Structural Mechanism and Morphology of Timber Towers in Japan

Masaru Abe¹ and Mamoru Kawaguchi²

¹Lecturer, Department of Architecture, Faculty of Engineering, Hosei University, Japan
²Professor, Department of Architecture, Faculty of Engineering, Hosei University, Japan

Abstract

The tower of Hohryuji, a typical traditional five-storied pagoda built approximately 1,300 years ago, plays an important role as a religious symbol, but it is also a great cultural asset for the harmony of its inventive high standard of traditional carpentry technology and its morphological beauty. There still exists over 300 of this kind of architecture in Japan today, and are considered as one of the typical Japanese beauty. The morphologies of our traditional timber towers are characterized by the tower’s height, and the deep carvings formed by piling roofs projecting outward from its slender body in triples and quintuples. By using data from restoration reports and making models of the traditional timber towers, this paper will focus on their unique morphology and their structures, and investigate their relationship to interpret those special qualities.

Keywords: timber towers; structural mechanism; morphology; structure of eaves; pagodas

1. Introduction

The attractiveness of Japanese timber towers exists in their height and its perpendicular directivity, representing the spiritual stretching out of their tips into the sky. Five-storied pagoda, Kyohgokokoji, in Kyoto that is said to be the largest of the existing timber towers, is over 54m high. Sohrin that covers 1/3 ~ 1/4 of the total height of the towers symbolizes the Buddha’s ashes (Busshari) and it is simultaneously an important factor in making us aware of its perpendicular directivity.

The one and most important morphological factor in the construction of pagodas is the very deep projecting span of eaves. According to the plan, of the square area that covers the edges of the eaves of a story the proportion of the main body is less than 1/4. The

Fig.1. The West Tower of Yakushiji

Fig.2. Skeleton of Yakushiji’s Tower

Fig.3. Yakushiji’s Sohrin
remaining space is what is referred to as projection of eaves (noki-no-de). This is a kind of architecture where such deep carvings create the unique exterior space not seen elsewhere in the world.

What is more important is the technical design that constructs this projection of eaves. This is mainly done by cross assembling blocks (masu), and arms (hijiki) and the use of rafters (taruki). Of all, the most important thing is that these are not simply decorations, but the most constructive design based on the statics of the way the eaves are held (Figs. 1, 2).

2. Formation of Timber Towers
2-1. Formation of Wooden Pagoda
Wooden pagodas in Japan are all Buddhist pagoda, having its origin in the Indian stupa. The name pagoda (toh) is also a Chinese transliteration of stupa. It changed from sotohba to tohba, and to toh. Therefore it can be thought that a wooden pagoda is a combination of the Indian stupa and multi-storied wooden buildings (roukaku architecture) originating in China with sohrin, a symbolized stupa placed on the tip of the tower. This was probably imported to Japan in almost the exact style.

There is a central pillar directly under the sohrin (Fig. 3) which is a symbolical expression of a stupa, which has its tip digging into the axial tube of the sohrin, just like a pen with its cap. The central pillar is most important, because it has a spiritual meaning as the resting place of the Buddha. Spiritually the central pillar can be considered as the entire pagoda. Therefore the remaining part of the pagoda protects the central pillar, and has been considered important to equip itself appropriately to declare the presence of the Buddha’s ashes.

This is seen well through the construction method of wooden pagodas. Four pillars (shiten-bashira) surround the central pillar (shin-bashira), and on the outside there are side pillars (gawa-bashira). The frame of the pagoda is formed by placing lateral members (yokozai) between these surrounding pillars (Figs. 2, 4). This kind of exterior frame is carefully constructed so as to keep gaps between the central pillar and itself. The central pillar is therefore by no means in physical contact with any parts of the surrounding structure. It may be interesting to know that the central pillar stands by itself without supporting any parts of the tower.

2-2. The Central Pillar
The structure of wooden pagodas changed with time. As we shall see later, pagodas are able to stand without their central pillars. As examples in the Edo era show, there were even pagodas that hanged their central pillars from the topmost layers.

Five-storied pagodas were reputed resistant earth-
Fig. 4. Section of Wooden Towers (2/2)

Figures 4. Section of Wooden Towers (2/2)

Figures 4. Section of Wooden Towers (2/2)

Figures 4. Section of Wooden Towers (2/2)

As stated above, the central pillar capped with sohrin is independently placed in the center of the pagoda with no connections with other parts of structure. On the other hand, as clearly shown on the cross section of the pagoda (Fig. 4), the surrounding part is constituted by a lot of horizontal members piled up on top of others (making up to 70 to 80 layers for five-storied pagoda). It is well know as the characteristic of woods that their drying shrinkage is small along the direction of the fibers but is several times larger in their perpendicular direction. Deformation due to forces is also much bigger in the latter direction. Due to such deformation of the horizontal members the top of the pagoda can sink up to tens of centimeters in several years after its completion. On the contrary, the change in length of the central pillar is very small, tending to push up the sohrin as the surrounding structure sinks. This creates a huge gap between the bottom of the sohrin and the tip of the top roof, allowing rain to leak in.

One solution to overcome this problem was to shorten the central pillar, but this required a lot of hard work for temporarily supporting the central pillar when its bottom is cut. Use of the first floor of pagodas changed as time progressed. In later time with change in use of the first floor, the central pillar became to be supported the beam above the ceiling of first floor (Figs. 4-d, -e). However, this was no attribution to solving the above problem encountered by many pagodas. The solution invented to overcome this problem was the method used in “Tohshogu’s pagoda”.

That was to hang the central pillar from the highest possible layer with sufficiently short hangers. The problem was thus completely solved. The method used in Tohshogu’s pagoda where the central pillar was hung with chains, was done so for the reasons stated above, and was not intended to create resistance against earthquakes. In this particular example, the bottom of the hanged pillar was even restricted by a sleeve-like hole to prevent the pendulum movements.
2-3. Structure of Eaves

As previously stated the deep projection of eaves is one of the most important factor contributing to the aesthetics of the Japanese wooden pagoda. Japanese structural method for these huge of the projection of eaves, was investigated statically, and it was found to have unique characteristics compared to that of western architectural technology. It is an interesting fact that since ancient times Japanese consistently used “beam action” when dealing with structure and hardly ever used “arch action” most commonly used in European arches and truss structures.

By extending the beam beyond one of the supporting points, and applying the principle of lever, it is able to support a certain load applied on the beam outside the span. It was understood through the survey of those the projection of eaves of the pagoda that the deep eaves was accomplished by thorough and repeated application of lever action (Fig. 5). Therefore the structure of eaves uses side pillars as the fulcrum, the eaves themselves acting as the levers. To avoid the turning around of eaves over the fulcrum, the side pillars of the upper layer are placed inside the fulcrum on the main rafters (ji-daruki). However this method and theory is not so efficient as the force counterbalance the loaded eaves decreases with increasing height, and in the topmost layer, this force is almost zero. On the other hand if the connection between the materials is ideal, we can easily expect a pair of forces in the horizontal direction (a couple), as shown in Fig. 6, which prevent turnover of the eaves. This, however, is a type of three dimensional truss effect. This kind of force system seems very difficult to be imagined by the carpenters of those days. It may be very interesting to know whether the engineers who made the pagodas would have been able to speculate the existence of this truss effect or not, but confirming this query can not be easily done. The authors think this problem was not contemplated by them. However, the truss action was actually effective, and it prevented the eaves from falling down, although very big sag of the eaves was seen in all pagodas after some years of their completion.

Table 1. List of Surveyed Towers

| No. | Towers       | Built (year) | Storied | Height (m) |
|-----|--------------|--------------|---------|------------|
| 1   | Hohryuji     | 7 cent.      | 5       | 32.45      |
| 2   | Hokkiji      | 706          | 3       | 24.26      |
| 3   | Ikuhashiji (West) | 730 | 3       | 33.63      |
| 4   | Gangohji (Model) | 8 cent. | 5       | 5.50       |
| 5   | Taimaji (East) | 8 cent. | 3       | 24.39      |
| 6   | Murohji      | 8 cent.      | 5       | 17.10      |
| 7   | Taimaji (West)| 9 cent. | 3       | 24.08      |
| 8   | Daigoji      | 952          | 5       | 38.16      |
| 9   | Ichiyoji     | 1171         | 3       | 21.34      |
| 10  | Jyojiruiji   | 1178         | 3       | 16.08      |
| 11  | Kohfukuji    | 13 cent.     | 3       | 19.07      |
| 12  | Kaijusenji   | 1214         | 5       | 17.70      |
| 13  | Myohosuji    | 1270         | 3       | 22.12      |
| 14  | Saimyoji     | 14 cent.     | 3       | 19.68      |
| 15  | Hoshukuji    | 1380         | 3       | 18.47      |
| 16  | Myohin       | 1384         | 5       | 29.14      |
| 17  | Nyoidera     | 1385         | 3       | 21.83      |
| 18  | Jyojiruiji   | 1400         | 3       | 22.82      |
| 19  | Henshojin    | 1416         | 3       | 21.34      |
| 20  | Saigoji      | 1429         | 3       | 22.29      |
| 21  | Kohjiruiji   | 1432         | 3       | 19.52      |
| 22  | Yoohkenji    | 1454         | 3       | 20.01      |
| 23  | Saimyoji     | 1543         | 3       | 17.93      |
| 24  | Kokubunji    | 16 cent.     | 3       | 18.88      |
| 25  | Shinkoji     | 16 cent.     | 3       | 18.24      |
| 26  | Chohmeiji    | 1597         | 3       | 24.35      |
| 27  | Onjyoji      | 1601         | 3       | 24.70      |
| 28  | Hoshkakaji   | 1604         | 3       | 19.57      |
| 29  | Homonji      | 1607         | 5       | 29.25      |
| 30  | Huzanji      | 1611         | 3       | 23.88      |
| 31  | Natadere     | 1642         | 3       | 11.60      |
| 32  | Kyoohgokokuji| 1644         | 5       | 54.84      |
| 33  | Nikkoh-Tohshoju | 1818 | 5       | 34.46      |
3. Morphology and Structure of Wooden Pagodas

Another very interesting aspect regarding the design of eaves is their morphology and the historical changes of their representation. We will investigate the relationship between the morphology and structure of wooden pagodas shown on Table 1.

3-1. Morphological Changes of Wooden Pagodas

One comprehensive morphological indicator for wooden pagodas is their proportion of body width of the first layer to its total height. Fig. 7-a shows the historical changes of this proportion of each pagoda. The ratio is relatively constant, between the range of 4.5 ~ 6.5 and it has not changed very much with time. However, there is a tendency for this ratio to slightly increase with descending time, meaning the pagoda becomes long and slender, which then becomes visually unstable.

The ratio of the height of sohrin to its total height (Fig. 7-b) is approximately 1/3 regardless of time, but with five-storied pagodas, as time goes down this ratio decreases significantly to 1/5 indicating the ill-balanced appearance of the pagoda. The ratio of the width of the roof to the width of the body (Fig. 7-c) can be used as an indicator for the deepness of carvings of the pagoda. The ratio for the first layer is approximately 2.2 regardless of time, but the same ratio for the top layer changes from 3.5 to 2.5 with descending time, which shows that the depth of carvings are inclined to becoming less significant.

From these data, Japanese pagodas have retained much of its overall proportion throughout history, but changes with time can be seen in the depth of carvings which make the eaves attractive. Fig. 8 shows the ratio of the roof width on the top layer to that on the first layer (the decreasing ratio with increasing height), the decreasing ratios for the width of the pagoda body and for the projection of eaves. There is a notable change of the ratio of roof width frame 60% to 85% up until before the 8th century, but little change is seen thereafter (Fig. 8-a). Looking at the main body and the projection of eaves separately, the decreasing ratio of the body widths changes rather gradually toward 13th century, and becomes constant thereafter (50% ~ 70%, Fig. 8-d), whereas the decreasing ratio of projection of eaves shows a similar tendency to that of the roof width, indicating a steep change in earlier days (80% to 98%, Fig. 8-c).

From the above we can see that those older pagodas built around 7 ~ 8 century (Hohryuji five-storied and
Yakushiji three-storied pagodas), have relatively large decreasing ratios for both the main body and the projection of eaves, and have stable morphologies, with deep carvings.

3-2. Changes in the Expression of Projection of Eaves and Their Cause

With the exception of a few examples, the type of eaves structures of wooden pagodas is triple cantilevers (mite-saki) and double rafters (futa-noki). That is to say the structural styles did not change throughout 13 centuries. However, when we examined it through its dimensions we got a rather unexpected result.

Transverse girder (gagyo) is the fulcrum to support the rafter which forms eaves. When looking at the ratio of the distance from the side pillar to a transverse girder to projection of eaves (Fig. 9-a), with the oldest pagoda it was about 50% with the transverse girder located near the middle point of the projection of eaves, but it then decreased to 35% in 2 centuries, and no changes seen thereafter.

Examining the ratio of the position of fulcrum of tail rafter (o-daruki) to that of transverse girder (Fig. 9-b) the old value of less than 60% moved forth, and it converges to 2/3 around the 13th century. In other words, after the 13th century, the dimension of the hijiki cantilever (tesaki) was determined from the equal interval distance between first cantilever (hitote-me) to third cantilever (sante-me). The relationships between second cantilever (futate-me) and first cantilever are all equal to 50%.

Fig. 9-c shows the ratio of cantilevered spans of rafters (i.e. span of main rafter / the overall rafter span). Historical changes here are contrary to the previous figure; the span of main rafter was relatively large (70%) with older pagodas, but it decreases to less than 60% up until the 13th century. The above data elucidated the fact that in the design of the eaves of the

![Fig.9. Change of Framing Proportions](image)

![Fig.10. Change of Slenderness of Rafters](image)

![Fig.11. Comparisons of Framing Proportions](image)
same design and the same structure, there are significant historical changes in morphology. The changes have been such that the arms and blocks (tokyoh) has been condensed compared to the projection of eaves and on the other hand the rafter part was extended (second rafter in particular). This implies that the design changed seemingly toward an irrational direction from the stational point of view.

Fig. 10 shows the changes in the slenderness ratio of the rafter (total cantilevered span of rafter / depth of rafter), which forms the eaves. This figure elucidates the previously mentioned problem. The original slenderness ratio was $\lambda<16$ but during 13th ~ 14th century it thins downs to $\lambda>20$. We now come to realize the difference in the structure of eaves of pagodas from earlier times to those made after the 13th century (Fig. 11). These morphological changes have been due to several factors, but the probable main reason is the nationalization (modularization) of imported technologies Buddhist architecture. The eaves structure (noki-gumi) of the Yakushiji’s west pagoda is the oldest of triple cantilevers, but its designing was difficult due to the large module unit (shaku unit). And the degree of completeness for its details is not very high (unrelated with the beauty and powerfulness of the pagoda as a whole). For several centuries thereafter, technological development was attempted in Japanese ways to improve those framing systems imported from China.

Three key points to the expression of under the eaves (noki-shita) were the introduction of cylindrical ceiling (noki-shirin), and small ceiling (noki-kotenjyouh) and the integration of the corner assembly members. The changing process is shown in Fig. 12, which indicates that the design was finalized at the point where the corners were integrated with the cross assembling members.

Modularization on the basis of single cantilever (hitote-saki) unit was one answer given at this point. Nationalization progresses with the invention of shiwari-ho, a modular system based on the intervals of rafters as smallest unit. However, the authors find it difficult to believe that the supposedly integrated corners have been strengthened structurally compared to that of the oldest Japanese style corners.

4. Structural Change of Eaves

The pagodas of Hohryuji and Yakushiji are considered to be most elegant and morphologically sophisticated. These simultaneously belong to the oldest style of pagodas. Common characteristic of these pagodas is that the structural members supporting the eaves are expressed as they are on the outside (members used for exterior decoration are called dress member). However, there was a big change during 12th ~ 13th century. The roofs of each layer originally supported by main rafter and second rafter became supported by true rafter (no-daruki, but hidden rafter), which increased the gradient of the roofs making it more efficient for rain to run down the roofs. A new method was invented where a big lumber called hanegi was placed in the gap between the false rafter and the true rafter to support the edge of the eaves (Fig. 13-a).

Focusing on how this situation affected the design of the following time is very interesting when we consider the time, Japanese sense of mind and their character. This is because those members that are no longer needed for structural purposes could now be eliminated, and it was then totally up to the designers how he/she will treat those members for expression.
However, it is clear from the previous chapter that the engineers of the time would never eliminate those main rafter and second rafter, neither of which were structurally inevitable any longer, from their design. They used these members as they were used in the olden days, and moreover they even extended the length of second rafter to make it appear that it is supporting the outskirted eaves with ease. This is a revolution against the previous design principle which was expressionally very honest to its structure. They have chosen a false role for main rafter and second rafter, and produced an image as if they had been important structural members supporting the big outskirted eaves.

As time goes down to the 14th century, a new use of big lumber was invented in which it was supported by the member called base girder (doi-geta) which was then supported by a horizontal cantilever (hari-dashi-bari) (Fig. 13-b).

This implies that the load of each layer will pass along in order from true rafter to big lumber, to base girder and horizontal cantilever. Thus there will hardly be any load on the original transmission route of second rafter to first rafter, to transverse girder, to tail rafter and to assembled arms and blocks. Those members seen beneath the eaves which seems without doubt to be supporting those eaves are in fact totally useless for the purpose of supporting the eaves.

5. Conclusion

As discussed in the above, pagoda’s design has been consistent in its style of supporting the eaves, that is with second rafter, main rafter, transverse girder, tail rafter and assembled blocks and arms. But in reality, there is a variety of extent to which these members actually support these eaves. Old pagodas represented by the five-storied pagoda of Hohryuji have these members actually support the eaves, yet there are pagodas such as the three-storied pagoda of Henshoin where these members do not support the eaves at all. For ordinary people, without knowledge of structural mechanics, or without actually laying down these members, no clues will be given to how or according to what statical principles these eaves are supported.

This is an important factor of the nationalization of imported pagoda construction technology (7th ~ 8th century), establishing by our ancestors over a long period of time. This is an example of Japanese sophistication they have always shown in establishing the traditional culture. This fact may be hinting to us a certain extent the way in which we have been and will treat and react in the future the western culture we have imported and introduced to the country since the Meiji era.

References

1) Abe M. and Kawaguchi M. (1995) Structural Development of the Japanese Timber Pagoda. SEI, 5 (4), 241-243.
2) Abe M. and Kawaguchi M. (1993) Forms and Structures of Traditional Timber Towers in Japan, Proceedings of the IASS-MSU Symposium 1993, Istanbul, 233-243.
3) Hamashima M. (1973) The Eaves of Japanese Tower, Trans. of AIJ, 208, 57-68 (Japanese).
4) Hamashima M. (1970) TOKYO of Japanese Tower, Trans. of AIJ, 172, 55-65 (Japanese).