Mechanical Role of Roller Ends of Historical Timber Structures

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1. Earthquake and timber structure

This paper traces some links between mechanical behaviour and failures of timber structure via the examples of the historical timber structures in Japan. Particularly it traces links of horizontal behaviour and structural damage by earthquake. In general disaster attacks several parts of a structure and major failure appears when it is damaged by strong force. So mechanical failure should be avoided well in advance.

It is of cause possible to introduce an appropriate structure newly, but it is also important to judge an appropriate structure historically. Then what is an appropriate structure in terms of timber structure?

2. In case of Japan

In case of Japan almost all of historical timber structures are timber-framed. A lot of historical timber structures survive in spite of several disasters like big earthquake throughout centuries. Why do they survive? The paper provides some examples of Japan to show mechanical role of roller ends of historical timber structures.

The roller ends do not fix an upper structure on its foundations. They make a structure slide on its foundations. In result they reduce damage by horizontal force. Such role of roller ends was not introduced newly in the modern. It had already existed in the ancient, applied to timber-framed structures in the medieval and spread to vernacular houses in the early modern.

3. Fixed end and unfixed end

The upper comprises many parts of timbers while the lower comprises foundations on the earth. Mechanical links between the upper and the lower is one of the most important points to keep structure safe because wrong links between them often cause destruction

Ends of posts are not necessarily fixed on foundations. In this meanings structures are mainly divided into two. One is the fixed end structure. The other is the unfixed end structure. Unfixed end is hinged but becomes roller when strong horizontal force is loaded.

The fixed end structure has posts that can stand independently but is easily damaged by earthquake, while unfixed end has posts that need rigid joints of upper structures but is less damaged by it.

The fixed end structure is very old. It is vernacular, dates from the pre-historical, is widely used through centuries and survives to the modern, but it is almost disappearing now. On the other hand the unfixed end structure is comparatively new. It is from the continent, dates back to the sixth century, is for the first time used only to

Buddhist temples, is later introduced widely to other structures and survives to the modern.

The fixed end structure puts posts into the earth. It makes their ends solid in the earth while the unfixed end structure puts posts on stones and keeps their ends hinged or roller on their foundations.

Later a new type of unfixed ends appears. The new one puts posts on footplates. Footplates are one of horizontal timbers on the foundations. Footplates are not fixed to foundations. So footplates can be said to be a sort of shoes of an upper structure. Footplates can slide on foundations when strong horizontal force is loaded.

One of Japanese architectural historians Eizo Inagaki (1926-2001) wrote in his book of 'Shrine and Mausoleum' published in 1968 that the role of footplates was for move and the meaning of footplates was mobility of an upper structure. Footplates, according to his book, were introduced to religious structures that would be imagined to be moved to other places. Some shrines for Gods could move from their original place and arrive at other places. Later footplates were widely introduced to secular structures like houses and shops that had had the fixed end structure originally. After introduction of footplates to secular structures, both secular structures and religious ones began to have the end unfixed structure. In this meaning it can be said that most of historical structures changed to have the unfixed end structure after introduction of footplates.

In fact a structure with unfixed footplates on their foundations helps structure move horizontally as well as vertically by men power or by natural force like earthquake and wind. Particularly horizontal force makes an upper structure with unfixed footplates slide horizontally on the surface of its foundations. Mechanical behaviour of horizontal move means that the unfixed footplates acted as roller ends.

4. Failure before 1945

In the first part of the twentieth century some footplates changed to be fixed on their foundations. So some structures with footplate still remained unfixed while other structures became fixed.

In 26th November 1930 the earthquake of magnitude 7.3 hit the northern part of Izu peninsula in Japan. The killed and the missed amounted to 272. The injured amounted to 572. The completely destroyed houses amounted to 2165. The partially destroyed houses amounted to 2165. The houses burnt down amounted to 75.

The centre was open for advising earthquake-proof buildings to people just after the earthquake. Several questions were colleted. One of the questions was, "Is right or wrong for timber structures to fix footplates to foundations?" Prof. Heigaku Tanabe (1898-1954) answered the question;

"It is true. It is better not to fix footplates on foundations for earthquake-proof. "

"It is rather worse for former structures to tighten footplates and foundations."

"The amount of damage increases 1.25 times in case of tight joint."

"Least damage can be seen in case of 7.5cm slide of an upper structure."

"The reason of these results depended upon a sort of 'isolated structure' that reduced horizontal force by earthquake. The shock from the earth did not hit the upper structures directly, while 'fixed structure' in case of tight joint of footplates and foundations could not stand because the shock hit the lower part of structures directly."

His answers can be read now in his writing of 'Q & A on earthquake-proof buildings' published in 1933.

5. Failure after 1945

It was reported after the survey of Tokyo in 1950 that the fifty percent of structures in Tokyo had footplates on stones while the forty-five percent of them had footplates on reinforced concrete. Footplates on stones had unfixed joint while footplates on reinforced concrete had fixed joint. The survey showed said that unfixed structures still covered the half part of Tokyo in 1950.

Yet, the authority at that time highly recommended to have fixed joint between the upper structure and its foundation. Upper structures should be tightened by anchor bolt between footplates and foundations. Footplates were made of timber while new foundations were made of reinforced concrete. Anchor bolt is put between them to fix their joint. The unfixed structures can be seen only in traditional old buildings at the present time.

In 23rd October 2004 the Mid Niigata Prefecture Earthquake of magnitude 6.8 hit the northern part of the central Japan. The killed amounted to 68. The injured amounted to 4805. The refugees amounted to 103, 000. The destroyed structures amounted to about 16000. Some structures burnt down could be seen.

In 16th July 2007 the Niigataken Chuetsu-oki Earthquake of magnitude 6.8 hit just near the earthquake in 2004. The killed amounted to 11. The injured amounted to 1959. The completely destroyed structures amounted to 993. The large-scale destroyed structures amounted to 493. The partially destroyed structures amounted to 2792.

The less destroyed traditional structures could be seen in the unfixed end structure both in 2004 and 2007. In fact the unfixed structure moved horizontally on stones on the ground. The unfixed end structure covered half of Tokyo in 1950 but it now belongs to the traditional one. They could be seen only in very old buildings or cultural assets' buildings.

6. Mechanical behaviour of historical timber structures by earthquake

The four typical examples are shown below to provide with examples how the historical timber structure did behave by the earthquakes in 2004 and 2007. Both the earthquakes in the northern part of central Japan hit the historical timber-framed structures in Japan. As mentioned before, most of historical timber structures had unfixed ends while most of modernized timber structures had unfixed ends.

Firstly the two examples in 2004 are shown.

Figure 1-1. Juni-jinja shrine just after the earthquake in 2004
Figure 1-2. Slide of post in Juni-jinja shrine by the earthquake in 2004

One is Juni-jinja shrine (Fig.1-1, 1-2). The very small shrine in the small village survived without any damage of the structure by the earthquake in 2004 (Fig.1-1). It moved 5 cm horizontally from the existing place (Fig.1-2). It had originally had posts on stones. It changed to have posts on concrete cubes on concrete plates on the earth. The new foundations did not fixed to the posts. In result the concrete cubes had 5 cm slide on the concrete plate and the post had a bit of slide on the concrete cube by the earthquake. The structure of no fixed joints at the ends of upper structures belongs to the traditional one while the material of concrete cubes and plates belongs to the modernized one. In the meaning the right integration of the traditional and the modernized caused less damage in Juni-jinja shrine.

Figure 2-1. Hasegawa-family house just after the earthquake in 2004
Figure 2-2. Subsidence of foundations in Hasegawa-family house by the earthquake in 2004

Other is the Hasegawa-family house (Fig.2-1, 2-2). It is a big vernacular house and one of cultural assets of Japan. It survived by the earthquake (Fig.2-1). It had damage of its walls made of soils and it had partial damage of the timber frames. It moved vertically as well as horizontally (Fig.2-2). It had footplates on the stones. The footplates had some cuts on their bottom. These cuts geared into stones on the ground. Some cuts gearing into stones prevented the upper structure from making a horizontal move smoothly. On the other hand it move a bit vertically. In fact stones beneath footplates sank from the existing level. The vertical move seemed to reduce serious damage of the upper structure. It had been better for the Hasegawa-family house to have footplates with no cut Because cuts on the bottom of footplates prevented the structure from moving on stones horizontally. The house is a traditional one, but it have already loosed the original role of footplates. In the meaning the lack of original role of traditional structures caused damage in Hasegawa-family house.

Secondly the two examples in 2007 are shown.

Figure 3-1. Tata-jinja shrine just after the earthquake in 2007
Figure 3-2. Inclination of the post in Tata-jinja shirine by the earthquake in 2007

One is Tatajinja-shrine (Fig.3-1, 3-2). It is a small shrine and one of cultural assets of Japan. It had much damage that was caused by wrong repairs in the late twentieth century (Fig.3-1). It changed to have repaired feet-ends. A post had a newly replaced part in the end. Another post had fixed on the ground (Fig.3-2). It is suggested that the structure had originally had unfixed end. It is much wrong to have repaired post-ends to be fixed on the ground. In the meaning the wrong repair during the modern period caused laege-scale damage in Tata-jinja shrine.

Other is Kannon-do in the Daisenji-temple precinct (Fig.4-1, 4-2). It had no damage of upper structure (Fig.4-1). The other structures in the same precinct had much damage of upper structures. Kannon-do is the oldest but had the least damage in the precinct. It had 5 cm move horizontally from the existing place (Fig.4-2). Only the stone-made staircases in front of the structure had small damage because the staircase had no move while the upper structure had 5 cm move. Yet, it is remarkable to have had no damage of the upper structure in spite of its age. It had completely unfixed ends on stones. In addition it is not so big and is not complicated plan. Its plan is square. Its structure is simple. Kannon-do is one of the most typical examples of horizontal move that reduced damage by big earthquake. In the meaning the traditional role caused no damage in Kannon-do.

Figure 4-1. Kannon-do in Daisenji-temple just after the earthquake in 2007
Figure 4-2. Slide of the post in Kannon-do by the earthquake in 2007

7. Conclusion: mechanical role of roller ends of historical structure

The timber structures in Japan were mainly timber-framed and had fixed ends originally. Most of the structures kept timber-framed but later changed to have unfixed ends. Unfixed ends cannot be seen only in the joint of posts and stones on the ground but in the joint of post and footplates on the ground. Some footplates had cuts on the bottom of it to gear into the tops of stones. The cuts prevented upper structure from sliding smoothly. Such sort of the cuts shows the tendency to have changed from unfixed ends to fixed ends. In fact some posts also repaired from unfixed ends to fixed ends.

In the twentieth century newly built structures began to have fixed ends again. It is remarkable at that time that Prof. Tanabe and his associates proclaimed the necessities of unfixed ends in 1930s just after the earthquake in the northern parts of Izu peninsula. He wrote that the total damage increases 1.25 times in case of tight joint of the upper structure and its foundation. According to his conclusion it is possible to reduce the degree of damage to 80 percent in case of all the historical structures keeping traditional unfixed ends.

One of major failure happed during the twentieth century when some authorities began to modernise Japanese traditional timber-framed structures. Drastic change from unfixed ends to fixed ends was crucial.

Today it is highly required to know again the meaning of unfixed ends of traditional timber structures. The mechanical role of unfixed ends is a roller. It reduces damage by horizontal force. Unfixed ends are not only historical but modern. In particular historical timber structures are highly recommended to keep their ends unfixed.