogalli, Felice. *Dell' Arte Pratica Del Carpentiere*. (Milano: Ponte Di S. Marco, 1827)

Barbisan, Umberto; Laner, Franco. *Capriate e tetti in legno: progetto e recupero : tipologie, esempi di dimensionamento, particolari costruttivi, criteri e tecnologie per il recupero, manti di copertura*. (Milano: Angeli, 2000.)

Barry, Fabio. *The Pediment of the Pantheon. Problems and Possibilities*, per Scritti sopra orgoglio di Lucos Mitilo. (Rome: Edizioni Quasar, 2014)

Benvenuto, Edoardo. *La Scienza Delle Costruzioni E Il Suo Sviluppo Storico*. p:778. (Firenze: Sansoni, 1981)

Bertolini Cestari, Clara; Marzi, Tanja; Seip, Elisabeth and Touliatos, Panos (eds). *Interaction between Science, Technology and Architecture in Timber Construction Proceedings of Culture 2000 Project Greek, Norwegian and Italian Action*. (Paris: Elsevier, 2004.)

Bertolini Cestari, Clara and Marzi, Tanja. "Conservation of historic timber roof structures of Italian architectural heritage: diagnosis,assessment, and intervention". *International Journal of Architectural Heritage: Conservation, Analysis, and Restoration*. Vol.12, No.4. (2018). pp: 632-665
https://www.tandfonline.com/doi/full/10.1080/15583058.2018.1442523

Bertolini Cestari, Clara; Invernizzi, Stefano; Marzi, Tanja and Spano, Antonia. "Numerical survey, analysis and assessment of past interventions on historical timber structures: The roof of Valentino Castle". Jasieńko, Jerzy and Nowak, Tomasz (eds). *Structural Health Assessment of Timber Structures*. (Wrocáaw: DolnoĞląskie Wydawnictwo Edukacyjne, 2015)

Bettiol, Giulia; Menichelli, Claudio; Valluzzi, Maria Rosa; Garbin, Enrico and Modena, Claudio. "Structural analysis of the timber roofs of the "Arsenale" of Venice". Conference: 10th World Conference on Timber Engineering. (Miyazaky, 2008)
https://www.research.unipd.it/handle/11577/2436605?mode=complete

Breymann, Gustav Adolf. *Trattato Generale Di Costruzioni Civili*. (Milano: Di Baio, 1985)

Brunetti, Gian Luca. *Coperture Tecnologie Materiali Dettagli*. (Milano: Wolters Kluwer Italia, 2012.)

Campbell. James W. P. "Wren and the development of structural carpentry 1660–1710". *Architectural Research Quarterly,* 6(1). (Cambridge: Cambridge University Press, 2002)

Campisi, Tiziana and Scibilia, Federica. "The Use of Wood with an Anti-seismic Function in the Architecture of Palermo During the 18th Century". Historical Earthquake-Resistant Timber Framing in the Mediterranean Area. Lecture Notes in Civil Engineering, Volume 1. (Switzerland: Springer International Publishing, 2015)
https://www.academia.edu/28740182/The_use_of_wood_with_an_antiseismic_function_in_the_architecture_of_Palermo_during_the_18th_century

Cangi, Giovanni. "Murature tradizionali e terremoto - Analisi critica del danno come presupposto per il recupero e la ricostruzione dell'edilizia storica danneggiata dal sisma in Abruzzo." Conference: Restaurare dopo il terremoto. (Pescara, 2009)
https://didattica-2000.archived.uniroma2.it//PARE/deposito/Reportage_Abruzzo_-_prof_Giovanni_Cangi.pdf

Carocci, Caterina F.; Macca, Valentina and Tocci, Cesare. "The roots of the 18th century turning point in earthquake-resistant building". *History of Construction Cultures*. Vol, 2. (Leiden: CRC Press/Balkema, 2021)

"Carpentry – [Plates I-XXVII]." *The Encyclopedia of Diderot & d'Alembert Collaborative Translation Project. Translated by Ann-Marie Thornton.* (Ann Arbor: Michigan Publishing, University of Michigan Library, 2012). Original from *Encyclopédie ou Dictionnaire raisonné des sciences, des arts et des métiers*, vol. 2. (Paris: 1765)

Ceserani, Giovanna; Caviglia, Giorgio; Coleman, Nicole; De Armond, Thea; Murray, Sarah and Taylor-Poleskey, Molly. “British Travelers in Eighteenth-Century Italy: The Grand Tour and the Profession of Architecture”. *American Journal of Ophthalmology*. 122 (2). (Oxford: Oxford University Press, 2017)
https://www.researchgate.net/publication/316114477_British_Travelers_in_Eighteenth-Century_Italy_The_Grand_Tour_and_the_Profession_of_Architecture

Chen, Mingda. “*独乐寺观音阁、山门的大木作制度* [The Woodworking System of Guanyin Pavilion and Mountain Gate in the Dule Temple]”. *建筑史论文集 [Essays on the History of Architecture]*. (Beijing: Tsinghua University Press, 2002)

Coomans, Thomas and Xu, Yitao. “Gothic Churches in Early 20th-Century China: Adapting Western Building Techniques to Chinese Construction Tradition”. Proceedings of the Fifth International Congress on Construction History. (Chicago: Construction History Society of America, 2015)

Coomans, Thomas. “East Meets West on the Construction Site. Churches in China,1840s-1930s”. *Construction History*. Vol 33, Issue 2, pp: 63–84. (2018)
https://www.jstor.org/stable/26562566.

Coradeschi, Ginevra; Beltrame,Massimo; Rafanelli, Simona; Quaratesi, Costanza; Sadori, Laura and Barrocas Dias,Cristina.. "The Wooden Roof Framing Elements, Furniture and Furnishing of the Etruscan Domus of the Dolia of Vetulonia (Southern Tuscany, Italy)". *Heritage* 4, no. 3: 1938-1961. p: 1950. (2021)
https://doi.org/10.3390/heritage4030110

Crocetti, Roberto. “Large-Span Timber Structures”. Conference: Proceedings of the World Congress on Civil, Structural, and Environmental Engineering. (Prague: 2016)
http://avestia.com/CSEE2016_Proceedings/files/paper/ICSENM/124.pdf

Dalla Costa, Mario; Lugato, Dario and Ruol, Matilde. *L’ Arsenale Di Venezia Una Metodologia per La Conservazione*. (Milano: Città Studi Edizioni, 1994)

Dinsmoor, William Bell. *Observations on the Hephaisteion*. (Princeton: American School of Classical Studies, 1975)

Dipartimento della Protezione Civile, 2022.
https://rischi.protezionecivile.gov.it/static/c7650fa8eac014a28ef074236bb234f7/mappa-classificazione-sismica-aggiornata-al-31-marzo-2022-provincia.pdf

Ferretti, Francesca; Pozza, Luca and Talledo, Diego Alejandro. "Robustness Analysis of Historical Timber Roofs: A Case Study of the Gaggiandre Shipyard at the Arsenale of Venice". *Buildings*. Vol.12, No.11. (2022)
https://www.mdpi.com/2075-5309/12/11/1773/htm

Fu, Xinian. *中国古代建筑工程管理和建筑等级制度研究 [A study of ancient Chinese construction project management and building hierarchy]*. (Beijing: China Architecture & Building Press, 2012)

Gandolfo, Domenico and Regia Scuola D' Applicazione per Gli Ingegneri in Torino. *Studi Sulle Congiunzioni Dei Legnami: Dissertazione E Tesi Presentate Alla Commissione Esaminatrice Della R. Scuola D' Applicazione Degli Ingegneri Di Torino*. (Genova : Mambilla, 1869)

Giordano, Guglielmo. *Tecnica Delle Costruzioni in Legno*. (Milano: Hoepli, 1999)

Gao, Dafeng; Zhao, Hongtie and Xue, Jianyang. "*木结构古建筑中斗栱与榫卯节点的抗震性能——试验研究* [Seismic performance of Dougong and mortise nodes in timber frame ancient buildings - an experimental study]". *Journal of Natural Disasters*. Vol.17, No.2. (Beijing: Science Press, 2008)
https://www.cnki.com.cn/Article/CJFDTotal-ZRZH200802012.htm

Giovanetti, Francesco. *Manuale del Recupero del Comune di Roma*. 2. Ed. Ampliata ed. (Roma: Tipografia Del Genio Civile, 1997)

Global Earthquake Hazard Map (2018)
https://www.globalquakemodel.org/gem-maps/global-earthquake-hazard-map

Guardigli, Luca. "Long span timber construction in Northern Italy from the sixteenth to the nineteenth century". Conference:CHS Sixth Annual Conference. (Cambridge: 2021) https://www.researchgate.net/publication/348778956_Long_span_timber_construction_in_Northern_Italy_from_the_sixteenth_to_the_nineteenth_cen-_tury

Hao, Ruisheng. "*中国传统古建筑对北方寒冷地区气候适应性探究——以太原市纯阳宫为例* [Climate Adaptation Research of Traditional Chinese Ancient Architecture in Northern Cold Region: Chunyang Palace, Taiyuan]". *Design & Research*. Vol, 4. (Beijing: Asia-Pacific Construction Science and Technology Information Research Institute, 2014)

He, Junxiao; Wang, Juan and Yang, Qingshan. "*摇摆状态下古建筑木结构木柱受力性能分析及试验研究* [Analysis and experimental study of the stressing performance of wooden columns of ancient buildings under swaying conditions]". *Engineering Mechanics*.Vol.34, No.11. (Beijing: Journal of Engineering Mechanics, 2017) https://pubs.cstam.org.cn/data/article/em/preview/pdf/20171107.pdf

Hodge, Trevor. *The Woodwork of Greek Roofs*. (Cambridge: Cambridge University Press, 1960)

Holzer, Stefan M. "The Polonceau Roof and its Analysis". *The International Journal for the History of Engineering & Technology*. Vol.80, No.1. (Oxfordshire: Taylor and Francis Ltd., 2010)

Kim, Young Jae and Park, Sungjin. "Tectonic Traditions in Ancient Chinese Architecture, and Their Development". *Journal of Asian Architecture and Building Engineering*. (2017) https://www.tandfonline.com/doi/pdf/10.3130/jaabe.16.31

Kjerulf, Hjalmar. *Heddal stavkirke*. (1848) https://www.nasjonalmuseet.no/en/collection/object/NG.K_H.B.06314

Klein, Nancy L. "Evidence for West Greek Influence on Mainland Greek Roof Construction and the Creation of the Truss in the Archaic Period." *Hesperia: The Journal of the American School of Classical Studies at Athens* 67, no. 4. pp: 335-336. (New Jersey: The American School of Classical Studies at Athens,1998) https://doi.org/10.2307/148449

Koolhaas, Rem, Stephan Trüby, Harvard University Graduate School of Design Scuola Di Design, and Office for Metropolitan Architecture AMO Ramo Progettuale. *Elements of Architecture*. (Köln: Taschen, 2018)

Lavan, Luke; Özgenel, Lale; Sarantis, Alexander; Ellis, Simon and Marano, Yuri. *Housing in Late Antiquity from Palaces to Shops.* Late Antique Archaeology 3.2. (Leiden: Brill, 2007)

Letarouilly, Paul-Marie. *Basilica di San Paolo fuori le mura*. (1849) https://digital-exhibits.library.nd.edu/44f213dbe9/exploring-architecture-through-early-publications/items/69725309d9

Li, Donglin, Jin, Yaqin and Xiang, Qibai. "*我国楠木属植物资源的地理分布、研究现状和开发利用前景* [The Geographical Distribution Research Status and Developmental Utilization Prospect of Phoebe Nees Plant Resource of Our Country]". *Journal of Fujian Forestry Science and Technology*. Vol. 31, No. 1. (Fuzhou: Fujian Science and Technology Press, 2004)

Li, Jie. *营造法式 [YingZaoFaShi]*. (Beijing: People's Press, 2006)

Li, Qianlang. *穿墙透壁*: *剖视中国经典古建筑 [Through the Walls: A look at classic Chinese architecture]*. (Guilin: Guangxi Normal University Press, 2009)

Li, Xianda and Liu, Yu. "The "shape" and "meaning" of the roof arts in Chinese classical architecture". Conference: 3rd International Conference on Energy Materials and Environment Engineering. (Bangkok: 2017)

Liang, Sicheng. *中国建筑史 [A history of Chinese Architecture]*. (Tianjin: Baihua Edition, 2005)

Liang, Sicheng. *A Pictorial History of Chinese Architecture*. (London: MIT, 1984)

Liang, Sicheng. "*蓟县独乐寺观音阁山门考* [Examination of Guanyin pavilion and Mountain Gate of Dule Temple in Jixian]". *中国营造学社汇刊 [Journal of the China Construction Society]*, 3 (2). (Beijing: China Construction Society, 1932)

Liang, Sicheng. "*记五台山佛光寺建筑* [Record of the Architecture of the Foguang Temple in Wutai Mountain] ". *中国营造学社汇刊 [Journal of the China Construction Society]*, 7(1). (Beijing: China Construction Society, 1944)

Liang, Sicheng. "*正定调查纪略* [A brief survey of Zhengding]". *中国营造学社汇刊 [Journal of the China Construction Society]*, 4(2). (Beijing: China Construction Society, 1933)

Liotta, Giovanni. *Gli insetti e i danni del legno. Problemi di restauro.* (Firenze: Nardini Editore, 1994)

Liu, Dunzhen. *中国古代建筑史 [History of Ancient Chinese Architecture]*. pp: 4-5. (Beijing: China Architecture & Building Press, 1984.)

Liu, Kai; Liao, Shunbao and Zhang, Sai. "*中国地震发生频率与烈度的空间分布*[Spatial distribution of frequency and intensity of earthquakes in China]". *Progress in Geography*. Vol.27, No.3.(Beijing: Science Press, 2008)
http://sourcedb.igsnrr.cas.cn/zw/lw/200906/P020090625754610606153.pdf

Liu, Laurence G. *Chinese Architecture*. (London: Academy Editions, 1980)

Liu, Yan and Yang, Jun. "*独乐寺辽代建筑结构分析及计算模型简化* [Structural Analysis and Simplification of the Calculation Model of the Liao Dynasty Architecture Dule Temple]". *Journal of Southeast University (Natural Science Edition)*, Vol. 37, No. 5. (Nanjing: Southeast University Press, 2007)

Ma, Bingjian. *中国古建筑木作营造技术 [Chinese ancient architecture and wooden construction technology]*. (Beijing: China Science Publishing & Media, 1991.)

Ma, Zimi; Jia, Chunhua; Guo, Jin; Gu, Haorong and Miao, Yanhuan. "Features analysis of five-element theory and its basal effects on construction of visceral manifestation

theory”. *Journal of Traditional Chinese Medicine*. 34(1).
https://reader.elsevier.com/reader/sd/pii/S0254627214600649?token=0445EE8DBA8064EF14CE3BA8E3FB7905D90AC94C44C1731B2376CAF5B3C1F3AC9B596B7D825192227988C42EE09305FC&originRegion=eu-west-1&originCreation=20221109105957

Macchioni, Nicola; Fabbri, Rita; Casali, Valeria and Crivellaro, Alan. “Strutture lignee di copertura a Ferrara fra fine ‘400 e fine ‘600: analisi dei sistemi costruttivi, identificazione delle specie legnose e studio delle marche incise nel legno”. Conference: Dalla conoscenza e dalla caratterizzazione dei materiali e degli elementi dell’edilizia storica in muratura ai provvedimenti compatibili di consolidamento. (Milan: 2004)
https://www.researchgate.net/publication/285592285_Strutture_lignee_di_copertura_a_Ferrara_fra_fine_%27400_e_fine_%27600_analisi_dei_sistemi_costruttivi_identificazione_delle_specie_legnose_e_studio_delle_marche_incise_nel_legno

Macchioni, Nicola and Mannucci, Massimo.“The assessment of Italian trusses: survey methodology and typical pathologies”. *International Journal of Architectural Heritage*: *Conservation, Analysis, and Restoration*. Vol.12, No.4. (2018)
https://www.tandfonline.com/doi/full/10.1080/15583058.2018.1442516?scroll=top&needAccess=true

Martin, Bruce. *Joints in Buildings*. (London: George Godwin Ltd, 1977).

Martini, Felice. *Progetti e lavori pel riordinamento ed ingrandimento dell'arsenale marittimo di Venezia, memoria del Maggior generale Felice Martini redatta al incarico del Ministero della Marina*. (Venice: Stabilimento Tipografia di G. Antonelli, 1877)

Meijs, Maarten and Knaach, Ulrich. *Components and Connections Principles and Construction*. (Basel/Boston/Berlin: Birkhäuser, 2009)

Menichelli, Claudio. et al. “Le strutture lignee dell'Arsenale di Venezia. Studi e restauri”. Conference: Internazionale Scienza e Beni Culturali - Conservare e restaurare il legno. (Bressanone: Arcadia Ricerche, 2009)

Nenci, Elio. *Bernardino Baldi’s in Mechanica Aristotelis problemata Exercitationes*. (Berlin: Edition Open Access, 2011)

Nicholson, Peter. *The Carpenter and Joiner's Assistant*. p:28. (England: J. Taylor, 1810)

Pagano, Enrico; Salerno, Ginevra and Zampilli, Michele."The baraccato anti-seismic constructive system: enhancement and preservation of the existing heritage in southern Italy". In 6th International Conference on Heritage and Sustainable Development. (Granada: Editorial Universidad de Granada Campus, 2018) https://www.academia.edu/36868425/The_baraccato_anti_seismic_constructive_system_enhancement_and_preservation_of_the_existing_heritage_in_southern_Italy

Pan, Dehua. *斗拱 [Dougong]*. (Nanjing: Southeast University Press, 2017.)

Pan, Guxi. *中国建筑史 [A History of Chinese Archietcture]*. (Beijing: China Architecture & Building Press, 2014)

Pan, Yiting and Campbell, James W. P. "A Study of Western Influence on Timber Supply and Carpentry in South China in the Early 20th Century". *Journal of Asian Architecture and Building Engineering*. (2017) https://www.tandfonline.com/doi/citedby/10.3130/jaabe.16.247?scroll=top&needAccess=true

Pryce, Will. *Architecture in Wood: A World History*. (London: Thames & Hudson, 2016)

Putzolu, Rossella and Bosch, Montserrat. "The 19th century iron architecture of industrial buildings. A formal and constructive comparison between two case studies". Conference: International Conference on Heritage and Sustainable Development. (Granada: 2018)

Que, Zeli; Li,Zherui; Zhang, Xiaolan; Yuan, Ziye and Pan, Biao. "Traditional Wooden Buildings in China''. *Wood in Civil Engineering*. (London: IntechOpen, 2017)

Rinke, Mario and Kotnik, Toni. "The changing concept of truss design caused by the influence of science." Conference: International Conference on Structures and Architecture. (Guimaraes, 2010) https://www.researchgate.net/publication/335542682_The_changing_concept_of_truss_design_caused_by_the_influence_of_science

Ripley, Renee L.and Bhushan, Bharat. “Bioarchitecture: Bioinspireds Art and Architecture—a Perspective.” *Series A: Mathematical, Physical, and Engineering Sciences 374*, no. 2073. (London: Royal Society, 2016)
https://royalsocietypublishing.org/doi/10.1098/rsta.2016.0192

Roberts, David. *Image of Monastery of St. Catherine beneath Mount Sinai*. Coloured lithograph by Louis Haghe after in 1849.
https://wellcomecollection.org/works/abda3s2r

Solarino, Fabio; Oliveira, Daniel V. and Giresini, Linda. “Wall-to-horizontal diaphragm connections in historical buildings: A state-of-the-art review”. Engineering Structures. (2019)
https://www.researchgate.net/publication/335609666_Wall-to-horizontal_diaphragm_connections_in_historical_buildings_A_state-of-the-art_review

Soprintendenza Archeologia, belle arti e paesaggio per il Comune di Venezia e Laguna archive.
http://www.soprintendenza.venezia.beniculturali.it/it/restauri/Cantieri/arsenale-di-venezia-tese-allisolotto/arsenale_tese

Strickland, Carol and Handy, Amy. *The Annotated Arch:A Crash Course in the History of Architecture*. (Kansas City, Missouri: Andrews McMeel Pub, 2001)

Tampone, Gennaro. Legno e Restauro. *Ricerche e Restauri su Architetture e Manufatti Lignei*. (Firenze: Messaggerie Toscane, 1996.)

Tang, Guohua. “*中国传统大屋顶排雨特点初探* [A Preliminary Study on the Characteristics of Chinese Traditional Large Roofs for Draining Rain]”. *Journal of South China Construction University West Campus*, Vol. 4, No. 2. (Guangzhou: South China Construction Institute West Campus, 1996)

Tegel, Willy; Elburg, Rengert; Hakelberg, Dietrich; Stäuble, Harald and Büntgen, Ulf. “Early Neolithic Water Wells Reveal the World's Oldest Wood Architecture”. *PLoS ONE*, 7(12). (2012)

https://doi.org/10.1371/journal.pone.0051374

Timber Frame Engineering Council. *Design Guide for Timber Roof Trusses*. (Alstead: 2020) https://dcstructural.com/wp-content/uploads/2020/09/TFEC-4-2020-Design-Guide-for-Timber-Roof-Trusses.pdf

Ulrich, Roger B. *Roman Woodworking*. (New Haven: Yale University Press, 2007)

Valcanover, Francesco, Wolfgang, Wolters and Istituto Veneto Di Scienze, Lettere Ed Arti. "La carpenteria lignea dei secoli XIV e XV". *L' Architettura Gotica Veneziana: Atti Del Convegno Internazionale Di Studio, Venezia, 27- 29 Novembre 1996*. (Venice: Istituto Veneto Di Scienze, Lettere Ed Arti, 2000)

Valeriani, Simona. "Monaci, dardi e colonnelli: genesi e caratteristiche delle capriate italiane". *Actas del Cuarto Congreso Nacional de Historia de la Construcción*. (Madrid: Sociedad Española de Historia de la Construcción, 2005) https://www.sedhc.es/biblioteca/paper.php?id_p=877

Valeriani, Simona. "The Roofs of Wren and Jones: A Seventeenth-Century Migration of Technical Knowledge from Italy to England". Conference: The Nature of Evidence: How Well Do 'Facts' Travel?. (London: 2006)

Valeriani, Simona. "Facts and Building Artefacts: What Travels in Material Objects?". *How Well Do Facts Travel?: The Dissemination of Reliable Knowledge*. (Cambridge: Cambridge University Press, 2012) https://www.cambridge.org/core/books/abs/how-well-do-facts-travel/facts-and-building-artefacts-what-travels-in-material-objects/F371ADE39B170158169713664BBA9519

Vivenzio, Giovanni. I*storia E Eoria De Tremuoti in Generale ; Ed in Particolare Di Quelli Della Calabria, E Di Messina Del MDCCLXXXIII*. (Napoli: Stamperia Regale, 1783)

Wen, Jing. "*中日寺庙建筑构架中世化过程的比较研究* [A comparative study on the structural medievalization of medieval architecture in China Japan]". Conference: Annual Meeting and Symposium of the Chinese Society of Architectural History. (Fuzhou: 2014)

Yang, Hongxun. "*斗拱起源考察* [Examination of the origins of the Dougong]". *杨鸿勋建筑考古学论文集 [The Collected Papers on Architectural Archaeology of Yang Hongxun]*. (Beijing: Tsinghua University Press, 2008)

Yeomans, David. "Inigo Jones's roof structures". *Architectural History*. Vol. 29. (Cardiff: SAHGB Publications Limited, 1986)

Yeomans, David. *The repair of historic timber structures*. (London: Institution of Civil Engineers, 2015)

Zamperini, Emanuele. "Structural Analysis of Timber Trusses in Italy (1800–1950)". Conference: Physics, Astronomy and Engineering. Critical Problems in The History of Science. 32nd International Congress of the Italian Society of Historians of Physics and Astronomy. (Rome: 2012) https://www.researchgate.net/publication/265727552_Structural_Analysis_of_Timber_Trusses_in_Italy_1800-1950

Zamperini, Emanuele. "Timber trusses in Italy: the progressive prevailing of open-joint over closed-joint trusses". Conference: 5th International Congress on Construction History. (Chicago: 2015) *https://www.researchgate.net/publication/278036950_Timber_trusses_in_Italy_the_progressive_prevailing_of_open-joint_over_closed-joint_trusses*

Zwerger, Klaus. *Wood and Wood Joints: Building Traditions of Europe, Japan and China*. 2. Aufl. ed. (Basel/Berlin/Boston: Birkhäuser Verlag, 2012)

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