Investigation of mechanical behavior of the Japanese historical timber arch bridge: Kintaikyo Bridge

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ABSTRACT: The Kintaikyo Bridge with the five span wooden arch structures over the Nishiki River in Japan was originally constructed in 1673. Each span of the three central arches is 35.10m, the total length being 193.3m and the roadway being 5.0m wide. The arch ribs are made of keyaki wood and pine, which have high working strength, while the covering and han-drail are hinoki wood, a species of cypress. As the floor follows the curve of the arches, the Kin-taikyo Bridge is available only for a pedestrian bridge. The Kintaikyo Bridge is vulnerable to natural disasters such as floods and earthquakes. In this paper, the structural characteristics of the Kintaikyo Bridge are dealt with in detail, in which each of the central three spans of the Kin-taikyo Bridge is proved to be a real arch structure. And finally the structural preservation of the Kintaikyo Bridge is fully discussed.

1 INTRODUCTION

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. Despite the bridge's unique five-span arch structure, which is designed to enhance durability, the bridge is vulnerable to natural disasters such as floods and earthquakes. As a way of long sustaining the 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. This solution is unique in the history of bridges in the world.

Figure 1 : Original Kintaikyo Bridge.

2 BACKGROUND OF BRIDGE CONSTRUCTION

The Nishiki River (Fig.2 and 3) flowed in a U curve around a mountain, 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 divided by the River, which required some means of linking the two districts (Iwakuni City 2007).

Figure 2 : Kintaikyo Bridge as of 2009

Figure 3 : Kintaikyo Bridge as of 2007

In response to the growing demand for a durable bridge, the first Kintaikyo Bridge─a five-span arch bridge─was constructed in 1673 (The present Kintaikyo Bridge is the fourth). 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 (Ohno 1936). 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 vulnerable to natural disaster. 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. This solution is indeed unprecedented and unique in the history of bridges in the world (Iwakuni City 2007).

The Kintaikyo Bridge was washed away on September 14, 1950 (Fig.4), 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.

Figure 4 : Arches being washed away

3 BRIDGE CONSTRUCTION SYSTEM

Many historic documents remain regarding the Kintaikyo Bridge. Of them, the oldest existing 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 it was carried away. To sustain the bridge building technology, we must also prepare and preserve such records for future generations (Aoki 1953, Iwakuni City 2007, Yoda 2008).

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. Each timber has a different and unique nature, which can be learned only by viewing and touching the timber, and using all five senses. Without knowing the nature of each timber, carpenters cannot use it for the appropriate purpose. Unfortunately, the wide spread of laminated lumber provides contemporary carpenters with few opportunities to learn from wood. In this environment, rebuilding the Kintaikyo Bridges, 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 (Iwakuni City 2007).

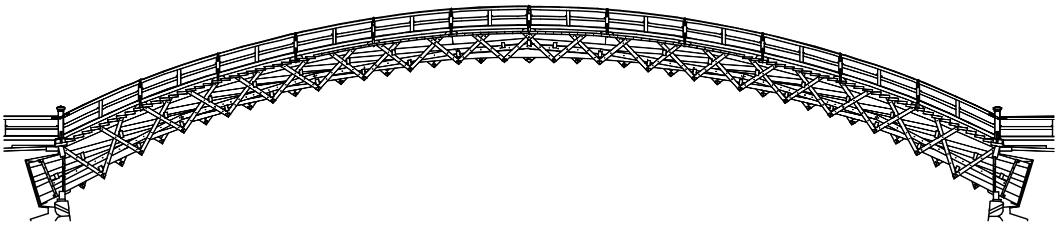


Figure 5 : Side view of an arch.

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 surface 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. However the authority placed orders with timber merchants and nail producers on an individual basis (Iwakuni City 2007).

Figure 6 : Wooden framework of Kintaikyo Bridge

4 STRUCTURAL CHARACTERISTICS

Each arch of the bridge consists of smoothly curved skeleton lines, its end support points 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 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, retained at the end support points, provides different rigidities against small rotation and large rotation.

As mentioned before, 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. The resulting Kintaikyo Bridge represents the essence of the wooden culture, in addition to the beauty of the appearance with Catenary curve (Fig.7).

Figure 7 : Form of the arch (Catenary curve)

5 STUDY OF MECHANICAL BEHAVIOR

5.1 Arch span composition

The three central spans of the Kintaikyo Bridge are arch bridges, and the other two end spans are girder bridges. The girder of each arch span comprises 1st through 11th girder members, a large ridge beam and a small ridge beam. To prevent girder member displacement, dowels are placed on the surface of each girder member that contacts other girder members. The overlapping girder members are bound together using pairs of C-shaped hoop irons, 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. Ten years later, in 1683, V-shaped bracings (unique to the Kintaikyo Bridge) were installed, and auxiliary bars were installed along each arch rib, to complete the present girder assembly structure (Fig.5).

5.2 Field tests and their evaluation

The Kintaikyo Bridge has been in continuous use although it has typically been either partially 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 (Horii 1969; Yoda 2004). 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.

Four load cases were used to maximize load effects in respective arches. The 112 students weighing 536N in an average (Total weight: 60kN) were positioned transversely four or two lines to the respective guide rails to balance the load effects in the arch ribs (Fig.8). 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 within a three span section located mid-span and quarter-span during the field-testing program.

Figure 8 : Weighing 6 tons by students and teachers

The maximum quarter-span displacement recorded, with static loading of semi uniformly distributed load, was approximately 2.5mm in the Center Arch as of 1998. And the displacements of both upstream and downstream sides are reasonably close to each other. It follows from this that the effect of load distribution is satisfactory ensuring the soundness of the arch ribs. It indicates that the bridge is expected to be safe at least up to the design pedestrian load (600kN), which was confirmed by the loading tests in 2001.

5.3 Numerical evaluation

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 (Fig.9 and 10). The load at failure was noted and the maximum average stress at failure was calculated.

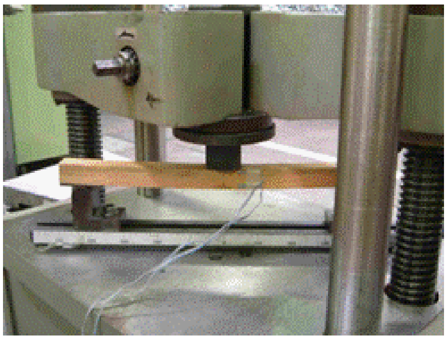


Figure 9 : Material tests for bending

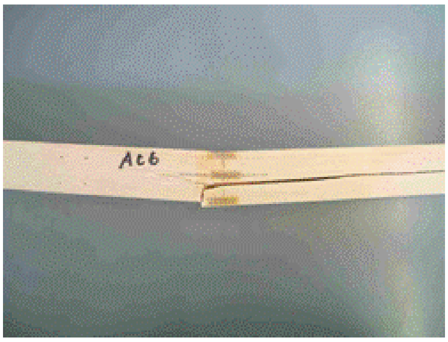


Figure 10 : Material test result

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.11). Figure 12 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.

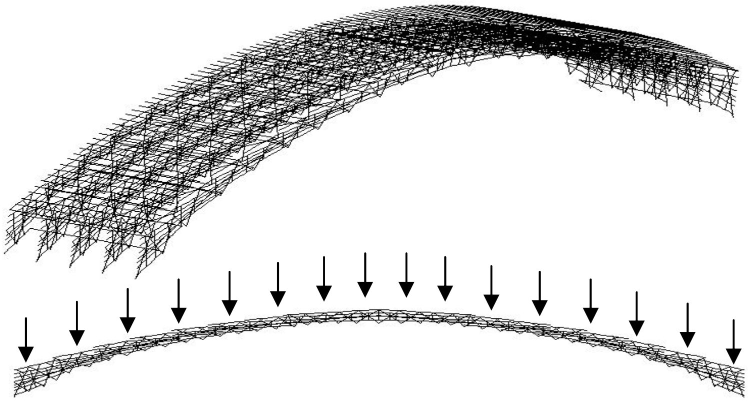
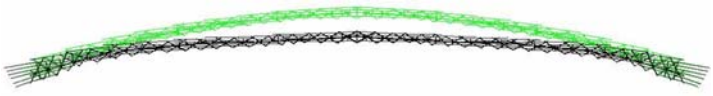
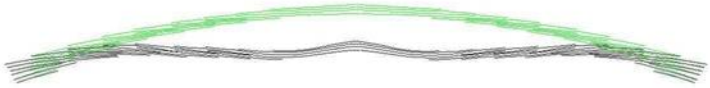


Figure 11: Analytical model and uniformly distributed load.



(a)



(b)

Figure 12: Deformation of the arch rib under uniformly distributed load (×100): (a)With Stiffeners, (b)Without Stiffeners

The Kintaikyo Bridge is a wooden arch bridge unlike any other in the world. Even by modern engineering standards, the structure of this bridge is considered to be extremely advanced. One test placed a uniform load of 60 tons (Fig.13) on the center span of the bridge before it was disassembled. Despite then advanced age of the bridge material, the center of the bridge sunk only 27mm under the load as shown in Fig.14. This result satisfies the present standards for pedestrian overpass.

Each arch of the bridge consists of smoothly curved skeleton lines, its end support points 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 timbers.

Figure 13: Uniform load of 60 tons

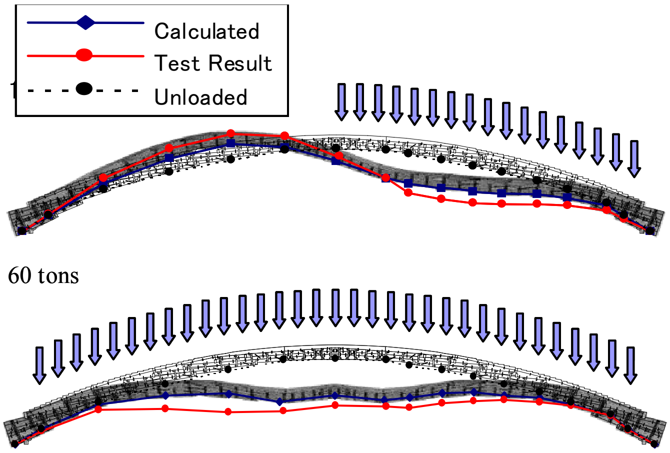


Figure 14 : Comparison between tests and numerical analyses.

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. With this view, in selecting builders the local authority adopts a single tendering method rather than a competitive tender, which is the most common way of ordering public works. Although the use of the single tendering method is rare, in the case of the Kintaikyo Bridge projects it is most effective in transferring traditional technology.

Whilst the present paper covers only a fraction of structural highness of the Kintaikyo Bridge, it is possible to draw some interim conclusions from the in-situ tests. The Kintaikyo Bridge was considered to be an arch structure 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.

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