A Study on the Construction History of Kintai Bridge in Japan

Congcong Ren* and Mikio Koshihara

1 Associate Professor, Institute for the History of Nature Science, Chinese Academy of Science, China
2 Professor, Institute of Industrial Science, University of Tokyo, Japan

Abstract
The aim of this research is to present a structured and comprehensive history of the rebuilding process of the Kintai Bridge and also to analyze the building knowhow of this particular structure that has been passed down to generations of carpenters. A great part of the information was obtained from interviews with the carpenters that worked on the most recent rebuilding process and also on available historical materials, such as drawings and tools that were used in past rebuildings. This research analyzes the history of the bridge by dividing it into three distinguished periods. In the first period, the bridge is considered to have maintained its original design and as such; in the Heisei Era rebuild, carpenters decided to restore the Kintai Bridge to this original form using the earliest available drawings from the Genroku Era. During the second period, carpenters developed their own design templates and measuring units in the form of rulers to guide the rebuilding process. The last and third period covers the modernization of the bridge since the Showa Era rebuild (1950).

Keywords: Kintai Bridge; timber bridges; rebuilding process; historic value; skill inheritance

1. Introduction
The Kintai Bridge is a 5 span timber arch bridge first constructed in the year 1673 in Yamaguchi prefecture, Japan. During the past 342 years it has been constantly repaired and rebuilt and its form has been properly maintained. Consisting of two spans of girder bridge on both ends and three spans of arch bridge in the middle, it is considered to be the only timber arch bridge of its kind not only in Japan but also in the world. Its unique carpentry knowledge has been kept in the hands of local carpenters for centuries. By means of a long-term interview with the master carpenter Mr. Nakamura who worked on the latest rebuilding process during 2003~2005, it was possible to fully comprehend how he approached the latest design building method of the Kintai Bridge informed by historic materials such as drawings, tools, available literature, etc.

Oda (1980) suggests that its design was inspired by some timber bridges in China. While other scholars believe that it is a great leap from the traditional Hanebashi (a type of cantilever bridge). So far we have not found any concrete evidence to affirm that the invention of Kintai Bridge was inspired by other similar bridges in Japan and abroad.

Not only is the bridge itself a rare example in the history of timber bridges, but its way of passing down the building technology through generations of carpenters is valuable as well. In this research, we try to clarify Kintai Bridge's historical value both in its creative design and its inheriting traditions.

2. Brief History of the Rebuilding Process of the Kintai Bridge
Traditional timber bridges in Japan were not customarily constructed as covered bridges. Unlike any other timber covered bridges in Europe and China which can last 200~300 years through necessary maintenance, timber bridges in Japan are maintained through a regular rebuilding process. Not only Kintai Bridge, but also many other timber buildings are rebuilt from time to time to maintain their function. The rebuilding process normally begins with a thorough disassembling of the entire building, while all timber sections are examined carefully the sound ones are kept for further use, the half-rotten ones are cut to smaller parts, the rotten ones are replaced and later on the building is assembled once more. By doing so, the wood material can be used as long as possible and also succedent carpenters always have the chance to witness the latest process of rebuilding and learn from predecessor carpenters at the construction site. Except some religious architecture like the Ise Grand Shrine to which renewal is quintessence, and therefore it has to be rebuilt every 20 years, other buildings are just rebuilt when it is necessary. However, it is worth mentioning that rebuilding too often is not economical and reasonable, while on the other hand, rebuilding...
after a too long time span may cause building technology to be forgotten.

During the 342 years of the Kintai Bridge's existence, the rebuilding process took place in about 42 of those years (or 77 years taking into account the times in which minor repairs and changing of the floor boards occurred). According to Table 1., it can be seen that sometimes all five spans of the bridge were rebuilt at one time in a year, and in other periods they were rebuilt one by one. If we count all of the bridge's 5 spans rebuilt as one complete rebuilding process, the Kintai Bridge has been rebuilt almost 16 times since its original construction, on an average of a 20-year rebuilding period.

Nevertheless, there seems to be no regular schedule concerning the rebuilding of the Kintai Bridge. Natural disasters, damages to the bridge itself, funding issues, all of these could have affected the rebuilding process. Despite all these interferences one can still differentiate some regular patterns in the schedule of Kintai Bridge's rebuilding process. By analyzing these patterns, this paper proposes to study the history of the Kintai Bridge in three different periods.

The first period is from its creation until the fifth rebuilding in the Shōtoku Era (1714). Despite the fact that the second rebuilding of the bridge happened one year after its establishment due to a severe flood, the other rebuildings in this period took place every 5 to 10 years. In this period, the rebuilding process involved all of the five spans or the 3 arched spans at one time. The second period starts from the 6th rebuilding in the Gembun Era (1737) until Shōwa 25 (1950) when the Kintai Bridge was brought down by a flood for the second time. In this period, the bridge was rebuilt one span at a time every 10 years or so (due to financial issues, the last two rebuildings were delayed for about 20 to 30 years. According to some local documents, the bridge was structurally unsound towards the end of this period.) This particular approach (rebuilding the spans one by one) had its advantages: the bridge not only lasted longer but it also provided more interval time and practice opportunities for the craftsmen involved. The third period is the modernization of the rebuilding of the Kintai Bridge. In the second year after the bridge was afflicted by another flood, Prof. Sato from Waseda University carried out the Shōwa Era rebuild. The crushed stone piers were changed to concrete ones and the shape of each bridge arch was standardized to the same size (They had slightly different shapes before).

According to Table 1., we can see that the last rebuilding process (hereafter termed Heisei Era rebuild) was carried out almost 50 years apart from the previous rebuilding (Table 2.). As noted before, the time length between rebuilding is crucial to develop
knowledge and technique; considering 20 years as an ideal time span, the latest 50 year period seems too long.

By the time of the latest rebuilding process, there were only two remaining carpenters that had participated in the precedent construction. Both were very young at the time (one was the 7-year old grandson of the master carpenter and the other a 17-year old apprentice). The local carpenters formed a team aimed not only at rebuilding the bridge but also rebuilding the tradition of the local carpentry. This team of carpenters began to study the old drawings and tried to make test models 2 years before the Heisei rebuild. In the end they chose the earliest drawing of the Genroku Era (hereafter termed Genroku drawing) as a reference and with the help of CAD software, they redesigned the 5 spans of the bridge.

3. Changes in Kintai Bridge’s Rebuilding Process

During the rebuilding process the old structure was completely disassembled and rotten timber parts were either replaced or cut to small parts for other use. It is an important experience for apprentice carpenters to learn and memorize how to build it. As Martinez (2012) has noted, such kind of rebuilding activity should not be equated with restoration in the Western context.

However, the goal of keeping the bridge in its original form is hard to achieve over 300 plus years. There are many factors that might disrupt this goal. According to this research on the past materials, it is likely that the design of Kintai Bridge has been amended twice (not including Heisei’s rebuild) in history.

The first time happened in the Kampō rebuild (1741). From the old drawing of 1741 (hereafter termed Kampō drawing), we can see that the curve of the arch had become flatter than the Genroku drawing (compare Figs. 3. and 4.). The arch ribs became thicker, thus better for load bearing. Besides the changes on the arch bridge’s shape and construction, the carpenters are also found to have added some dimensions on the drawings. There are 2 sets of dimensions that measure the position of each cantilever beam’s starting point (hereafter termed the horizontal and vertical dimensions). In 2013 we discovered a set of standard rulers with these dimensions, which explained how they used these numbers in the actual construction (These will be introduced and discussed later in item 5).

The second time of major alteration happened during the Shōwa Era rebuild (1952). As was mentioned before, scholars from Waseda University have done some restoration research. They analyzed the arch bridge’s structural mechanics and certified its safety. Stone piers were replaced by concrete ones due to the then construction technique limitations. The 5 pieces of 2-meter high stones (named Hedateishi) buried in the center of the original stone piers bearing the 2-side thrust were replaced also. New arch-ribs were fixed by bolts onto pieces of steel casing attached directly to the concrete piers (See Fig.2.). The Hedateishi was a brilliant invention. There is a loss in the historical value of the structure by changing it for safety reasons.

Besides these improvements in structural safety, the size of each bridge span was standardized to simplify the design method. The 5 spans of the bridges were slightly different in the span distance and the middle 3 arch bridges were slightly different in height also. However a survey report in 2003 shows that the 3 arch bridges were built differently during the Shōwa rebuild from how they used to be. The third span was the highest and the second and forth spans were lower. This indicates that the carpenters may have neglected
4. Design Policy of the Heisei Rebuild

Most of the designers in the Heisei Era rebuild were carpenters themselves. They studied the past material to speculate the previous carpenters' ideas. Old drawings in scale of 1:10 containing rich details became the most important references. According to Table 1., we know that there are 12 elevation drawings remaining that represented Kintai Bridge's design at different times. They chose the Genroku drawing as a reference not only because it is the oldest remaining drawing but also because they believed that only the Genroku drawing can be seen as a design drawing, while the others are seen as the results of later surveys.

They believed that the master carpenter who carried out the Genroku Era rebuild had approached the creator carpenter himself and marked geometric principles in the design drawing. From the interviews with carpenter Mr. Nakamura, the author summarized some of his profound insights on the design method he discovered in the Genroku drawings. These principles also guided the bridge's design in the Heisei Era rebuild.

1) The distance from the center of each pier should be equal and is 1/5 of the total length of the bridge which is 132 shaku (尺) (1 shaku = 30.3 cm).

2) The curve of the arch bridge starts from the center of each pier and the chord of this arch (132 shaku) equals the radius, which means each arch is 60 degrees.

3) The Hanabari (the beam that connects each 5 cantilever beam orthogonally) are arranged evenly on an arch that gave Mr. Nakamura the idea to divide the arch evenly and arrange the timber members along the segments.

Although with no written records to back them up it is hard to confirm that these ideas are really part of the original design theory. The inaccuracy caused by drawing technique or the shrinking of the paper may cause differences from what was initially meant to be drawn. However, analysis of the graphic may lead us closer to the original ideas of the design. By measuring the scanned file of the Genroku drawings, one can observe the result as shown in Fig.3.

There is also some additional information in the Genroku drawing, including a complete record of timber and iron materials they used for one span of the arch bridge and 3 sets of heights and widths of each arch bridge. However we should distinguish between the designed or measured dimensions for the 3 sets of height and width numbers. According to these numbers, the middle arch is 7 sun (21 cm) and 6 sun (18 cm) higher than the second and fourth spans of the bridge. Compared to the nearly 40 meters span, this level of difference is hardly observed. It is most probable that
Fig. 3. An Analysis of the Genroku Drawing Source: Created by Scanned File of the Genroku Drawing

Fig. 4. An Analysis of the Kampō Drawing Source: Created by Scanned File of the Kampō Drawing

Fig. 5. One Set of the Restored Standard Rulers. The Dotted Line Pieces are Missing Parts. (Top) The Horizontal and Vertical Dimensions are Written on the Rulers. (Bottom)
the 3 sets of dimensions are measured numbers (実寸) and the difference was an error that occurred during construction and reviewing. However, these different sizes were inherited and used as reference dimensions since then. In the Shōwa Era rebuild, despite the unified shapes in the design drawing, the 3-arch bridges were built in different heights. They remained this way during the Heisei process—the middle arch being higher than both sides.

5. Use of Standard Rulers

The style of the drawing and the shape of the bridge changed from the Kampō Era onwards. There is no longer any record of materials. The same horizontal and vertical dimensions were recorded for the first time (see Table 3.) and the curve looks much flatter than the Genroku drawings. For these reasons, Mr. Nakamura believes that drawings made after the Kampō Era are measured drawings which present the forms of sunken arch bridges after long-term use and therefore could not be trusted.

However it is doubtful that after the Kampō Era people would make such detailed measured drawings. Hamashima's (1995) research on traditional architectural drawings indicates that 1:10 section drawings were popular for construction use in the Edo Era. The arches are also present in these drawings but are of a larger radius. According to Fig.4., we can see that the radius becomes 145 shaku in the Kampō drawing. It seems that the proportion between the length of the span and the radius was forgotten. Instead, the horizontal and vertical dimensions specifying the position of each beam were recorded.

In 2013, with the help of Mr. Nakamura, the rulers were found among a pile of old timbers dating back to the year Shōwa 2 (1927). Their existence had been forgotten for decades. They consist of a group of planks about 5 to 8 cm in width and 0.5 to 2 m in length. The horizontal and vertical dimensions of the 3 arch bridges are written on both sides (the dimensions of the fourth span are written in one side, while the second and the middle span's dimensions are written on the back). Each plank was marked in a brilliant way that made it possible for them to be assembled without difficulty (see Figs.5. and 6.).

The discovery of these rulers reveals a rather simple way of rebuilding the bridge. Using the templates to process the timber and the rulers to assemble them, one does not need to browse through the drawings every time. The simplification of the assembling process by using these rulers with the same dimensions for generations of carpenters to come is essential for Kintai Bridge's continuation.

6. Conclusion

In this research we have reviewed the history of Kintai Bridge's rebuilding process and investigated its building technique from the aspects of the design of the form and the way it has been passed down. There are 3 important turns in Kintai Bridge's rebuilding processes, the Kampō Era (1741) rebuild, the Shōwa Era rebuild (1950) and the Heisei Era rebuild (2003).

By analyzing the old drawings after the Kampō Era we find that the rebuilding tradition itself has kept developing in a way such that the rebuilding became simpler (due to the invention of the standard rulers) and the bridge became more structurally sound (the arch ribs became thicker), meanwhile the form of the bridges remained almost unchanged.

Table 3. Horizontal and Vertical Dimensions Recorded in Drawings

| Drawings' years | Horizontal dimensions | Vertical dimensions |
|-----------------|-----------------------|---------------------|
|                | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10| 11| 11 |
| span           | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
| height         | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |
|                | 2.17 | 2.47 | 7 | 8.8 | 11.8 | 13.9 | 14.7 | 16.4 | 16.2 | 17.5 |

Fig.6. One Piece of the Standard Rulers
bridge—determined largely by the 3 sets of span and height dimensions—remained as close to the earliest Genroku drawing as possible.

When the bridge was torn apart once again in the Shōwa Era (1950), in consideration of safety and efficiency, the previous 3 slightly different arches were designed to be standardized regulated by a group of integral metric numbers. However the rebuilding process was still carried out by local carpenters and they neglected the expert advisors' design and built the bridge in the old way.

The Heisei Era rebuild took place 51 years after the Shōwa Era rebuild. On the one hand local carpenters tried to restore the traditional way of construction, on the other hand an extended time period between the two restorations had caused them to forget about some traditional skills, such as use of the standard rulers. Instead, they turned to the earliest Genroku drawings to seek the original design philosophy by analyzing the form of the bridge as depicted. As a result some geometry rules were reinterpreted and according to them, the bridge was re-designed by AutoCAD.

When it comes to assessing a built heritage's historical value, especially in Japan where many historical timber buildings have been rebuilt multiple times, there are always criticisms concerning the application of modern techniques. It is quite difficult to tell to what extent new technology can be applied to building heritage such that it could still maintain its authenticity. In the case of Kintai Bridge, we found that the building technique has always been innovated, and different value judgments have led to different choices of building technology.

Considering the materials that were used in this research, we were not able to represent a complete view of the construction history of Kintai Bridge. There remains future research on other external factors that can affect Kintai Bridge's rebuilding process.

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