# Design of Arch and Transfer of Technology in Kintaikyo-Bridge

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## Summary

Kintaikyo-Bridge is a very special wooden five-span bridge with three arches across the Nishiki River, the largest river of Yamaguchi Prefecture, Japan. The central wooden rib arch is very rare in the world. Its structure has become a landmark because of its elegant beauty and harmony with the beautiful views of the surrounding area. It attracts many tourists. Rebuilding was carried out many times since its inauguration in 1673. The latest rebuilding was made in 2004 which was about 50 years after its previous rebuilding.
The original Kintaikyo-Bridge span length was close to the limit for construction techniques of wooden bridges at that time. In order to make a strong bridge against flood, the best mix of wood and stone was used. Arch structure was adopted in the superstructure, and hollow stone piers of spindle-shaped cross-section were adopted in the substructure. In this paper, the origin of the arch of Kintaikyo-Bridge is investigated because the arch is different from voussoir arch or corbel arch, resulting in amazing elegance.
In addition, the issue of transfer of technology in wooden structure was examined. This includes some serious problems with respect to the reduction of skilled carpenters who specialize in building wooden structures such as bridges, shrines and temples. A unique periodic inspection on Kintaikyo-Bridge conducted by Waseda University every five years since 1953 was introduced, in which the weight of local high school students was used as load.

**Keywords:** Kintaikyo-Bridge, Wooden bridge, Design of Arch, Rebuilding

## 1. Idea of wooden arch bridge

In Japan before and after the construction of Kintaikyo-Bridge there is no record of such a wooden arch bridge. This section deals with how the original arch structure of Kintaikyo-Bridge was produced.

The oldest stone arch in Japan is Megane-Bridge in Nagasaki Prefecture. Since its construction in 1634, at that time when Hiroyoshi had already envisioned Kintaikyo-Bridge, it is supposed that he had already studied arch structure and had understood the arch structure principle, too. The principle of stone arch was applied to the Kintaikyo-Bridge.

About wooden arch, it is said that Kintaikyo-Bridge design was given a hint from Saruhashi-Bridge of Kai [4]. (Fig. 8). Saruhashi-Bridge is a wooden cantilever bridge. The girder is on the overlaying beams. One side of the beams is embedded in the rock and the other side is overhanging [5] (Fig. 9). The first to the eleventh girder of Kintaikyo-Bridge (Fig. 10), are superimposed beams while overhanging, in the same way as Saruhashi-Bridge. However, where beams of Saruhashi-Bridge are substantially parallel to each other, the girders of Kintaikyo-Bridge are superimposed on the lower girder by inserting Atobari which is at the base position of the lower girder. Each girder tip (center span side) is superimposed directly on the lower girder through Hanabari. Thus, the angle of the girders change gradually with overhanging forward to center span side. By simplifying the structure of the two bridges, the girder of Saruhashi-Bridge is replaced by a straight line and the one of Kintaikyo-Bridge is a curve for the above reasons (Fig. 11). From these, Kintaikyo-Bridge can be

inferred to have been designed with the intention to create an arch shape with girders, on a base of cantilever structure of Saruhashi-Bridge. It was considered to be a breakthrough at that time that Hiroyoshi produced an arch shape by reducing loads to the foundation with light wooden superstructure.

## 2. Creation process of arch

Arch shape of Kintaikyo-Bridge is a catenary curve, the most stable arch shape, constructed at the time of the foundation (Fig. 12). This has been confirmed by Matsutsuka [6]. According to Matsutsuka, the catenary is an arch curve anyone can make immediately when there is a rope or chain, even without a computer. He also said that Kintaikyo-Bridge was constructed by a genius master carpenter, Kodama Kurouemon, who used a catenary at the time of the foundation.

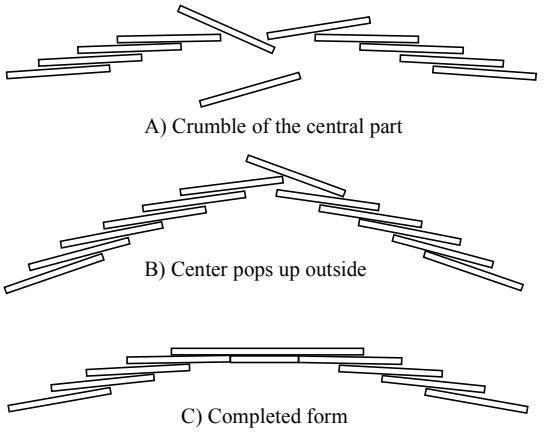


*Fig. 14: Creation Process of Arch*

In the study of how Kodama Kurouemon reached catenary shape, it is inferred that there was a process similar to the origin of the stone arch in "Brücken vom Balken zum Bogen" [7] of Belt Heinrich. He speculated that the stone arches evolved through three processes described below. 1) Cantilevered arch was collapsed and became arch (Fig. 13). 2) Two stone plates falling towards each other and the inclination became arch. 3) Single long stone girder was divided into a plurality of stones and became arch.

Therefore, as shown in Fig. 14, various angles are tested in the process of protruding from both sides as wooden cantilever. It is considered that center horizontal part collapsed or was lifted on the outside by the degree of angle or overhanging. With repeated trials and errors, it is inferred that they succeeded in achieving a stable arch shape. And the shape at that time was consequently Catenary.

Whether catenary curve was intentionally used or not, perhaps Kodama Kurouemon surely wanted to make a beautiful bridge. Since he intended to achieve an unprecedented structure, his instincts as an engineer produced a beautiful shape.

## 3. Arch structure

Recently, from studies of Yoda, it has been demonstrated by experiments using a model that Kintaikyo-Bridge is an arch structure mechanically for reasons described below [8]. 1) Both fulcrums have been constrained in the horizontal direction and the reaction force in the horizontal direction is caused by vertical loads. 2) Compressive stress is prominent in the cross section caused by the vertical uniformly distributed load. 3) Symmetric deformation mode and asymmetric deformation mode come from the arch structure-specific form.

Large compressive stress occurs in the central keystone (Ohmunagi) during numerical analysis simulation using FEM, and keystone is the keystone in the arch structure [9].

After Kintaikyo-Bridge construction, one of the reasons why wooden arch structure has not been constructed is supposed to be the existence of keystone. The size of keystone in the center span becomes an important point of arch structure; this has been told only to generations of master carpenter by word of mouth [10]. It was the most difficult decision that how long keystone should be cut in length in the latest rebuilding [11].