SUSTAINABLE TECHNOLOGY OF THE JAPANESE HISTORICAL TIMBER FOOTBRIDGE - THE KINTAIKYO BRIDGE -

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Summary

The Kintaikyo Bridge having been designated a national cultural property, the City of Iwakuni, home of the Kintaikyo Bridge, bears the responsibility of preserving the Bridge for present and future generations. The Bridge's unique five-span arch structure is a treasure that was created from the wisdom, effort and ingenuity of our ancestors. As a way of long sustaining the Bridge, the City of Iwakuni decided to guarantee the succession of bridge building technology, so as to ensure repeated rebuilding of the Bridge. This solution is unique in the history of bridges in the world. In this paper, the background of bridge construction, the bridge construction system and the structural characteristics of the Kintaikyo Bridge are dealt with, in which each of the central three spans of the Bridge is proved to be a unique arch structure. And finally the sustainable technology of the Bridge is fully discussed.

Keywords: historical bridge; timber bridge; footbridge; arch bridge; Catenary curve; sustainable technology

1. Introduction

The Kintaikyo Bridge over the Nishiki River at Iwakuni in Japan was originally constructed in 1673. The five-span wooden arch bridge is one of the most historically significant bridges not only in Japan but also in the world. Each span of the three central arches is 35.10m, the total length being 193.3m and the roadway being 5.0m wide. Each arch of the bridge consists of smoothly curved skeleton lines, its end supports restrained so that when vertical load is applied to that curved surface of an arch, a horizontal reaction force is generated in the supports. When subjected to free vibration, each arch prominently shows the asymmetric mode of deformation inherent to an arch structure, as well as the symmetric mode of deformation. In view of these characteristics, each of the central three spans is considered to have an arch structure. As the floor follows the curve of the arches, the Bridge is available only for a pedestrian bridge.

In this paper, the background of bridge construction, the bridge construction system and the structural characteristics of the Kintaikyo Bridge are dealt with in detail, in which each of the central three spans of the Bridge is proved to be a unique arch structure. And finally the sustainable technology of the Bridge is fully discussed [1], [2].

2. Background of Bridge Construction

The Nishiki River flowed in a curve around mountains, the first feudal lord Kikkawa decided to locate his castle on that mountain, since the River surrounding the mountain could serve as an ideal outer moat. At the foot of the mountain, he ordered upper-class warriors to build their residences. On the River's opposite shore, the lord constructed a town for middle and lower-class warriors, as well as for the merchants who would support residents' daily life. As a result, the castle town comprised two districts by the River, which necessitated some means of linking the two districts [3].

There is no evidence that proves the existence of a bridge at that time, since the oldest document indicating the presence of a bridge was written in 1639. However, it is possible to consider that an ordinary girder bridge with many piers was washed away by a storm.

Fig. 1 Kintaikyo Bridge.

In response to the growing demand for a durable bridge, the third feudal lord of Iwakuni, Kikkawa Hiroyoshi hit upon a new idea under the suggestion of a Chinese Buddhist priest Du Li (Dokuryu in Japanese). Then Lord Kikkawa Hiroyoshi organized a project team to build a bridge that cannot be washed away easily, and nominated a young talented carpenter Kodama Kurouemon as a chief carpenter. In 1673, the third Lord Kikkawa Hiroyoshi built an improved bridge after many failures and studies. It is probable that the bridge was named by the Chinese Buddhist priest Du Li, or Lord Hiroyoshi named it after the Bridge of the same name which exists even now from the time of birth of the Chinese Buddhist priest in the White Dike of the West Lake, based on the information given to Lord Hiroyoshi by the Chinese Buddhist priest Du Li. The two bridges with the same name in Japan and China symbolizes the close and long friendship between the two countries.

Fig. 2 Pedestrian Bridge: Kintaikyo Bridge.

For the initial 195 years, until 1868, the Kintaikyo Bridge was used only by successive feudal lords of the Domain and their vassals. Since 1868, however, local residents have been using the Kintaikyo Bridge as an essential means of crossing the River [3].

Despite the Bridge's unique five-span arch structure, which is designed to enhance durability, the Kintaikyo Bridge, which is primarily made of wood, is strong against any natural disaster so long as the pertinent maintenance is done. As a way of long sustaining the Kintaikyo Bridge, the City of Iwakuni decided to establish a unique system: instead of reinforcing the existing Bridge structure, the City decided to guarantee the succession of Bridge building technology, so as to ensure repeated rebuilding of the Bridge.

The Kintaikyo Bridge was washed away on September 14, 1950 (Fig. 3), when the River's flow volume increased to 3,700 m^3 per second at the point of the Bridge. This flow volume exceeded the bridge's designed flood control level of approximately 2,470 m^3 per second.

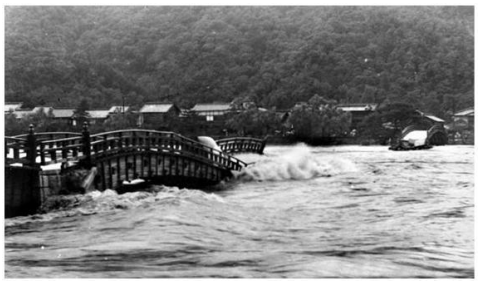

Fig.3 Arches being washed away.

3. Bridge Construction System

During the Edo Period (1603-1868), important technologies were primarily handed down from the father to the eldest son, or sometimes from the master to his first disciple. This system is indicated by old documents that list the chief carpenter's names. During the Edo Period, the Kintaikyo Bridge projects were implemented by the Iwakuni Domain. Carpenters engaged in the projects were vassals of the lord of Iwakuni. Among the vassals, those who belonged to a specific family succeeded to the role of bridge construction. Accordingly, the bridge building technology was inherited in that family. In handing down technologies, it is essential that successors have first-hand experience. Regarding the technologies involved in building wooden structures, there are aspects that even the best drawing or text cannot record. Without experiencing actual bridge construction, no carpenter can build a wooden bridge like the Kintaikyo Bridge [3].

Fig.4 Okagumi (Shop Assembly)

Many historic documents remain regarding the Kintaikyo Bridge. Of them, the oldest extant material is the drawing prepared in 1699. The oldest drawing indicates in detail the types, dimensions and production centers of the timbers used for the Bridge; types and number of necessary metal fittings; primary dimensions and gradients of beams used for the three arches in the Bridge's central portion etc. Without these documents, it would have been impossible to rebuild the Bridge each time. To long sustain the bridge building technology, we must also prepare and preserve such records for future generations [1], [3], [4].

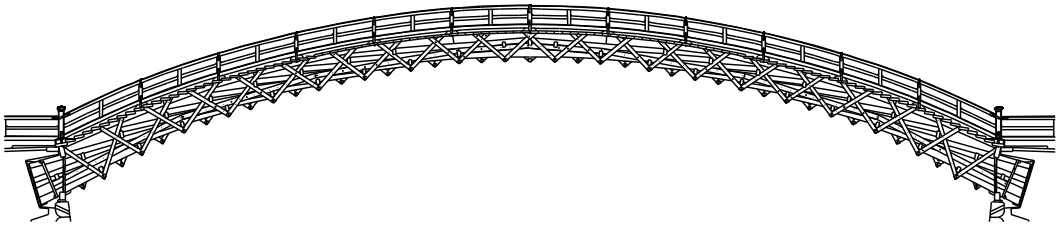

Fig.5 Side view of an arch.

Since the Edo Period, carpenters have passed down verbally the secrets of their technology, or aspects that are difficult to express either in text or in drawing. Among such secrets, an important thing is the method of learning from wood nature inherent in each respective wood type. Without knowing the nature of each timber, carpenters cannot use it for the appropriate purpose. In this environment, rebuilding the Kintaikyo Bridge, which employs authentic timbers, is a golden opportunity for carpenters to acquire the skill of learning from wood nature inherent in each type of wood [3].

Rebuilding the Kintaikyo Bridge requires various types of work, including temporary structure construction, civil engineering (preparing work yard), carpentry (timber processing and bridge building), metal processing (processing steel and copper plates), painting (painting timbers and steel members for antiseptic treatment), procurement (purchase of timber) and nail production (producing traditional Japanese nails). Since from the standpoint of managerial efficiency it is unwise to place separate orders for individual types of work, in the recent project the local authority placed orders —orders for temporary structure construction, civil engineering, carpentry, metal processing and painting — collectively with a local builders' union [3].

Fig.6 Wooden framework of Kintaikyo Bridge.

Only carpenters who have received sufficient training can process timbers and build a bridge like the Kintaikyo Bridge. To build a structure using traditional technology, carpenters must have expertise in processing timbers, as well as skills in identifying the inherent nature of individual timbers. Recently, however, carpenters primarily use precut, laminated timbers. Contemporary carpenters therefore have fewer opportunities to use and process authentic, live timbers. Therefore, rebuilding the Kintaikyo Bridge affords carpenters an opportunity to learn the traditional technology of wood building. In the rebuilding project conducted during the Heisei Period (1989-), carpenters of various generations were recruited to take part in the project, so as to transfer processing and bridge building technologies to younger generations. To foster future carpenters, the workers who were engaged in the most recent project are currently organizing various training programs, including seminars. The City of Iwakuni believes that such programs are essential for handing down the traditional technology to future generations. With this view, the Iwakuni City is considering establishing an appropriate system to support such activities [3].

4. Structural Characteristics

Each arch of the three central spans consists of smoothly curved skeleton lines, its end support points are restrained so that when a vertical load is applied to that curved surface of an arch, a horizontal reaction force is generated in the support points. When subjected to free vibration, each arch prominently shows the symmetric and asymmetric modes of deformation inherent to an arch structure, as well as the asymmetric mode of deformation. In view of these characteristics, each of the central three spans of the Kintaikyo Bridge is considered to have an arch structure, and is the prototype of an arch bridge made of large-section, glue-laminated timbers. Each arch, resiliently retained at the end support points, provides different rigidities against small rotation and large rotation. This highly original idea was brought by the young chief carpenter Kodama Kurouemon who had not only design creativity but also construction technology.

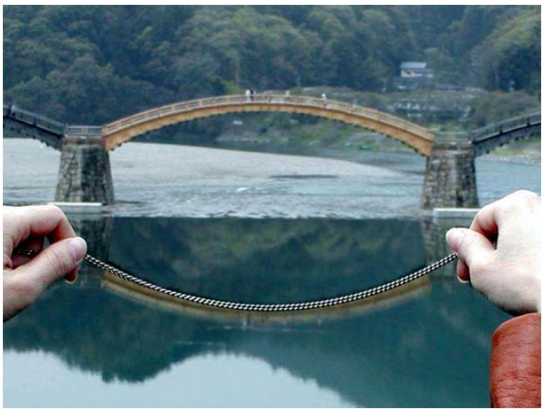

Fig.7 Form of the arch (Catenary curve).

As previously mentioned, the kinds of timbers used for this bridge, locations of their use, sizes, and other details are specified in the ancient drawing created in 1699. These specifications are followed even today. The skill of identifying timber characteristics, cultivated over years through the Japanese wooden culture, enabled the use of appropriate types of timber in the right places, taking advantage of the characteristics of hard wood, soft wood, decay-resistant wood, smooth wood and so on. Each type of lumber is used in specific points where its characteristics are put to their best use. Heartwood, which is said to be particularly resistant to deterioration, is used for most of these materials in order to improve their endurance in the harsh bridge environment, where they are exposed to wind, rain, and river mist. The resulting Kintaikyo Bridge represents the essence of the wooden culture, in addition to the beauty of the appearance with Catenary curve (Fig. 7) [5].

5. Sustainable Technology

5.1 Bridge Engineering

The Kintaikyo Bridge, a five-span wooden bridge, is 193.3m long and 5m wide (4.3m effective width of road). The three central spans are arch bridges, and the other two end spans are warped girder bridges. The span of each arch bridge is 35.1m; that of each girder-bridge is 34.8m. The girder of each central span comprises 1st through 11th girder members, a large ridge board and a small ridge board. The rear ends of the 1st through 4th girder members are inserted and bolt-clamped in the iron shoe mounted on the upper part of the substructure. The 5th through 11th girder members are longitudinally staggered so that each member protrudes by approximately one-third of its length from the girder member immediately beneath it. Girder members are sequentially installed in this way from each end of the span. A large ridge board is mounted between the 9th girder members from both ends; a small ridge board is mounted between the 10th girder members which are installed on the large ridge board. A long thin wedge is inserted between each overlapping girder member, causing the front-end portion of each member to bend slightly downward, so that an arch is formed by all girder members. To prevent girder member displacement, dowels are placed in the surface of each girder member that contacts other girder members. The overlapping girder members are bound together using pairs of C-shaped hoop steels, called girder binders, which are positioned on the lateral sides of the girder members. This assembly technique, unique to the Kintaikyo Bridge, is called voussoir arch method. The original Kintaikyo Bridge constructed in 1673 was such a girder assembly structure. After the reinforcing members are completed, copper plating is installed in order to protect the girder framework from corrosion. Once the copper plating is installed, the bridge deck is at last assembled. The bridge deck is composed of step planks at the stepped portion and decking at the flat portion. Water drips are also made on the underside of the deck planks as another means of preventing rainwater from contacting the girder framework. In this way a great many parts are assembled over many steps to complete the central three arch spans of the Kintaikyo Bridge.

Ten years after the original Kintaikyo Bridge completion, in 1683, V-shaped bracings were installed, and stiffener beams were installed along each arch rib (Fig. 8), to complete the girder assembly structure [3]. Stiffener beams and V-shaped bracings were installed on the sides of the girder framework, where they improve the structural rigidity. These items are unique to the Kintaikyo Bridge, where they function to control to the slight initial vibration which occurs when people cross the Bridge.

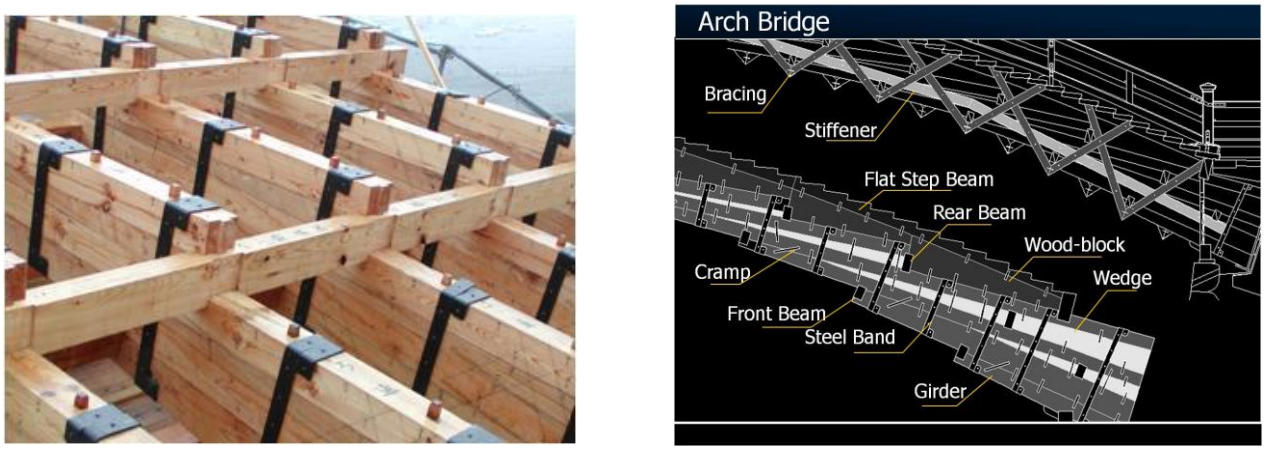

Fig.8 Girder assembly technique and Half model of an arch.

5.2 Field Tests and Their Evaluation

The Kintaikyo Bridge has been in continuous use although it has typically been either partial or extensively rebuilt at periodic intervals. Waseda University (Department of Civil & Environmental Engineering and Department of Architecture) was commissioned by the municipal authorities of Iwakuni City to carry out an inspection and assessment of the Kintaikyo Bridge in line with the current requirements to ensure the safety and serviceability. The inspection has been carried out with the help of the students of Iwakuni Senior High School every five years [2], [6]. A field inspection was performed to identify and assess deterioration. Conditions varied throughout the bridge, with most of the deterioration due to decay caused by the accumulation of dirt and moisture.

The objectives of the assessment were to estimate the present load carrying capacity, to identify any structural deficiencies in the original design and to determine reasons for existing problems identified by the inspection. Load carrying capacity is an important aspect affecting the safety of the bridge. Pedestrian bridges are no exceptions. Information regarding the ultimate strength of the bridge is required for appropriate allocation of bridge maintenance funds. Measurements of the response to static loading may be used to measure the elastic response of the bridge. However, this type of test requires significant extrapolation of the measurements, if used to predict the strength at design load level. The load carrying capacity here does not refer to the ultimate capacity, rather a lower level referred to as serviceability level.

Fig.9 Weighing 6 tons by students and teachers.

Four load cases were used to maximize load effects in respective arches. The 112 students weighing 536N in an average (Total weight: nearly 60kN) were positioned transversely four or two lines to the respective guide rails to balance the load effects in the arch ribs (Fig. 9). Structural responses were recorded immediately before and after students were moved. No tourists were allowed on the bridge during testing. The load tests were limited to recording displacements.

Instrumentation involved the use of strain gages to determine displacements under static and dynamic loading. The only type of sensors used was resistance strain gages. A total of 18 strain gages were installed in the three sections located mid-span and quarter-span for the central three spans during the field-testing program.

5.3 Numerical Evaluation under Design Load

For comparison purposes, the analysis has been performed. The three-dimensional model was used for static and dynamic analysis. The behavior of timber as a construction material is complex. Timber is an anisotropic material; its strength properties vary with the direction of loading to grain direction, its shrinks and swells in response to changes in atmospheric moisture, characteristically to varying extents in different directions. Fluctuating moisture content causes dimensional movements in timber, increasing stresses in structural connections and causing splits and fissures. The localized decay of a timber member may have a more specific cause than generally high relative humidity in the bridge. The material test specimens were tested on a universal test machine. The load at failure was noted and the maximum average stress at failure was calculated.

However, for the purpose of structural analysis all the members had been assumed to be sound. It is for this reason that data is most appropriate for a determination of trends rather than for evaluating a specific value.

All simulations have been performed with three-dimensional finite elements using general-purpose finite element code. The model consists of two materials: wood and steel. The wood and the steel are treated as linear elastic continua. The Young's moduli of wood and steel are set to 12 GPa and 210 GPa, respectively. The model consists of approximately 20,000 nodes and 17,000 elements (Fig.10). Figure 11 shows the result of calculation. Total averages indicate generally satisfactory and acceptable level of accuracy. None of the member was over-stressed under pedestrian loadings.

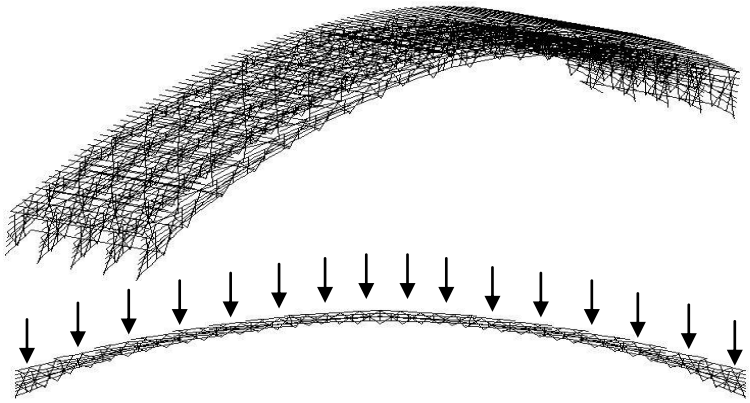

Fig.10 Analytical model and uniformly distributed load.

One test placed a uniform load of 60 tons on the center span of the bridge before it was disassembled. Despite the advanced age of the bridge material, the center of the bridge sunk only 27mm under the load as shown in Fig. 11. This result satisfies the present standards for pedestrian overpass. These tests also identified much what was new concerning the effectiveness of the reinforcement beams, V-shaped bracings, and other reinforcement materials, and renewed our admiration for the wisdom and efforts of our ancestors.

Each arch of the bridge consists of smoothly curved skeleton lines, its end support points are restrained so that when a vertical load is applied to the curved surface of an arch, a horizontal reaction force is generated in the support points. When subjected to asymmetric uniform loading, each arch prominently shows the asymmetric mode of deformation inherent to an arch structure. In view of these characteristics, each of the central three spans of the Kintaikyo Bridge is considered to have an arch structure, and is the prototype of an arch bridge made of large-section, glue-laminated.

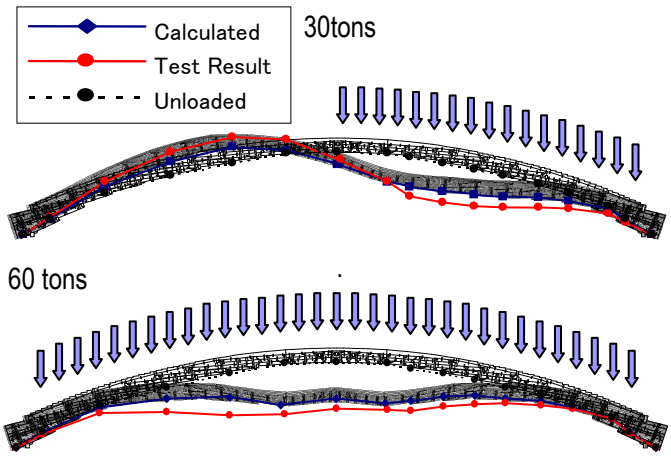

Fig.11 Comparison between tests and numerical analyses.

6. Conclusions

Since the construction of the first Kintaikyo Bridge, the Bridge has been rebuilt and maintained by local people. To long sustain the traditional bridge building technology, it is best that such technology be passed down to local people. The City of Iwakuni decided to guarantee the succession of bridge building technology, so as to ensure repeated rebuilding of the Bridge.

In comparison with modern bridge engineering technology, the structure of the Kintaikyo Bridge during the Edo period is considered extremely advanced. The project to rebuild the Bridge during the Heisei Period shows us the great skill of the Bridge, resulting in further efforts to increase the rigidity and to extend the service life.

The central three spans of the Kintaikyo Bridge are considered to be arch structures with Catenary curve from the mechanical point of view for the deflection modes and measured strains. This draws upon both existing knowledge and experimental investigation, leading to a new era of timber bridge construction. Passing down this traditional construction technology to younger generations is our generations' duty.

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