# Structure, Construction and Craftsmanship

## of the Timber Woven-Arch Bridge in China

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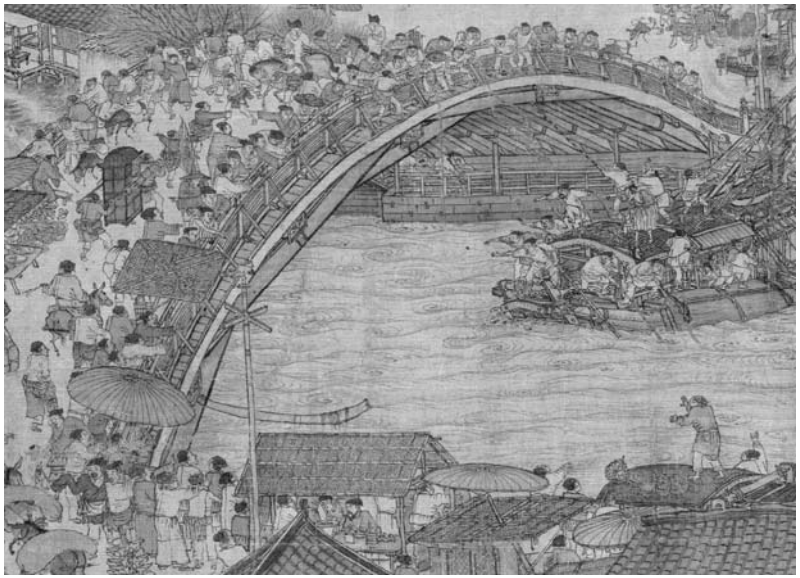
### Rainbow Bridge structure – woven arch



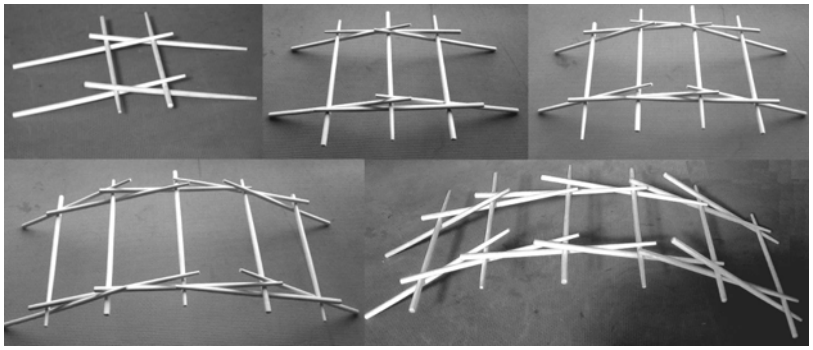
The Research of the Woven Arch Bridge begins from a very famous Chinese scroll painting, drawn in the early 12th century with an age of nearly one thousand years, the Qing Ming Scroll or the “Life along the River at the Qingming Festival”.

When the painting was first exhibited in the Forbidden City in the 1950s, the “Rainbow Bridge” which is depicted in detail in the central high tide of the composition caught the attention of a bridge engineer Mr. Tang Huancheng.

He soon realized that the bridge is of a peculiar structure, with no similar example known before. For more than two decades from then on, the Rainbow Bridge and its sisters built during the same period across the same river according to the historical record were thought to be of a lost technique and the lonely examples of such structure ever in the history.
This structure is named today as the “timber-woven-arch”, the name pinpoints the most vital feature of this structure: weaving.

As we can see from the painting, the structure was constructed by timber members, the wood are chopped into roughly rectangular section, they follow one after another along the span, each of them is supported by its two neighbors at its ends with crossbeams clamped in

between. By the mean time it also supports the same two elements at its mid, thus forming a coadjutant system of the structure.



This reciprocal structure reminds people the weaving craft in the bamboo culture, taking the basket as a representative.
This weaving idea is also spread broad all over China by a folk game called “building a bridge with chop sticks”.

A most fascinating feature is that, when we develop the arch according to its own constructional logic (with proper joinery, namely, notch here), it will form a circle with inherent stability. This circle can have theoretically infinity numbers of sides, while the smallest is the “five-pointed star”. The larger, the softer the structure will be. When the polygon is formed in limited number of sides, the structure could be quite rigid.

**Definition discussion: arch or curved beam?**

It is hard to define this structure with the normal term “arch”, because it is quite distinct on the essential structural principles.

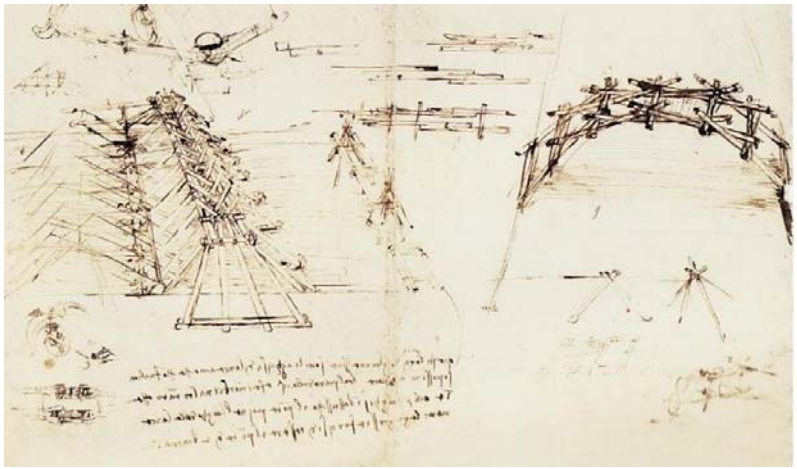
The normal arch will suffer from an outwards collapse mode, Which means, when the arch feet have an outwards movement, the arch will fall apart. It thus requires an inward action to retain it from collapsing.
The woven arch, on the contrary, suffers from an inwards collapse mode. When the arch feet move towards, the weaving function will lose efficacy and crash down.
It requires always an outward force at its feet to maintain the shape, the thrust generated under static load could serve well for this purpose, thus a considerable load on the bridge is always benefit to the structure.

For the normal arch, a pair of strong abutments is a must. The abutments must be able to

afford enough inwards counterforce to offset the thrust. The internal stress is mainly axial force.
For the woven arch, it's ok to have no abutment, the arch will expand under the load, since there is no horizontal force at the feet of the structure, theoretically there is no axial force either. This deformation is elastic, and the arch will return to its original shape when the load is gone.

So the terminology "arch" by its common sense might not be accurate enough for this kind of structure.
I would like to quote the words of Prof. Philip Caston from our discussion on the question that "is the woven arch an arch or a curved beam?" We finally agreed that it is both an arch and a curved beam, otherwise it is neither of them.

**Leonardo Bridges**



Surprisingly, we are not that lonely in the history. Another brilliant brain had also invented this structure at the other side of the continent. He was Leonardo da Vince. As we all know, he was an excellent engineer and inventor, and in his letter to the Duke asking for a job of military engineer, he listed his capability, and the first one on the list is that, he is able to build light and convenient bridges during the war time. His manuscript shows that he had studied this structure over and over again.
According to my recent study, he invented this structure independently without influence from the eastern world.
So let I boast that only the genius could figure out this structure.

**Southeast China Bridges**

In 1980, cultural relics conservators of Zhejiang province noticed a type of local bridges which had been misrecognized as slanted struts bridges for decades. This bridge structure was soon recognized by scholars on its kinship with the Rainbow Bridge.

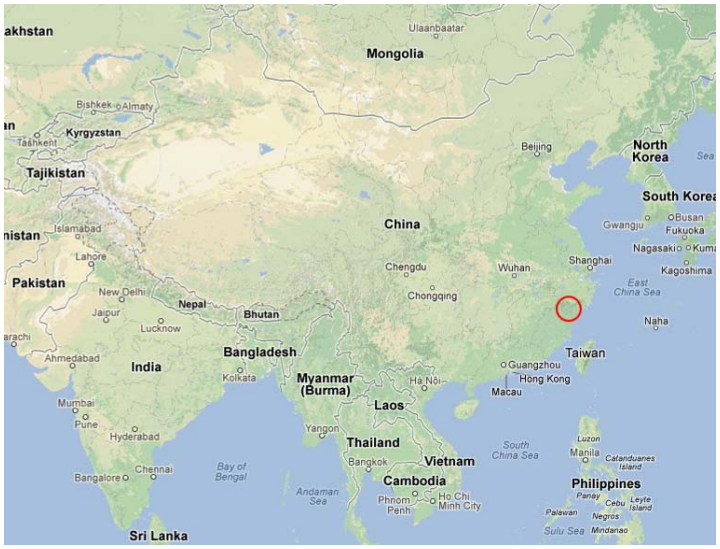
These bridges are found almost exclusively in the mountains of the boundary area between Zhejiang and Fujian provinces, the total number of them was thought to be over 200 in the early 1990s, but only a little more than 100 historical bridges standing today.

Luckily, there are still carpenter families and carpentry tradition specialized on this kind of bridge surviving in this area, and after its technique and craftsmanship was listed into the UNESCO “Intangible Heritage List” in 2009, the historical bridges are receiving more attentive care, and today new bridges are being built everywhere.

During my investigation on these bridges in the past 2 years, I have had opportunity to interview carpenters from several pedigrees. Their methods are different from family to family and from county to county, so comparing the observation on the historical structures and the technique of the living carpenters will enable me to draw out a pedigree map at last.

Besides these heard and seen information, I have experienced the bridge building technique by my own hands, including a 1:20 scale bridge model which was made in cooperation with Prof. Philip Caston in his workshop in Neubrandenburg University of Applied Sciences, and the opportunity to participate as a carpenter in an complete process of a bridge construction with the bridge masters in a village in Zhejiang.

I would like take my personal experience of the woodworking practice to give the introduction of this special technique and craftsmanship.



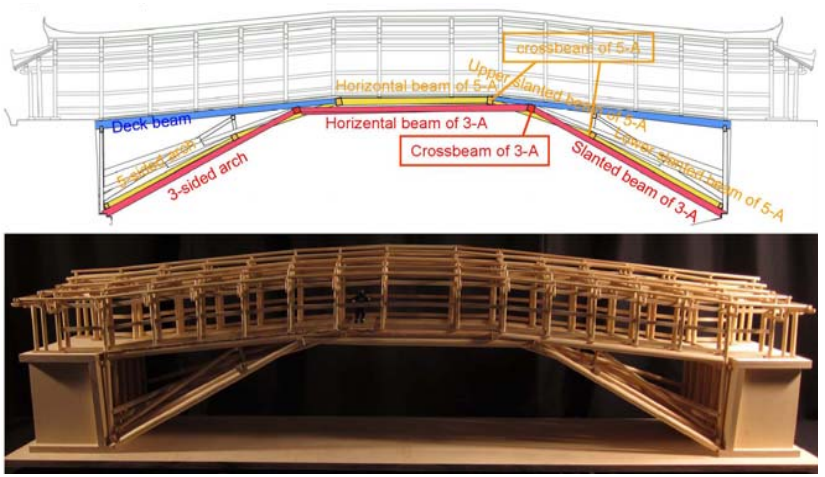

**Structural principle of the Southeast China bridges**

First let's have some general idea of this structure of these covered bridges.

Though looks quite different in its appearance, the Southeast China bridges also have a woven arch as a main composition of the structure. It is quite most obvious seen from underneath.

It is formed by a three-sided arch, shown in red and a five sided arch, shown in yellow.

While the woven arch is almost equal to the whole structure of the Rainbow Bridge, it serves only partial for that of the mountain bridges. Beyond the two woven-together systems, the deck system works as the third arch system, shown in blue, and the diagonal elements and struts in between help to form a 3-dimensional spatial structure.




However, these two kinds of woven arch are actually quite different from multiple levels.

First of all, the Rainbow Bridge is much closer to the folk game or the woven “circle” on its conformation principle, it is much more a homogenous system, namely, every beam is of the same size and servers equally to the shape.
But the Southeast China bridges have two distinct systems: a main system shaped in three-sided arch, shown in red in the graph. It is built first and with thicker timber.
Then a secondary system shaped in five sided arch, in yellow, which is woven into the readily finished three sided arch, and its elements are much shorter and thinner.

From the joinery level, namely, the connection between the longitudinal beam and the crossbeam, the elements of the Rainbow Bridge, according to the historical record, are nailed together. Some scholars believe it also uses rope to tie up. No matter in which case, the crossbeam is clamped between the longitudinal beams just as the latitude of textile.
The Southeast China bridges on the contrary, rely on the woodworking joints, namely dovetail and mortise-and-tenon. Then the crossbeams have an affiliation to one of these two systems, they belongs to either 3-sided arch or the 5-sided arch.

Joint type is fatal to the analysis of the structure, but it was easily forgotten in the research before. It decides if or not the axial force in the structure can take the place from the bending moment or how much they could be. The more it does, the more the structure functions as an arch.

From the constructional level, the building steps of these two types of wood arch bridges are quite different from their structural principle.

To build a Rainbow bridge we need to build up the whole woven frame at the side as the first step, just as the game shows, and then add in the rest of the beams side by side.
But for the Southeast China type, we need to finish the 3-sided arch at the first, then the 5-sided arch.

**How to build the bridge**
Now, let’s begin to build the bridges.

**1. Location**
The two cases of my woodworking practice are different. The prototype bridge of our model, the Jielong Bridge, has an age of around 100 years. It is high over a cliff, and has a span of 30 meters. Most bridges of this kind have a span from 20 to 30 meters, the largest single span of the standing historical bridge is 37 meters, so this one must be classified into the “large span” group.
It locates some distance from the nearest village, served as an important traffic node for the local communication before the modern times.

The new bridge project is a reconstruction of an old one which was destroyed in fire some 30 years ago. It is immediately outside a village at the end of a valley facing a small plain, and servers as a Fengshui spot.
The village shares a family name YU which has the same pronunciation with Fish in Chinese language. So the bridge as part of the water culture is highly respected by the villagers. The organizers are three common local families, they raised the money, engaged the master carpenter, arranged the material, and all their efforts for the bridge are thought to be a merit in the Buddhism sense.

**2. The material.**
The main wood used in the bridge construction in this area is Chinese fir. People say that the fir for construction in Southeast China is as common as the rice for eating in Southern

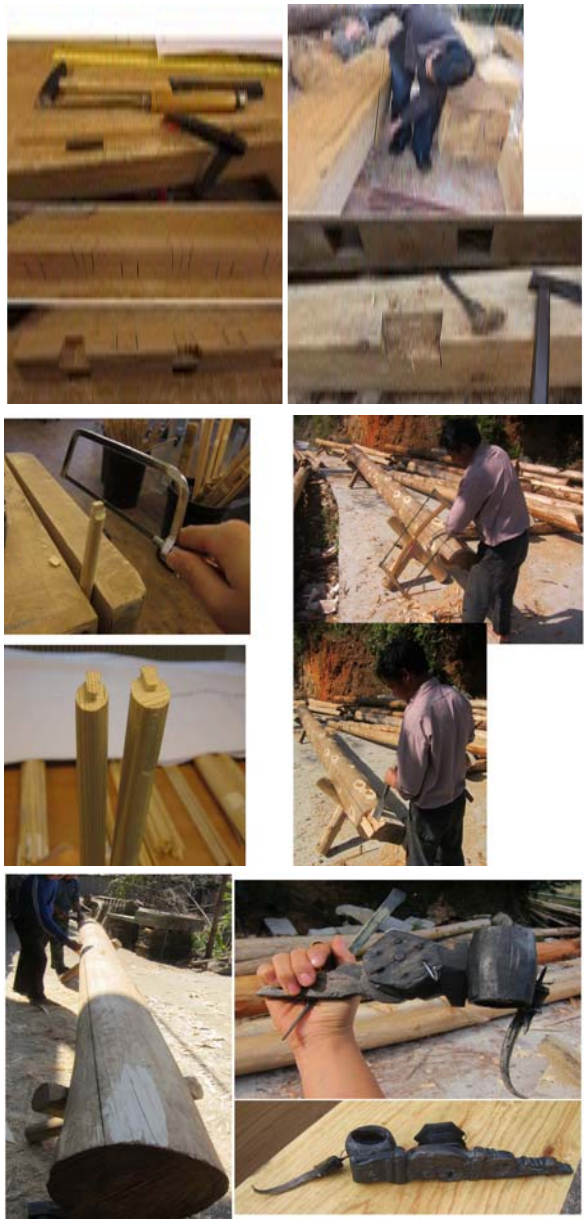
China.
The crossbeam are normally made of harder timber, cater for the dense cutting of the joints. For example the Chinese red pine, and only those with an age around 100 years, they are especially suitable under water, or some kind of Chestnut wood. All the timbers are collected from the local mountains.
For the model we use ready made model material, we use birch for the crossbeam, and European white pine for all the other elements.

**3. The basic woodworking method**

The wood cutting methods, esp. for the joints are almost loyal to the real construction.
In both scale of cases, the mortises are dug by Chisel,
The tenons are sawn.

One special implement to decide an intersection cutting line on the irregular timber, is the ink string which functions the same way as a chalk string.
Bamboo pen are used for marking on the timber.

The carpenter master had made templets in advance for the angle of the tenons.
The longitudinal beams, because of the retreat on the plan, inclined inward with different degrees the master has a special ruler especially designed and made by himself to decide the angle of the beam axis.



**4. Base**

After all the elements are ready-made, the construction will begin.

Before the carpenters' arrival, the masonry work for the foundation is already done. The first rule of choosing a bridge site is to take any possibility to utilize the nature rock. When the nature solid foundation is not available, the abutment is laid of ashlers.

The first step for the carpentry on site is to lay down the ground cross beams. Serving as a base of the entire structure, this pair of beams are also commonly taken place by a row of ashlers.
There are two examples respectively made by wood and stone here.

**5. Commander column**

Then, before the erecting of the arch, the pair of frame at the ends of the arch must be erected first. The pillars reach up and serve also as the corridor columns, they are the only structural elements that connect the corridor and the under-deck structure, this role grants them the name "commander column".

The erecting of this frame is the first great event for the construction. The work began in the early morning one hour earlier the common days, the whole village came to help. After the erection, villagers gathered to the organizers' houses for a rich breakfast.

**6. Scaffolding**

Before the arch construction, is the problem of scaffolding. Most of the new projects today take the dense modular scaffolding, the traditional material is fir, but today iron tube is a more common choice.

The traditional type of the scaffolding, the so-called “water post frame” is a pair of swing-frame-shaped scaffolding. They must be assisted by rope or struts to keep stability.
Both types of scaffolding aim to give support to the arch at the intersection between the slanted beam of the 3-sided and the 5-sided arch, they must support the beams of the 3-sided arch, while at the same time leave enough gap to allow the beam of the 5-sided arch to get through.

While the photos from the real project are showing the dense scaffolding construction, I demonstrate the traditional method with the model.

**7. Slanted beam of the 3-sided arch**

One of the main conveniences for the dense scaffolding is to form a working platform in the middle above the water, and crossbeams could be transported there in advance.
But this might be not available when the bridge is to be built over the cliff, in that case the swing-formed scaffolding in the only choice, and all the members are pulled to place by rope.
Then the arch construction begins with the slanted beam of the 3-sided arch.
The beams are of tones of weight and require the cooperation of a crowd of people including the carpenters and villagers who volunteer to help when needed.
They are tied with rope on the foot and in the middle, the ropes are held separately by two groups of people.
The beam takes the log fixed on the edge of the shore as the pivot point and is rotated down

by lowly releasing the ropes.

Before the foot of the beam reaches the ground, the carpenter waiting aside gets into the cooperation and sets it to its right position.
Then the beam takes the logs laid between the shore and the center platform as a railroad to “slide” towards the middle.
The carpenters waiting on the platform then take over the top of the beam and set it to the right position according the mortise hole on the crossbeam which is transported there by the log railroad in advance.

Please take notice of the cushion blocks under the crossbeam, the space under the beam is set for the weaving of the 5-sided arch.

**8. Horizontal beams of the 3-sided arch**

A number of such wedge-shaped blocks are prepared in advance.
The crossbeams is a little bit lower than its right position at the beginning to give allowance for adjustment, which is made when the horizontal beams are being set into their place.
Wedges are added and knocked in to raise the crossbeams until the horizontal beams fit in and their tails settle down into the sockets on the crossbeam.

**9. 5-sided arch**

After the finish of the 3-sided arch, most carpenter masters will begin to erect the 5-sided arch from the lower slanted beam to the top of the arch. This is the case for most the historical bridges I have visited. We can tell this constructional process by observing the joints: If the longitudinal beams use tenons to get through the crossbeam, it must be settled into place first, while those use dovetail at both ends could be put in after others.

The master carpenter whom I worked with takes this unique method, and this makes him distinct into a separated carpentry pedigree. After we have experimented both of these

methods with the model, we are able to understand the reason of his choice.

Since the upper slanted beams are the only part of the 5-sided arch with a woven function, as soon as they take their place, the arch become stable enough by itself, in our model experiment, it even get rid of the support of the abutment.

To insure the weaving mechanism functions well, multiple equipments are involved to make it tight. In the past time it replied mainly on the huge hammer made by an entire log which must be handled by four strong men together.
Nowadays the iron pulley and iron hammer are the first choice of the carpenters.

Then after the installing of the lower slanted beams and the top horizontal beams, the arch structure is finished.

**11. Rest of the Structure.**

Since the Southeast China arch bridges have lateral stability problem, the so-called “scissors struts”, the X-shaped diagonal struts are essential. The accurate dimensions of these elements are hard to decide during the design period, they are measured and cut on site.

For bridges with large span, two or even three pairs of scissors struts are applied, and the middle struts supporting the deck system are necessary.
Our model looks exactly the same with its prototype inside the structure.

The finish of the whole bridge structure.

**12. The Corridor**

The finish of the bridge corridor and especially the settling of the central ridgepole is of great religious significance. A large celebration including a feast afterwards is feted as a festival.

This is the whole process of a typical small scaled wooden arch bridge.