HISTORY AND
STRUCTURAL BEHAVIOR OF
THE CHINESE TIMBER ARCH BRIDGES

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Chinese woven timber arch bridges are an important part of the precious cultural heritage handed down from ancient. I began to research this unique bridge structure at the suggestion of Prof. Chen in 2007. In the summer of 2011, due to kind encouragement and help of Prof. Nakamura, Prof. Chen and Prof. Wu, I had chance be a candidate for doctoral degree of Nagasaki University. From December 2012 I started to work on this dissertation. This dissertation would not have been possible without the guidance and the help of several individuals who contributed and extended their valuable assistance in the preparation and completion of this dissertation. Now this dissertation has been completed and will be submitted to examine to the requirement for degree of Doctor of Structural Engineering Laboratory of Department of Civil and Environmental Engineering in Nagasaki University. I would like to take this opportunity to express my gratitude to the people who contributed to successful completion of this dissertation.

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Timber is credited as one of the first natural materials used to construct bridges. It made its debut as a beam formed by fallen trees, with the help of which the primitive men could cross water barriers or gorges. Timber is light with high tensile, compressive strength and flexural capacity; which is rich in nature and easy to process; therefore, it has been widely used for both short and medium span bridges in ancient times, especially in beam bridge. As time elapsed and technology improved, the ancients gradually realized that the arch structure would allow for a greater span length. Hence, arch bridge appears and has become the predominant bridge type for a long time. Compared with other materials, timber is suitable for linear items, featuring compression and tension and bending forces. Stone is not proper for making this type of item because it is complicated, costly to extract and transport large pieces from a quarry. That's the reason why timber has been used for arch bridges [1].

Timber arch bridges have been built in many countries, but due to the rotten character of timber and insects attack, few timber arch bridges have survived up to date. According to the structural types of historical records and the existing timber arch bridges, timber arch bridges can be classified into four types, namely, timber rib arch, timber truss arch, woven timber arch and others. Timber rib arch bridges and timber truss arch bridges are widespread in Europe, and perhaps close examination of these bridges reveals that they were strongly influenced by stone arch structures that once dominated in church architecture [2]-[4].

1.1.1 Structural form of timber arch bridge

Timber rib arch bridge

Timber rib arch bridge is the most primitive timber arch bridge. Its main arch ring is made from bending the logs into the desirable shape. Construction of timber rib arch bridge is not convenient because the logs should be bent into a curve shape with more complicated processes. In ancient times, timber rib arch bridges were all made of the logs as they entirely depended on the log's length, the span length were rather small. **Fig. 1-1(a)** shows a timber rib arch bridge in Italy. With the development of laminated wood, an increasement on span length of the timber arch bridge works.

Some long span rib arch bridges have been built in Europe. **Fig. 1-1 (b)** shows a long span timber rib arch bridge in Croatia made by laminated wood [5].

(a) Timber rib arch bridge in Italy

(b) Timber rib arch bridge in Croatia

Fig. 1-1 Timber rib arch bridge

Timber truss arch bridge

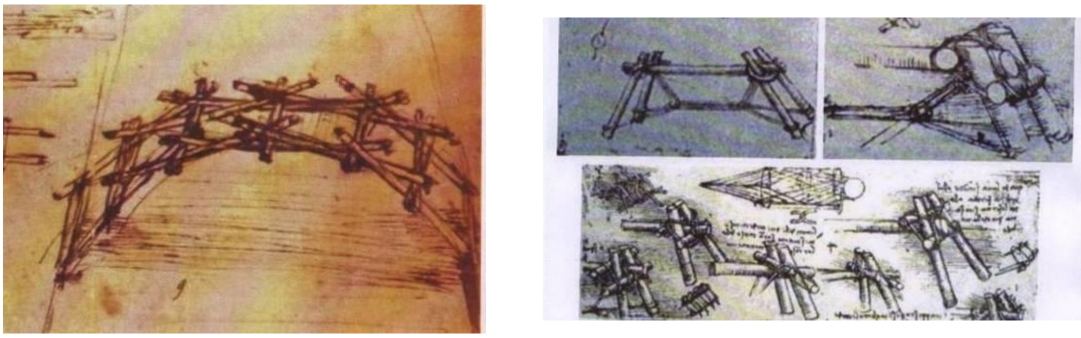
As early as in the Renaissance era, Andrea Palladio, a great Italian architect, described the structure of timber truss arch in his treatise *I Quattro Libri dell' Architettura* (The Four Books of Architecture) [1][2]. Timber truss arch is made up of primarily short logs that are joined together to form a truss structure. Few materials are needed in such a case so that the bridge tends to be lightweight, at the same time, timber truss arch is at an advantage over the simply supported beam and timber arch rib in terms of span length, as it exploits the stable triangular structure and the balance of compressive and tensive load applied to the members. Therefore, the span is larger than timber beam bridge and timber rib arch bridge. For instance, Ponte dell'Accademia, a magnificent timber truss arch bridge across the Grand Canal near the Accademia di Belle Arti di Venezia (Venice) in Italy, as shown in **Fig. 1-2 (a)**, has a single span of about 50 m, which is significantly longer than any previous architecture in Italy. Thanks to careful protection and maintenance, it has been still in use now. **Fig. 1-2 (b)** shows the longest span timber truss arch bridge, which is built in Suzhou in 2013. It has a single span of 75.7 m with the length of 120m and the width of 6m [5].

(a) Ponte dell' Accademia in Italy (b) Xujiang Bridge in China

Fig. 1-2 Timber truss arch bridge

Woven timber arch bridge

As shown in **Fig. 1-3**, in Europe, the imaginary woven timber arch bridge had been described in the Atlantic Code in word and picture by Leonardo in the last decade of the Fifteenth Century, as shown in **Fig. 1-3 (a)** [6]. It consists of two longitudinal arch center systems. The logs were interlaced and tied using ropes, as shown in **Fig. 1-3 (b)**. The force is transmitted to the logs through the ropes which is used to fix them. The logs belonging to the same arch center system are not at the same plane, thus resulting in a great load at the hinge. Unfortunately, the imaginary woven timber bridge had not been built in Europe [5].



(a) Imaginary woven timber arch bridge (b) Binding joint

Fig. 1-3 Imaginary woven timber arch bridge by Leonardo

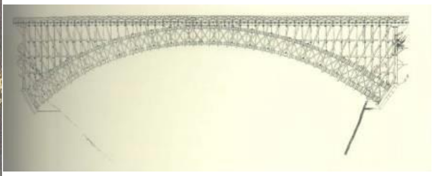
The real woven timber arch bridge has only been built in China. They achieve large span by weaving longitudinal and transverse logs in a special way; in addition, the longitudinal system has two different polygonal arch systems in two planes. It takes full advantage of the parallel to grain compressive strength of the wood and successfully utilizes the short construction element to achieve a large span. The details of structure will be described in Chapter 2.

Other form of timber arch bridges

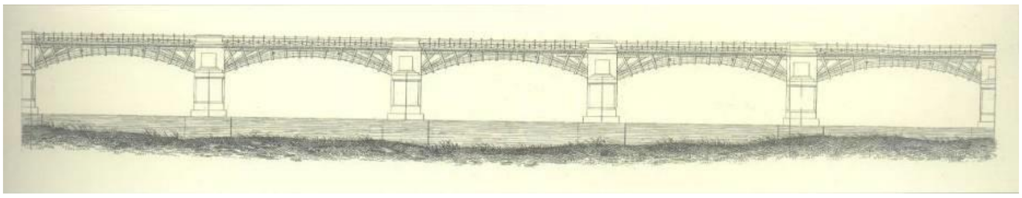
Many other timber arch bridges that can be hardly classified into any of the categories are mentioned above. **Fig. 1-4 (a)** shows a continuous multiple-arch bridge, Apollodorus Bridge, which is depicted in the relief of Trajan's Column. It was designed and engineered by Apollodorus of Damascus in 105 AD under the command of the Emperor Trajan. Several wooden arches, each spanning 35 to 38 m, were set on twenty high-rising masonry pillars. The original bridge was estimated to be made about 1100 m in total length, and the longest arch bridge to more than 1,000 m in both total and span length. **Fig. 1-4 (b)** shows Walton Bridge with 40m of central span across the River Thames at Walton-on-Thames in Surrey, England. The United Kingdom and the United States were ahead of the other countries in bridge construction techniques in the first half of the nineteenth Century. A detailed account was provided by a German structural engineer Karl Culmann in his studying tour to these countries in 1950. For instance, the Cascade bridge with a span length of 90 m built in 1848, as shown in **Fig. 1-4 (c)**, was considered to be the best timber structure in the United States, or even in the world at that time. **Fig. 1-4 (d)** and **4 (e)** show Tournus bridge, a five-span arch bridge with a span length of 27.3 m for each arch was built in 1801 across the Sanoe river and Choisy bridge, a five-span highway deck bridge with a span length from 21 to 24 m built in 1811 over the River Seine in France, respectively [1][5].

(a) Apollodorus Bridge

(b) Walton bridge

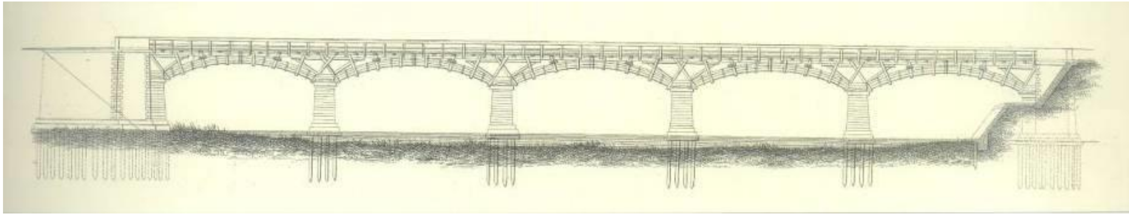


(c) Cascade Bridge



(d) Tournus Bridge

Fig. 1-4 Other form of timber arch bridges[1]



(e) Choisy Bridge

Fig. 1-5 Other form of timber arch bridges[1] (contd.)

Fig. 1-5 displays the Kintaikyo Bridge in Japan. The bridge is composed of five sequential wooden arches on four stone piers and two wooden piers. The total length of this bridge is about 193 m, including a central span of 35m and side span of 34m. What's more, the width is 5 m [5][7]. Its wooden members are connected piece by piece with hoop irons, U-shaped irons or iron wires, as shown in **Fig. 1-5 (c)**.

(a) Panorama

(b) Upward view of the main arch ring

(c) Detailed structure

Fig. 1-6 Kintaikyo Bridge in Japan

1.1.2 Research value of Chinese woven timber arch

From the scope of international, wood is regarded as a kind of environmental protection material. It will be gotten in good graces of more and more architects due to the importance of ecological environment and the sustainable development. At the same time, with the development of industrial technology, the disadvantage of the wood as building component can be overcome with the industrial technology and its superiority will become more and more obvious. Some new timber bridges and timber composite bridges have been built in recent year.

Both timber structure and its construction technology are relatively successful in many developed countries. The design of timber structure is convenient, and timber structure displays a variety of architectural styles, which is one of the most elegant appearances and delectable structures. Timber structure achieved great effects and made a big difference in ancient China, and it had a large practical potential in long span structure. At the same time, China was in the period of large-scale bridge construction. Research on the Chinese woven timber arch bridge from the perspectives of bridge and structure engineering, it can provide references for further study, which is to design and construct timber arch bridges as well as to inspire people to use the structure in bridge engineering and structural engineering in the future.

Due to differences of architectural culture between China and west, we can find there are some differences in the main structural form of timber arch bridge between them. The timber rib arch and the timber truss arch are mainly structural forms in west, while the woven timber arch is the unique structural form in China [8]. Woven timber arch bridge has only been built in China, so in this dissertation we can call it Chinese timber arch bridge [9]. In terms of bridge structure, the rib arch and truss arch are not special for the timber arch; actually, they have been widely used in other material arch bridges, such as concrete arch bridges and steel arch bridges. But woven arch has not been used in other material arch bridges except timber arch bridge [10]. The conception of woven timber arch bridge is ingenious. It can achieve a large span by using short straight loges through weaving longitudinal and transverse logs in an ingenious way. On the one hand, from the view of structural mechanics, there is no corresponding analysis method for it as its structure is neither the general two-dimensional plane structure nor three-dimensional space structure [11]. So it is one of the most important structural forms in the global bridge history with its significant effects.

On the other hand, Chinese timber arch bridges include abundant cultural heritage and intangible cultural heritage. *Traditional construction technology of Chinese Timber Arch Bridges* was listed in the *Urgent Safeguarding List of Intangible Cultural Heritage* by UNESCO in 2009 [12]. Meanwhile, Chinese timber arch bridge was listed in the world cultural heritage tentative list in China in 2012. Therefore, it is also a very important cultural heritage in the world [10].

Since many existing woven timber arch bridges had been discovered in 1970s in

China, the woven timber arch bridges have both attracted particular attention because of its special structure forms and cultural values, and great research interests in recent years. Its research and protection are hot topics in the fields of cultural heritages and ancient bridges in China. Many researches have been carried out by cultural relics workers and architects in China, focusing on the construction history, aesthetics, social function, cultural value and so on. But bridge engineers are busy in building new bridges or focusing on the maintenance of highway and railway bridges, few of them have time and interests to study ancient bridges in China. So the research on the basis of structural engineering and bridge engineering is insufficient.

Essentially, due to the lacking of a systematic scientific research on the woven timber structure, we cannot explain the mechanical behavior and its superiority in structure of the Chinese timber arch bridge now. Many questions have not been solved yet. So Recording down the structure of Chinese timber arch bridge and the traditional construction technology of the Chinese timber arch bridge, carrying out the research work focus on the investigation of the extant Chinese timber arch bridge, model experiments, field static test, the structural behavior analysis, the FE analysis and the structural parametric analysis are the key issues to safeguard Chinese timber arch bridge on the basis of the modern bridge engineering science. The research results will explain the mechanical behavior and its superiority in the structure of the Chinese timber arch bridge, and provide scientific evidence for the application of Chinese timber arch bridge as the world cultural heritage, which gives the theory support for the inheritance of the "traditional construction technology of the China timber arch bridge". It will also supply scientific approaches for maintenance and construction of the China timber arch bridges, and influence the modern bridge structural analysis theory and offer references for the innovation of the modern bridge structures and the drafting of timber bridge structure standard. Those promotions in the research will be listed in this dissertation. This forms **a part of a study conducted under grant No.51408129 from the National Natural Science Foundation in China and No. 2017I0009 from the foreign cooperation projects of science and technology agency in Fujian Province, China.**

1.2 Review of Relative Research Works

According to the present situation, location, and structural details of Chinese timber arch bridges, the characteristics of Chinese timber arch bridges can be further divided into two branches: the one is represented by Bianhe Rainbow Bridge (Bianhe is the transliteration of Bian River, because this kind of bridge was very popular in several places over the Bian Rivers in the North of China). Unfortunately, no one was survived. Therefore, this branch of Chinese timber arch bridge can only be seen in the famous painting of *Chhing-Ming Shang Ho Thu* shown in **Fig. 1-6**. The other is extant Min-zhe Timber Arch Bridges (Min and Zhe are the short names of Fujian Province and Zhejiang Province respectively after all of extant Chinese timber arch bridges are located in Fujian and Zhejiang Province), typified by the Guangli Bridge, as shown in **Fig. 1-7** [13].

Fig. 1-7 Bianhe Rainbow Bridge

Fig. 1-8 Min-zhe Timber Arch Bridge (Guangli Bridge)

Unlike many other existing ancient bridges in China, such as stone arch bridge, stone beam bridge, timber cantilever beam bridge, and suspension bridge, the existing Chinese timber arch bridge was not discovered until 1970s. Because they are mostly in remote mountainous areas with limited accessibility, the research begins later. Fortunately, it attracts great interests by normal people as well as domestic and foreign experts because of its genius structure.

The research can be classified into three stages. The first stage, it lasts from Bianhe Rainbow Bridge in the Painting, as a representative branch of Chinese timber arch bridges, was discovered to 1970's (the other branch of Chinese timber arch bridge called as the existing Min-zhe Timber Arch Bridge was discovered). The second stage, it lasts from the existing Min-zhe Timber Arch Bridges were discovered (1970's) to 1990's. The third stage, it lasts from 1990's to present [14].

1.2.1 First stage: Bianhe Rainbow Bridge was discovered in the painting

According to historical records, many ancient Bianhe Rainbow Bridges had been built in several places over the Fen and Bian Rivers in the North of ancient China, the local people were greatly benefited from those bridges. This kind of bridge is called *Without Foot Bridge* (a single span bridge without pier) in *Song Kui Yao, which* is one of the earliest, important and precious historical literature. It is also a compendium and record for compendium of government and social institutions record or social backgrounds in Song Dynasty. In addition, it is called *Flying Bridge* and *Rainbow Bridge* in some other historical literatures during Song Dynasty; these names are just form the arch shape [13]. However, no figures and drawings can be found to describe and express from the structure in these literatures result in no one knows the detailed structure of Chinese timber arch bridges.

Until 1954, the famous painting of "Chhing-Ming Shang Ho Thu" (Festival of Pure Brightness on the River) was exhibited in Beijing, shown in **Fig. 1-4** by Zhang Zeduan, who is an artist living in the Northern Song Dynasty (1119 to 1125). Mr. Huangcheng Tang is a famous bridge expert. He discovered that the Bianhe Rainbow Bridge is drawn in this famous painting with a realistic way. He made an in-depth research on the structure of the bridge, and then wrote the first paper for the Chinese timber arch bridges. The paper was published in the *New Observation*. He dubs the bridge as *Combined Beam-arch Bridges* and considers that the timber arch bridge is made up of combined structure. This article initiates the new era for research on Chinese timber arch bridges [15].

From then on, many famous researchers, such as, Yisheng Mao, Ying Luo and Dr. Joseph Needham begin to make researches on it. *The Ancient Chinese Bridges* is published in 1957 by Huangcheng Tang, the *Bianhe Rainbow Bridge* was being described and discussed, and the illustration of model had been shown in the book [15]. This book includes five chapters: beam bridge, covering house, arch bridge, cable bridge and suspension bridge. The Bianhe Rainbow Bridge is instructed in Chapter One, mainly beam bridges. The author thinks it looks like an arch bridge, but it is a composite structure and the beam is the main structure. It is also called

Combined Beam-arch Bridges, so it is not classified as arch bridge but beam bridge in this book [15].

The Science and Civilization in China, one of Dr. Joseph Needham's masterpieces, is published in 1962. Dr. Joseph Needham considered the *Bianhe Rainbow Bridge* is one kind of the cantilever beam structures, which is called *the Multi-angular Soaring Cantilever Bridge* [14].

The *Bianhe Rainbow Bridge* is introduced as a representative of the cantilever type in *Bridges in China, Old and New,* which is published in 1978 by Yisheng Mao, who is the famous bridge expert. He holds the view that the Bianhe Rainbow Bridge is a kind of cantilever bridge [16].

In this research stage, because the existing Min-zhe Timber Arch Bridge has not been discovered, the research works only focuses on the Bianhe Rainbow Bridge according to the structure in the painting. All the researchers consider the Bianhe Rainbow Bridge as a kind of special bridge. Unfortunately, its structure only has few information and cannot be definitely confirmed from the view of structure because no one knows the truth of the Bianhe Rainbow Bridge. The most important thing is that people have no idea about its structure type. In general, people believe that the Rainbow Bridge is a composite structural with the beam. For the structure type, their viewpoint is more based on the beam bridge.

1.2.2 Second stage: Min-zhe Timber Arch Bridge was discovered (1978-1990)

Yisheng Mao begin to edit *History of Technique of Archaian Bridges in China* at the end of 1970s. The first editor conference had been hold in Hangzhou in 1980; cultural relic workers of Zhejiang province have described a kind of new type bridges and called them as "八" strut-framed bridge，which was found in mountainous areas in the southeast of Zhejiang Province. A field survey was carried out by some experts after the conference, all experts considered that this kind of bridge is not strut-framed bridge, and that it is similar to the Bianhe Rainbow Bridges in the painting, the existing Chinese timber arch bridge. Afterwards, more and more existing Min-zhe Timber Arch Bridges have been discovered in both Zhejiang and Fujian Provinces [17].

The Min-zhe Timber Arch Bridges have been regarded as one of the most important research works in the second editor conference for *History of Technique of Archaian Bridges in China*, which is called as *combined beam-arch—Rainbow Bridge*. Many research works have been carried out by the experts during those days. The research results can be found in the *History of Technique of Archaian Bridges in China*, which was published in 1986 [17]. The Rainbow Bridge and the Min-zhe Timber Arch Bridge have been called *arch type timber bridge* and *Rainbow type timber arch bridge*. The results show that the timber cantilever beam bridge should be regard as a beam bridge type, and that the Bianhe Rainbow Bridge and the Min-zhe Timber Arch Bridge belong to arch bridges. The Bianhe Rainbow Bridges and the Min-zhe Timber Arch Bridges were introduced as the arch bridge and be clearly considered arch structure at first in this book [17]. At the same time, the author brings out the opinion about the origin of Chinese timber arch bridges. They considered the technology of the existing Min-zhe Timber Arch Bridges were deprived from the ancient Bianhe Rainbow bridge when the capital of Northern Song Dynasty moved from Dongjing to Lin'an (now in Hangzhou, Zhejina Province), which means a new period in China, i.e., the South Song Dynasty. There is abundant wood in the mountainous areas in the northeast of Fujian Province and the southeast of Zhejiang Province, and many timber arch bridges have been built and some of them are still existing [17].

In the second edition of *Ancient Chinese Bridges*, Chinese timber arch bridges have been introduced and analyzed in detail. It can be found that the elevation drawing, cross section drawing, model figure of the Bianhe Rainbow Bridge and perspective drawing of Min-zhe Timber Arch Bridge in this book. The book has eleven chapters; one of which is combined beam-arch bridge. Chinese timber arch bridges were introduced as a single bridge type between the beam bridge and arch bridge, and it is called *Special Timber Bridge (Combined Beam-arch Bridges)*. In this book, the viewpoint about origin of Chinese timber arch bridge is similar to the *History of Technique of Archaian Bridges in China* [18].

The research work had made great progress in this stage, because the existed Chinese timber arch bridges have been discovered. Firstly, the cantilever beam bridges and the Chinese timber arch bridges had been clearly defined. All the experts were sure that Chinese timber arch bridges were not belongs to cantilever beam bridges from the view of the structure type. Secondly, all experts thought the Rainbow Bridge and the Min-zhe Timber Arch Bridge belong to the same bridge type. Most of experts were sure that the Chinese timber arch bridges were arch bridges, although some experts have some doubts whether the Min-zhe Timber Arch Bridge is arch structure or not. However, they agree that it wasn't the beam bridge. Thirdly, some experts brought out the speculation about origins of the Chinese timber arch bridges.

But in this stage, research on the Chinese timber arch bridges has not been a hot topic yet. Only few people were interested in researching on this kind of ancient bridge, so the research work is not adequate. For example, the research work for investigation on Min-zhe Timber Arch Bridge is very insufficient. Only seven and four Min-zhe Timber Arch Bridges have been introduced in the *History of Technique of Archaian Bridges in China* and *Ancient Chinese Bridges*; only Meicong Bridge in Yunhe of Zhejiang province has been recorded in the second editor of *History of Technique of Archaian Bridges in China* [17] [18]. On the other hand, as for the origin of Chinese timber arch bridges, several experts have brought out their conjectures. However, because of no enough evidence to prove its reasonableness and correctness, it has not gone far. Meanwhile, few scholars have mentioned and delved into the comparation between the Bianhe Rainbow Bridge and Min-zhe Timber Arch Bridge in this stage.

1.2.3 Third stage: Comprehensive study stage, after 1990

With the development of research work of ancient bridges, Chinese timber arch bridges become one of the hot topics since 1990. Great changes have taken place in the timber arch bridges, many experts have begun to take part in the investigation and research on the Chinese timber arch bridges, who excel in architecture, architectural history, archeology, folklore, cultural heritage protection and intangible cultural heritage protection, and bridge enthusiast *etc*. There are a series of research results in this stage.

Firstly, research on the academic name and type of the Chinese timber arch bridges have made great progress. The research results show that the timber cantilever beam bridges should be belonging to the type of the beam bridges, and that the Bianhe Rainbow Bridges and the Min-zhe Timber Arch Bridges are belonging to the type of the arch bridges. Bianhe Rainbow bridges and Min-zhe Timber Arch Bridges were called *Transfixion-wood arch bridge*, and the word of *Transfixion-wood* comes from one masterpiece, which describes how to build the Bianhe Rainbow Bridge. This word emphasizes the Chinese timber arch bridge which consist of two systems by weave timber and identify the mechanical behavior of arch structure in [14]. At the same time, it is important that the Chinese timber arch bridges have been introduced alone in detail as an arch structure, and the structure system of Bianhe Rainbow Bridges and the Min-zhe Timber Arch Bridges have been scientifically analyzed. In 2001 Hongxun Yang, an architectural history expert, thinks the Bianhe Rainbow bridge is not very correct if called beam wood arch, and suggests that Bianhe Rainbow bridge should be called *woven beam timber arch bridge* [14]. He said that the woven beam timber arch bridge can describe its structure from three characteristics, including the structure, material and structural mechanics behavior, which prefer to other names. From the combined beam timber arch bridge, we found Mr. Yang considered it was *beam-arch combine structure* and emphasized the combined beam structure. The Bianhe Rainbow bridges and Min-zhe Timber Arch Bridges were called as "*Woven Timber Arch Bridge*" and "*Woven Timber Arch-Beam Bridge"*, respectively in WCTE2004 by Mr. Jie Liu. The structure features of Bianhe Rainbow bridges and Min-zhe Timber Arch Bridges had been emphasized in his key notes of this conference [14]. He was sure that Bianhe Rainbow bridges were arch bridges and that Min-zhe Timber Arch Bridges are arch-beam combine structures, or even the woven wood structure [14].

In addition, many experts and scholars of the Chinese covering house seminar called Min-zhe Timber Arch Bridges as *timber arch covering house bridges*, emphasized the covering house and thought the covering house is the most important structure of the Min-zhe Timber Arch Bridges. They suggested the Min-zhe Timber Arch Bridges should be classified into the covering house bridge for research and publicity. These views have been presented at that time. At the same time, many literatures have been published, which the main topics are covering houses [19]- [24].

In [25], [26], the Bianhe Rainbow bridges were called *Rainbow timber arch bridges*, and Min-zhe Timber Arch Bridges are called as *Transfixion-wood arch bridges*. The author thinks they are all arch bridges and carried out calculation and analysis of them. The results show Chinese timber arch bridges are a kind of statically indeterminate structure and prove that the structure of Chinese timber arch bridges is reasonable from the view of structural mechanics behaviors.

In [9], Chinese timber arch bridges, not only in bridge structure but also in bridge architecture culture, have high achievement, and they should have a recognizable name and therefore are called the Chinese Timber Arch Bridges. However, for the Bianhe Rainbow bridge and the Min-zhe Timber Arch Bridges, they are some differences in appearance and structure, they have two branches of Chinese timber arch bridge, and are called Bianhe Timber Arch Bridges and Min-zhe Timber Arch Bridges, respectively. At the same time, the authors think it will separate the Min-zhe Timber Arch Bridge with covering house from the Bianhe Rainbow bridge without covering house. If some experts always emphasize the attribute of the covering house in Min-zhe Timber Arch Bridges, it is not good for research on the Chinese timber arch bridges from the view of bridge structure and holistic approach.

Secondly, many basic research works have been carried out by basic level cultural relics workers and scholars from universities. The quantity of the existing Min-zhe Timber Arch Bridges has been investigated and statistically analyzed. Research on Min-zhe Timber Arch Bridge was carried out by the author in mountain areas of Fujian and Zhejiang Province [27] [28]. The author believes two hundred timber arch bridges survived, which are all located in the scope of the center of 100km radius, whose center is the first peak in Zhejiang Province called Huang Maojian. In this paper, the wood qualification of the Min-zhe Timber Arch Bridge has been researched on some timber arch bridges. Eight timber arch bridges in Zhejiang and seven timber arch bridges in Fujian have been presented. Six timber arch bridges in Taishun County of Zhejian province have been introduced from the view of the architecture and folklore, and it focuses on the culture of covering house, which presents twenty-two timber arch bridges. From the view of cultural relics and archaeological survey, the information of seventy-nine timber arch bridges had been collected and introduced, which include fifty-two timber arch bridges in Ningde, seven in Nanping, five in Fuzhou, six in Wenzhou and nine in Lishui [29]. Base on the covering house, twelve timber arch bridges in Qingyuan County have been introduced from the view of the architecture and folklore [21]. The folk culture and the cultural heritage are one of the most important contents. Fifty timber arch bridges have been presented, which are located in the Pingnan County [30]. The distribution and current situation of Min-zhe Timber Arch Bridges have been investigated. An investigation was carried out by the authors and the results show 109 Min-zhe Timber Arch Bridges in service today [31]. The main technical parameters of seventeen timber arch bridges of Nanping in Fujian province have been investigated [32]

Thirdly, for the origin of the Chinese timber arch bridges, some experts including bridge engineering and architecture experts, bringing out the idea in the second stage. They believe Min-zhe Timber Arch Bridge is the development on the basis of Bianhe Rainbow bridge, and the technology is spreading from north to south with the Song Dynasty perish because the capital movement in southern Song Dynasty. The craftworkers brought the technology to the south, meanwhile local craftworkers added the local technology of timber structure and make the structure better than Bianhe Rainbow bridges [16], [17] [18], [25] [26] [30]. However, some experts brought out a new viewpoint, that the Min-zhe Timber Arch Bridge is easier than the Bianhe Rainbow bridge in the Tang Dynasty. The Min-zhe Timber Arch Bridge has a clear context and system in the local. It is the result of the development of native struggle with nature in the long time. They think the Min-zhe Timber Arch Bridge is the origin of the Chinese timber arch bridge, and that the Min-zhe Timber Arch Bridge is the most advanced structures in timber structure bridge. From the view of structure development, the author thinks Min-zhe Timber Arch Bridge independent development system develops from simple structure to the complex one. A series of bridges were found in Fujian and Zhejiang Province, which can prove the Min-zhe Timber Arch Bridge had gone through a long development stage. Under the culture and technology exchange, the woven timber arch bridge has been brought from the Min-zhe mountain area to the north of China. They think the Min-zhe Timber Arch Bridge is origin of the Chinese timber arch bridge [19] [33] [34] [35]. The Min-zhe

Timber Arch Bridge has a clear context from the view of history development, which is evolved from the inchoate San Tiao bridge (which was built earlier than Bianhe Rainbow bridge), the Shuang Men bridge and the Rulong bridge. Therefore, they thought the Min-zhe Timber Arch Bridge develops in Fujian and Zhejiang province. At the same time, the tiles found in the San Tiao Bridge were made in Tang Dynasty. They think the San Tiao bridge may be built in Tang Dynasty at first, which is earlier than Bianhe Rainbow bridge, so the Chinese timber arch bridge is the origin of Min-zhe Timber Arch Bridge. In [28] [29], the author thinks both viewpoints perhaps are all good. Investigation on many bridges was carried out by the author, such as archaeological investigation on the San Tiao Bridge, Shuang Men Bridge, Wan'an Bridge and GuiSi Bridge. The research shows theirs earliest construction time which are earlier than South Dynasty, and that they can find a series of technology, developmental systems and architectural culture. Therefore, they think it originated in Tang Dynasty and became matured in the middle period of Ming Dynasty. What's more, the Min-zhe Timber Arch Bridge had made great progress in the late-mid period of Qing Dynasty. The Min-zhe Timber Arch Bridge got a very good continuation and development in these Dynasties, so it still was been built in several areas after 1911. A series timber bridge had been found in Fujian and Zhejiang Province, and the "八" strut-framed bridge with the pillar, the "八" strut-framed bridge without the pillar and the extant Min-zhe Timber Arch Bridge, shows the development evolution of the timber arch bridge in Fujian and Zhejiang province. Hence, they come to the conclusion that the Min-zhe Timber Arch Bridge is earlier than the Bianhe Rainbow Bridge. However, the researcher also found something weird. First: most of timber arch bridge families are from north of China. Second, they can't find any record, that the Min-zhe Timber Arch Bridge was built before the Song Dynasty moved to the south. Many textual researches on the ancient bridge site was carried out, but they cannot prove the timber arch bridge had ever been built there before the Song Dynasty move to the south. They cannot prove the timber arch bridge was built before the Song Dynasty move to the south in Fujian and Zhejiang Province either, although some of the existing timber arch bridges were built earlier than the Bainhe Rainbow bridges. Perhaps they were others bridge types and not timber arch bridge. Third, the researcher think that the culture of central plains has made great influence on the culture of Fujian and Zhejiang Province in the northern Song Dynasty. It is possible that the Bianhe Rainbow Bridge had been taken to the Fujian and Zhejiang Province with the development of technology, so the Min-zhe Timber Arch Bridge had been innovated.

Fourthly, many cultural relic's experts and architects focus theirs researches on the history of construction, aesthetics, social function and cultural values, *etc*. Many research works have been carried out in depth and the main is the intangible cultural heritage, including the construction technology, the custom of the construct and the bridge culture *etc*. The timber arch bridge has been investigated from the view of science and humanities, social science. Many references have been collected, organized and published, and the main are the historical accounts [30]. More and more people pay attention to protect the Chinese timber arch bridge, many conferences research on protection the Chinese timber arch bridges had been hold and the conference proceedings had been published [36] - [48]. *Joint Declaration of Protecting Covering House Bridges and Declare the World Heritage*, *Shouning Joint Declaration of China Covering House Bridge Declare the World Heritage*, *Joint Declaration of China Through Wooed Arch Covering House Bridge Declare the World Heritage* had been cosigned in these conferences. The consign units include the counties, which are have Min-zhe Timber Arch Bridge in Fujian and Zhejiang province. Many research works focusing on the cultural heritage had been carried out [49] - [54].

The traditional construction technology of Chinese timber arch bridges also has drawn greater attention attach [55] - [58]. Some of craftsmen had been listed in provincial and national intangible cultural heritage representative inheritance. The traditional construction technology of Chinese timber arch bridges was listed in the *Urgent Safeguarding List of Intangible Cultural Heritage* by UNESCO on Oct.1, 2009. Chinese timber arch bridges have been listed in the China world cultural heritage tentative list in 2012.

Fifthly, some bridge engineering experts and structural engineering experts recognized that it was necessary to carry out the research works on the China timber arch bridge from the view of structural engineering and bridge engineering. The investigation is based on the main technical parameters, and some of timber arch bridges had been investigated and statistics analyzed [31] - [32]. The safety and the resist overturning stability under the wind load of the main structure had been discussed with the simplified calculation model [59] - [63]. By using the space finite element method, the differences of the mechanical behaviour of the timber arch bridge are compared with or without the second system. The result shows the similarity of the deformation of two systems of the timber arch bridge, and the internal force has been appropriately redistributed. However, in this paper, it has not been discussed and analyzed how to transfer load of the two systems of timber arch bridge [63]. More and more new timber arch bridges have been built with the traditional construction technology in recently years, and structural calculation is very important for new Min-zhe Timber Arch Bridge, Structural simplified calculation of security of one of rebuilt Min-zhe Timber Arch Bridge had been carried out. However, in this paper, the author adopts the simplified calculation model [62]; we think the result is needed to prove whether it is right or not. The computational analysis method has been introduced. The author believed that the woven timber arch bridge structure will have great development in modern steel-tube construction and good application prospects. Therefore, the paper brings out a new thinking research on the Chinese timber arch bridge. Preliminary research on mechanical behaviors of Min-zhe Timber Arch Bridge had been carried out by the author [64]. The result shows the mortise and tenon joint are regarded as hinge joint in simplified calculation. The uniform distribution load of covered house and some of section loads such as the double eaves in the mid-span are all beneficial for Min-zhe Timber Arch Bridge, which can make the axial force increase and make the bending moment reduce. Literature [65] review from a grassroots cultural relics' worker, a preliminary study has been carried out on architectural structure and construction technology in the south of Zhejiang Province, and then, the author has made a research compared with Bianhe Rainbow bridge and Min-zhe Timber Arch Bridge. He thinks that the Min-zhe Timber Arch Bridge is better than the Bianhe Rainbow bridge from the view of structure, so its life is longer and can survive today in the Min-zhe mountainous areas.

Chinese timber arch bridge is a very hot topic today. Many research works have been carried out, but the majority are focused on the architecture, folklore and sociology *etc*. Although the bridge and structural engineering experts had recognized that it is a very important research to the Chinese timber arch bridge from the view of structural engineering and bridge engineering, the research results still lack. So many problems have not been studied in the field of research on the Chinese timber arch bridges, as follows:

1) The accurate name has been given from the view of the structure by some scholars. However, it is very regretful that their accurate name has not been confirmed from the view of structure mechanical behavior based on the bridge engineering and structure engineering. Some people still considered the Binahe Rainbow bridge as a real arch bridge. However, as for the Min-zhe Timber Arch Bridge, they still have some doubts: they think the bending moment is major in the first system arch ribs.

2) A completed database of the Chinese timber arch bridges has not been created until now. A few bridges have often been missed, mistaken or repeatedly counted in the literature. Although many experts have carried out the investigation on the current situations of the bridges, most of them do not focus on structural and bridge engineering perspectives. The major structural parameters such as the length, span as well as the rise-to-span ratio have not been investigated by field survey.

3) The research works for test and theory analysis are insufficient. No one can explain the mechanical behavior and superiority of such structure with scientific ways, because its structural principle is still not clear, and some people doubt that whether the Min-zhe Timber Arch Bridge belongs to arch bridges.

4) Its static mechanical behavior is still not clear, because it cannot break away from traditional construction technology, and design and construct with the modern bridge engineering theory. The FEM and the planar simplified model of Chinese timber arch bridge have not been proposed until now.

1.3 Objectives of This Dissertation

1.3.1 Scope of this dissertation

As reviewed above, considerable researches have been done by workers of cultural relics and architects in China, focusing on the construction history, aesthetics, social function, cultural value and so on. However, the research works from the view of structural engineering and bridge engineering are insufficient. In order to investigate the mechanical characteristic and superiority in structure of the Chinese timber arch bridge, it is necessary to conduct comprehensive studies on structural property base on the bridge engineering science. The research reported in this dissertation focuses on mechanical characteristics of woven arch in the elastic stage. To fulfill this goal, the nonlinear and the load-carrying capacity should be avoided. This is done by the following preconditions:

1) All the tests and finite element analysis are limited in the elastic stress stage; all the nonlinear problems should be avoided, in which both material and geometric nonlinearities.
2) The mechanical characteristic of woven arch should be researched and analyzed, when the mortise and tenon joints should be in two kinds of limit state, one state is hinge joints, the other is rigid joints.

The scope of this research is:

1）From a brief review of the history of Chinese timber arch bridge, the structure of Chinese timber arch bridge should be described in detail, and the traditional construction technology and intangible cultural heritage of the Chinese timber arch bridge should be recorded based on the bridge engineering science.

2）All the existing Chinese timber arch bridges should be investigated by field focusing on the main structural parameters, a complete database of the Chinese timber arch bridge should be created. Then, the structural parameter should be analyzed base on modern bridge engineering.

3) The research work primarily focuses on the mechanical behaviors of the two systems of Chinese timber arch bridges, and it should be carried out by the

model test in indoor and finite element analysis.

4) A field testing on an existing bridge should be carried out and analyzed by the finite element method.

5) The simplified planar model of Chinese timber arch bridge should be proposed.

The research involves interlaced experimental and analytical procedures to broaden the existing state of knowledge of the behavior of woven arch and Chinese timber arch bridge. 130 existing Chinese timber arch bridges are investigated by field and the structural parameters are also carried out; the material characteristic and a total of 4 scale model are tested in the Structural Laboratory at Fuzhou University, including 2 bare arch and 2 full-bridge. The tests are then simulated using linear finite element analysis (FEA), and a finite element procedure is developed to analyze the mechanical property of woven arch; as a case, field test of an actual Chinese timber arch bridge is carried out and analyzed by linear finite element method. Finally, the simplified planar model of Chinese timber arch bridge is proposed. Validations show that the predictions by the numerical methods developed in this dissertation fit with test results. Therefore, the research results will explain the mechanical behavior and superiority of such structure with scientific ways and provide scientific evidence for Chinese timber arch bridge with world cultural heritage value. The traditional construction technology of timber arch bridge will be lost and can be in a better inheritance service. Maintenance and construction of Min-zhe Timber Arch Bridge will be supplied, and it also offers references for the application in construction of modern bridge engineering and draft of timber structure standard of such structure. The dissertation provides a profound background for design and implementation of Chinese timber arch bridge with modern bridge engineering theory.

1.3.2 Layout of this dissertation

In this dissertation, on the basis of the modern bridge engineering science, the research work which focuses on the existing Chinese timber arch bridges, including field survey, model experiments, field static loading test, and FE analysis, have been carried out by the author. It is composed of eight chapters as described below.

Chapter 1 is an introduction. The research backgrounds of this dissertation are introduced first. Then, the published research works on the Chinese timber arch bridge are categorized into three stages and reviewed. The topics of the works are the literature review, the academic name of the Chinese timber arch bridge, how to definite the bridge type of the Chinese timber arch bridge, the origin of the Chinese timber arch bridge and the existing quantity of Chinese timber arch bridge, etc. Lastly, the objectives and layout of this dissertation are introduced.

In chapter 2, a brief history of the construction of Chinese timber arch bridges is presented at first; secondly, the structure of two branches of Chinese woven timber arch bridges is compared in detail; thirdly, the construction technology of the Chinese timber arch bridges as an important intangible cultural heritage is introduced in detail.

In chapter 3, firstly, the significant technical parameters of Chinese timber arch bridge such as length, width, clear width, clear span, clear and calculate rises are defined with the same standard; secondly, all the existing Chinese timber arch bridges grasped by literature survey are investigated at the site, and a complete database of the Chinese timber arch bridges is created; thirdly, statistical analysis of significant parameters of the existing Chinese timber arch bridges is carried out.

In chapter 4, the scale model tests were carried out. The material of scale model is organic glass, which has a more stable and uniform physical and mechanical properties. The research work focuses primarily on the mechanical behaviors of the two systems of woven timber arch bridges. The details of loading and testing method, as well as the test results, are described.

In chapter 5, based on the scale model test results, a finite element model of the woven arch bridge is proposed. Its static mechanical behaviors are compared with the two-hinged arch by using the FE model. The origin of the Chinese timber arch bridges is also discussed from the viewpoint of structural behavior.

In Chapter 6, a field test of an existing Chinese timber arch bridge is carried out. Details of loading and testing method as well as the test results are described. Based on the indoor and field experimental studies on the woven arch, a finite element model is presented. This FE model is used to study the static mechanical behaviors of Chinese timber arch bridge.

In Chapter 7, the simplified calculation model of Bianhe Rainbow bridge is presented and its applicability to Min-zhe Timber Arch Bridge is verified. Then, the effect of the detachment of two systems on the load transfer performance of the woven arch is studied by FEA. Consequently, the practical simplified planar calculation model of Min-zhe Timber Arch Bridge is proposed.

In Chapter 8, the conclusion in each chapter are summarized and further research works need to be carried out in the future are addressed.

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CHAPTER 2

BRIEF INTRODUCTION OF CHINESE TIMBER ARCH BRIDGE

2.1 Introduction

According to the present situation, location, and structural details, Chinese timber arch bridge can be further divided into two tranches, one is the non-extant ancient Bianhe Rainbow Bridge, which had been built over the Fen and Bian Rivers in central and northern areas of China, the Bianhe is the literal translation from the Bian river. The other is the extant Min-zhe Timber Arch Bridge, because all of them are located in the Fujian Province and Zhejiang Province, in which the "Min" and "Zhe" are the short names of Fujian Province and Zhejiang Province, respectively[1].

In this chapter, firstly, the brief construction history of Chinese timber arch bridges is introduced; Secondly, the structures of Chinese timber arch bridges are described in detail, and the two branches are being compared; Thirdly, from the view of the intangible cultural heritage and cultural heritage, some contents are presented, which are related to the extant Chinese timber arch bridges.

2.2 Brief History of Chinese Timber Arch Bridge

2.2.1 Brief history of Bianhe Rainbow Bridge

According to historical records, the first Bianhe Rainbow Bridge was built by Xia Shouqing, the military commander of Qinzhou, Shandong Province, in years of 1032-1033[2], who adopted the idea of a jailer, to consolidate the river banks with large stones, and then tying dozens of large timbers together so that they spanned the river without piers, the first bridge was called the Rainbow Bridge in that time. Later, this kind of bridges was also built in Suzhou, Anhui Province, by Chen Xiliang (a military commander of the city). After that time, this kind of bridges were set up in several places over the Fen and Bian rivers, greatly benefiting the local people [3]. Because the bridges were crossed the Bian rivers, we call them "Ancient Bianhe Rainbow Bridges" in this dissertation.

The Ancient Bianhe Rainbow Bridges are described and recorded in many famous literatures and local chronicles in Song Dynasty although we cannot know how many Bianhe Rainbow bridges were built in that time. The literatures are enough to prove that the Ancient Bianhe Rainbow Bridge is a kind of popular bridge types in the Song

Dynasty for a long time.

However, along with the breaking of wars, reduction of the timber resources, and the development of the other bridge types, the Bianhe Rainbow Bridges were built less and less. The Ancient Bianhe Rainbow bridges are all destroyed because of bridge itself and various outside effects. No one ancient Bianhe Rainbow Bridges has survived in China nowadays. In the central and northern areas of China where at ancient time there were many ancient rainbow bridges, we can only find the Bianhe Rainbow Bridge technology heritage in the Baling Bridge in Gansu Province, which was completed in 1398 and rebuilt in 1919 and 1923. It has 40.2 m in total length with the span of the largest arch measuring 27.4 m, as shown in **Fig. 2-1**. The bridge is a combination structure but not real Bianhe Rainbow Bridge, in which it is a timber cantilever at the spring and timber arch at the crown[4][5].

Fig. 2-1 Baling Bridge in Gansu Province

Therefore, we can say that no Rainbow Bridge survived and no details of their design and construction technology have been recorded. It was considered that the Bianhe Rainbow Bridge techniques had disappeared in a long time. Until 1950s, a Bianhe Rainbow Bridge has been discover in the painting of "Chhing-Ming Shang Ho Thu" by a bridge expert[2], as shown in **Fig. 2-2**.

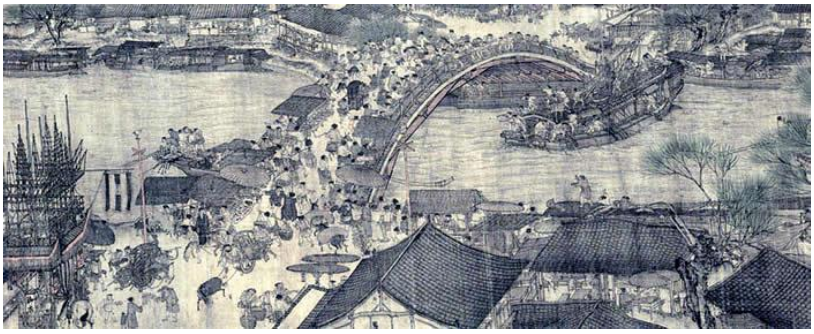


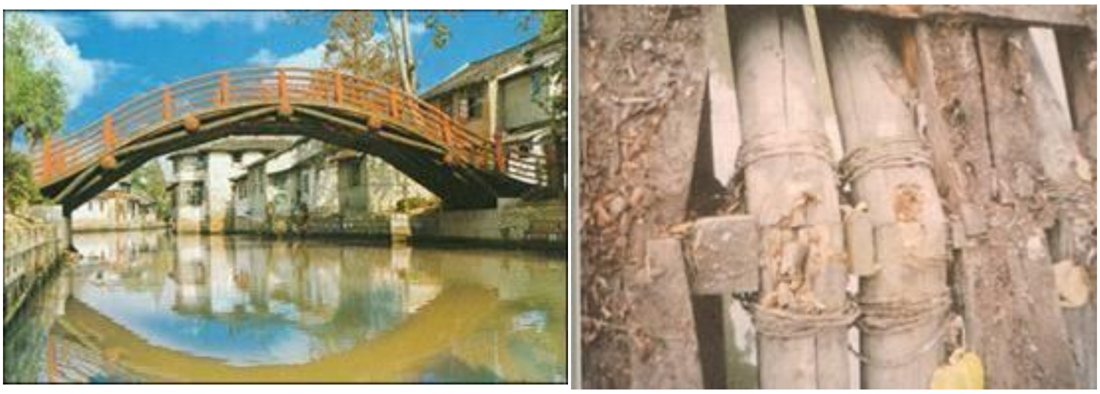
Fig. 2-2 Rainbow Bridge in Chhing-Ming Shang Ho Thu (part)

Since the bridge was discovered in the painting, it has attracted particular attention because of its special structure forms. Some imitated Bianhe Rainbow Bridges have been built in parks or other places for business in China. Some of them are real timber arch bridges, while some of them are virtual.

The first imitated Ancient Bianhe Rainbow Bridge was built in Hanyang Park, which is located in one side of Wuhan Yangtze river bridge, as shown in **Fig. 2-3**, the bridge crossed the Lianhua lake. Unfortunately, it had been damaged in the 1970' s for a variety of reasons[6].

Fig. 2-3 First imitated Bianhe Rainbow Bridge in Hanyang Park

In 1999, the second imitated Ancient Bianhe Rainbow Bridge was built in the town of Jinze, Shanghai, as shown in **Fig. 2-4 (a)**, called Pu Qing Bridge. Its length is 21.2 m, width is 4 m, the span is 13.2 m, and the rise- span ratio is 1/4.8. The foundation is made of timber piles and the abutment is made of block stones [7]. The bridge was invested by WGBH company, the whole construction process has been shot for a science and educational film, the film called Chinese Rainbow Bridge. Its construction without supports and the nodes use bamboo ropes binding. Because financial matter, the woods without preservative treatment. After five years later, many woods had been corroded, as shown in **Fig. 2-4(b)**; instead, many timber arch ribs have been constructed with the steel tube today by maintenance [6]. Therefore, it is not a really woven timber arch bridge now.



(a) Elevation view (b) Joint

Fig. 2-4 Puqing Bridge

Except the two bridges had been described above, with the development of the landscape bridge, several imitated Ancient Bianhe Rainbow bridges were built in some parks. **Fig. 2-5 (a)** shows one bridge, which was built in Hangzhou, the other bridge was built in Fuzhou, as shown in **Fig. 2-5 (b)**. The other two bridges, as shown in **Fig. 2-5 (c)-(d)** were built in the new campus of Fuzhou University [8]. They are all real new Bianhe Rainbow Bridge.

(a) In Hangzhou (b) In Fuzhou

(c) In Fuzhou University (d) In Fuzhou University

Fig. 2-5 Real imitated Bianhe Rainbow Bridge

Fig. 2-6 False Bianhe Rainbow Bridge

Besides, there is a false Bianhe Rainbow bridge in a garden in Kaifeng, Henan Province, as shown in **Fig. 2-6**, which is built follow the famous painting “Chhing-Ming Shang Ho Thu”, from which the timber arch bridge in China was discovered, because it is not built by timber but by reinforced concrete and built in 2001[9].

It can be found that many Bianhe Rainbow bridges were built in ancient China, but none of them have survived. Only a few of the real imitated Bianhe Rainbow Bridge can be counted in China today.

2.2.2 Brief history of Min-zhe Timber Arch Bridge

There is no accurately historical record to prove the time the first Min-zhe Timber Arch Bridge was built. We can know that the origin of Min-zhe Timber Arch Bridge has still not the final conclusion from the Chapter one. According to the historical document, some monumental writing and investigation, the Min-zhe Timber Arch Bridges have a strong coherence in history, the extant Min-zhe Timber Arch Bridges were constructed or rebuilt in different Dynasties since the Song Dynasty, the detailed introduction will be present in Chapter 3. In some cases, some existing Min-zhe bridges are presented, which are built in different dynasty.

The Santiao Bridge **(Fig. 2-7)** is one of existing ancient Min-zhe Timber Arch Bridges, which has the earliest records. It is located in Taishun County. It crosses the brook, which is in the common boundary about Zhouling Village and Yangxi Village. The existing bridge was built in 1843. However, according to the historical documents recorded, its first build time is Tang Dynasty. This is one of reasons why some people think Min-zhe Timber Arch Bridge is built earlier than Bianhe Rainbow Bridge.

The Shuangmen Bridge **(Fig. 2-8)** is located in Daji Village of Qingyuan County in Zhejiang Province. It is the other one that has the earliest records, which was built in Song Dynasty, and the extant bridge was built in Ming Dynasty.

Fig. 2-7 Santiao Bridge

Fig. 2-8 Shuangmen Bridge

Fig. 2-9 Rulong Bridge

Fig. 2-9 shows a bridge, which is a famous ancient Min-zhe Timber Arch Bridge, the Rulong Bridge, which is located in the Yueshan village of Qingyuan County in Zhejiang Province. It was built in 1625 (The Ming Dynasty). It is the oldest existing timber arch bridge in China today with an exactly recorded.

Many Min-zhe Timber Arch Bridges were built in Qing Dynasty, at the same time, some of them survived, the quantity will be presented in Chapter 3. Afterwards, with the high-speed development of traffic and economy in China, the modern bridge had been widely used, few Min-zhe Timber Arch Bridge had been built. Especially, because the timber arch is only used for foot with poor durability, and it had rarely been built in 1970-2000.

After 2000, with the recognition of this precious cultural heritage and unique bridge structure, some new Min-zhe Timber Arch Bridges have been built by various reasons. For most bridges, the traffic function isn't the main function of these timber arch bridges, they are often regard as the landscape architectures or building technology in the demonstration, most of them are located in the beauty spots.

For example, the Huayang Bridge **(Fig. 2-10)** in Shunchang, Fujian Province. It is located in the gate of the Huayang beauty spot and is an imitation from the extant Fujian-Zhejiang timber arch bridge, designed by Huangcheng Tang, a famous bridge expert in China. The bridge was built by Duojing Zheng and Duoxiong Zheng (who are representative heir of the traditional construction technology of the timber arch bridge of the intangible cultural heritage in China) with the tradition technology in 2005. The bridge was opened in 1 October 2007. The bridge is not only a landscape but also the main traffic line and the place to rest for the travelers in the Huayang beauty spot.

(a) General view (b) Up view of arch

Fig. 2-10 Huayang Bridge

The other New Min-zhe Timber Arch Bridge is the Shijin Bridge shown in **Fig. 2-11**, which is located in Pingnan County, Fujian Province. It is 12 m long single span bridge with the span length of 10 m and was built by Huang Chuncai (who is also a representative heir of the traditional construction technology of the timber arch bridge of the intangible cultural heritage in China) and two of his sons. The bridge perhaps is the smallest timber arch bridge in China. During its construction by the traditional construction technique with traditional construction tools, the workers in traditional suits also played the folk-custom activities for building a new bridge. The discovery program of the Chinese Central TV Station (CCTV) made a video record of the construction of this bridge as a part of the video film to UNESCO for declaring the *intangible cultural heritage project of the traditional construction technology of the timber arch bridge*.

(a) General view (b) Install the main arch rib (c) Raising of ridgepole

Fig. 2-11 Shijin Bridge

As stated above, although it is not clear the time the first Min-zhe Timber Arch Bridge built, many ancient Min-zhe Timber Arch Bridges have been retained now, and then, the extant Min-zhe Timber Arch Bridges show it has a strong coherence construction history in China.

2.3 Structural Description of Chinese Timber Arch Bridge

2.3.1 Structure of Bianhe Rainbow Bridge

The brief history of Bianhe Rainbow Bridge presented in Chapter 2.1,1, has shown no one ancient Bianhe Rainbow Bridge survived, and all the new Bianhe Rainbow Bridges are imitate built from *the famous painting of Chhing-Ming Shang Ho Thu.* Therefore, the structure can only be seen from the painting. The bridge abutments on both banks were made of hard rocks to bear the thrust of the arch, and road was designed in front of the abutment. Consequently, the structure of this kind of bridge was rational and the design was ideal. From the painting, we can find the bridge consists of abutment, main arch ring and deck system. Based on the painting, the structural sketch of Bianhe Rainbow Bridge was drawn as shown in **Fig.2-12**, and according to the scale of the characters and scenery, some structural data was estimated as follows: It was about 18.5 m long and 9.5 m wide, and the diameter of the logs was about 40 cm [10].

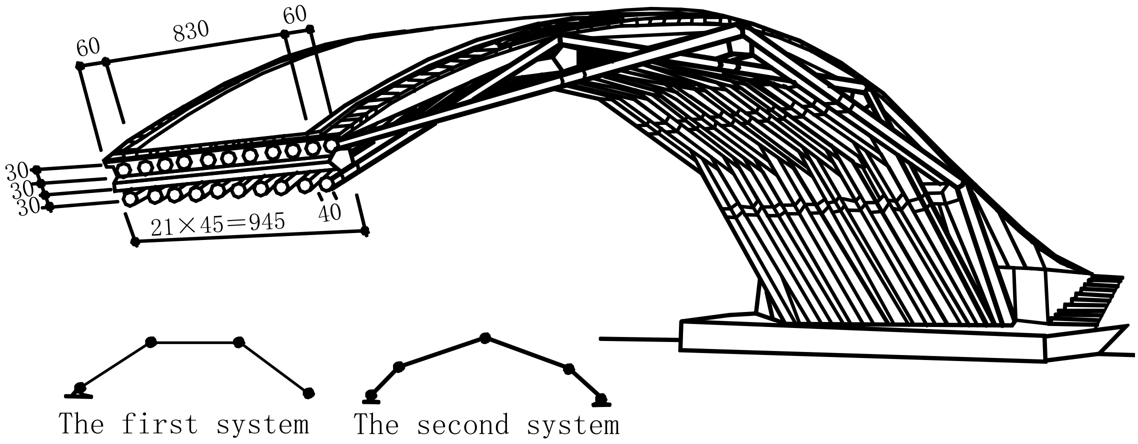
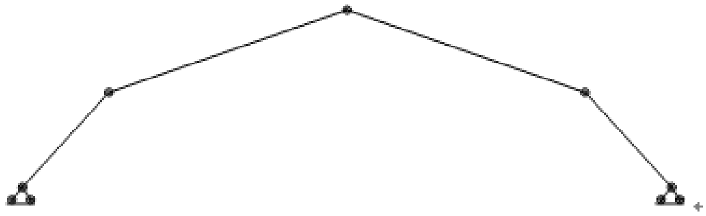


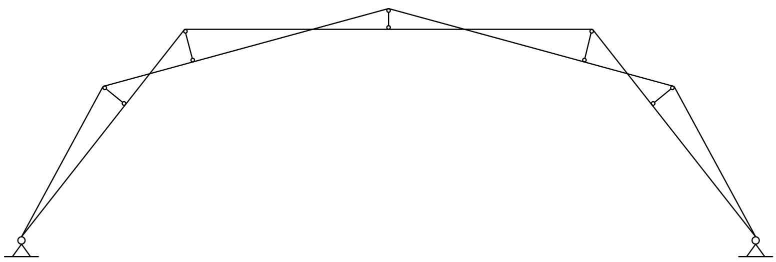
Fig. 2-12 Three-dimensional view of the Bianhe Rainbow Bridge structure

It can be seen from the **Fig. 2-12**, the main arch ring consists of longitudinal and transverse systems, and then, the longitudinal system is composed of two systems. The first system is composed of a three-line polygonal arch rib system with three same length logs on a plane, as shown in **Fig. 2-13 (a)**, which has ten groups of three-line polygonal arch ribs in transverse section. The second system is composed of a four-line polygonal arch rib system with two long logs and two short logs on other plane [11], as shown in **Fig. 2-13 (b)**, which has eleven groups of four-line polygonal arch ribs in transverse section. The two systems are tiered and interwoven by five transverse timber beams to form the skeleton, as shown in **Fig. 2-13 (c)**. The longitudinal members are pressed on the transverse ones and likewise the transverse one is pressed on the next longitudinal ones. Five transverse logs were laid to traverse the whole bridge, playing the role of connecting arch frameworks, stabilizing the structure and distributing the live load in the transverse direction. According to the recording and painting, the arch frameworks and the transverse beam of the Bianhe Rainbow Bridge were bounded together by ropes as shown in **Fig. 2-14**[6].

(a) 1st system



(b) 2nd system



(c) Bianhe Rainbow Bridge

Fig. 2-13 Main structure of Bianhe Rainbow Bridge

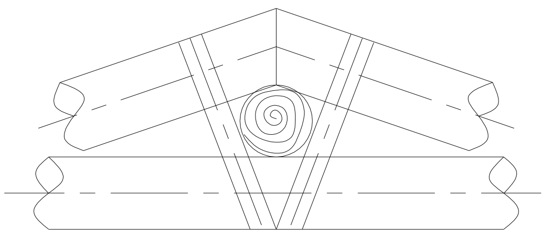


Fig. 2-14 Binding of Bianhe Rainbow Bridge

The deck system of Bianhe Rainbow Bridge is an arch shape, because it is shaped in arc with the extrados stepped for pedestrians. Therefore, the bridge has a good-looking appearance, which is like a rainbow.

2.3.2 Structure of Min-zhe Timber Arch Bridge

A typical structure of a Min-zhe Timber Arch Bridge is illustrated in **Fig. 2-15**. It consists of abutments, arch ring, spandrel structure, deck system and covered house, *etc.* [12].

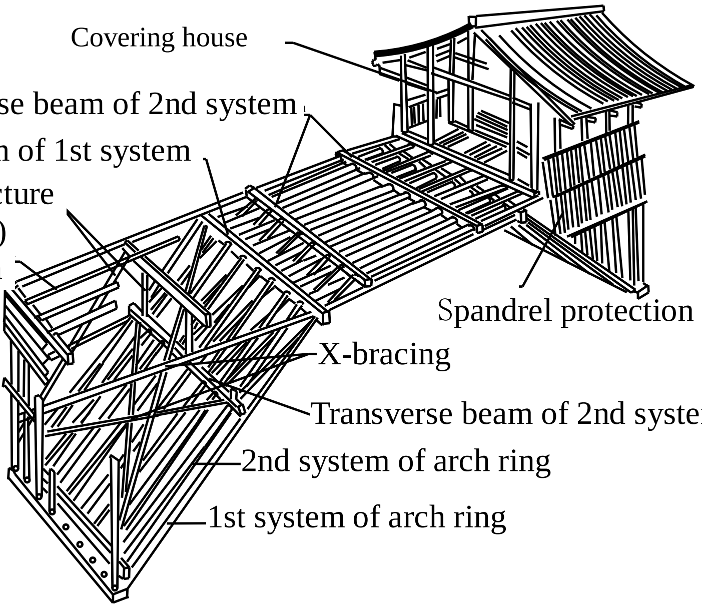


Fig. 2-15 Three-dimensional view of the Min-zhe Timber Arch Bridge structure

2.3.2.1 Abutment or pier and foundation

Arch structure produces horizontal thrust, there are great horizontal thrusts at the arch springing of timber arch bridges, the timber arch bridges have often been built in the location, where has solid rock. According to the field survey, the abutments of the existing timber arch bridges can be classified into two types. The first one directly utilizes the natural cliff and crag with shallow carve and treatment, for example: the Ruanfeng Bridge (as shown in **Fig. 2-16 (a)**) and Fushou Bridge (as shown in **Fig.2-16 (b)**). The second one is built by big gravel (as shown in **Fig. 2-16 (c)**) or block stone (as shown in **Fig. 2-16 (d)**) [12]. For multi-span bridges, the piers are built by block stone with beautiful diversion stone face the water flow carved in bird head shape, as shown in **Fig. 2-17**[4].

(a) Ruanfeng Bridge

(b) Fushou Bridge

(c) Hongjun Bridge

(d) Desheng Bridge

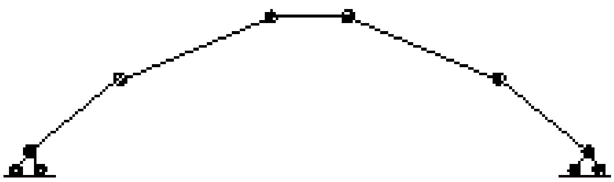
Fig. 2-16 Abutment of Min-zhe Timber Arch Bridges

Fig. 2-17 Abutment of Yuqing Bridge

2.3.2.2 Main arch structure

The structures of Min-zhe Timber Arch Bridge is similar to the structure of the Bianhe Rainbow Bridge. The main arch ring consists of longitudinal and transverse systems, and then, the longitudinal system is composed of two systems consisting of straight logs. The two systems with different polygonal sides are interlaced to form a structure, in which the longitudinal members are mainly subjected to compressive forces. In most of Min-zhe Timber Arch Bridges, the first system is a three-line polygonal arch ribs, as shown in **Fig.2-18 (a)**. According to the different width of bridge, it can be composed of seven, nine or eleven parallel members connected by two transverse beams at the two knees. The second system is a five-line polygonal arch ribs, as shown in **Fig. 2-18 (b).** The parallel members are always one member less than the first system, which can be composed of six, eight or ten parallel members connected by four transverse beams at the four knees. The two systems are tiered and interwoven by six transverse timber beams to form the skeleton, as shown in **Fig. 2-18 (c)**. The longitudinal members are pressed on the transverse ones and likewise the transverse one is pressed on the next longitudinal ones. Six transverse logs were laid to traverse the whole bridge, playing the role of connecting arch frameworks, stabilizing the structure and distributing the live load in the transverse direction. It is different from Bianhe Rainbow Bridge. The logs of the two systems of Min-zhe Timber Arch Bridge are connected by the transverse beams with the mortise and tenon nodes, as shown in **Fig. 2-19**, respectively. Wood blocks are inserted between springing members as shown in **Fig.2-20**.

(a) 1st system



(b) 2nd system

(c) Min-zhe Timber Arch Bridge

Fig. 2-18 Main structures of Min-zhe Timber Arch Bridge

Fig. 2-19 Mortise and tenon nodes

Fig. 2-20 Wood blocks

Besides, the main arch ring of the Min-zhe Timber Arch Bridge has X-bracings. According to the span, the arrangement of the X-bracings has two ways. In general, long span bridges have two sets of X-bracings, as shown in **Fig. 2-21 (a)**, every system all has a set of X-bracings. While short span bridges have only one, as shown in **Fig. 2-21 (b)**, only the first system has s set of X-bracings. One side of the X-bracings is inserted into transverse beams with the Swallow Tail tenon, and the other side is inserted into vertical columns in an abutment with a straight tenon [12].

Fig. 2-21 X-bracings

2.3.2.3 Spandrel structure and deck system

The deck system of Min-zhe Timber Arch Bridge consists of deck transverse beams, longitudinal beams and deck slabs. Generally, there are six deck transverse beams (each side of three), in which the one close to an abutment is supported by columns as shown in **Fig. 2-15**, and the transverse beam near the crown utilizes the transverse beam in the second arch ring system. Only the deck transverse beam in quarter span needs spandrel struts to support it. This spandrel struts, called as horse-leg in Chinese Folk, consist of a pair of inclined members standing on the springing and two or three vertical or inclined members standing on quarter transverse beam in the second system [12], as shown in **Fig. 2-22**.

Fig. 2-22 Spandrel structure (called as Horse leg in folk of China)

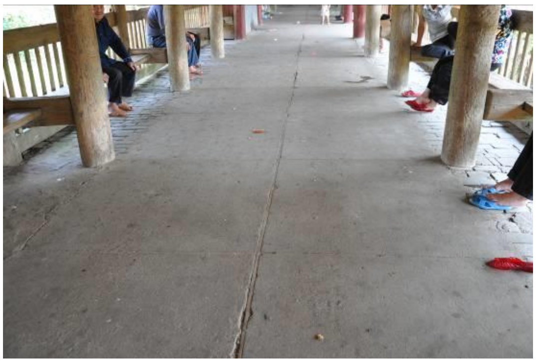
Because of the different local characteristic, the deck paving of Min-zhe Timber Arch Bridges often chooses different materials, besides most bridges use the plank, there are some bridge using tiling, brick, cobblestone, stone and concrete, etc., as shown in **Fig. 2-23**[13].

(a) Xinrong Bridge

(b) Yueyuan Bridge

Fig. 2-23 Types of deck paving

(c) Jielong Bridge



(d) Lanxia Bridge

Fig. 2-24 Types of deck paving (contd.)

2.3.2.4 Covering house

It is rich in rain in the border mountainous area of north Fujian Province and south Zhejiang Province (southeast mountainous area in China), so they are covered by the house to against abundant raining, this bridge type is called Covered House Bridge [14]. All the extant of Min-zhe Timber Arch Bridges are built with the covering house. Most covering houses are constructed in exactly the same fashion as local house and temples; they make the extant timber arch bridges rich and colorful in their appearances with obviously local architecture culture, and it will be presented in the section 3 of this chapter.

2.3.3 Comparison of two branches of Chinese Timber Arch Bridge

2.3.3.1 Similarity

The structure of Bianhe Rainbow Bridge and the Min-zhe Timber Arch Bridge had been introduced in Section 2.2.1 and 2.2.2. We can find that all the main arch rings of them consisting of longitudinal and transverse systems, and then, the longitudinal systems are composed of two systems, consisting of straight logs and connected to the transverse beams by tenons. The two systems with different polygonal sides are interlaced to be a raft structure, in which the longitudinal members are mainly subjected to compressive forces. They have the same characteristics as follow[1]:

1) Both of them have a structure made by weaving longitudinal and transverse straight logs in a special way. This structure is successes to achieve a large span by short elements. The first system in both of them is a three-line polygonal arch ribs with three longitudinal straight logs of the same length and two transverse beams.

2) All the members in these two branches of Chinese timber arch bridges are straight and need not be to curved. This makes the member processing more easily than the rib timber arch bridge with curved members. And the joint numbers in them are less than that of the truss timber arch bridges, which is also benefit for construction.

3) They are all take full advantage of the parallel to grain compressive strength of the wood. The arch structure with straight logs by weaving can improve the bearing capacity. The transverse members contribute to an improvement of the load bearing capacity by integrating the whole structural system.

2.3.3.2 Differentia

Although both of the Bianhe Rainbow Bridge and the Min-zhe Timber Arch Bridge are the same type bridge from their structure behaviors and construction from the point of view of bridge structure, there are some differences between them not only in appearance but also in structural details.

1) Appearance

Firstly, covered or uncovered is the most distinct difference between the Min-zhe Timber Arch Bridge and the Bianhe Rainbow Bridge. The Bianhe Rainbow Bridges does not have covering house, the Min-zhe Timber Arch Bridges have covering house. In terms of function, the covering house protects its arch structure from heavy rainwater in the southeast mountain area, giving a more reasonable design than the Bianhe Rainbow Bridge, and makes it possible for many Min-zhe Timber Arch Bridges to survive until today. At the same time, the covering houses also serves as a resting place for travelers through the mountainous path, and also serves as a public place for talking, trading, and religion activities, and even as a shrine for idols where villagers offer sacrifices, which will be presented in the next section.

Secondly, the ancient rainbow bridge is shaped in arc, the Min-zhe Timber Arch Bridge has the spandrel structure and the side-covering boards for the arch, which make it look like a polygon structure. Therefore, for a long time it was considered as a strut-framed bridge, this is one of the reasons why the Min-zhe Timber Arch Bridge was discovered so late. The Bianhe Rainbow with the extrados steps for pedestrians, while there is no step in the Min-zhe Timber Arch Bridge, which improves its traffic function for both people and animal-carts.

2) Structure details

Firstly, the first system of the Bianhe Rainbow Bridge and the Min-zhe Timber Arch Bridge are composed of the three-line polygonal arch ribs with three longitudinal straight logs of the same length and two transverse beams, but the second system of the two branches of the bridges has obvious difference. In the Bianhe Rainbow Bridge, it consists of four longitudinal straight logs and three transverse beams, whereas in the Min-zhe Timber Arch Bridge it consists of five longitudinal straight logs and four transverse beams.

Secondly, for the cross section, the group number of the first system is one less than that of the second system in the Bianhe Rainbow Bridge. However, the situation of the Min-zhe Timber Arch Bridge is opposite, and the group number of the first system is more than that of the second system in general.

Thirdly, the joints in the longitudinal system are different in these two bridge branches. The logs of the Bianhe Rainbow Bridge were banded together by ropes, while mortise and tenon nodes are used in the Min-zhe Timber Arch Bridge.

Fourthly, there are X-bracings in the Min-zhe Timber Arch Bridge and many wood blocks are inserted between springing members, which are good for integrity and stability of the bridge structures, while these two structure approaches have not found in the Bianhe Rainbow Bridge.

Thus, it can be seen that the Bianhe Rainbow Bridge and the Min-zhe Timber Arch Bridge have the same woven structure system. However, there are some different structural details between them. From the view of structure and function, the Min-zhe Timber Arch Bridge has better traffic performance than the Bianhe Rainbow Bridge. The spandrel structures, X-bracings, as well as the inserted wood blocks among the logs in the Min-zhe Timber Arch Bridge enhancing the integrity and stability of the arch structure. The mortise and tenon connection method is more convenient for erection and the joint has better performance for sustainability than the lashing joint as in the Bianhe Rainbow Bridge. The covering house of the Min-zhe Timber Arch Bridge can additionally serve as a public space where passengers and villagers can relax, and it can protect its arch structure from heavy rainwater in the southeast mountain area, giving a more reasonable design than the Bianhe Rainbow Bridge.

2.4 Intangible Cultural Heritage

2.4.1 Introduction

The Min-zhe Timber Arch Bridge is not only the essence of architecture in China, but also a part of the precious cultural heritage handed down from the ancient people. It includes abundant intangible cultural heritage. For example, in 2009, *the traditional construction technology of China timber arch bridges* was listed in the Urgent Safeguarding List of Intangible Cultural Heritage by UNESCO[12]. Besides, the covering house is the main carriers of the local intangible cultural heritage, all kinds of covering houses all reflect the social and architectural characteristics and have important cultural value.

2.4.2 Traditional construction technology

2.4.2.1 Introduction

From ancient times to nowadays, Min-zhe Timber Arch Bridges are designed and built by bridge craftsmen. Inherited craftsmanship handed down from masters to their apprentices with the oral instruction. Because many of them have a relationship of father and son, and the techniques have been translated generation by generation to form timber arch bridge family with stable characteristics in their construction technologies[15]. However, there is only one or two such old bridge craftsmen good at building timber arch bridges in Fujian Province today and no young person likes to learn this technology because it is difficult to find an opportunity to build a timber arch bridge today, and this technology is at risk of disappearing. In 2009, the construction technology of Chinese timber arch bridges was listed in the *Urgent Safeguarding List of Intangible Cultural Heritage* by UNESCO. Therefore, recording down this technique is one of the key issues to safeguard this intangible cultural heritage. This section gives a brief introduction to the traditional construction technology of timber arch bridges in China.

In traditional Chinese society, almost all the construction activities are always accompanied with some important religious ceremonies for folk behavior about belief, so is the bridge-building, which is one of the important contents of the civil engineering. As the Min-Zhe Timber Arch Bridge has thousands of years of construction history, artisan forms a variety of customs about bridge-building in the long-term labor. And the timber arch bridge as a kind of public building in country of China, various local customs for construction bridges have developed among bridge artisans. The whole process of construction the timber arch bridge has a close relationship with Chinese folk culture[16].

Bridge and highway building are always a charity to benefit some of the people, even a public welfare project activity, which is supported by the official and public easily. The existing Min-Zhe Timber Arch Bridges are built by contribution of clan or family. According to the traditional construction technology of timber arch bridge, after the fundraising is provided under normal circumstances, the venerable person in the family will be elected as the first matter who is responsible for searching and selecting of craftsmen to build the bridge, budgeting and writing these contents into a specific treaty. This treaty is called “bridge approval”, “bridge treaty” or “the treaty of request”, signed off by all personnel before the bridge-building[15][17]. There are more than 20 bridge treaties of ancient bridges existing in China, as shown in **Fig. 2-24**.

Fig. 2-25 Contract of ancient Min-zhe timberaarch bridge

According to the Chinese traditional building techniques, in the process of constructing the Min-Zhe Timber Arch Bridge, traditional folk activities include the following procedures: site selection of the bridge, choosing a day to start, getting festival beams, offering sacrifices to river for construction, cheering on the beam, taking money to reward people, walking on the bridge, blessing ceremony of completion. These bridge-building customs are also important parts of the unique Chinese architectural culture.

The traditional construction technology includes the following five steps[12],[18]-[22]:

(1) Selection of bridge location;

(2) Construction of abutments and piers;

(3) Erection of arch ring;

(4) Installation of spandrel structure and deck system;

(5) Building of covered house, rails, etc.

2.4.2.2 Selection of bridge location

Just as other construction engineering activities, building bridge also has some important religious rituals and folk beliefs' behavior. Selection of a bridge location is generally followed the *Fengshiu* (wind and water) to meet a quest for an auspicious location[16]. Many Chinese timber arch bridges are located at the site called *Shuikou* (the mouth of water), the downstream of a river of a village, which could bring peace lives and prospects for the local people by the *Fengshiu*. However, selection of the bridge location by *Fengshiu* does not mean it has no consideration of bridge construction condition. It can be found that some consideration of the site hydrological and geological conditions is hided in the rules of *Fengshiu*. The majority of Chinese timber arch bridges, the arches are directly stand in natural cliff and crag with shallow carves without an abutment, as shown in **Fig. 2-16.** This shows that craftsmen have rich experience, high techniques and wisdom in selection of bridge location. Many China timber arch bridges survived can be seen as a proof of the reasonability of the traditional site selection method. At the same time, most of the bridges are located in the entrance or exit of the village, which has a special meaning. The traditional Fengshui doctrine is popular in ancient China, people believe that the water will take good luck away from their village and the bridge standing there can hold, keep and even bring the good luck for them. When selecting a bridge site, not only the natural condition for construction of the bridge should be taken into account, but also the *Fengshui* should be considered, and in most time, the latter will be the dominate factor. The results of the bridge location in the entrance or exit of the village can meet the psychological needs of the local people and in fact make it be the symbol of the village. Therefore, the appearance of the bridge should reflect the local architecture style and characteristics to enjoy the owners and users, giving a deep and good impression for the passengers.

2.4.2.3 Construction of abutments and piers

Elevation measuring is the most important process during abutment construction. However, there was no advanced equipment which can be used for surveying at past, so craftsmen invented a simple and effective way, for example, utilizing a half section bamboo pipe filled with water in which the knots have been cut off, as shown in **Fig.2-25**. If the bamboo is not long enough for the bridge span, several bamboo may be used with temporary supports. Two pieces of bamboo are jointed together, with the yellow wet clay sealing the joint bottom which prevents the water from seeping out. The level could be reached by adjusting heights of the bamboo in the supports.

Fig. 2-26 Measuring the level

Beside some bridge utilizing the natural rock as arch seats, most abutments of the China timber arch bridges are built by big gravels or block stones. Piers in multi-span bridges are generally built by block stone with spread foundation. These structures are all built by manual method as other masonry structures and no special techniques should be described herein.

2.4.2.4 Treatment of structural members

A China timber arch bridge is built without nails and ropes, and all the components are joined with various mortise and tenon joint, as shown in **Fig. 2-19**. Trees with suitable sizes in local area are selected as the bridge materials. After cutting down and transporting to bridge site, simple treatments are conducted according to the design of craft master. Construction is a completely manual operation. Mortise and tenon joints are made by traditional tools, such as the Luban rulers, carpenter's ink markers, wooden fork horse, axes, chisels, planers, saws, etc., as shown in **Fig. 2-26**.

(a) Luban ruler

(b) Carpenter's ink marker

(c) Wooden fork horse

(d) Axe

(e) Chisel

(f) Planer

Fig. 2-27 Treatment of timber members with traditional tools

2.4.2.5 Erection of arch ring

During the whole process of construction of a timber arch bridge, erection of the arch ring is the most important process. The four steps for a single span bridge illustrated in **Fig. 2-27** are as follows: (1) Standing vertical columns in the abutment as elevation scales; (2) Election of the first system(three-lines polygonal arches); (3) Election of the second system (five-lines polygonal arches); (4) Installation of the X-bracings[12],[18]-[22].

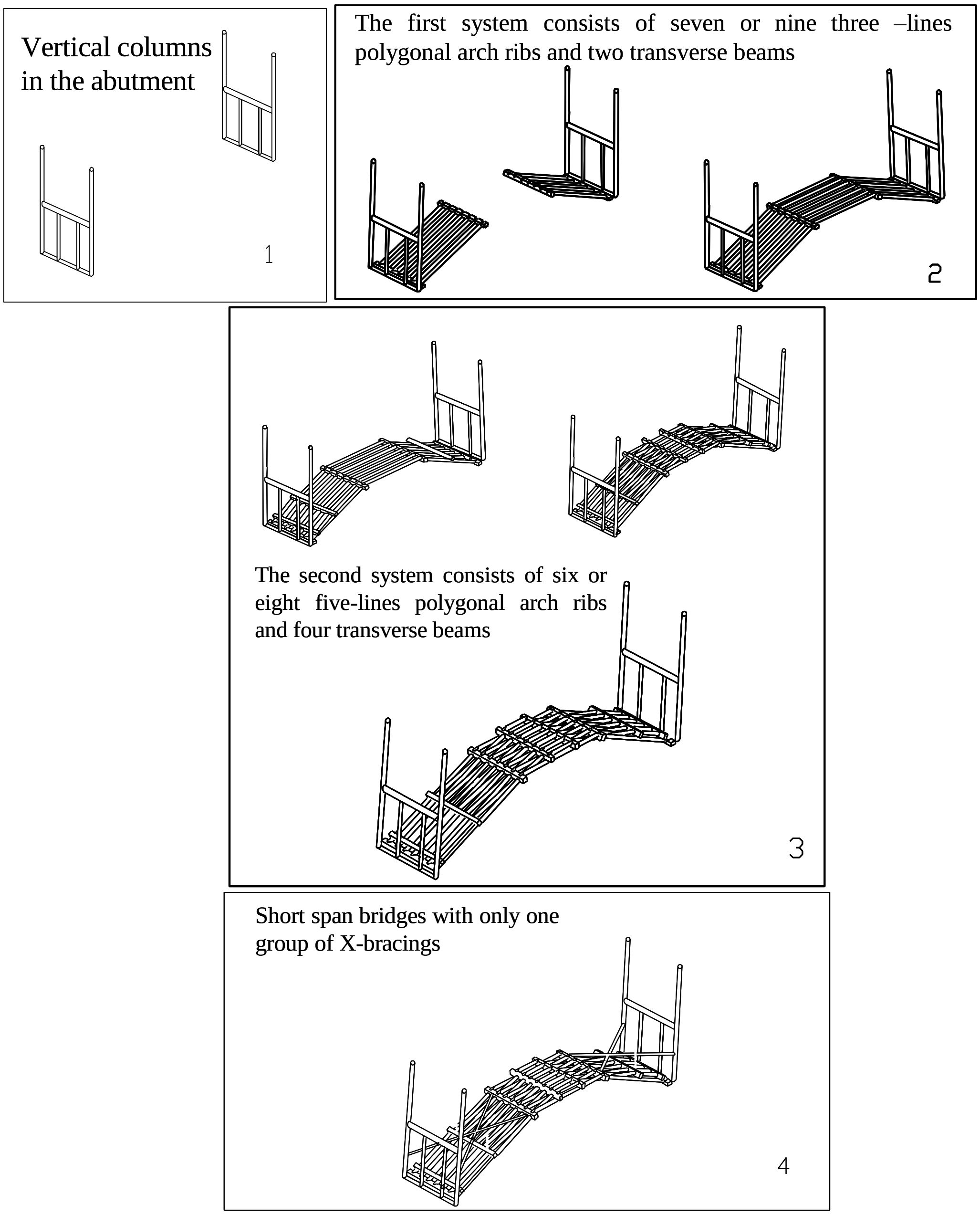


Fig. 2-28 Erection process of the arch ring

The main primitive machine used for erection of the arch rings is a wood winch as shown in **Fig. 2-28**. It is used to erect log members in arch ring and bracket for supporting the members during construction. Two brackets located near the two knee position of the first system are built as shown in **Fig. 2-29** in order to support springing members of the first system erected by wood winches (**Fig. 2-30**). The bracket is made of two main columns, a cross beam and several diagonal strut members.

Fig. 2-29 Wood winch

Fig. 2-30 Bracket

Fig. 2-31 Lifting arch ring members

Fig. 2-32 End of springing members

Fig. 2-33 Installation of transversal beam [12]

Fig. 2-34 First system

After all the springing members (see **Fig. 2-31**) in the first system have been erected in position, two transverse beams are hoisted up (**Fig. 2-32**), and tenon joints of the members are inserted into straight mortises of transverse beam. All the members in one side are jointed together and form two frames laid on the brackets. Then the crown members are inserted into the Swallow Tail mortise of the transverse beams to unite the two springing frames together and form three-lines polygonal arches as shown in **Fig. 2-33**.

The second system of the five-lines polygonal arch ring is easier to erect after the first system is completed. The arch members of the second system are placed on gaps of the members of the first system and erected from the springing members to quarter members. When all the crown members are installed to close the arch (**Fig. 2-34**), the second system is completed and the basic arch structure of the bridge has been formed.

It should be pointed out that punner and hammers made of wood instead of iron or steel are employed as common tools in construction of China timber arch bridges, as shown in **Fig. 2-35**, to prevent serious damage of the wood members during construction.

The last step to complete the arch ring is to install X-bracings shown in **Fig. 2-36**. One side of the X-bracings is inserted into transverse beams with the Swallow Tail tenon, and the other side is inserted into vertical columns in an abutment with a straight tenon. Finally, wood blocks are inserted between springing members to enhance the integrality of the arch ring as shown in **Fig. 2-37**.

Fig. 2-35 Installation of crown members [12]

(a) Punner (b) Hammer

Fig. 2-36 Wood punner and hammer

Fig. 2-37 X-bracings [12]

Fig. 2-38 Wood blocks

2.4.2.6 Construction of spandrel structures and covering house

A bridge deck system consists of deck transverse beams, longitudinal beams and deck slabs. Generally, there are six deck transverse beams (each side of three), in which the one close to an abutment is supported by columns as shown in **Fig. 2-15** and the transverse beam near the crown utilizes the transverse beam in the second arch ring system. Only the deck transverse beam in quarter span needs spandrel struts to support it. This spandrel struts, called as *horse-leg* in Chinese folk, consist of a pair of inclined members standing on the springing and two or three vertical or inclined members standing on quarter transverse beam in the second system.

A covering house is similar to a local general house and is built from the central part to two side parts **(Fig. 2-38)**. Names of craft masters and their chorography and pedigrees are written on the ridge of the covered house for recognition of their participation and contribution **(Fig. 2-39)**. Raising of the ridgepole **(Fig. 2-40)** is a high point in building the covered house with a ritual as in houses and temples in Chinese traditional folk-custom. Since building the covered house is similar to build a house in the local area, no special techniques should be described herein. But the covering house, it not only is suitable for the rainy southern mountains, fierce floods, steep mountains, but also improves the structural performance and adds other functions. At the same time, the covering house is a kind of beautiful structure, which has rich cultural connotation and local characteristics. It is an important carrier of material and intangiblecultural heritage, rich in Chinese characteristics of architecture and humanistic elements, includes folk customs, culture and religion. It will be presented in next section.

Fig. 2-39 Building covered house

Fig. 2-40 Ridges of the covered house

Fig. 2-41 Sacrificial rites

After the bridge is finally completed, a ceremony of completion will be hold in an auspicious day and then the bridge is open to public use.

2.4.3 Architectural feature of covering house

2.4.3.1 Function feature of covering house

All the Min-zhe Timber Arch Bridges are covered house, the covering house makes the bridge not only have the basic traffic function, but also have the function of society, signs, landscape and sacrifice; these functions are closely related to the politics, economy, culture and folk custom in China[14][16]. The diversified function is the greatest architectural feature for Min-zhe Timber Arch Bridge.

All the existing Min-zhe Timber Arch Bridges are the footbridges, due to the limitation of productivity level and timber structure. The traffic function is the most basic function for all the bridges. Most existing Min-zhe Timber Arch Bridges are located in the mountain area in northeast Fujian Province and southwest Zhejiang Province, where the communication and transportation condition is poor. According to the history recorded, Min-zhe Timber Arch Bridge is the main traffic facilities in a long time, many timber arch bridges were built in these regions in ancient China, these bridges promote the contact and communication between villagers, and make the contact convenient for the villagers with outside world[14].

The second function of the Min-Zhe Timber Arch Bridge is the social function. Along the longitudinal direction of covering house, there is a long corridor in the middle and there are many columns in the both sides. The most distinct feature is that there are installed with many benches between in the columns, the conception is cleverly combined its use function with the structure function. It not only provides a temporary resting place for passing pedestrians but also makes all the columns as a whole structure.

These covering houses on the timber arch bridges provide public spaces in the rural villages where the social activities are under developed and lack of public spaces for villagers. The covering house is an important place for parties, communication and entertainment, which provides a public place for talking, trading and religion activities for villagers. The social function is very outstanding for some Min-zhe Timber Arch Bridges, which are located in the village. The villagers often have the activity and party in the covering house (**Fig. 2-41**). Especially, it is extraordinarily lively in weekend and holiday, for example, villagers often hold cultural and artistic performance in some special festivals[16], as shown in **Fig. 2-42**.

Fig. 2-42 Recreational activities

Fig. 2-43 Dragon dance performance

For some bridges, which are located in the main traffic artery, the villagers often have spontaneous trading activities for agricultural products on the bridge, this kind of bazaar called as bridge market in ancient China. Although, with the society and economy developing, the bridge market is seldom in today, we can see that there is shop in the covering house for several bridges, as shown in **Fig. 2-43**.

Fig. 2-44 Shop in covering house

Fig. 2-45 Lanxia Bridge

Fig. 2-46 Dabao Bridge

Except for benches can provide convenience for the village **Fig.2-44**. Some of the ancient Min-zhe Timber Arch Bridges even have beds in the covering house, as shown in **Fig. 2-45**. In the ancient China, the traffic and lodging is not very easy convenient, the timber arch bridge is the only way which must be passed, when many people from a place to the other place, the covering house is the best hotel for the travelers through the mountainous path, which supplies ancient people with a good place to temporarily rest for trudge

The third function of the Min-Zhe Timber Arch Bridge is that it enriches the landscape of the village, which is very spectacular. It is an important landscapes and landmarks of a place and has a strong logo function. Most bridges are located in the entrance or exit of the village. This arrangement has a special meaning, the traditional Fengshui doctrine is popular in ancient China, the people believe the water will take good luck away from their village; the bridge can help them and bring good luck for them. Therefore, the people think the arrangement can bring peace lives and prospects for them. In fact, the arrangement is not only meet the psychological needs of the villagers, from the view of planning; the bridge is the identification for the entrance or exit of the village. As a symbol of the village, people are willing to make it become unique exterior, so most bridges are very beautiful and often very easy to make a deep impress on people. It is an important feature for covering house of Min-zhe Timber Arch Bridge, focusing on the unique combination of covering house, kiosk, and pavilion. Many bridges became very beautiful and magnificent because of the memorial archways, stele pavilions and Chinese gates, which are built at the both side entrance of covering house, as shown in **Fig. 2-46**.

(a) Bazi Bridge (b) Shuangmen bridge (c) Yuqing Bridge

Fig. 2-47 Entrance of covering house

There is a proverb that *where there is a bridge, there is a temple*; *where there is a temple, there is a bridge* in ancient China, so a close connection between the bridge and temple is also a major characteristic of the Min-Zhe timber arch bridge, the sacrifice function is also a main function of Min-zhe Timber Arch Bridges [16]. There is always a shrine of idols for villagers to offer sacrifice, as shown in **Fig. 2-47**; it may be arranged in the covering houses or next to the bridge or facing the entrance of the bridge. In the covering house, the idol is always rested by the side of downstream direction, facing the river flow.

Fig. 2-48 Shrine in the covering house

Fig. 2-49 Sacrificial rites

The devout people always come to offer sacrifices in every month in the fifteenth day of lunar calendar, as shown in **Fig. 2-48**. In some large scale timber arch bridges, the most solemn sacrifice rite was hold in the first month of the New Year. The religious villagers gathered at the bridge from all sides praying for blessing. The prayers are praying for the peace of the corridor bridge, family reunions, young and old safe, peace in the coming year and treasures fill the home. Their worship of the gods is like the attachment to the country customs and the ancestors. It has become a part of the spiritual life.

2.4.3.2 Architecture feature of covering house

The covering house of the Min-zhe Timber Arch Bridge can be classified into three types, the closed, semi-closed and open style, according to the degree of enclosure of the covering house.

The closed-style covering house, as shown in **Fig. 2-49**, is separated in completely for inner and out space of covering house; there are covering planks in the both sides of bridge, the lighting depends on the little windows, which is opened in the planks. Although this kind of the covering house offers a strong shelter function, the visual field is restricted to the covering house. What's more, watching the outside scenery through a small window.

Fig. 2-50 Closed-style covering house

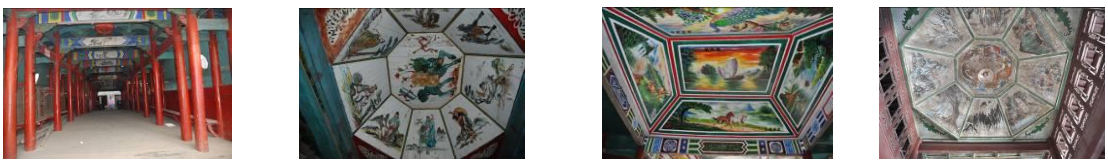
The semi-closed style covering house is showing in **Fig. 2-50**. In general, it is closed in the substructure with planks but opened in the superstructure. The lighting of this style is better than the closed style, and it is very convenient for people to watch the outside scenery.

Fig. 2-51 Semi-closed style covering house

Fig. 2-52 Open style covering house

The open style covering house is showing in **Fig. 2-51**. There are no covering planks in both side of covering house, while wooden handrail existing in the substructure of covering house. This kind of covering house is similar to the semi-close style, which is better lighting and convenient for people to watch the outside scenery; but its shelter function is not as good as the other styles.

Due to the special versatility of the Min-Zhe timber arch bridge, it is to be a place which shows the economic strength, cultural taste and human landscape. Especially, the men of literature and writing are fond of it. Therefore, bridge record, inscription, couplets, poetry, sculpture, covering drawing and calligraphy are available in the covering house, as shown in **Fig. 2-52**, and the themes of these decorations are rich and colorful. There also have a pattern of plants and animals, character image, drama scene, historical legend and so on.



(a) Shengping Bridge (b)Feiyun Bridge (c) Qixian Bridge (d)Mengzhou Bridge

Fig. 2-53 Interior decoration

Sculptures

Handwritings

Fig. 2-54 Interior decoration (contd.)

Fig. 2-55 Windows

Fig. 2-56 External decorations

The decoration is very distinctive, we also can see from the window shape for the closed style covering house, such as n-shape, hexagon, pentagon, octagon, heart shape, peach shape and so on, as shown in **Fig. 2-53**.

It is not only focusing on interior decoration, but also paying attention to the external decoration for Min-zhe Timber Arch Bridge. The bridges are often painted the rich colors, as shown in **Fig. 2-54**, the traditional decoration not only becomes a good corrosion protection measures, but also makes the bridge look very harmonious with the surrounding natural environment.

The China ancient architecture is very graceful and gorgeous; the roof is the most outstanding delegate. The flush gable roof, overhanging gable roof, gable and hip roof, pavilion roof and hipped roof are the most common roofs in traditional China timber structure architecture. The hipped roof is the noblest roof type in them with four slopes with solemn and magnificent; which is generally used for large buildings such as palaces, temples, mausoleums and so on, and it is seldom used in folk. Except for the hipped roof has not been found, the other five kinds of roofs all had been used in Min-zhe Timber Arch Bridge, the majorities of the forms are double slope type, with swallowtail - shaped ridge and covered the grey tiles.

The flush gable roof is divided into the front slope and back slope by the transverse ridge in the middle[23]. Both sides of the gables can be as high as the roof of the covering house, or higher than the roof of the covering house. The higher gable is called “Fire Wall”; its main function is to prevent the spread of the fire along the house when the fire broke out, as shown in **Fig. 2-55** (Lanxi Bridge in Qingyuan County).

Fig. 2-57 Flush gable roof

Fig. 2-58 Overhanging gable roof

The overhanging gable roof (**Fig. 2-56**) has two slopes and five ridges, which has an upright ridge and four vertical ridges[23]. Both sides of the upright ridge are over the both sides gables, so the roof can protect the house by wind and rain. This type is the most commonly roof in Min-zhe timber arch. For example, Xiao Dong Bridge in Shouning County.

The gable and hip roof consists of the overhanging gable roof and the hipped roof.

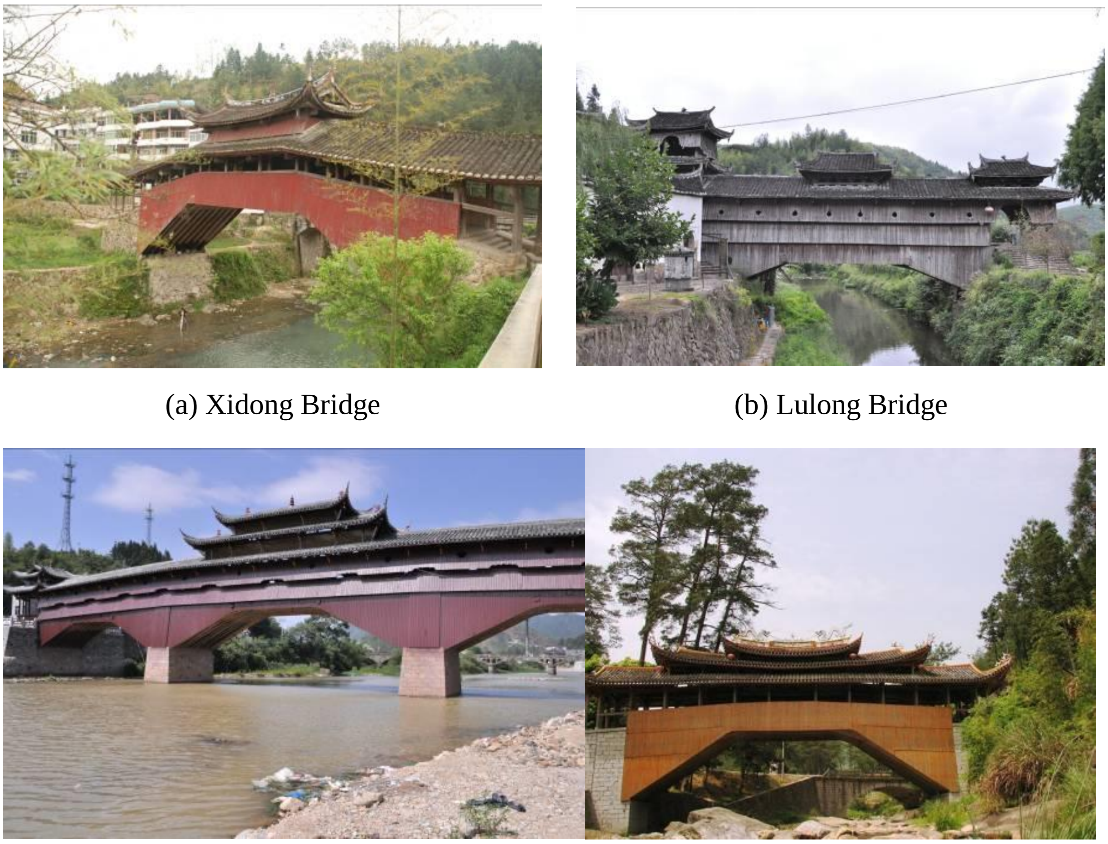
In general, two-thirds of the upper part is the overhanging gable roof, while one-third of the underpart is the hipped roof [23]. For example, the Jinzao Bridge in Pingnan, as shown in **Fig. 2-57**. The ingenious combination of straight lines and curves, which forms the upturned eave with an upward warp, not only expands lighting surface which is good for draining off rainwater, but also adds the beauty of lightness. The form and curves of the eave forms are full of change. The eave has a special handling and creation with a slightly upward warp in opposite direction, which forms a soft concave surface. In addition, the intersection of eaves suddenly warped high, like a flying bird. This kind of roof is called cornice. It can make the covering house more spectacular, alive and vibrant.

Fig. 2-59 Gable and hip roof

The pavilion roof has not main ridge, and the eave is converge in the top of the roof center[23]. It is usually used in the round and regular polygon building in ancient China. Therefore, it often used in the Min-zhe Timber Arch Bridge combine with the overhanging gable roof. The outstanding example is the Xiangong Bridge in Shouning, as shown in **Fig. 2-58** this style not only is easy to drain the rainwater, but also can provide aesthetic feeling of light flying

Fig. 2-60 Pavilion roof

In addition, the hybrid roof (**Fig. 2-59**) is often used in the covering house of Min-zhe Timber Arch Bridge. In generally, the covering house often can be divided into five parts, two sides and the middle of the covering house are always special embellish, so the roof often becomes the double eaves roof in these parts.



(a) Xidong Bridge (b) Lulong Bridge

(c) Buliang Bridge (d) Tongle Bridge

Fig. 2-61 Double eaves roof

2.5 Summary

The construction history, the detailed structure of two branches of Chinese timber arch bridge have been reported; the structural comparison of two branches had been done; and the abundant intangible cultural heritage has been presented in this chapter. The results can be summarized as follows:

1) According to the present situation, location, and structural details, Chinese timber arch bridge can be further divided into two types, one is the ancient Bianhe Rainbow Bridge, and the other is the Min-zhe Timber Arch Bridge. None of ancient Bianhe Rainbow Bridge has survived, while many ancient Min-zhe Timber Arch Bridges have retained.

2) The Bianhe Rainbow Bridge and the Min-zhe Timber Arch Bridge have the same woven timber structure, but there are some differences between them not only in appearance but also in structural details. The Min-zhe Timber Arch Bridge gives a more reasonable design than the Bianhe Rainbow Bridge.

3) The Min-zhe Timber Arch Bridge is not only the essence of architecture in China, but also part of the precious cultural heritage handed down from the ancient people, because it includes abundant intangible cultural heritage. It is the paragon in the history of bridge and architecture in the world, which is a combination of science, technology, architectural art and architectural culture.

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CHAPTER 3

FIELD SURVEY ON EXISTING CHINESE TIMBER ARCH BRIDGES

3.1 Introduction

Research and protection of Chinese timber arch bridge are hot topics in the fields of ancient bridges and cultural heritage. Many researches have been carried out by cultural relics workers and architects in China, focusing on the construction history, aesthetics, social function, cultural value and so on. But the research works from the view of structural engineering and bridge engineering are insufficient, a complete database of the China timber arch bridge focusing on bridge engineering perspective has not been created until now. A few bridges have often been missed, mistaken or repeatedly counted in the literature.

Based on the collected mass information of Chinese timber arch bridges, a survey on the bridges has been carried out by the authors since 2008. In this chapter, firstly, the main technical parameters of Chinese timber arch bridge has been defined according to the modern bridge design theory by author, because of main technical parameters are incomplete, confusion, wrong in all kinds of references; secondly, based on the collection information about the Chinese timber arch bridge, an investigation on the current situations of the bridges and the main arch ring structures include the longitudinal two systems and the cross-section, the major structural parameters such as the length, span as well as the rise-to-span ratio are carried out by field survey, then the main structural parameters have been analyzed from the view of bridge engineering,

3.2 Field and Time of Investigation

According to the description in Chapter 2, we found that no one ancient Bianhe Rainbow Bridge had survived now, and only several imitate bridge had been built in the modern, but many ancient Min-zhe Timber Arch Bridges were survived, and then some new Min-zhe Timber Arch Bridges had been built since 2000. So only Min-zhe Timber Arch Bridge has been investigated in this dissertation. The area is limited in southwest of Zhejiang Provinces and northeast of Fujian Provinces, which is area of build the traditional Min-zhe Timber Arch Bridge. The bridges include all the Min-zhe Timber Arch Bridge (historic Min-zhe Timber Arch Bridge and new Min-zhe Timber Arch Bridge), which are built by traditional structure, material and technology.

Investigation from 2008 to 2015, the ways include collecting the document, literature and the field survey, all existing Min-zhe Timber Arch Bridges are investigated by field survey base on the literature survey.

3.3 Current Situation of Min-zhe Timber Arch Bridge

3.3.1 Amount and area distribution

There are 130 Min-zhe Timber Arch Bridges in service today, the detail information as shown in Appendix I [1] - [8]. All of them are located in mountainous areas in northeast Fujian Province and southeast Zhejiang Province, as shown in **Fig. 3-1**. There are 81 in Fujian Province, over half of the total, while the rest 49 are in Zhejian Province. For county, five counties have over 10 timber arch bridges, they are Shouning, Pingnan in Fujian Province, and Taishun, Jinning as well as Qingyuan in Zhejiang Province. The number in Shouning County is the largest one with a marvelously 19 bridges, accounting for 14.6% of the total. The detail distribution of the bridges is shown in **Fig. 3-2**.

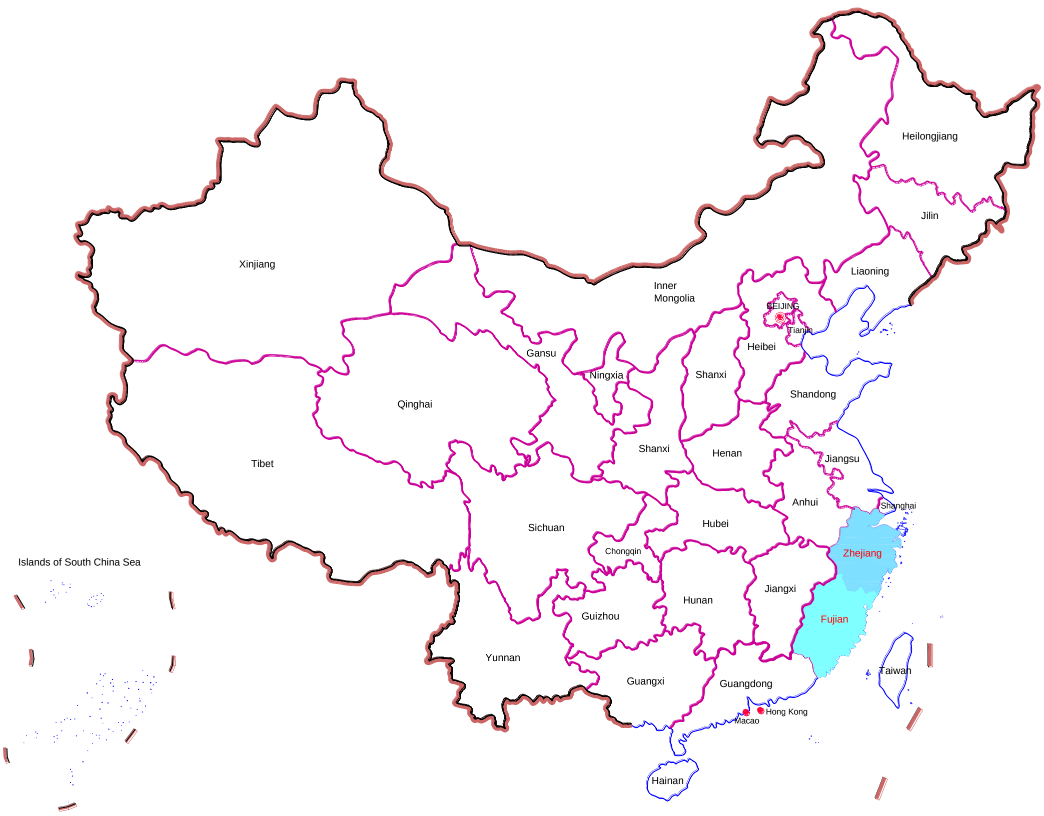


Fig. 3-1 Map of China

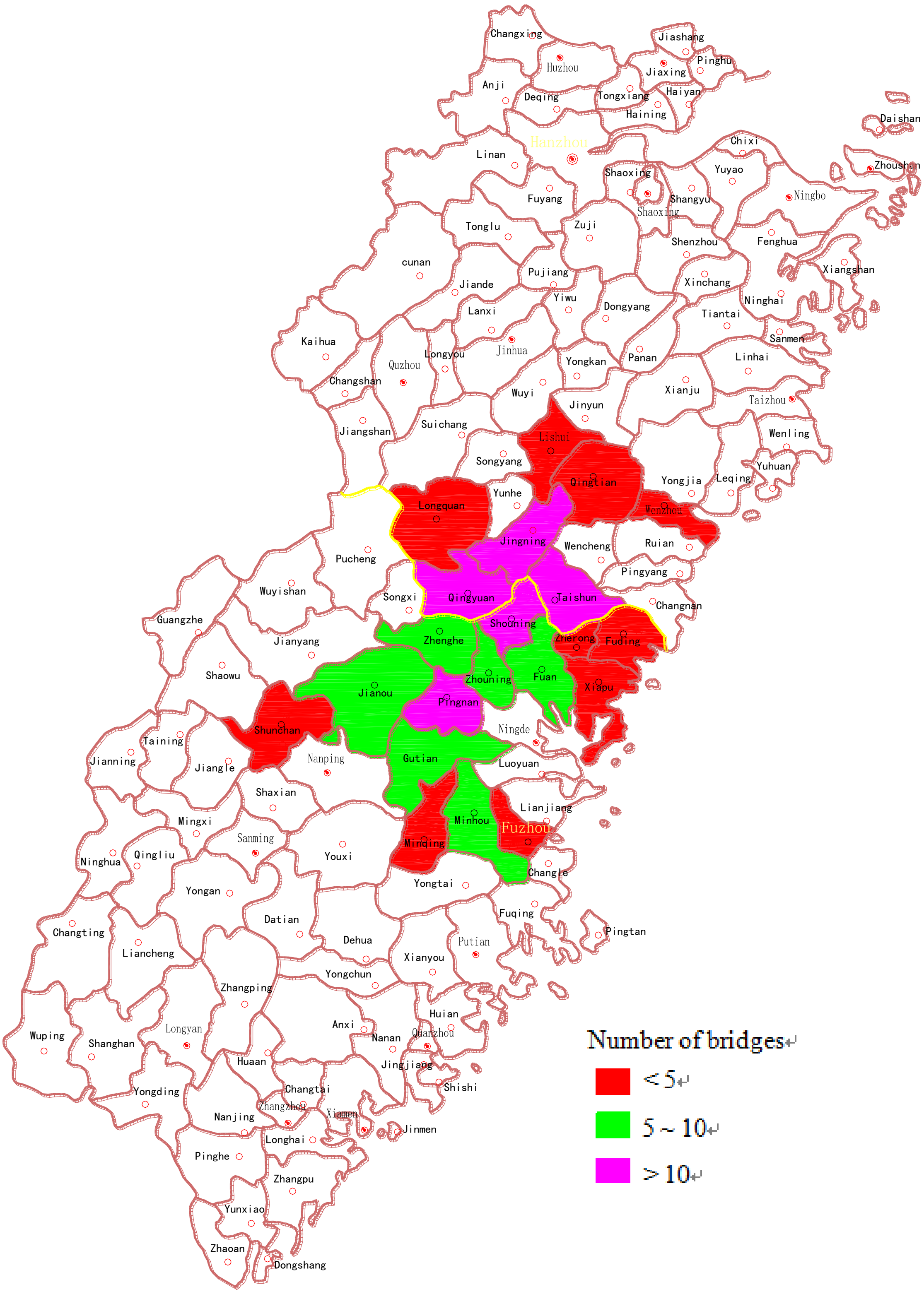


Fig. 3-2 Distribution map of Chinese timber arch bridges

3.3.2 Construction time

It is quite common for a bridge to be date in China, In the earliest construction time, periodic maintenance time and the latest rebuilt time often been recorded in the genealogies, county annals, and bridge plaques, steles and covering houses. But for the extant Min-zhe Timber Arch Bridges, it is still a complex issue for theirs first built time, the build history of some timber arch bridges hasn't record or lost. According to the specific records, which are been recorded in the genealogies, county annals, and bridge plaques, steles and covering houses [7]. The results of field survey show many timber arch bridges were built from the Ming Dynasty (1368-1644) to 1960s. No timber arch bridges were built during 1966 and 2000 due to scarcity of timber resources and the development of the other bridge types, etc. However, 14 bridges were built after 2000, because more and more people have recognized the technology and culture value of the Chinese timber arch bridges. The time distribution of the last rebuilding of the existing timber arch bridges is shown in **Fig. 3-3**. It can be seen that 53.9% of the existing Min-zhe Timber Arch Bridges were built in Qing Dynasty. In this dissertation, I consider rebuilt as the construction age. It should be pointed out that 'rebuilt' here does not include maintenance, repair and relocation which does not change the structure form.

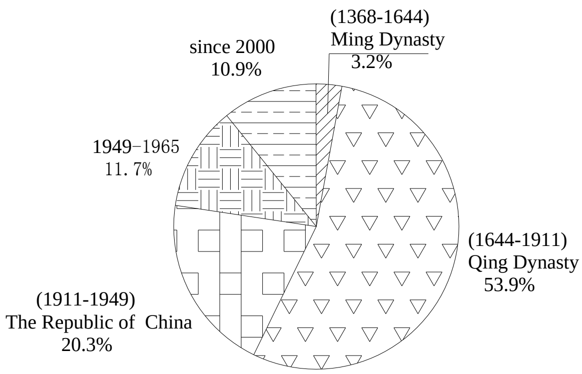


Fig. 3-3 Construction time of the extant Min-zhe Timber Arch Bridge

3.3.3 Current situation of protection

Not like the ancient Bianhe Rainbow Bridge, Min-zhe Timber Arch Bridges had been built in the mountainous area where traffic was inconvenient and social development was relatively slow. People are very simple in these areas and they are filled with fear and love in these bridges. For a long time, the vulnerability and damage components of these bridges are often regular maintained and replaced. So many wooden arch bridges can exist hundreds of years. Although, the ancient Min-zhe Timber Arch Bridges had been protected with some good ways, but according to the investigation, we found that the phenomenon of degradation and damage of the timber arch bridge is commonplace with the reduction of the traffic function, the importance of maintained the timber arch bridge to reduce. At the same time, the closed mountain areas opened to the outside and the dependence among the traditional village people became gradually weak. The excellent tradition protection way began to be ignored. Every year many timber arch bridges have been destroyed and taken down because of the natural and human reasons.

The survey shows more than one hundred Min-zhe Timber Arch Bridges have been destroyed since 1949. Some bridges had been destroyed by fire, wind and flood, etc.; some bridges had been replaced by new bridges for the sake of economic development; especially, rebuild the road and build new hydropower station.

According to the preliminary investigation, about fifty-two timber arch bridges had been destroyed in Ningde after 1949 [3]. Among them, nine had been destroyed by rush of water. One had been destroyed by tornado. Six had been destroyed by man-make fire (including the Baixiang Bridge shown in **Fig. 3-4**, which is a major historical and cultural site under state protection, and it was destroyed in 2006). One had been destroyed by forest fire. Thirty-one had been taken down because the traffic function had changed. Two had been destroyed by build the power station.

Fig. 3-4 Quondam Baixiang Bridge

About eleven had been destroyed and rebuilt by other type bridge in Taishun

County, including the Yeshuyang Bridge built in 1454. It had a long historical standing of timber arch bridges and had been destroyed to build the road in 1965. The Santan Bridge is one of exceeding the span of the Chaw-Zhou Bridge, which is the longest span of the stone arch bridge in the ancient China. t was destroyed by rush of water in 1950.

In Jingning County, the Tuowan Bridge was destroyed by fire in 1990 and the Guangji Bridge was destroyed by rush of water. In 2005, the Rongtan Bridge and Baihe Bridge **(Fig. 3-5)** were destroyed by rush of water; The Meicong Bridge was destroyed by fire in 2006, which was been recorded in the History of Technique of Archaian Bridges in China in 1986.

In Qingyuan County, the Mengyu Bridge as shown in **Fig. 3-6** was destroyed by man-made fire in 1995.

Fig. 3-5 Baihe Bridge

Fig. 3-6 Mengyu Bridge

Unfortunately, in the investigation period, three timber arch bridges in Nanping were destroyed by rush of water in 2009, as shown in **Fig. 3-7** to **Fig. 3-9**; only one timber arch bridge in Wuyishan city, called Yuqing Bridge, it was destroyed by fire in 2011 yet, as shown in **Fig. 3-10**.

Fig. 3-7 Yueyuan Bridge

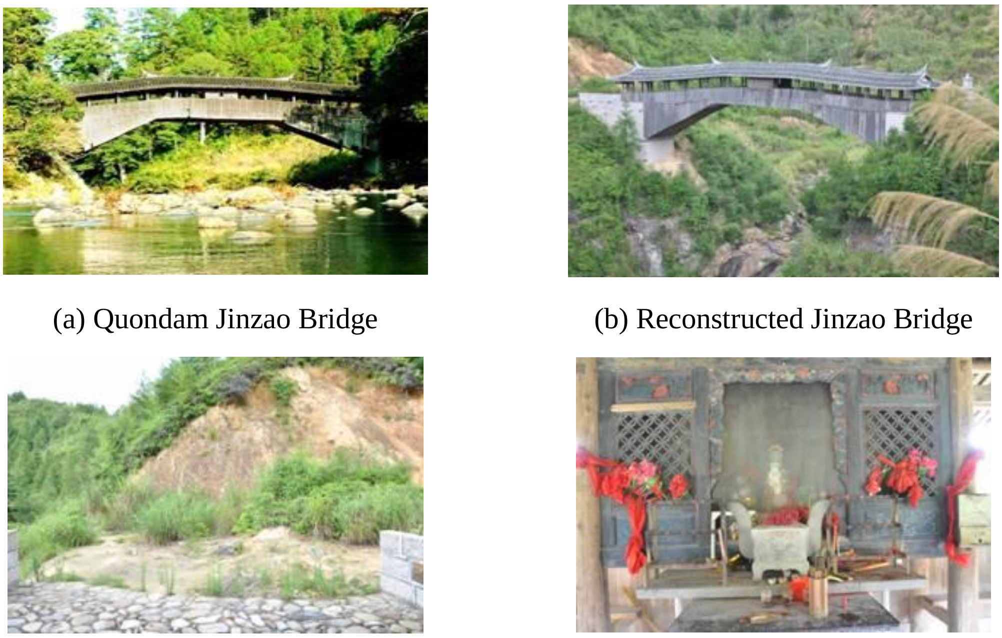
Fig. 3-8 Ruotuo Bridge

Fig. 3-9 Bazi Bridge

Fig. 3-10 Yuqing Bridge

In addition, in a long time in order to develop the economy, many hydropower stations are being constructed, many timber arch bridges had been taken down, under calling for the protection of the arch bridge, some of the ancient timber arch bridges had been relocated.

For example, The Jinzao Bridge in Pingnan County, Fujian Province. The original Jinzao Bridge shown in **Fig. 3-11(a)** was built in 1808 and rebuilt in 1948. It is 41.7m in total length with a single span of 32.5m and a width of 4.8m. It located in the south of the village of Jitou village, crossing the Jinzao brook. The bridge was very beautiful, surrounding with tall trees and rugged mountains on both sides. The bridge has been listed in the Cultural Heritage Unit of County in 2001. In order to build a new hydropower station, the Jinzao Bridge was removed in 2005, from the original site to a new place, where is beside of the secondary roads in Pingnan County crossing over the Yingji brook, as shown in **Fig. 3-11(b)**. The new bridge is located in a very precipitous geographical location and it can be serviced as a good sightseeing. However, there is no road connecting to this bridge at the other side, see **Fig. 3-11(c)**. In other words, this bridge has lost its communication function in the new site. Moreover, it is far away from the village, the bridge also cannot pay other functions as other timber arch bridges in this area, like a gathering place for villagers, resting place for travelers. And the shrine of idols in the central of the bridge has been covered by heavy dust with few people use it, as shown in **Fig. 3-11 (d)**. Unfortunately, these bridges had lost the use function and lost the significance of the bridge as a kind of functional construction, it only become a kind of furnish and decorate [9].



(a) Quondam Jinzao Bridge

(b) Reconstructed Jinzao Bridge

(c) Site of the reconstructed bridge

(d) Shrine in the reconstructed bridge

Fig. 3-11 Jinzao Bridge

These bridges not only carry traffic, but also enable communications, trade etc. They represent the essence of traditional architecture of China and are an important part of the precious cultural heritage handed down from the ancient China. They all reflect the social and architectural characteristics of the time of their construction. Thus, these timber arch bridges are the main symbols of material and intangibleheritage of the local civilization. The timber arch bridge stands out among other bridges for its value, classified as cultural heritage, rather than a mere engineering structure. Fortunately, with the development of research on Chinese timber arch bridge, people realized the timber arch bridges have important cultural value and the technology connotation and pay attention to protect the timber arch bridge since 1990. According to their value and condition, timber arch bridges have been divided into different levels, considering the protection approaches by relevant management authorities.

Table 3-1 List of world cultural heritage in China

No.	Bridge Name	Location
1	Yanghou Bridge	Zhenghe county of Fujian province
2	Houshan Bridge	Zhenghe county of Fujian province
3	Cixi Bridge	Zhenghe county of Fujian province
4	Wan’an Bridge	Pingnan county of Fujian province
5	Qiancheng Bridge	Pingnan county of Fujian province
6	Guangli Bridge	Pingnan county of Fujian province
7	Guangfu Bridge	Pingnan county of Fujian province
8	Longjin Bridge	Pingnan county of Fujian province
9	Sanxian Bridge	Zhouning county of Fujian province
10	Luanfeng Bridge	Shouning county of Fujian province
11	Yangmeizhou Bridge	Shouning county of Fujian province
12	Dabao Bridge	Shouning county of Fujian province
13	Yonggui Bridge	Qingyuan county of Zhejiang province
14	Banluting Bridge	Qingyuan county of Zhejiang province
15	Rulong Bridge	Qingyuan county of Zhejiang province
16	Zhangkeng Jielong Bridge	Jingning county of Zhejiang province
17	Dajun Dcikeng Bridge	Jingning county of Zhejiang province
18	Dongkengxia Bridge	Jingning county of Zhejiang province
19	Xidong Bridge	Taishun county of Zhejiang province
20	Beijian Bridge	Taishun county of Zhejiang province
21	Santiao Bridge	Taishun county of Zhejiang province
22	Wenxin Bridge	Taishun county of Zhejiang province

Among 130 timber arch bridges, among them, 22 timber arch bridges have been collected in the world cultural heritage tentative list in 2012[8], as shown in **Table 3-1**.

17 timber arch bridges have been listed in the national preservation list of cultural relics, as shown in **Table 3-2**. 18 timber arch bridges had been listed in the Provincial Cultural Relics Protection Unit of Fujian or Zhejiang Province, as shown in **Table 3-3**, and 49 in the local county's preservation list. The specific locations, as shown in **Table 3-4**. We can find that, the Pingnan County and Shouning County have the greatest number of them.

Table 3-2 National major Cultural Relics Protection Unit

No.	Bridge Name	Location	List Time
1	Rulong Bridge	Qingyuan county of Zhejiang province	2001
2	Santiao Bridge	Taishun county of Zhejiang province	2006
3	Xianju Bridge	Taishun county of Zhejiang province	2006
4	Wenxing Bridge	Taishun county of Zhejiang province	2006
5	Xidong Bridge	Taishun county of Zhejiang province	2006
6	Beijian Bridge	Taishun county of Zhejiang province	2006
7	Xuezhai Bridge	Taishun county of Zhejiang province	2006
8	Tiandi Bridge	Gutian county of Fujian province	2006
9	Dongyuan Bridge	Zherong county of Fujian province	2006
10	Dengyun Bridge	Shouning county of Fujian province	2006
11	Yangmeizhou Bridge	Shouning county of Fujian province	2006
12	Luanfeng Bridge	Shouning county of Fujian province	2006
13	Xiangong Bridge	Shouning county of Fujian province	2006
14	Feiyun Bridge	Shouning county of Fujian province	2006
15	Shengpin Bridge	Shouning county of Fujian province	2006
16	Wan'an Bridge	Pingnan county of Fujian province	2006
17	Qiancheng Bridge	Pingnan county of Fujian province	2006

Table 3-3 Provincial Cultural Relics Protection Unit

No.	Bridge Name	Location	List Time
1	Guisi Bridge	Zherong county of Fujian province	2005
2	Xiaodongshang Bridge	Shouning county of Fujian province	2005
3	Denglong Bridge	Zhouning county of Fujian province	2005
4	Guangfu Bridge	Pingnan county of Fujian province	2005
5	Guangli Bridge	Pingnan county of Fujian province	2005
6	Fushou Bridge	Shouning county of Fujian province	
7	Yanghou Bridge	Zhenghe County of Fujian province	
8	Longtan Bridge	Zhenghe County of Fujian province	
9	Houshan Bridge	Zhenghe County of Fujian province	
10	Chixi Bridge	Zhenghe County of Fujian province	
11	Jiaolong Bridge	Zhenghe County of Fujian province	
12	Helong Bridge	Minqing county of Fujian province	
13	Yuanji Bridge	Minhou county of Fujian province	
14	Lanxi Bridge	Qingyuan county of Zhejiang province	1997
15	Dadi Bridge	Jingning county of Zhejiang province	2005
16	Dongkengxia Bridge	Jingning county of Zhejiang province	2005
17	Longjng Bridge	Minhou county of Fujian province	
18	Kengping Bridge	Minhou county of Fujian province	

Table 3-4 Number of timber arch bridges in China

Province	County	Total	On preservation list		
			National Level	Provincial Level	County 's Level
Fujian (81)	Shouning	19	6	2	11
	Pingnan	15	2	2	8
	Zhouning	7		1	6
	Gutian	6	1		4
	Fu'an	5			4
	Zherong	2	1	1	
	Fuding	1			1
	Xiapu	1			1
	Fuzhou	1			1
	Minhou	7		3	2
	Minqing	2		1	1
	Zhenghe	7		5	2
	Jian'ou	5			4
	Shunchang	3			
Zhejiang (49)	Taishun	11	6		
	Wenzhou	1			
	Qingyuan	16	1	1	4
	Jingning	15		2	6
	Longquan	2			
	Qingtian	2			
	Lishui	2			
Total		130	17	18	55

The Rulong Bridge is the earliest national major Cultural Relics Protection Unit, which is located in the Yueshan Village of Qingyuan County in Zhejiang Province, as shown in **Fig. 3-12**. It was built in 1625 (The Ming Dynasty). The bridge has a clear span of 19.5 m, a length of 28.2 m, a width of 6 m and the rise of 6 m, with nine covering houses. It is the oldest existing timber arch bridge in China today with an exactly recorded. It has aesthetically pleasing, complicated structure, exquisite craft, fully functional and certain representative ness and high historical, artistic or scientific value. Therefore, it was listed in national major Cultural Relics Protection Unit in

2001[10].

Generally, the existing bridges on the list have better condition than the bridges unlisted. However, our survey revealed that some of the listed bridges are still in poor condition, due to the timber material itself and the lack of enough money for maintenance, because of poor local economic development. Many timber arch bridges had become into warehouse and very dangerous, as shown in **Fig. 3-13 (a)** and **(b)**. Some of the timber arch bridges are in shreds and patches, many arch ribs of main arch are lost, the deck system are in badly, even in an unsafe situation as one in **Fig. 3-13 (c)** and **(d)** due to the lack of maintenance. It is imperative to maintain or strengthen these bridges [11].

(a) General view

(b) Roof

(c) Inner view of roof

Fig. 3-12 Rulong Bridge

(a) Ranxia Bridge in Shunchan

(b) Xinrong Bridge in Shunchan

(c) Ruoling Bridge in Zhenghe

(d) Jierong Bridge in Jian'ou

Fig. 3-13 Bridges under poor condition

3.4 Glossary of Min-zhe Timber Arch Bridge

All the Min-zhe Timber Arch Bridges are the footbridge, located in the ancient pedestrian paths or ancient villages, and all of them are constructed with the traditional construction technology by craftsman, who inherited the craftsmanship from father or a qualified worker. According to the description in section 3.3, we can find all of them are managed by the department of cultural relic and local government. It has not been included in the modern bridge engineering system in China. Many glossaries often have been mistaken in the literature. In order to unify the glossary and make the Min-zhe Timber Arch Bridge fit for the modern bridge theory, the glossary will be defined in this section from the perspective of modern bridge engineering and structure engineering. The structure parameters will be analyzed according to the new glossary.

3.4.1 Bridge length and width

The rule for the length of bridge in General code for design of highway bridges and culverts: for the bridge with abutment, the distance is from one side of flank of abutment or end of wing wall to the other side; for the bridge without abutment, it is bridge deck of length [12]. According to the definition of the total length of arch bridge and the particularity of the timber arch bridge, we choose the total length of the covering house as the length of the timber arch bridge in this dissertation [7], as shown in **Fig. 3-14**. There are three reasons to explain: firstly, many abutments of Min-zhe Timber Arch Bridges directly utilize the natural cliffs and crags with shallow carvings and treatments. Secondly, some bridges are built by big gravels or block stones, so the lank of abutment is not clear. Thirdly, all Min-zhe Timber Arch Bridges are built with covering houses, which also embody the most important characteristics. The length of the covering house is longer than that of the floor system.

In general, the width of bridge refers to the structure of the bridge width, including the width of carriageway, median strip, both side of guardrail or sideway. The clear width of bridge deck refers to the width of carriageway or the distance between the two sideways. Chinese timber arch bridge is footbridge and all the Min-zhe Timber Arch Bridge are built covering house. There are equipped with the bench for people to have a rest in the two sides. In this dissertation, the distance between the two sides of outboard of the deck is bridge width; the distance between the benches in the covering house is clear width, as shown in **Fig. 3-15**[7].

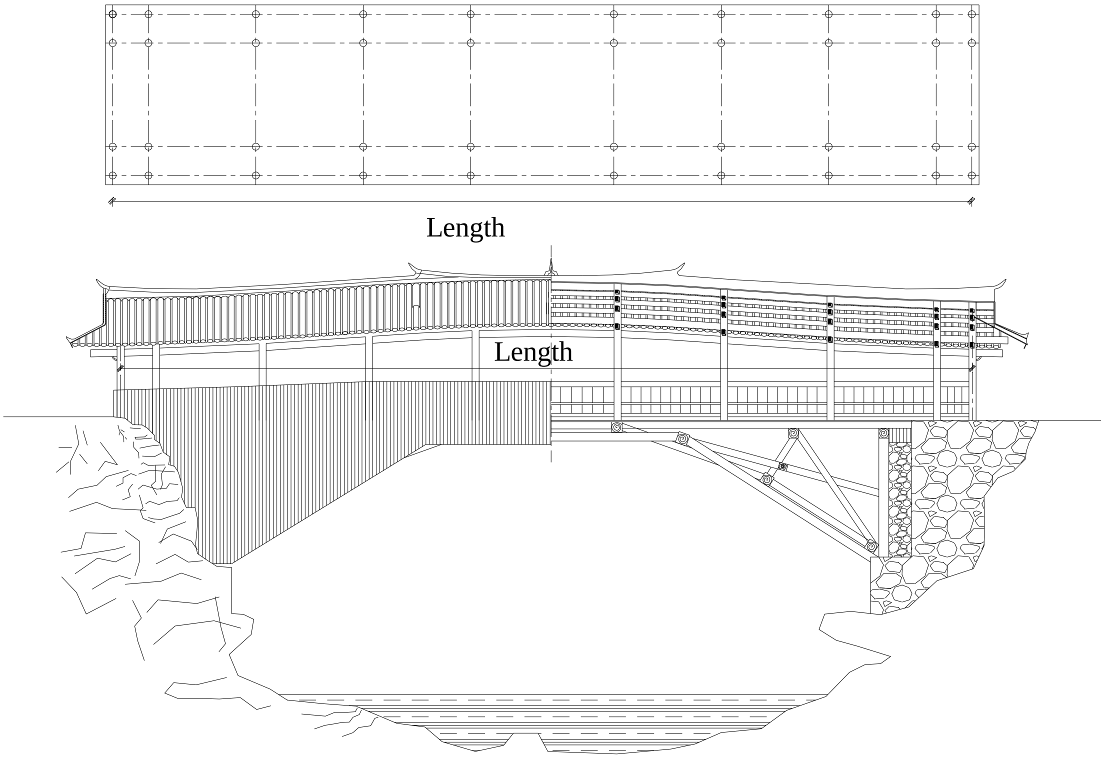


Fig. 3-14 Sketch map of length of Min-zhe Timber Arch Bridge

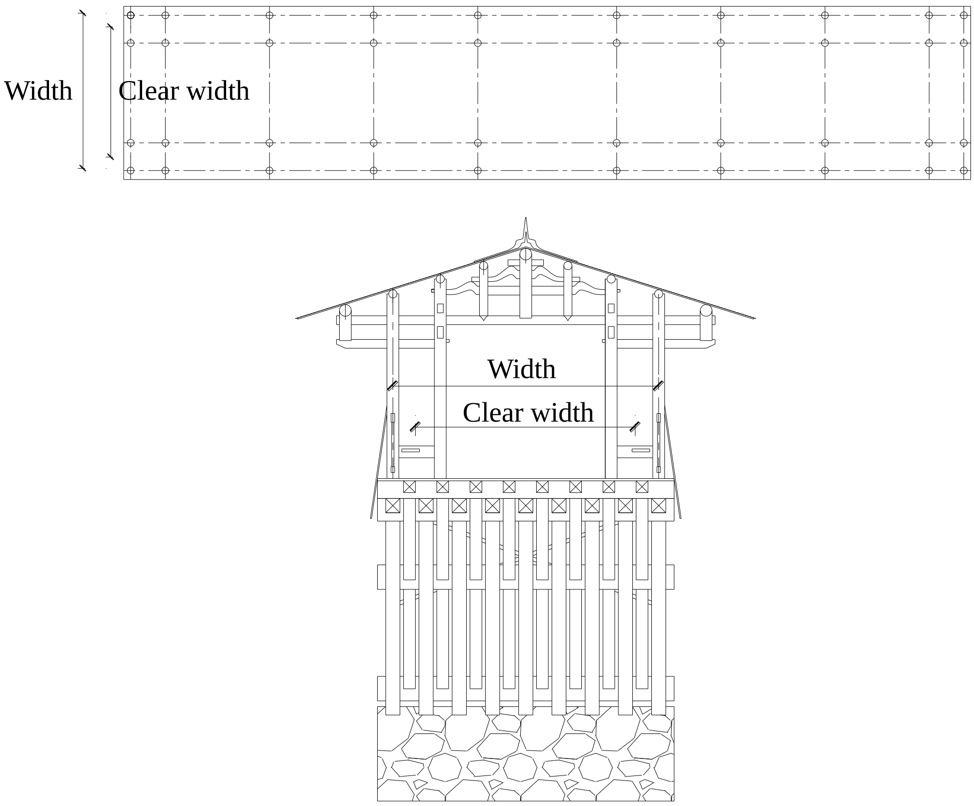


Fig. 3-15 Sketch map of width of Min-zhe Timber Arch Bridge

3.4.2 Clear span and rise

The span is inferred to the horizontal distance between in structure or structures supporting. The clear span for the arch bridge, is infers to the horizontal distance between both sides of spring lines. The calculated span for the arch bridge inferred to the horizontal distance between the centers in the border upon arch springing sections.

The Min-zhe Timber Arch Bridge consisting of two longitudinal systems and two systems are not in the same plane. The clear spans of two systems are different. In this dissertation, the clear span for the Min-zhe Timber Arch Bridge denotes the horizontal distance between both sides of spring lines of the first system. The calculate span denotes the horizontal distance between both sides of the center of the two systems, as shown in **Fig. 3-16**[7].

The rise of arch denotes the elevation difference from the arch crown to springing of the main arch ring, the clear rise of arch denotes the elevation difference from the lowest of the arch crown to the springing. The calculated rise of arch denotes the elevation difference from the arch crown to springing of arch axis.

For the Min-zhe Timber Arch Bridge, the rise of arch denotes the elevation difference from the lowest of arch crown to springing of the first system. The calculated rise of arch denotes the elevation difference from the center of arch crown section of the two systems to the center of springing of the two systems arch axis, as shown in **Fig. 3-16**.

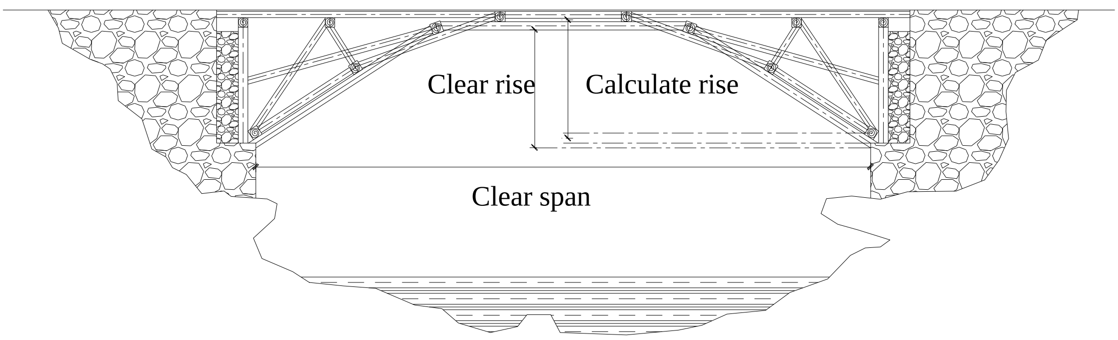


Fig. 3-16 Sketch map of span and rise of Min-zhe Timber Arch Bridge

3.4.3 Clear rise-to-span ratio

The clear rise span ratio denotes the ratio of the calculated rise of arch and the calculated span. As for the Min-zhe Timber Arch Bridge, it denotes the ratio of the calculated rise of arch and the calculated span, which are defined in this dissertation.

3.5 Statistical Analysis on Major Parameters of Min-zhe Timber Arch Bridge

In this section, the statistical analysis on major parameters of Min-zhe Timber Arch Bridges had been carried out according to the definition of the structure parameter, which is descripted in section 3.4.

3.5.1 Span system and span length

Most timber arch bridges are located in ancient village and the ancient way, crossing the main rivers, streams or ditches in the area. Because the stream is not wide， most of the Min-zhe Timber Arch Bridges have only one span. There are only seven timber arch bridges among the 130 bridges have multi-spans, in which four are located in Fujian Province and three are located in Zhejiang Province, just as the main technical specifications of the all multi-span timber arch bridges listed in **Table 3-5**. The Helong Bridge, the Qiancheng Bridge and the Jiajing Bridge are the double-span bridges, the Shuanglong Bridge, the Jingning Bridge and the Menzhou Bridge are the three-span bridges, the Wan'an Bridge is the six-span bridge.

The Wan’an Bridge, as shown in **Fig. 3-17**, has a length of 96.6 m. It is a bridge with six spans with five piers and two abutments. It is also called as Gongji Bridge, crossing the Changqiao River in Pingnan County, Fujian Province. The bridge was built in 1090, refaced in 1708 and rebuilt in 1845, 1932 and 1953 respectively. and 4.7 m wide. The longest span is 15.3 m and the shortest one is 10.6 m. The piers were built by granite material. The bridge has 37 lounge houses and 152 pillars with a single-eaves roof [13].

Table 3-5 Multi-span Min-zhe Timber Arch Bridges

No.	Bridge Name	Place	Construction time	Type	Length (m)	Span (m)
1	Wan'an Bridge	Pingnan, Fujian	1954	Six spans	96.6	13,16
2	Suanglong bridge	Pingnan, Fujian	2006	Three pans	66	19.9, 18.9
3	Qiancheng Bridge	Pingnan, Fujian	1820	Two spans	62.7	27.5
4	Helong Bridge	Minqing, Fujian	1927	Two spans	53	12.5, 14.7
5	Mengzhou Bridge	Qingyuan, Zhejiang	2008	Three pans	115	29.6, 23.4
6	Buliang Bridge	Qingyuan, Zhejiang	2012	Three pans	76.37	18.37
7	Jingning Bridge	Jingning Zhejiagn	2011	Three pans	69.18	15.27

(a) General view (b) Inner view

Fig. 3-17 Wan'an Bridge

(a) Photography in Qing Dynasty (b) Photography in 2009

Fig. 3-18 Qiancheng Bridge

The Qiancheng Bridge is one of the oldest existing timber arch bridge, shown in **Fig. 3-18**. It was built in Lizong of the Song Dynasty (1225-1264) at the first time, after a continues process of maintenance, repair and rebuilding, the extant Qiancheng Bridge is rebuilt in 1820. The bridge has two spans. Its length is 62.7 m, one clear span is 27.5 m. The width is 4.9 m.

The original Shuanglong (Double dragons) Bridge was built in 1862 and was destroyed by fire before 1949. In 2005, a new Shuanglong Bridge was rebuilt in Baishuiyang, a beauty spot of Pingnan, where a super large flat rock bed lies on the river.

The bridge has three spans with a total length of 66 m and 4.5 m wide, rebuilding after the original one by photos and records. The new bridge **(Fig. 3-19)** connects the two sides of the river, which provides a convenient communication for the tourists. It is also a good place for them to take pictures of Baishuiyang and the Wulaofeng (five peaks like five old men), to have a cup of tea with friends, to rest and enjoy time for playing Chinese Chess and so on.

(a) Shuanglong Bridge General view

(b) Entrance of the bridge

(c) Inside the covering house

(d) Up view of the arch

Fig. 3-19 Shuanglong Bridge

The shortest multi-span timber arch bridge is the Helong Bridge, as shown **Fig. 3-20**, has a total length of 53 m, two spans with one pier, the span is 12.5 m and 14.7

m, respectively. It is located in Mingqing County.

The longest multi-span arch bridge is the three-span Mengzhou Bridge , as shown in **Fig. 3-21**, in Qingyuan County of Zhejiang Province. Its construction was started in Nov. 30, 2006 and completed in August 31st, 2008. The project with a total investment of 9.35 million RMB. The total length is 114.37m. The central span is 29.6 m and each of the two side spans is 23.4 m. There are many exquisite paintings, couplets and calligraphies inside the covered house, as shown in **Fig. 3-21 (b)**.

Beside the seven multi-span timber arch bridges mentioned above, the rest 123 Min-zhe Timber Arch Bridges are single span bridges. Their span distribution is listed in **Table 3-6**. Form the table, we can see that the span of the single span bridge is mainly distributed in 10 m-30 m, the span from 10 m to 20 m accounts for 35.8%, and the span from 20 m to 30 m accounts for 42.3%. The concentrated area of span distribution is 20 m-30 m, near half of them. The results show twenty timber arch bridges span is over 30 cm, and it also can prove the span ability of timber arch bridge is better.

(a) General view

(b) Inner view

Fig. 3-20 Helong Bridge

(a) General view

(b) Inner view

Fig. 3-21 Mengzhou bridge

Table 3-6 Span distribution of the single span timber arch bridges

Span (m)	$0 \le L < 10$	$10 \le L < 20$	$20 \le L < 30$	$30 \le L < 40$
Quantity	3	44	52	24
Percent	2.4%	35.8%	42.3%	19.5%

Most noteworthy is the longest single span timber arch bridge, which is the Luanfeng Bridge with the span of 37.6 m, as show in **Fig. 3-22**. Luanfeng Bridge crosses Chang Brook in Shouning County, Fujian Province. It was rebuilt in 1800 and 1963 respectively, but it is not clear when it is the first built time. It is 47.6 m in total length and 4.9 m wide. One spring of the arch was built on the rock directly (as shown in **Fig. 3-22 a**); the other one was on the stone abutment (as shown in **Fig. 3-22 b**). The main arch ring was constructed with round log and the deck slab utilized boards. The bridge is still in good condition as footway. There are 17 covering houses over the bridge with 72 pillars and a single-eaves roof.

(a) Natural abutment

(b) Stone abutment

Fig. 3-22 Luanfeng Bridge

It is well-known that stone arch bridge has a long history and has achieved high prestige in China, such as the Chaw-Zhou Bridge completed in 605, which has a span length of 37.4 m, the longest span in ancient China. It is also the first open spandrel arch bridge with segmental arch shape in the world. However, it is very surprising that the Ruanfeng Timber Bridge with longest single span of 37.6 m exceeds the span of the Chaw-Zhou Bridge.

The fact that the Ruanfeng Bridge with a span some longer than that of the Chaw-Zhou Bridge indicated that timber arch bridge can be used to cross a wide river and the construction technology of the timber arch bridge has achieved a high prestige in China. It not only shows the excellent bridge construction technology and the originality craft of the timber arch bridge in ancient China, but also explains that the timber arch bridge can be widely used in the southeast of Zhejiang Province and northeast of Fujian Province, which is rich in stones. The construction technology of the stone arch bridge is quite mature at that time.

3.5.2 Bridge length and bridge width

The length of the timber arch bridges specific distribution as shown in **Fig. 3-23** and **Table 3-7**. According to the investigation and statistical analysis, we found that the bridge length distribution of Min-zhe Timber Arch Bridge is from 11.6 m-115 m. For the multi-span bridge, the length distribution is from 53 m to 115 m and most of them have a length over 60 m. For the single span bridge, the distribution is from 11.6 m to 62 m and only one has a span over 60 m. The concentrated area of the length distribution of all the bridge is 20 m-40 m, accounting for 66.9% of the whole.

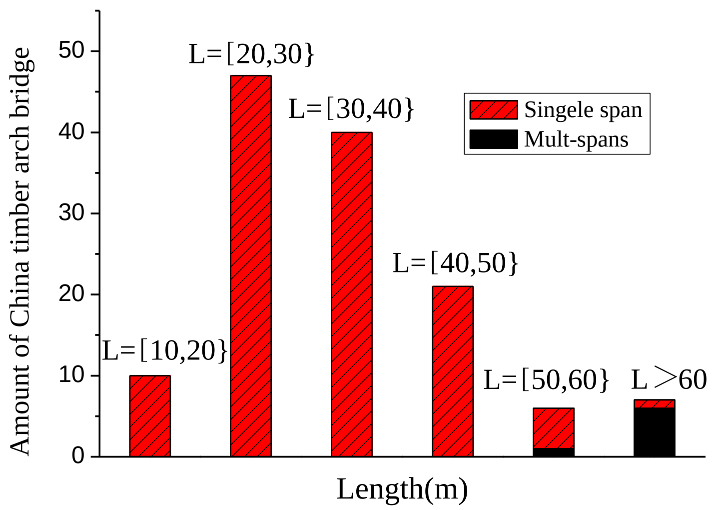


Fig. 3-23 Length of Min-zhe Timber Arch Bridge

Almost all the timber arch bridges in China are served as footbridge. The bridges are not very wide and there are no unified specifications. The width of main distribution is in 4 m-6 m; concentrated width distribution is 4 m-5 m, accounting for 64.6%. The width distributions are listed in **Table 3-8**.

Table 3-7 Length distribution of the timber arch bridges

length（m）		10≤L<20	20≤L<30	30≤L<40	40≤L<50	50≤L<60	L>60
Amount	Total	10	47	40	21	5	7
	Single-span	10	47	40	21	4	1
	Multi-span	0	0	0	0	1	6
Percent		7.7%	36.1%	30.8%	16.2	3.8%	5.4%

Table 3-8 Width distribution of the timber arch bridges

Width (m)	3≤w<4	4≤w<5	5≤w<6	6≤w<7
Quantity	5	84	40	1
Percent	3.8%	64.6%	30.8%	0.8%

3.5.3 Rise-to-span ratio

The rise-span ratio is an important parameter for timber arch bridges, it is not only used to characterize the degree of the flat or steep of the arch, but also a key parameter of the figuration of the bridge in aesthetics. It is mainly used to characterize the degree of the flat or steep of the arch. In general, when the rise-to-span ratio is less than 1/5, the arch is called a flat arch; while when it is larger or equal to 1/5, the arch is called a steep arch. For the stress performance, the rise-span ratio not only affects the internal force of the main arch ring, but also affects to choose the structure form and construction method, so as the arch bridge if suitable for the around landscape. Choosing the rise-span ratio must consider many factors, including the horizontal thrust and bending moment of the substructure and foundation, internal force and stability of the main arch. The timber arch bridge is deck type arch bridge; the rise span ratio will affect the general arrangement of arch bridge, design of spandrel structure.

According to the investigated data China timber arch bridges, the rise-to-span ratios are from 1/3 to 1/7, mostly in 1/5 - 1/7, as given in **Fig. 3-24**. Only one exception is found to be 1/10. **Fig. 3-25** shows that there is no obvious relationship between the rise-to-span ratio and the arch span in China timber arch bridges.

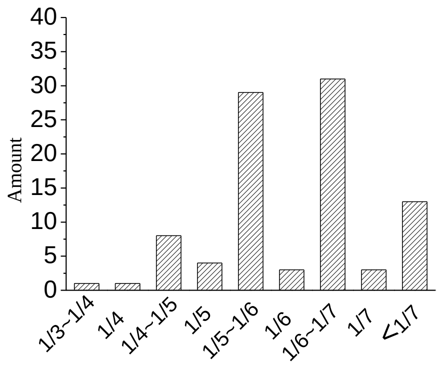


Fig. 3-24 Rise-to-span ratio of Min-zhe Timber Arch Bridge

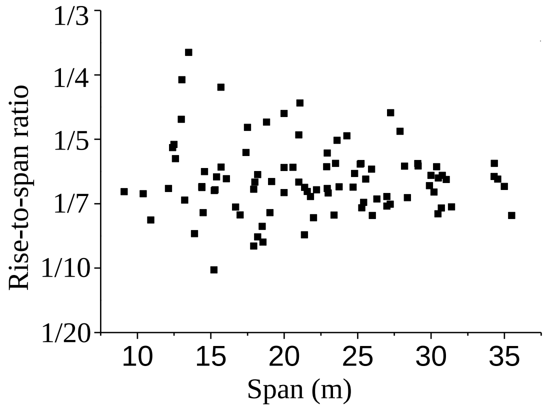


Fig. 3-25 Relationship between rise-to-span ratio and main span

3.5.4 Diameter of arch ring member

Since the logs of the arch rings are the main resistant members of the bridge, their diameters were measured as an important structural parameter in the field survey.

According to the field survey, the diameters of arch ribs of two systems are between 18 cm and 40 cm, and the diameter of the members in the first system is always larger than that of the second system. From the preliminary statistical results in **Fig. 3-26**, there is a tendency that the longer the span of the bridge, the larger the diameter of the logs. However, the relationship between the diameter and span is not so clear and definite.

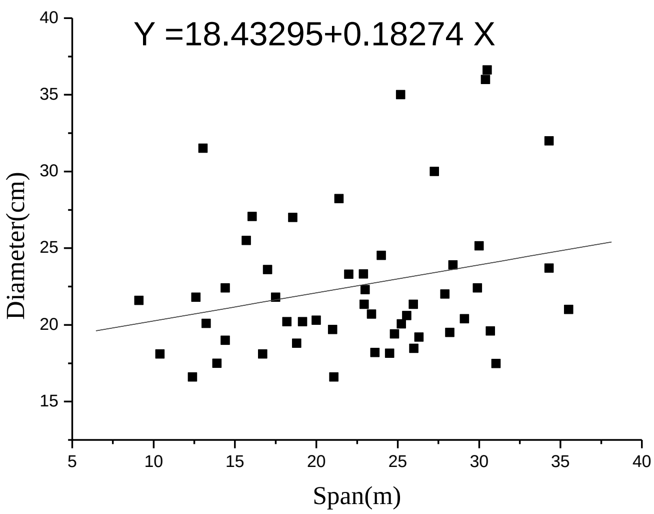


Fig. 3-26 Relationship between diameter of arch ring members and span

3.6 Summary

The results of a comprehensive field survey of Timber Arch Bridges with respect to field, construction time, current station, and main structural parameter including length, width, span, rise-to-span ratio have been reported in this chapter. The results have been briefly addressed.

Chinese timber arch bridge has a long and consistent construction history. All the extant Chinese timber arch bridges are located in the in mountainous areas in northeast Fujian Province and southeast Zhejiang Province. The field survey results can be summarized as follows.

1) There are 130 timber arch bridges in use today, and most of them were built in the Qing Dynasty (accounting for 53.9%).

2) The extant Min-zhe Timber Arch Bridges are managed by the department of cultural relic and local government. 22 timber arch bridges have been listed in the world cultural heritage tentative list in China in 2012. 17 Min-zhe Timber Arch Bridges have been listed in the national preservation list of cultural relics

3) Among 130 timber arch bridges, 123 of them are single-span bridges, only 7 of them are multi-span bridges. The length of the multi-span is between 53 m to 115 m, six of them have a length over 60 m; while for the single-span bridges, only one single span bridge over 60 m. Among them, 108 bridges have a span between 20 m and 50 m, accounting for 83.1% of the total.

4) The spans are mainly in 10 m-30 m, and the concentrated area of span distribution is 20 m-30 m, accounting for 42.3%. The longest span is 37.6 m. The width of bridges is in 4 m-6 m, mostly in 4 m-5 m. The rise-span ratios are from 1/3 to 1/7, usually in 1/5-1/7, and similar to the other arch bridges in China.

5) The diameters of arch ribs of two systems are between 18 cm and 40 cm, and the first system is always bigger than the second system. There is a tendency that the diameter of the logs becomes bigger with the increase of span length. However, the relationship between the diameter and span is not so clear and definite.

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CHAPTER 4

EXPERIMENT STUDY ON WOVEN ARCH

4.1 Introduction

The main arch ring of Chinese timber arch bridge consisting of longitudinal and transverse systems, the longitudinal system is composed of two systems consisting of straight logs in the different plane. Its structure is neither the general two-dimensional plane structure and nor three-dimensional space structure. Until now, the core value and the mechanical behavior of woven arch is not clear. The field testing of bridge is the best way to research on the mechanical behavior. But for Min-zhe Timber Arch Bridge, some factors make the field testing and finite element analysis difficult. They include followings:

1) All the existing Chinese timber arch bridges are designed and built by bridge craftsmen with the traditional construction technology, and the members of bridges are usually with different sizes and asymmetric structures.

2) Wood is well known to be an anisotropic material that has different properties in different directions [1], thus making it difficult to obtain consistent experimental results with the scale model.

3) Arch ribs and transverse beams are connected by mortise and tenon joints, and the joint rigidity can vary significantly with load [2]-[7], and thus is difficult to simulate in the finite element model. Due to our knowledge, few experiments have been conducted to study the mechanical behaviors of Min-Zhe woven timber arch bridges.

In this chapter, a real Min-zhe Timber Arch Bridge take as a case, the scale model tests had been carried out in the laboratory. Wood is replaced by acrylate resin, which has more stable and uniform physical and mechanical properties [8] for the model. The mortise and tenon joints are reduced to hinge joints and rigid joints, respectively. The research work focuses primarily on the mechanical behaviors of the two systems of Min-Zhe woven timber arch bridges. Static loading tests of two bare-arch scale models and two full-bridge scale models were carried out to reveal their basic mechanical behavior.

4.2 Engineering Background

Xi'nan Bridge as shown in **Fig. 4-1**, is located in Xi'nan village, Nanyang town, Shouning County, Fujian province. It is a single span Min-zhe Timber Arch Bridge with a covering house, which has 9 rooms, 40 columns, a single eaves and double pitched roofs. The superstructure of Xi'nan bridge, including main arch ring, spandrel structure and the covering house are made of Chinese firs woods. The two abutments of the bridge are built with block stones. It was re-constructed with traditional construction technology by some experienced craftworkers in 1966. Under the careful protection by local government and local people, the bridge is in a good condition. No obvious damage, corrosion and weathering were found in the whole structure and components [9].

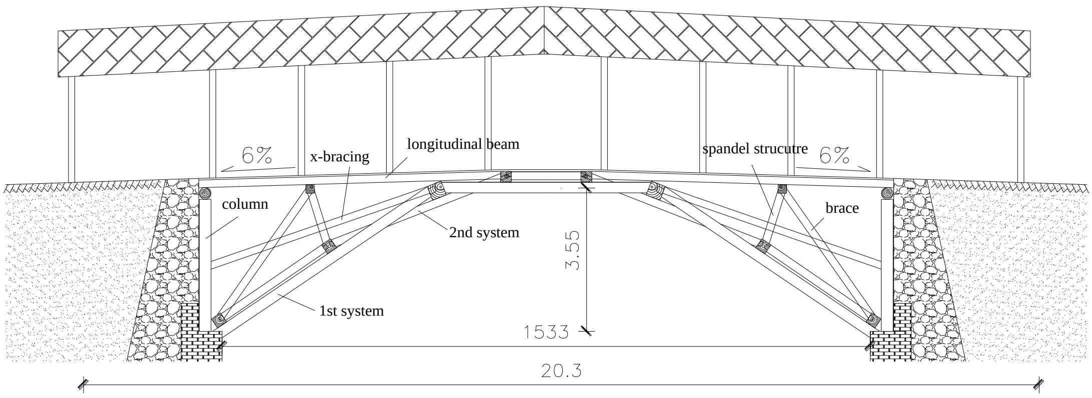
(a) Side view

(b) Elevation view

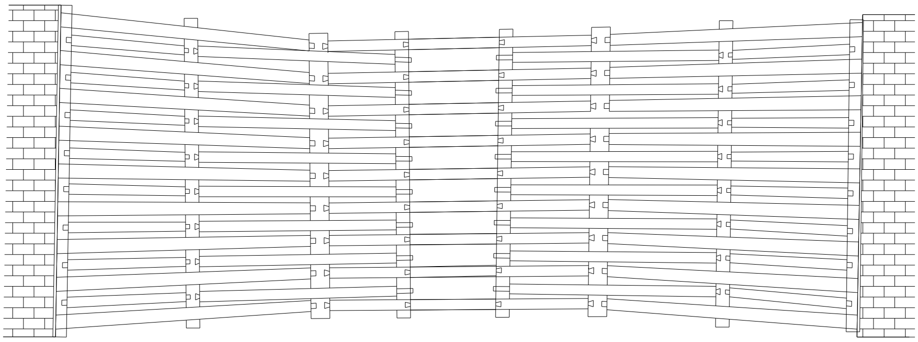
(c) Arch springing

Fig. 4-1 Photos of Xi'nan Bridge

The general layout of the bridge is shown in **Fig. 4-2**. The field measurement result shows that it has a length of 20.3 m, a width of 5 m and a clear span of 15.33 m. The clear rise of the arch is 3.4 m with a span-rise ratio of 1 to 4.5[9].



(a) Elevation drawing

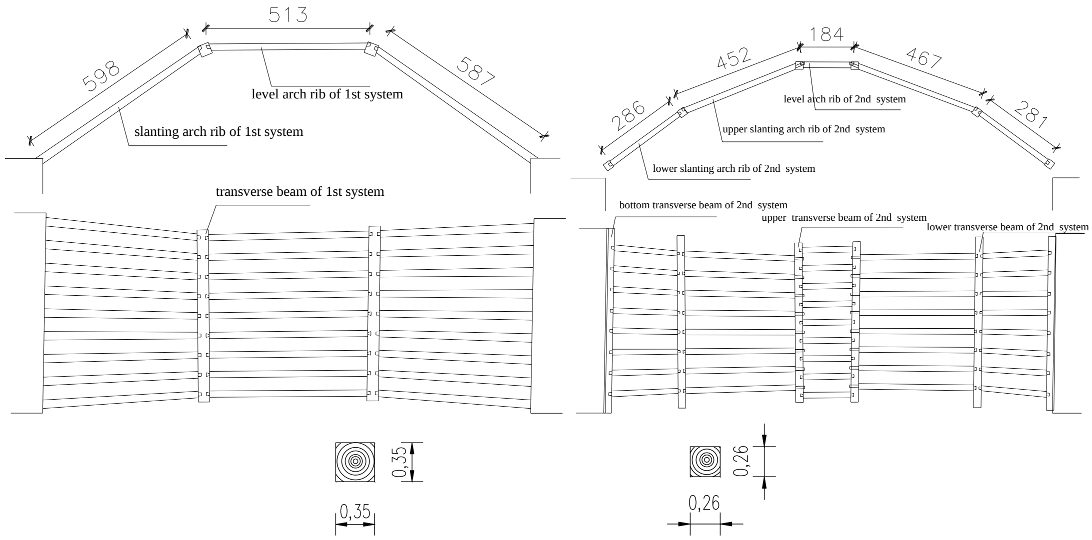


(b) Plane of main arch ring

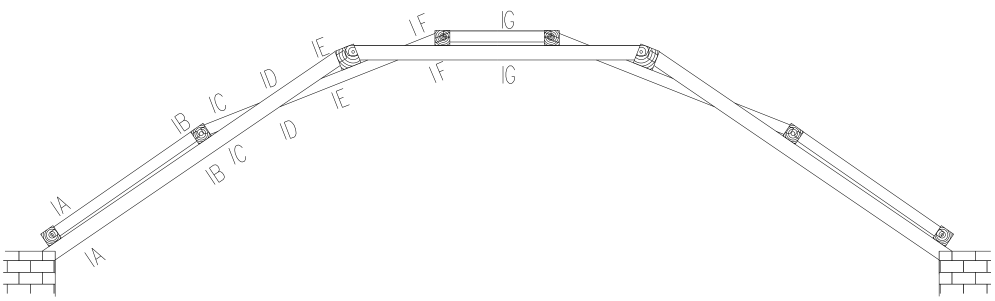
Fig. 4-2 General layout of Xi'nan Bridge (Unit: m)

Its main arch ring consisting of longitudinal and transverse systems constituting a polygonal arch ring on a plane; the longitudinal system is formed by two sub-systems. The first one is formed by parallel three-segment polygonal arch ribs connected by two transverse beams at two joints，the structure members size is shown in **Fig. 4-3 (a)**. The second one is generally formed by parallel five-segment polygonal arch ribs connected by six transverse beams at four joints as shown in **Fig. 4-3 (b)**. The first sub-system has nine longitudinal arch ribs in the cross-section and one more than the second system. However, in the top part, both sub-systems have the same number of longitudinal arches. The two sub-systems are tied and interwoven by transverse members to form a raft-like structure, as shown in **Fig. 4-3(c-g)**. The longitudinal members were compressive dominant. The transversal beams act as connecters to link the two longitudinal structures together so that the forces on one longitudinal system is transferred to the second through the transversal system, and vice versa. The transverse beams also help to distribute the forces between adjacent parallel longitudinal arches. The length of each member of the arch ribs are shown in **Fig. 4-3**

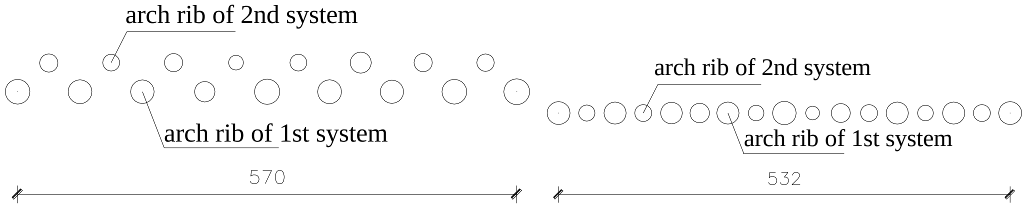
(a) and **(b)**. The diameter of arch ribs in different cross-section as shown in **Table 4-1**, it can be found that the first system is always greater than the second system. The first systems are between 25 cm and 30 cm, and the second systems are between 20 cm and 25 cm. The transverse beam of the two systems are rectangular section., as shown in **Fig. 4-3**.



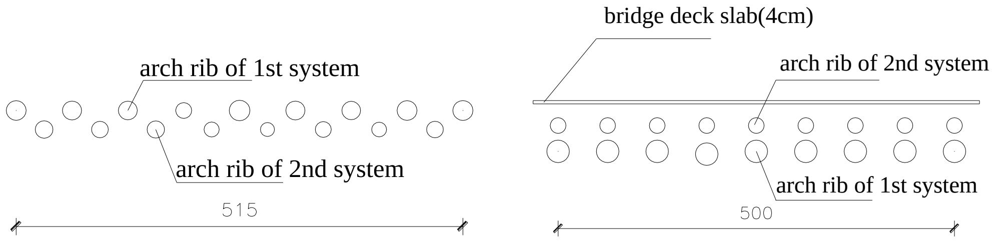
(a) The first system (Unit:cm) (b) The second system (Unit: cm)



(c) Elevation drawing of main arch ring



(d) A-A section (e) D-D section



(f) E-E section (g) G-G section

Fig. 4-3 Main arch ring of Xi’nan Bridge (Unit: cm）

Table 4-1 Diameter of arch ribs (Unit: cm)

Section	System	Arch Ribs Number									Average
		1	2	3	4	5	6	7	8	9	
A-A	1st system	28.02	27.06	26.74	23.24	28.64	27.06	26.42	28.02	28.28	27.05
	2nd system	20.69	19.10	20.69	16.87	19.10	23.87	20.69	19.74		20.09
B-B	2nd system	18.14	17.51	19.74	17.19	14.32	18.14	16.87	19.74		17.71
C-C	2nd system	21.65	20.37	20.69	18.14	20.37	19.42	19.10	21.01		20.09
E-E	1st system	22.88	22.04	21.78	18.42	23.88	22.05	21.46	22.98	23.19	22.08
F-F	2nd system	19.10	18.14	19.42	16.87	12.10	17.51	15.28	17.51		16.99

The Xi'nan Bridge is built without nails and ropes, and all the components are joined with various mortise and tenon joint. Two kinds of mortise and tenons joint are utilized as connect the main arch ring, the one is straight tenon, the other is swallow tail tenon. The longitudinal members of two systems connected transverse beams with these joints, as shown in **Fig. 4-4**.

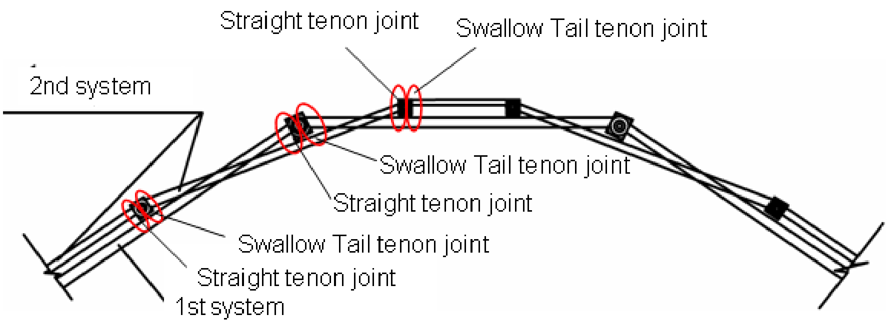


Fig. 4-4 Mortise and tenon joint of main arch ring

The Xi’an Bridge only has one group of X-bracings for the first system, see **Fig. 4-5**. One side of the X-bracings is inserted into transverse beams with the Swallow Tail tenon, and the other side is inserted into vertical columns in an abutment with a straight tenon. The spandrel structure consists of a pair of inclined members standing on the springing and three inclined members standing on quarter transverse beam in the second system, as shown in **Fig. 4-5**. The deck system has nine longitudinal beams in the cross-section, the deck pavement is used by plank as shown in **Fig. 4-6**, and the thickness is about 2 cm.


Fig. 4-5 X-bracing and spandrel structure

Fig. 4-6 Deck pavement of Xi'nan Bridge

4.3 Design Scale Model of Xi’nan Bridge

4.3.1 Material test

4.3.1.1 China fir

All the China timer arch bridge are built with the China fir, in order to get the material characteristics of China fir, the author measured the elasticity modulus of arch rib of Xi'nan bridge with the ultrasonic method and the static bending method.

Using ultrasonic measuring elastic modulus does not need to be made into standard specimen. The result of measurement accuracy is good and the damage of material is small. And it can be repeated measurement on the component directly. It is suitable for the real bridge [10]. The test method as shown in **Fig. 4-7.**

(a) Test process (b) Ultrasonic equipment

Fig. 4-7 Ultrasonic method measuring elastic modulus

According to the Eq. (4-1),

$$E = \rho c^2 \quad (4\text{-}1)$$ [10]

The elastic modulus of arch ribs of Xi'nan bridge is shown in **Table 4-2.**

Table 4-2 Elastic modulus (Ultrasonic method)

Item	Propagation speed (km/s)	Elastic modulus (MPa)
The slant rib of 1st system	4.98	9131
The lower slant rib of 2nd system	5.19	9899
Stand column	4.95	9018
Average value		9349

Because the material is limited, only thirty-three standard specimens had been measured with the static method. The size of standard specimen is 300 mm×20 mm×20 mm [11]-[14]. The testing process is shown in **Fig 4-8**. According to the Eq. (4-2), the calculate value of elastic modulus is shown in **Table 4-3**.

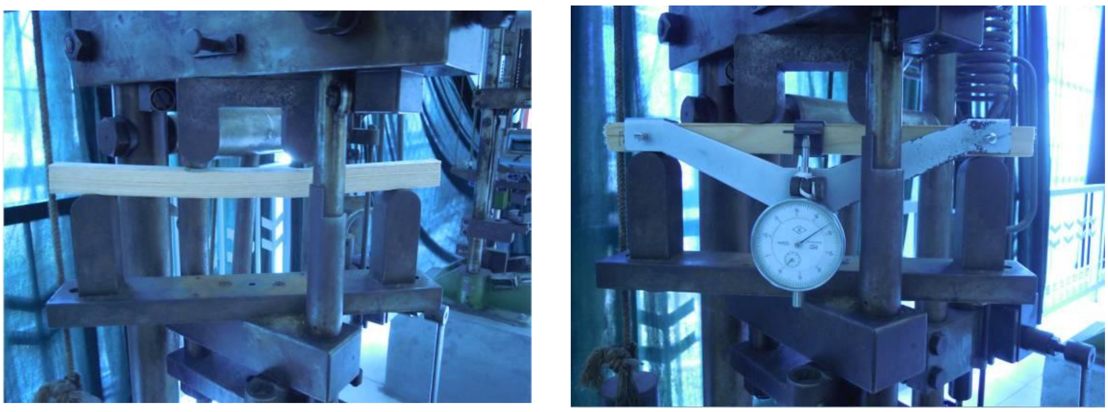


Fig. 4-8 Static bending method measuring elastic modulus

$$E = \frac{23Pl^3}{108bh^3 f} \tag{4-2}$$

Table 4-3 Elastic modulus (Static bending method)

Serial number	Width b (mm)	Height *h* (mm)	Span *l* (mm)	Load *P* (N)	Difference value of Deformation *f* (0.01mm)	Elastic modulus (MPa)
1	20.03	20.02	240	400	79.90	9170
2	19.78	19.95	240	400	81.00	9257
3	20.01	20.01	240	400	81.00	9068
4	19.76	19.96	240	400	79.90	9380
5	20.15	19.99	240	400	72.40	10105
6	20.18	20.21	240	400	70.00	10099
7	20.26	20.50	240	400	74.80	9020
8	20.73	20.19	240	400	71.08	9711
9	20.17	20.00	240	400	75.40	9679
10	20.45	20.44	240	400	78.45	8595
11	20.64	20.49	240	400	70.00	9475
12	20.53	20.11	240	400	76.50	9220
13	20.84	20.37	240	400	61.90	10800
14	20.05	19.80	240	400	71.20	10627
15	20.11	20.05	240	400	89.90	8081
16	20.84	20.37	240	400	52.45	12746
17	20.08	20.10	240	400	69.30	10421
18	20.19	19.76	240	400	66.00	11454
19	20.52	20.22	240	400	74.80	9281
20	19.78	19.92	240	400	77.95	9662
21	20.13	20.22	240	400	69.60	10167
22	20.43	20.45	240	400	87.10	7738
23	20.75	20.18	240	400	71.15	9706
24	20.51	20.12	240	400	71.20	9901
25	20.82	22.38	240	400	60.20	8382
26	20.05	19.92	240	400	72.30	10277
27	20.09	20.04	240	400	90.50	8048
28	20.04	20.07	240	400	51.70	14059
29	20.52	20.25	240	400	76.20	9070
30	20.20	19.76	240	400	67.05	11269
31	20.12	20.11	240	400	71.15	10115
32	19.78	19.92	240	400	78.10	9644
33	20.24	22.07	240	400	60.00	9020

According to the General Rules of Test Method for Physical Mechanics of Wood and the test result shown in **Table 4-3**, the statistical parameter of elastic modulus of Xi'nan Bridge can be obtained. The results are shown in **Table 4-4**. We can find the variable coefficient is 13% and smaller than the average variable coefficient, which is 20%; the accuracy index is 4.5% and smaller than the average accuracy index, which is 5%. Therefore, the test result is available.

Table 4-4 Statistical parameter

Material	Average value $\bar{X}$ (MPa)	Standard deviation *S* (MPa)	Standard error *Sr* (MPa)	Variable coefficient *V* (%)	Accuracy index *P* (%)
China fir	9795	1276	222	13.0	4.5

The value of elastic modulus of arch rib of Xi'nan Bridge is shown in **Table 4-5** with different measured method. It can be found the value is greater with the static bending method than ultrasonic method, and the difference is 4.6% and small than 5%. At the same time, the measured value of elastic modulus is greater than 9000 MPa, which is provide in design code of timber structure. It also shows the Xi'nan Bridge is in good condition.

Table 4-5 Comparison of elastic modulus

Test method	Elastic modulus (MPa)	Ratio (%)
Ultrasonic method	9349	4.6
Static bending method	9795	

4.3.1.2 Acrylate resin

In order to get the real material characteristics of polymethyl methacrylate, the material test had been carried out with compression test method. The test bars are the same batch acrylate bars with scale model. There are six standard samples, the specimen size is 200 mm × 40 mm × 40 mm, shown in **Fig. 4-9**. The size sectional dimension and mass parameter of each specimen are shown in **Table 4-6**.

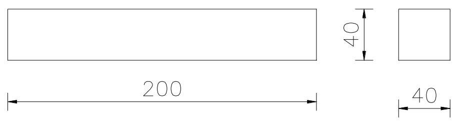


Fig. 4-9 Size of standard specimen (Unit: mm)

Table 4-6 Sectional dimension and mass parameter

Number / Parameters	1#	2#	3#	4#	5#	6#
b (mm)	40.06	40.25	40.21	40.12	40.02	39.88
h (mm)	39.56	39.64	39.73	39.98	39.87	40.22
L (mm)	200.12	200.02	199.85	200	199.89	199.98
m (kg)	0.446	0.469	0.464	0.461	0.462	0.465
ρ (kg/m^3)	1406	1470	1453	1437	1449	1450

The test instrument is microprocessor control electro-hydraulic servo tester with 100T. The axial compressive strength of three specimens had been measured. The whole test process with the constant speed upload until the specimen is broken, and the failure load had been recorded. The test results are shown in **Table 4-7**.

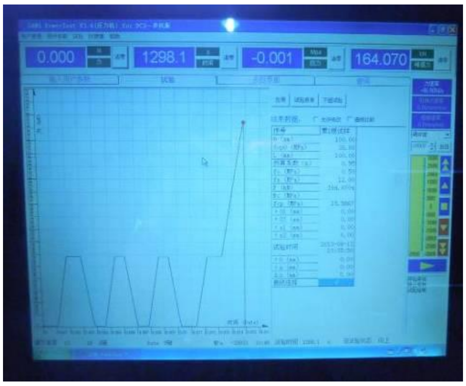
Table 4-7 Axial compressive strength of polymethyl methacrylate

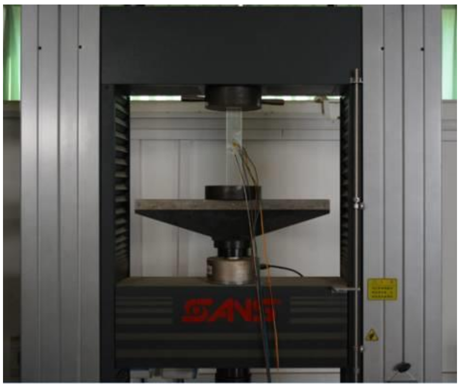
Serial Number	Width *b* (mm)	Height *h* (mm)	Axial compressive strength f_p (MPa)	Ultimate pressure F_p (kN)
1#	40.06	39.56	113.84	180.41
2#	40.25	39.64	107.01	170.73
3#	40.21	39.73	114.08	182.25
Average	40.17	39.64	111.64	177.79

Compressive modulus of elasticity of other three specimens had been measured. There are two pieces of strain gages along the midcourt line of two sides of specimens. The load with a speed of 0.5 MPa/s continuous evenly loading, the loading value of upper limit (F_0) is 0.5 MPa, which is the initial load; the loading value of lower limit is a third axis compressive strength load (Fa). The test processes are shown in **Fig. 4-10**.

(a) Loading device

(b) Pick device





(c) Set the load control mode

(d) Loading procedure

Fig. 4-10 Loadding device and procedure

The elastic modulus of acrylate is recalculated as follows,

$$E = \frac{F_a - F_0}{A\left(\varepsilon_a - \varepsilon_0\right)} \tag{4-3}$$

The calculate result is shown in **Table 4-8**.

Table 4-8 Elastic modulus of polymethyl methacrylate

Serial Number	A (mm^2)	Fa-F_0 (kN)	Longitudinal strain		Transverse strain		Elastic modulus E (MPa)	Poisson's ratio
			$\varepsilon_0(\mu\varepsilon)$	$\varepsilon_a(\mu\varepsilon)$	$\varepsilon_0(\mu\varepsilon)$	$\varepsilon_a(\mu\varepsilon)$		
4#	1603.998	57.2	-356.5	-11304.5	87.0	4513.5	3257	0.404
5#	1595.597	57.2	-248	-11613	64.0	4648.5	3154	0.403
6#	1603.974	57.2	-268	-11694.5	103.5	4719.0	3121	0.404
Average	1601.19	57.2	-290.8	-11537.3	84.8	4627.0	3178	0.404

From the test of materials used for the scale model arch, the following values were identified. The density ρ is 1444 kg/m^3; the axial compressive strength *f*p is 111.6 MPa; the elastic modulus *E* is 3178 MPa; Poisson's ratio is 0.404.

4.3.2 Calculate the ratio of similitude [15]

In order to ensure the scale model will not too small, the section of arch rib of the first system had been as a control parameter of the scale model. The diameter of arch rib of the first system is 4cm. According to the diameter of the arch rib, which is shown in **Table 4-1**, the average diameter of arch rib of Xi'nan Bridge can been calculate, the results as following:

The diameter of arch rib of the first system:

D= (27.05+22.08)/2=24.56 (cm)

The diameter of arch rib of the second system:

D= [(20.09+17.71)/2+(20.09+16.99)/2]/2=18.72 (cm)

So, the ratio of similitude of scale: $C_l = l_p / l_m = 24.56/4 = 6.14$

According to the similarity theory and the test result shown in **Table 4-9**, the similarity coefficient of Xi'nan Bridge and the scale model of acrylate resin is shown in **Table 4-10**.

Table 4-9 Material characteristics of China fir and acrylate resin

Item	China Fir	Acrylate resin
Elastic modulus (MPa)	9795	3178
Density (kg/m^3)	368	1444
Poisson’s ratio	0.25	0.404

Table 4-10 Similarity coefficient

Item	Affinity constant
Elastic modulus	$C_E = E_p / E_m = 9795 / 3178 = 3.08$
Area	$C_A = C_l^2 = 37.70$
Moment of inertia	$C_I = C_l^4 = 1421.26$
Linear displacement	$C_\delta = C_l = 6.14$
Angular displacement	$C_\varphi = 1$
Stress	$C_\sigma = C_E = 3.08$
Strain	$C_\varepsilon = 1$
Poisson's ratio	$C_\mu = \mu_p / \mu_m = 0.25 / 0.404 = 0.619$
Concentrated force	$C_F = C_E C_l^2 = 3.08 \times 6.14^2 = 116.11$
Linear load	$C_q = C_E C_l = 3.08 \times 6.14 = 18.91$
Bending moment	$C_M = C_F C_l = C_E C_l^3 = 712.94$
Shearing force	$C_Q = C_F = C_E C_l^2 = 116.11$
Axial force	$C_Q = C_F = C_E C_l^2 = 116.11$

4.4 Scale Model Test

4.4.1 Description of models

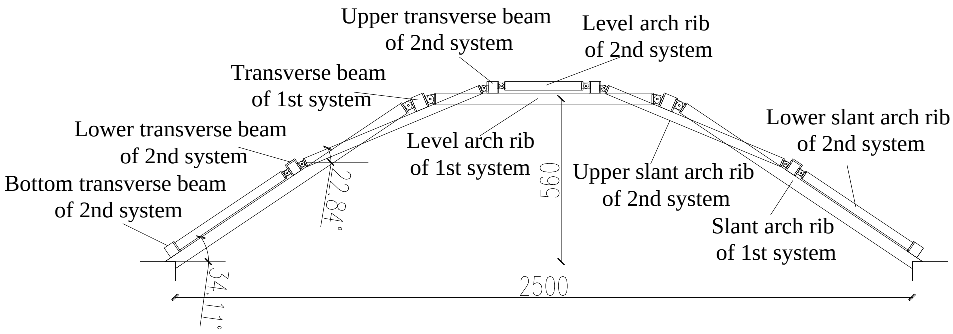
Four scale models are taken from the Xi'nan Bridge designed by author. The details of structural systems are presented in Section 4.2 of this chapter. They are including two bare arch models (the mortise and tenon joints are reduced to hinge joints and rigid joints, respectively) and two full-bridge models (the mortise and tenon joints are reduced to hinge joints and rigid joints, respectively).

According to the ratio of similitude, the physical dimension of scale model is shown in **Table 4-11.**

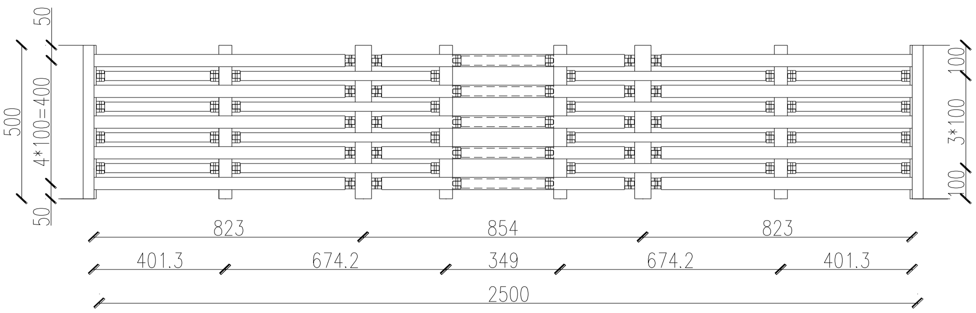
Table 4-11 Physical dimension of scale model

Item	Section of Xi'nan Bridge (cm)	Section of model (cm)	Length of Xi'nan Bridge (cm)	Length of model (cm)
Span			1533	250
Transverse beam of 1st (b×h)	35	5	534	90
Upper transverse beam of 2nd (b×h)	26	4	534	90
Lower transverse beam of 2nd (b×h)	26	4	575	90
Bottom transverse beam of 2nd (b×h)	26	4	605	90
Transverse beam of spandrel structure (D)	20	3	570	90
Transverse beam of stand column of arch springing (b×h)	25.8	4	595	90
Slant arch rib of 1st (D)	24.56	4	597.7	95.5
Level rib of 1st (D)	24.56	4	476.6	77
Lower slant rib of 2nd (D)	18.8	3	288.5	45.4
Upper slant rib of 2nd (D)	18.8	3	418.6	69.9
Level rib of 2nd (D)	18.8	3	164	28.7
Stand column of arch springing (D)	19.5	3	314	50.5
Longitudinal beam of deck (D)	19.3	3	699.5	112.4
Spandrel column (D)	18	3	120	18.5
Diagonal bracing of spandrel structure (D)	17.9	3	352.3	52.6
X-bearing (D)	18	3	658.2	112.7

Two scale models of bare arch were constructed, as schematically shown in **Fig. 4-11** and **Fig. 4-12**. The clear span is 250 cm, the clear rise was 55.7 cm, and the width was 50 cm. The first system consisted of 5 arch ribs of 4 cm in diameter spaced 10 cm apart in the transverse direction, while the second system consisted of 4 arch ribs of 3 cm in diameter spaced 10 cm apart in the transverse direction. The two systems were interlaced and formed a stable structure. The transverse beams had a rectangular cross section of 5 cm × 5 cm for the first system, and of 4 cm × 4 cm for the second system, respectively. The inclination angle of the oblique ribs of the first system and the lower oblique ribs of the second system was 34.1º, and that of the upper oblique ribs of the second system was 22.8º, respectively.

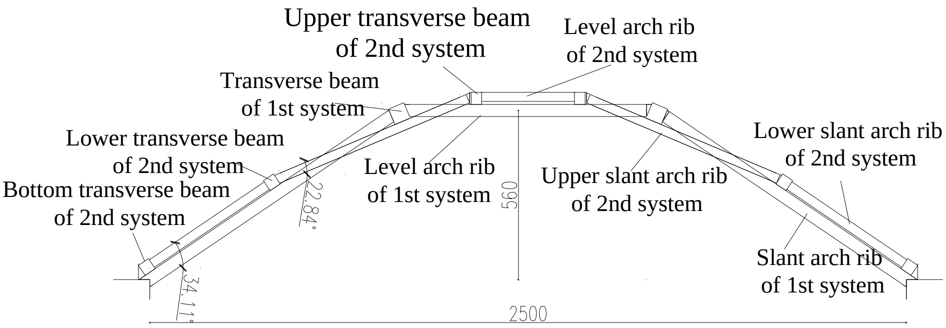


(a) Elevation of hinged model

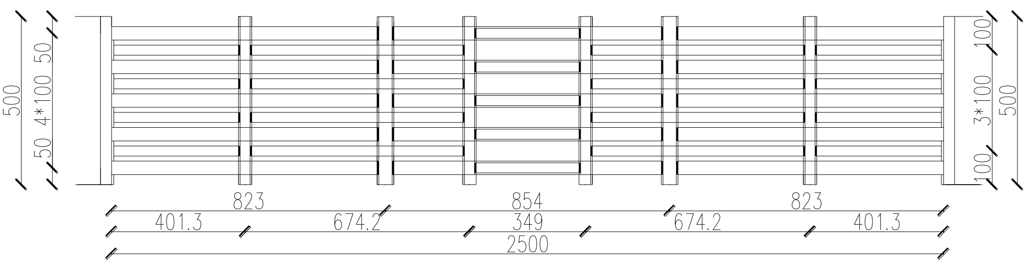


(b) Plan of hinged model

Fig. 4-11 Model of bare arch with the hinged joint (Unit: mm)



(a) Elevation of rigid model



(b) Plan of rigid model

Fig. 4-12 Model of bare arch with the rigid joint (Unit: mm)

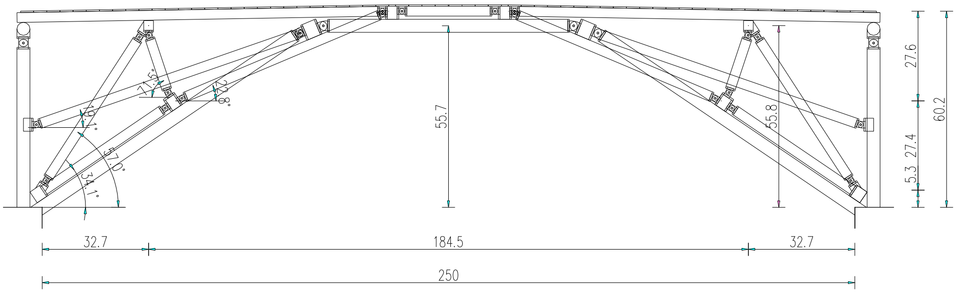


Fig. 4-13 Model of full-bridge with the hinged joint (Unit: mm)

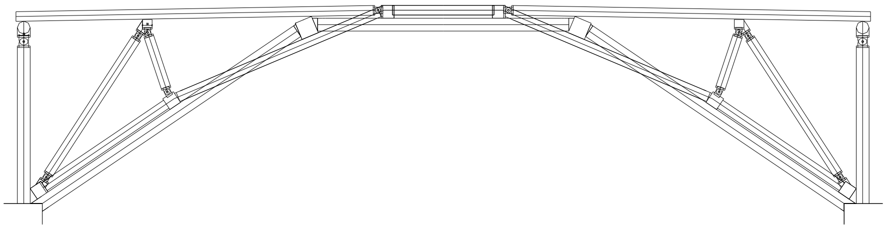
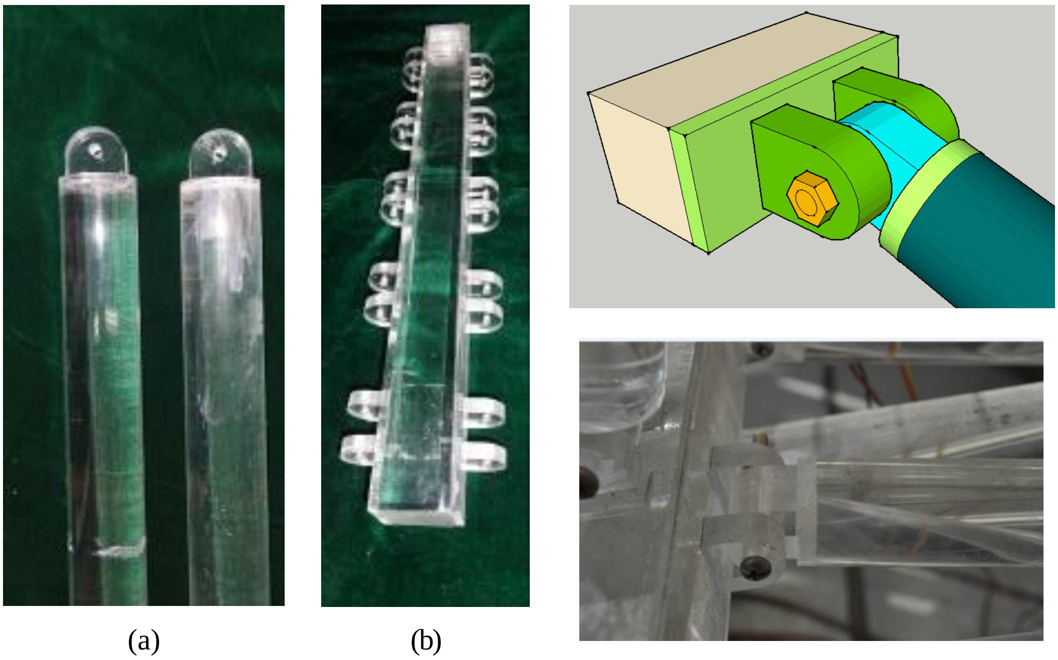


Fig. 4-14 Model of full-bridge with the rigid joint (Unit: mm)

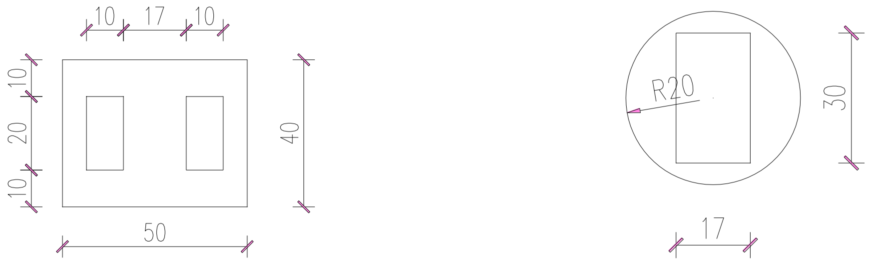
Two scale models of full-bridge were constructed, as schematically shown in **Fig. 4-13** and **Fig. 4-14**. The structure parameter is similar to the models of bare arch, except for add the spandrel structure.

For the hinged model, the longitudinal element (**Fig. 4-15(a)**) and transverse beams (**Fig. 4-15(b))** were joined by pins of 6 mm in diameter, as shown in **Fig. 4-15(c).** Their pin plates are inserted into the holes of a 5-mm-thick acrylate resin shims **(Fig. 4-16)** which are fixed by glue to members. The details of the hinged joints of the model is shown in **Fig. 4-15(d)**.



(a) (b) (c) (d)

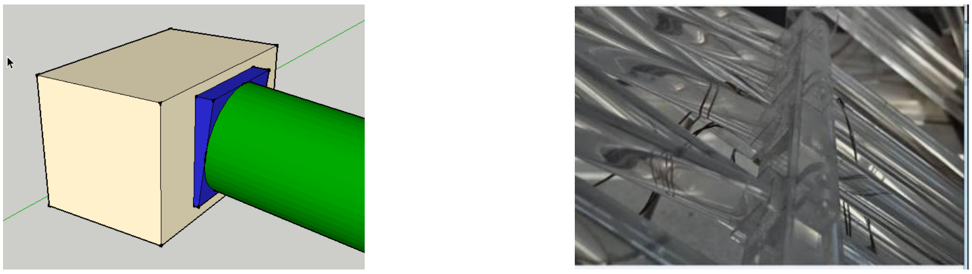
Fig. 4-15 Hinged joint of the model



(a) Transverse beam shim (b) Arch rib shim

Fig. 4-16 Shim of the hinge joint (Unit: mm)

For the rigid model, the longitudinal members and transverse beams were connected by a sphenoid (the blue color one in **Fig. 4-17 (a)**), and the details of the joints are shown in **Fig. 4-17(b).**



(a) schematic diagram (b) Actual struc actual structure ture

Fig. 4-17 Rigid joint of the model

Erect the model according the following steps:

1) The first system: the lever arch rib of the first system connect with the transverse beam of the first system, the slant arch rib of the first system connect with the transverse beam of the first system (the first system has been erected).

2) The second system: the lever arch rib of the second system connect with the upper transverse beam of the second system, the slant arch rib of the second system connect with the upper and lower the transverse beam of the second system, and the lower slant arch rib of the second system connect with the lower and bottom transverse beam (the second system have been erected).

3) Erect stand column of abutment.

4) Erect the spandrel structure, x-bracing and deck system.

All the models are shown in **Fig. 4-18**.

(a) Bare arch models (b) Full-bridge models

Fig. 4-18 Photograph of scale models

4.4.2 Description of the experiment

4.4.2.1 Bare arches

Only concentrated loads acting at the joints were employed in the tests. Eight load cases including four asymmetrical cases and four symmetrical cases shown in **Fig. 4-19** and **Table 4-12** were used. The load was acted to the model by placing weight to the transverse beams uniformly as shown in **Fig. 4-20.** The test is for the mechanical behaviors of the woven arch under service load but not for the load-carrying capacity. Each concentrated load acting on the model arch is 295.5 N, which is the loading level similar to the design live load.

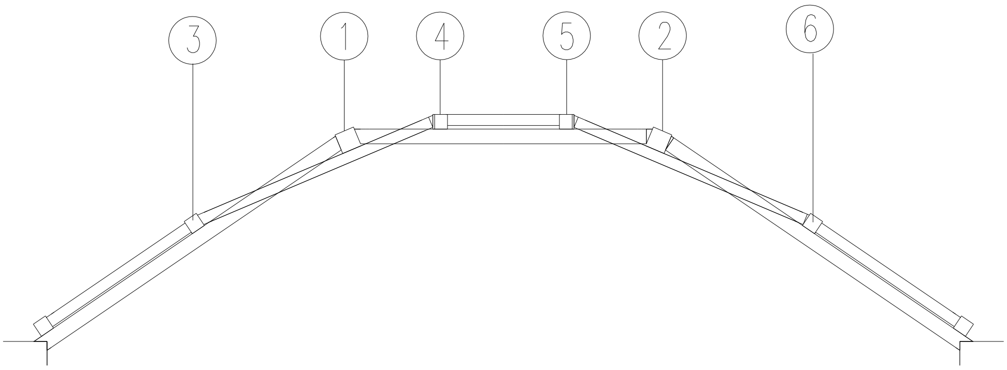
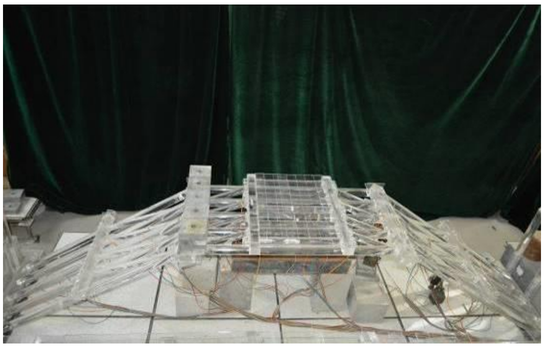


Fig. 4-19 Transverse beam number

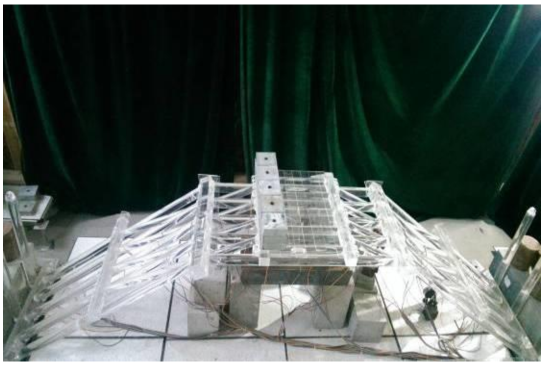
Table 4-12 Location and value of the load

Asymmetrical	Load position (Number of transverse beam)	Load value (N)	Symmetrical	Load position (Number of transverse beam)	Load value (N)
Case 1	3	295.5	Case 5	3,6	295.5*2
Case 2	1	295.5	Case 6	1,2	295.5*2
Case 3	4	295.5	Case 7	4,5	295.5*2
Case 4	1,3,4	295.5*3	Case 8	1,2,3,4,5,6	295.5*6

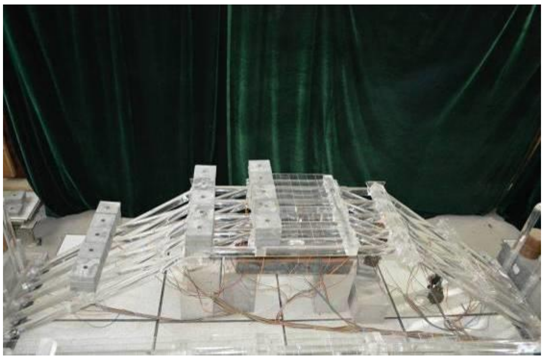
(a) Case 1



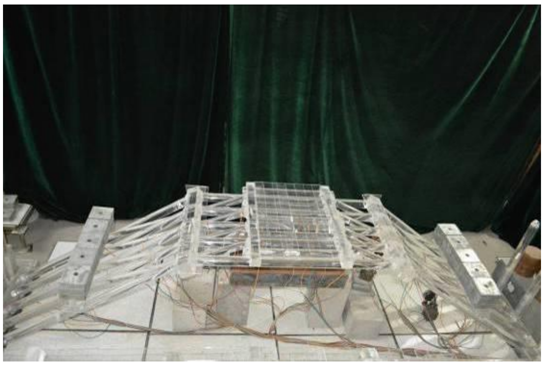
(b) Case 2



(c) Case 3



(d) Case 4



(e) Case 5

(f) Case 6

Fig. 4-20 Photograph of test (Bare arch)

(g) Case 7 (h) Case 8

Fig. 4-21 Photograph of test (Bare arch) (contd.)

The other key issue of the woven arch is the connection of the two longitudinal systems. These two systems are not in the same plane and are not connected by structural measure, but they will work together through the touch of the transverse beams of one system to the longitudinal members of the other system. In the bridge, timber blocks are inserted into the gap of the connection places of the two systems, such as A1 and B1 in **Fig. 4-21.** When B1 has a downward displacement, the force in the second system will transfer to the first system through A1. However, if B1 has an upward displacement, the two systems will separate, and no force will transfer from the second system to the first one.

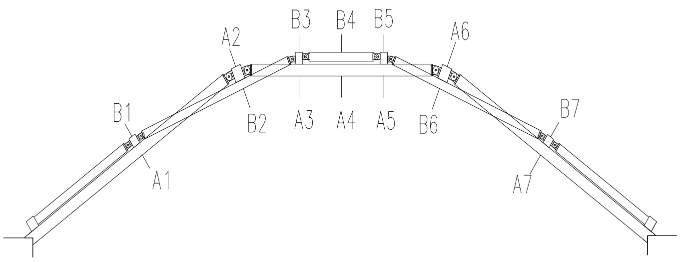


Fig. 4-22 Arrangement of measurements

The vertical displacements of each transverse beam and the corresponding position of the longitudinal members of the other system were measured. Total of 14 dial gages were used in a model, A1-A7 for the first system and B1-B7 for the second system. For example, in the first system, A2 and A6 were installed at its transverse beams (joints), while A1, A3, A5 and A7 were installed at the corresponding position of the transverse beams of the second system, as shown in **Fig. 4-21.** From the difference of the displacements of the two systems, such as A1 and B1, A3 and B3, the coordination of the two systems can be investigated.

Before the formal test, preliminary test with three load cases was carried out to check the setup and instrumentation. In the formal tests, the concentrated loads were applied in three steps with the value of 9.85, 19.70, and 29.55kg, respectively. Testing loads were applied twice in each load case, and measurements were taken after the test loads were applied for thirty minutes to obtain steady data. One more measurement was taken after the loads were removed from the model. **Fig. 4-20** are photos of the model under load case 1 to load case 8.

4.4.2.2 Full-bridge

The same to the bare arch experiment, only concentrated loads acting at the joints were employed in the tests. Eight load cases including four asymmetrical cases and four symmetrical cases shown in **Fig. 4-22** and **Table 4-13** were used. The load was acted to the model by placing weight to the transverse beams uniformly as shown in **Fig. 4-23**. The test is for the mechanical behaviors of the woven arch under service load but not for the load-carrying capacity. Each concentrated load acting on the model arch is 394 N, which is the loading level similar to the design live load.

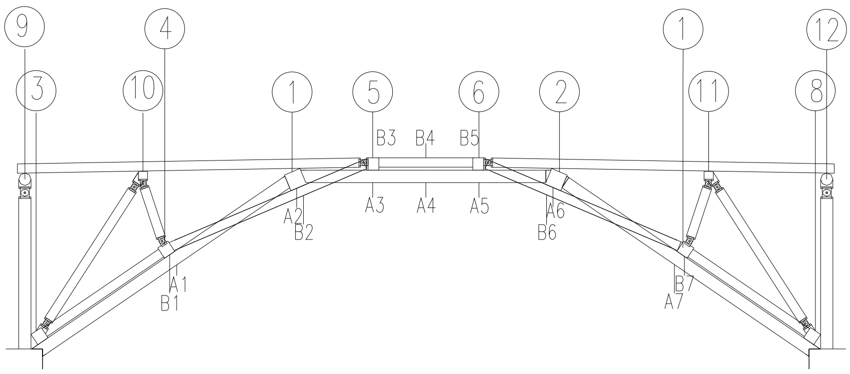


Fig. 4-23 Arrangement of measurement points

Table 4-13 Loading cases

Asymmetrical	Load position (Number of transverse beam)	Load value(N)	Symmetrical	Load position (Number of transverse beam)	Load value(N)
Case 1	10	394	Case 5	10, 11	394*2
Case 2	1	394	Case 6	1,2	394*2
Case 3	5	394	Case 7	5,6	394*2
Case 4	1,5,10	394*3	Case 8	1,2, 5,6,10,11	394*6

(a) Case 1 (b) Case 2

(c) Case 3 (d) Case 4

(e) Case 5 (f) Case 6

(g) Case 7 (h) Case 8

Fig. 4-24 Photograph of test (Full-bridge)

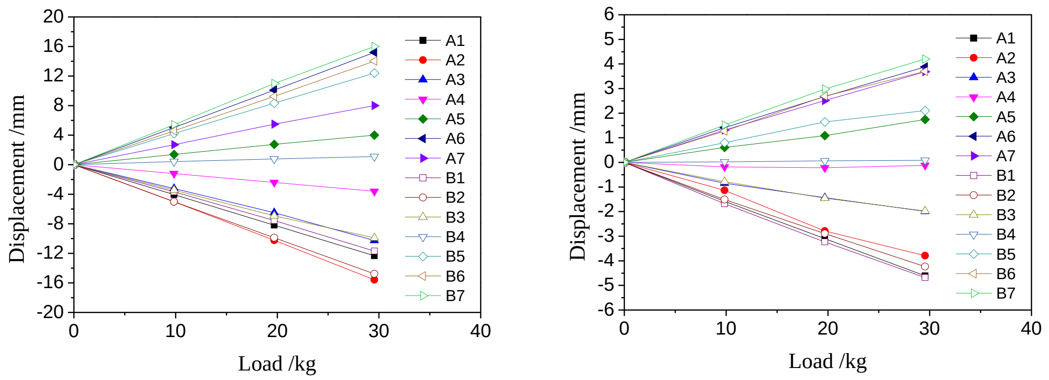
The arrangement of measurements is the same as bare arch shown in **Fig, 4-21**. Total of 14 dial gages, A1-A7 for the first system and B1-B7 for the second system in the test.

Before the formal test, preliminary test with three load cases was carried out to check the setup and instrumentation. In the formal tests, the concentrated loads were applied by four steps with the value of 9.85, 19.70, 29.55 and 39.40 kg, respectively. Testing loads were applied twice in each load case, and measurements were carried out after the test loads had been applied for thirty minutes to obtain steady data. One more measurement was carried out after the loads were removed from the model. Photos of the model under load cases 1 to 8 are shown in **Fig. 4-23**.

4.5 Detailed Test Results

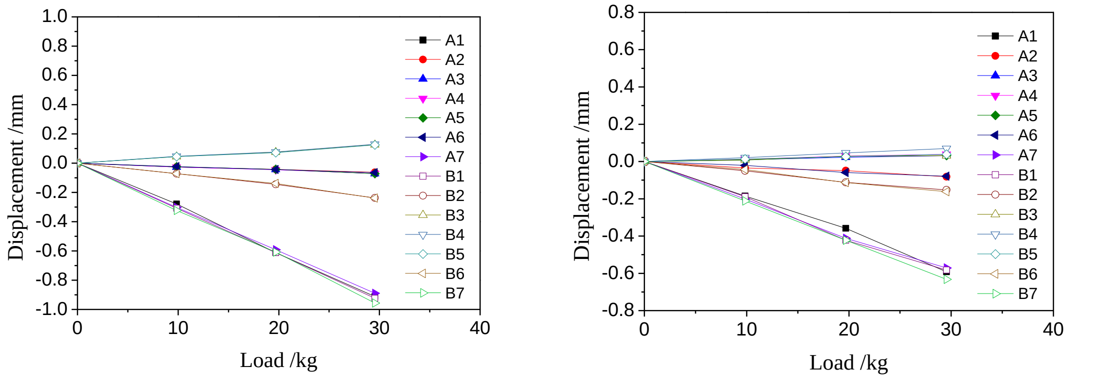
4.5.1 Bare arch

Fig. 4-24 and **Fig. 4-25** show the load-displacement curves at each measurement point under asymmetrical loads (Case 4) and symmetrical loads (Case 8), respectively, where the positive values indicate upward displacement and the negative values indicate downward displacement. They show that the displacement changes linearly with the increase of applied load. In all the other load cases, displacements are smaller than Case 4 and Case 8. The model arches remained in the elastic state throughout the experiments.



(a) Hinged model (b) Rigid model

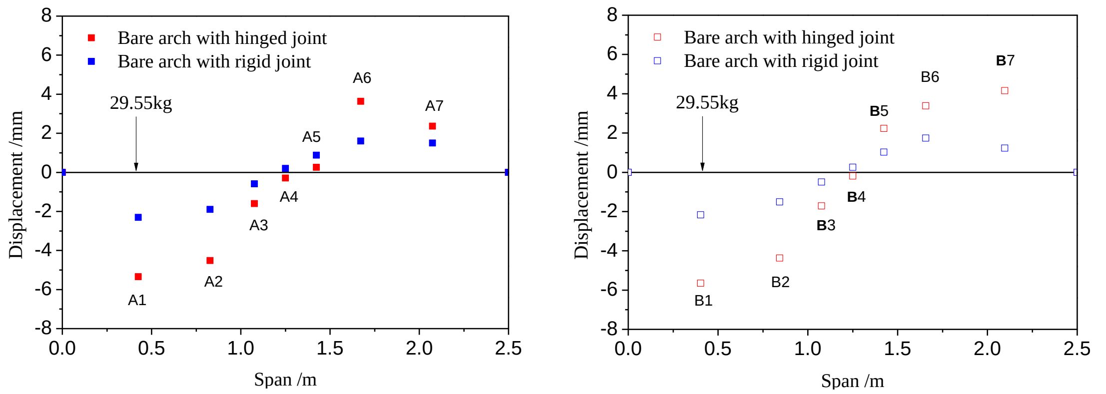
Fig. 4-25 Load-displacement curves under asymmetrical loading



(a) Hinged model (b) Rigid model

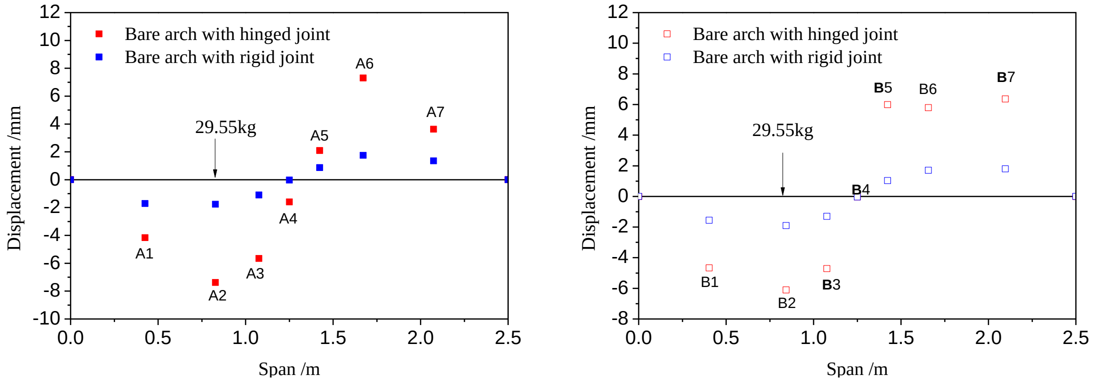
Fig. 4-26 Load-displacement curves under symmetrical loading

Fig. 4-26 to Fig. 4-31 show the displacement of the two systems of two bare arch models under asymmetrical loads (case 1, case 2 and case 3) and symmetrical loads (case 5, case 6 and case 7). The deflection is antisymmetric with respect to the midpoint of the bridge under the asymmetrical loads. In addition, downward displacement was observed at the loading side, while upward displacement and detachment between the two systems were observed at the other side. The deformation was symmetrical with respect to the midpoint of the bridge under symmetrical load. Deformation tendency of two systems of two models are similar, and the branch points of the positive and negative vertical displacement of two systems are basically identical, but the deformation of model with hinged joint is obviously greater than the model with rigid joint, it shows the joint rigidity of mortise and tenon will influence the deformation of two systems.



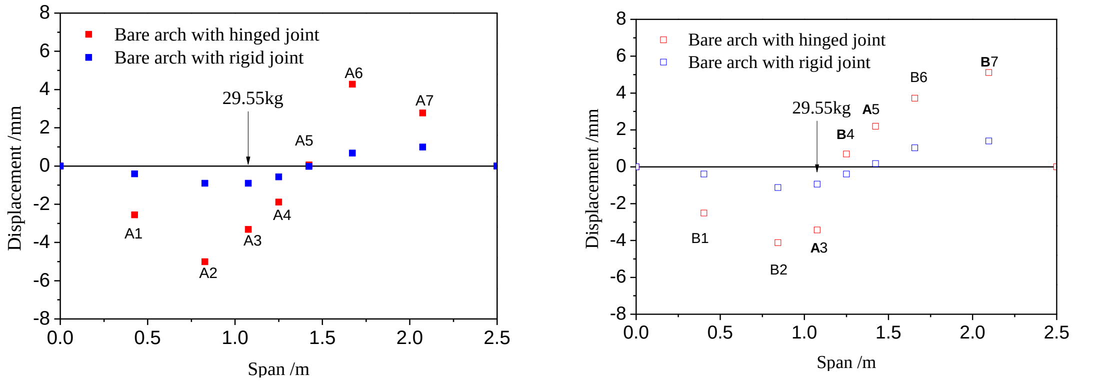
(a) 1st system (b) 2nd system

Fig. 4-27 Displacement under load case 1



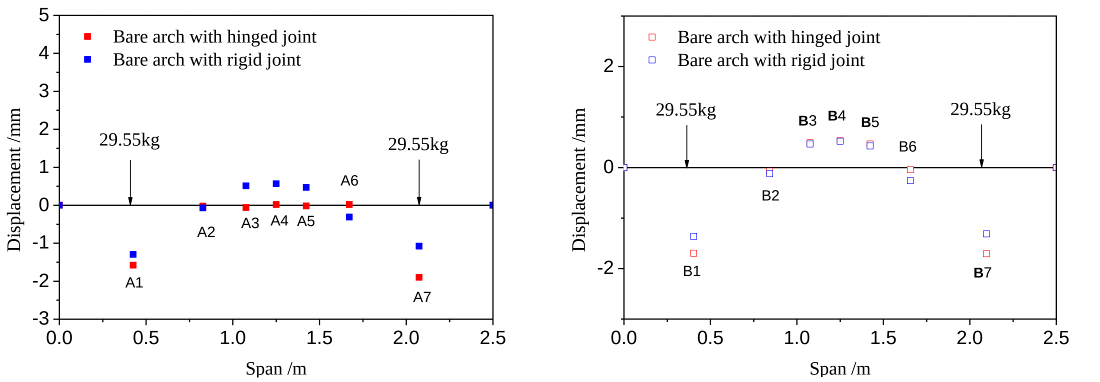
(a) 1st system (b) 2nd system

Fig. 4-28 Displacement under load case 2



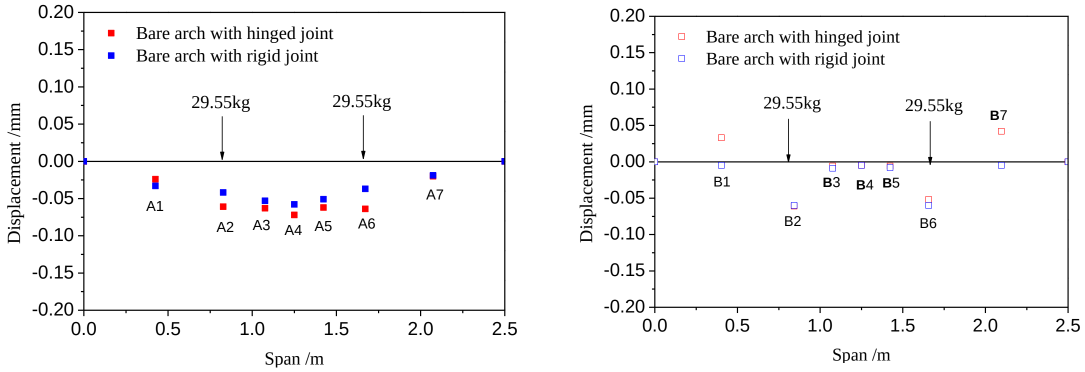
(a) 1st system (b) 2nd system

Fig. 4-29 Displacement under load case 3



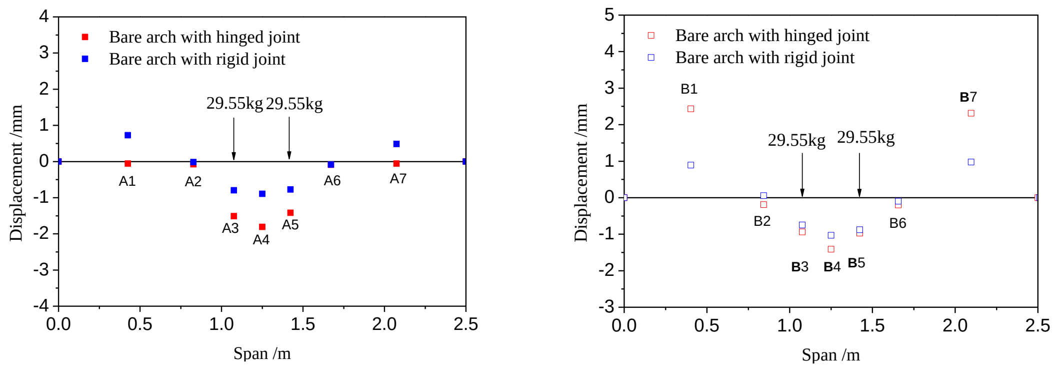
(a) 1st system (b) 2nd system

Fig. 4-30 Displacement under load case 5



(a) 1st system (b) 2nd system

Fig. 4-31 Displacement under load case 6



(a) 1st system (b) 2nd system

Fig. 4-32 Displacement under load case 7

It also can be found from **Fig 4-29**, the level arch rib of the first system has not obvious deformation, but the upper transverse beam of the second system occurs the upward displacement. It indicates that detachment occurred between transverse beams of the second system and level ribs of the first system for hinged joint model bare arch when it is under load case 5.

The same phenomenon can be found from **Fig. 4-30.** The slant arch rib of the first system has the downward vertical displacement, while the lower transverse beam of the second system has the upward vertical displacement. It indicates that detachment occurred between the lower transverse beams of the second system and the slant ribs of the first system for the hinged joint bare arch when it is under load case 6. In addition, for the two models, there is downward displacement at the A3 measuring location of the level arch rib of the first system. However, there is upward displacement at the B3 measuring location of upper transverse beam. It indicates that detachment occurred between the upper transverse beams of the second system and the level arch ribs of the first system.

The same to **Fig. 4-31**, there is downward displacement at the A1measuring point of slant arch rib of the first system, but there is upward displacement at the B1measring point of the lower transverse beam of the second system. It indicates that detachment occurred between the lower transverse beams of the second system and the slant arch ribs of the first system for the hinged joint bare arch when it under load case 7.

Table 4-14 and **Table 4-15** show the measured maximum deflection of the two models under symmetrical and asymmetrical loadings, respectively. It can be found that most of the maximum deflection of the two models occurred at the same position. However, the deflection values of the hinged model are obviously greater than that of the rigid model. The ratio of the maximum downward displacement of the first system is 2.319, 4.167 and 5.520 under case 1, case 2 and case 3, respectively. The ratio of the maximum upward displacement of the first system is 2.269, 4.169 and 4.324 under case 1, case 2 and case 3, respectively. The ratio of the maximum downward displacement of the second system is 2.604, 3.197 and 3.642 under case 1, case 2 and case 3, respectively. The ratio of the maximum upward displacement of the second system is 2.394, 3.533 and 3.651 under case 1, case 2 and case 3, respectively. The ratio of the maximum downward displacement of the first system is 1.219, 1.241 and 1.352 under case 5, case 6 and case 7, respectively. The ratio of the maximum downward displacement of the second system is 1.244, 1.350 and 1.389 under case 5, case 6 and case 7, respectively. The ratio of the maximum upward displacement of the second system is 1.019 and 2.734 under case 5 and case 7, respectively.

Table 4-14 Value and location of the maximum deflection under asymmetrical loading

(a) 1st system

Load Case	Maximum of downward displacement				
	Hinged model		Rigid model		Ratio
	Value	Location	Value	Location	
Case 1	-5.346	A1	-2.305	A1	2.319
Case 2	-7.380	A2	-1.771	A2	4.167
Case 3	-5.007	A2	-0.907	A3	5.520
Load Case	**Maximum of upward displacement**				
	Hinged model		Rigid model		Ratio
	Value	Location	Value	Location	
Case 1	3.637	A7	1.603	A6	2.269
Case 2	7.295	A6	1.750	A6	4.169
Case 3	4.272	A6	0.988	A7	4.324

(b) 2nd system

Load Case	Maximum of downward displacement				
	Hinged model		Rigid model		Ratio
	Value	Location	Value	Location	
Case 1	-5.650	B1	-2.170	B1	2.604
Case 2	-6.107	B2	-1.910	B2	3.197
Case 3	-4.115	B2	-1.130	B2	3.642
Load Case	**Maximum of upward displacement**				
	Hinged model		Rigid model		Ratio
	Value	Location	Value	Location	
Case 1	4.160	B7	1.738	B6	2.394
Case 2	6.353	B7	1.798	B7	3.533
Case 3	5.112	B7	1.400	B7	3.651

Table 4-15 Value and location of the maximum deflection under symmetrical loading

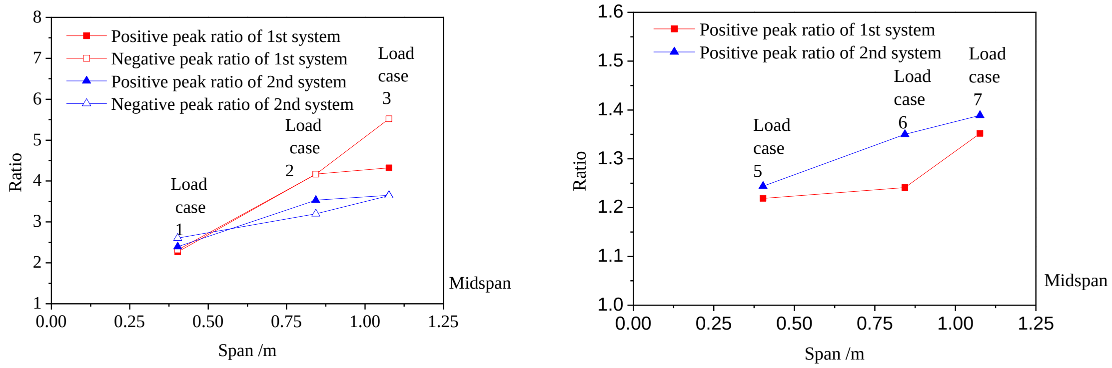
(a) 1st system

Load Case	Hinged model		Rigid model		Ratio
	Value	Location	Value	Location	
Case 5	-1.580	A1	-1.296	A1	1.219
Case 6	-0.072	A4	-0.058	A4	1.241
Case 7	-1.210	A4	-0.895	A4	1.352

(b) 2nd system

Load Case	Maximum of downward displacement				
	Hinged model		Rigid model		Ratio
	Value	Location	Value	Location	
Case 5	-1.700	B1	-1.365	B1	1.244
Case 6	-0.080	B2	-0.060	B2	1.350
Case 7	-1.430	B4	-1.030	B4	1.389
Load Case	Maximum of upward displacement				
	Hinged model		Rigid model		Ratio
	Value	Location	Value	Location	
Case 5	0.530	B4	0.520	B4	1.019
Case 6	0.033	B1			
Case 7	2.433	B1	0.890	B1	2.734

The ratio of the maximum deflections of the hinged model to the rigid model vary from 2.269 to 5.520 under asymmetrical load, from 1.019 to 2.734 under symmetrical load. In other words, the rigidity of mortise and tenon joint has larger influence on the behaviors of the woven arches under asymmetrical loading than those under symmetrical loading. The relationships between the ratio and the location of the maximum deflection are demonstrated in **Fig. 4-32**. It can be found the ratio is increasing when the load from springing moving to crown, so the influence of the rigidity of mortise and tenon joint become more and more obvious from springing to crown. At the same time, under asymmetrical load the rigid of mortise and tenon joint has more influence on restrain the deformation of two systems than under symmetrical load.

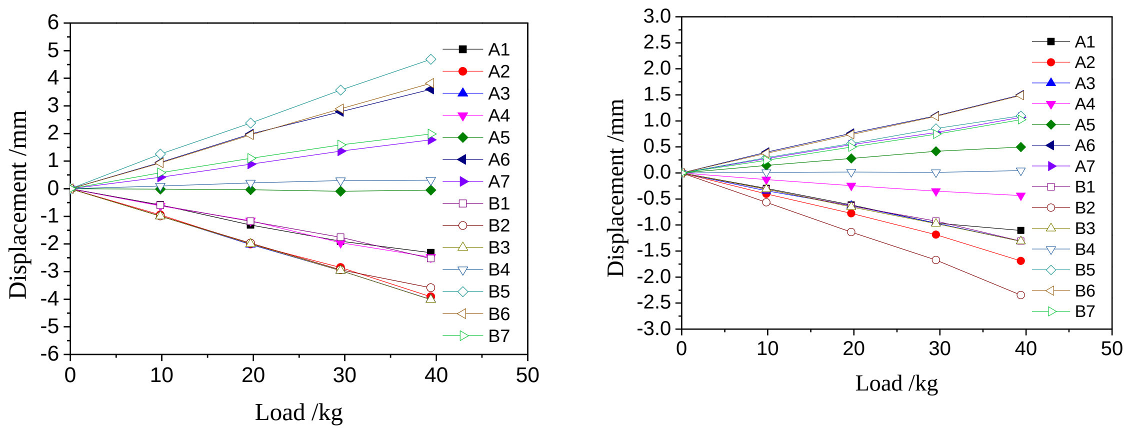


(a) Under asymmetrical load (b) Under symmetrical load

Fig. 4-33 Ratio of maximum deflections of the two models

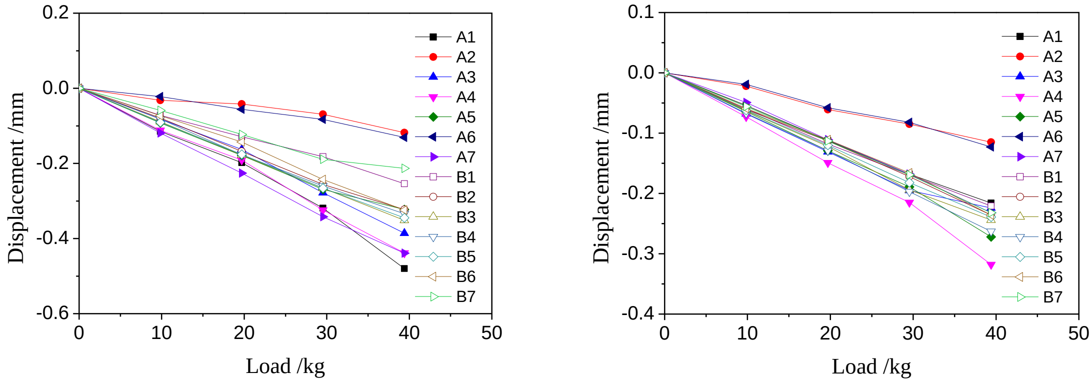
4.5.2 Full-bridge

Fig. 4-33 and **Fig. 4-34** show the load-deformation curves of full-bridge at each measurement point under asymmetrical (case 4 and 8) and symmetrical (case 4 and 8) loading, where the positive values indicated upward displacement, while the negative values indicated downward displacement. The results showed that the displacement changed linearly with the increase of load applied load, because all the load values of other cases are smaller than the case 4 and case 8, the results indicating that the woven structure remained in an elastic stage throughout the experiments.



(a) Hinged joint model (b) Rigid joint model

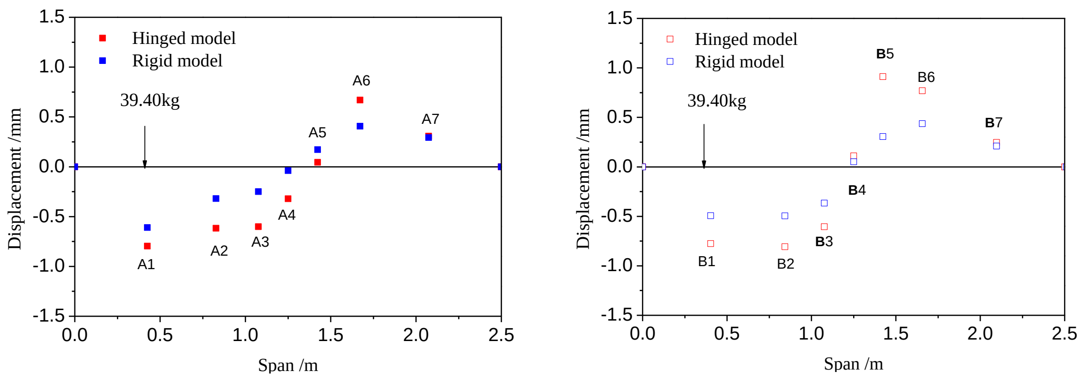
Fig. 4-34 Load-displacement curves of the two arch models under load case 4



(a) Hinged joint model (b) Rigid joint model

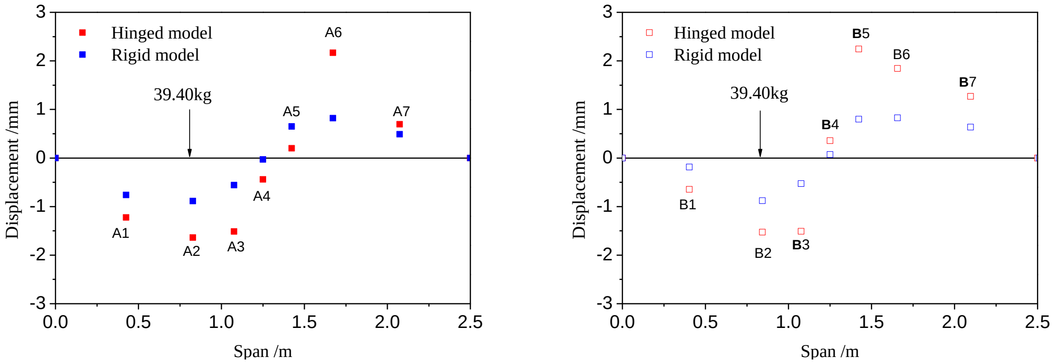
Fig. 4-35 Load-displacement curves of the two arch models under load case 8

Fig. 4-35 to Fig. 4-40 show the displacement of the two systems of two full-bridge models under asymmetrical loading (case 1, case 2 and case 3) and symmetrical loads (case 5, case 6 and case 7). The deflection is antisymmetric with respect to the midpoint of the bridge under the asymmetrical loads. In addition, downward displacement was observed at the loading side, while upward displacement and detachment between the two systems were observed at the other side. The deformation was symmetrical with respect to the midpoint of the bridge under symmetrical load. Deformation tendency of two systems of two models are similar, and the branch points of the positive and negative vertical displacement of two systems are basically identical, but the deformation of model with hinged joint is obviously greater than the model with rigid joint, it shows the joint rigidity of mortise and tenon will influence the deformation of two systems. At the same time, all the results are similar to those of bare arch models. It shows the spandrel structure cannot change the tendency of deformation of woven arch.



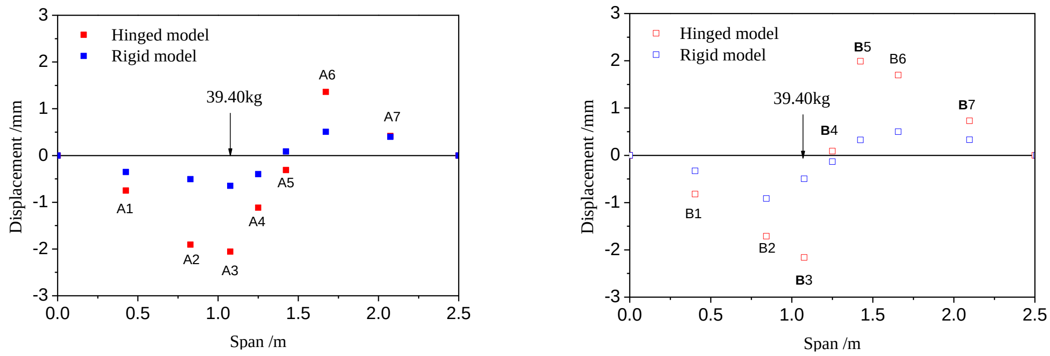
(a) 1st system (b) 2nd system

Fig. 4-36 Displacement under load case 1



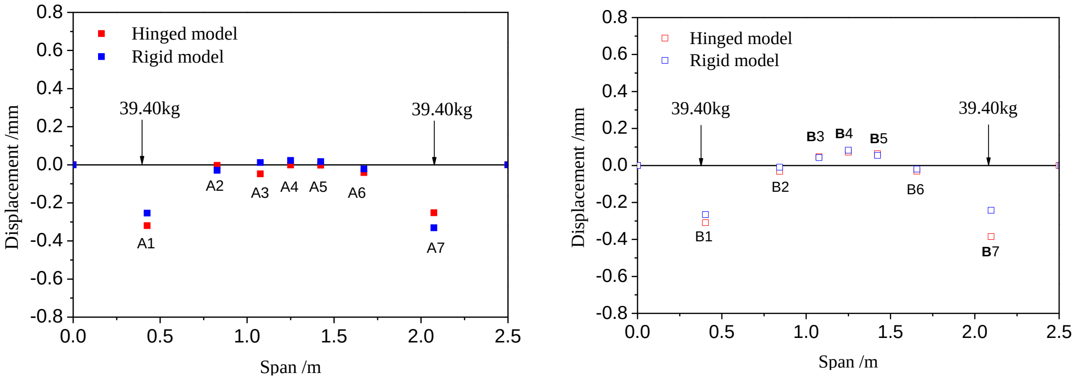
(a) 1st system (b) 2nd system

Fig. 4-37 Displacement under load case 2



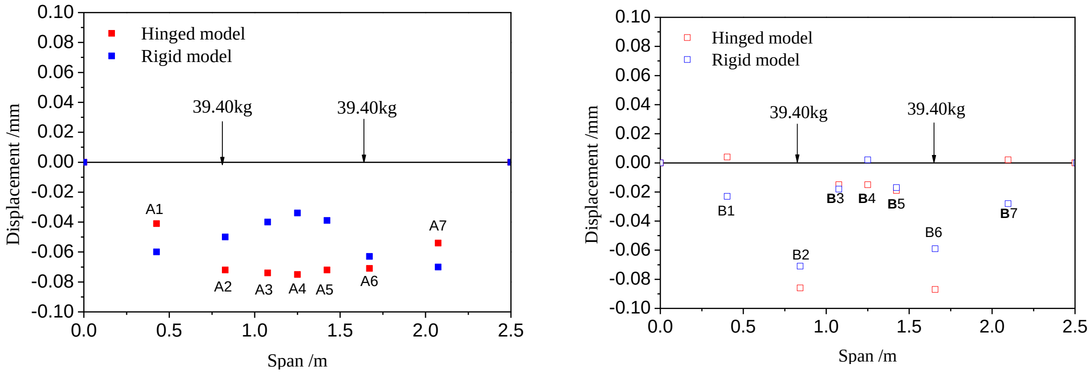
(a) 1st system (b) 2nd system

Fig. 4-38 Displacement under load case 3



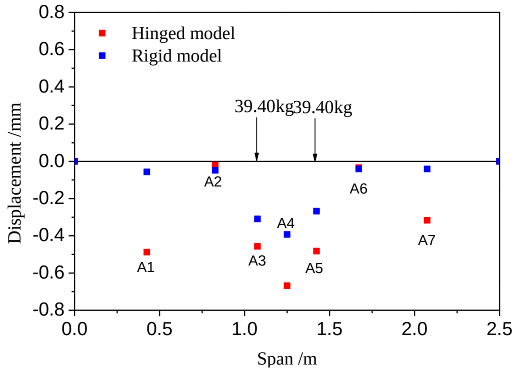
(a) 1st system (b) 2nd system

Fig. 4-39 Displacement under load case 5

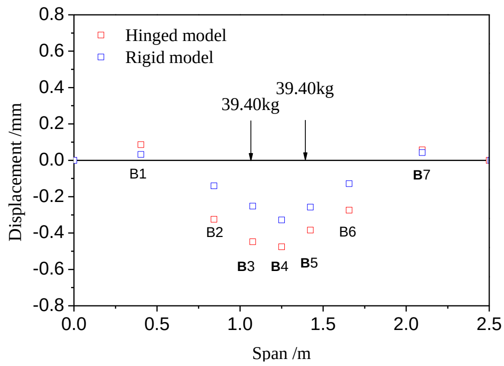


(a) 1st system (b) 2nd system

Fig. 4-40 Displacement under load case 6



(a) 1st system



(b) 2nd system

Fig. 4-41 Displacement under load case 7

It also can be found from **Fig 4-38**, the deformation tendency of the level arch rib of the first system and the upper transverse beam of the second system are obvious opposite, which the level arch rib of the first system occur the downward displacement and the upper transverse beam of the second system occur the upward displacement, it is indicate that detachment occurred between the upper transverse beams of the second system and level ribs of the first system when the full-bridge model with hinged joint under load case 5.

The same phenomenon can be found from **Fig. 3-39.** The measuring point A1 at the slant arch rib of the first system occur the downward displacement, but the measuring point B1 at the lower transverse beam of the second system occur the upward displacement. It indicates that detachment occurred between the lower transverse beams of the second system and slant ribs of the first system when the full-bridge model with hinged joint under load case 6.

The same to **Fig. 4-40,** the measuring point A1 at the slant arch rib of the first system occur the downward displacement, but the measuring point B1at the lower transverse beam of the second system occur the upward displacement. It indicates that detachment occurred between the lower transverse beams of the second system and slant ribs of the first system.

Table 4-16 and **Table 4-17** show the measured maximum deflection of the two models under symmetrical and asymmetrical loadings, respectively. It can be found that most of the maximum deflection of the two models occurred at the same position. However, the deflection values of the hinged model are obviously greater than that of the rigid model. The ratio of the maximum downward displacement of the first system is 1.307, 1.851, 3.171 under case 1, case 2 and case 3, respectively. The ratio of the maximum upward displacement of the first system is 1.646, 2.644 and 2.693 under case 1, case 2 and case 3, respectively. They are smaller than the ratio of bare arch. The results evidence that the spandrel structure will participate in bearing the loading of the structure, and then, it will reduce the influence of deformation of woven arch, which is caused by the rigidity of joint of the first system.

The ratio of the maximum downward displacement of the second system is 1.630, 1.788 and 2.363 under case 1, case 2 and case 3, respectively. The ratio of the maximum upward displacement of the second system is 2.087, 2.712 and 3.990, under case 1, case 2 and case 3, respectively.

Because the models take the negative displacement as the principal displacement under symmetrical load, the analysis of result focus on the negative displacement. The ratio of the maximum downward displacement of the first system is 1.210, 1.250 and 1.700 under case 5, case 6 and case 7, respectively. The ratio of the maximum downward displacement of the second system is 1.169, 1.211 and 1.451 under case 5, case 6 and case 7, respectively.

It can be found the maximum negative value of the second system occur at the same position under case 1 and case 2, there is different in case 3. The maximum downward deformation occurs at the upper transverse beam of the second system (B3) for hinge joint model, but the maximum downward deformation is occurring at the upper slant arch rib (B2) of the second system, which is connected with the transverse beam of the first system for rigid joint model. Because the first system of full-bridge model is unstable with the hinged joint, the measuring point B3of the second system has the same deformation with the measuring point A3 of the first system, for rigid joint full-bridge model, the first system is more stable than the model with hinged joint, the level arch rib of the first system prevent the measuring point B3 occur the downward displacement, so the maximum downward deformation is occur at the upper slant arch rib (B2) of the second system, which is connect with the transverse beam of the first system.

Table 4-16 Value and location of the maximum deflection under asymmetrical loading

(a) 1st system

Load Case	Maximum of downward displacement				
	Hinged model		Rigid model		Ratio
	Value	Location	Value	Location	
Case 1	-0.797	A1	-0.610	A1	1.307
Case 2	-1.638	A2	-0.885	A2	1.851
Case 3	-2.058	A3	-0.649	A3	3.171
Load Case	Maximum of upward displacement				
	Hinged model		Rigid model		Ratio
	Value	Location	Value	Location	
Case 1	0.670	A6	0.407	A6	1.646
Case 2	2.168	A6	0.820	A6	2.644
Case 3	1.360	A6	0.505	A6	2.693

(b) 2nd system

Load Case	Maximum of downward displacement				
	Hinged model		Rigid model		Ratio
	Value	Location	Value	Location	
Case 1	-0.807	B2	-0.495	B2	1.630
Case 2	-1.528	B2	-0.879	B2	1.738
Case 3	-2.162	B3	-0.915	B2	2.363
Load Case	Maximum of upward displacement				
	Hinged model		Rigid model		Ratio
	Value	Location	Value	Location	
Case 1	0.912	B5	0.437	B6	2.087
Case 2	2.243	B5	0.827	B6	2.712
Case 3	1.991	B5	0.499	B6	3.990

Table 4-17 Value and location of the maximum deflection under symmetrical loading

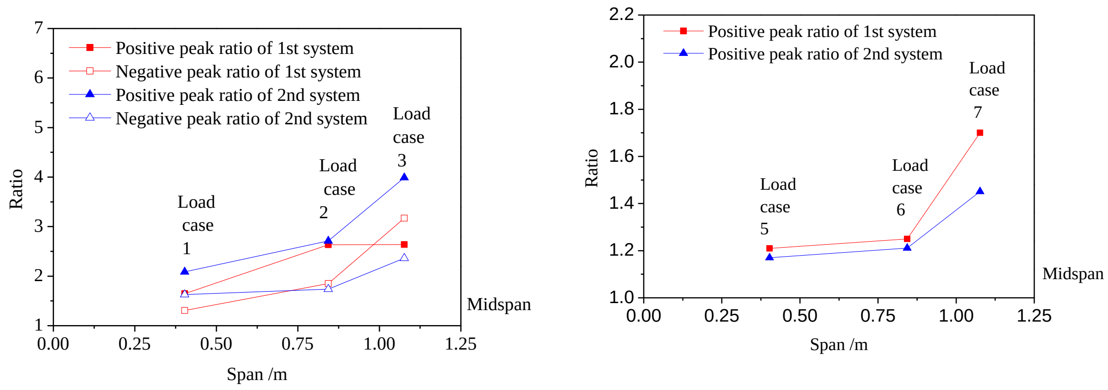
(a) 1st system

Load Case	Hinged model		Rigid model		Ratio
	Value	Location	Value	Location	
Case 5	-0.320	A1	-0.264	A1	1.210
Case 6	-0.075	A4	-0.060	A1	1.250
Case 7	-0.668	A4	-0.393	A4	1.700

(b) 2nd system

Load Case	Maximum of downward displacement				
	Hinged model		Rigid model		Ratio
	Value	Location	Value	Location	
Case 5	-0.310	B1	-0.265	B1	1.169
Case 6	-0.086	B2	-0.071	B2	1.211
Case 7	-0.476	B4	-0.328	B4	1.451

The ratio of the maximum deflections of the hinged model to the rigid model vary from 1.307 to 3.990 under asymmetrical load, from 1.170 to 1.700 under symmetrical load. In other words, the rigidity of mortise and tenon joint has larger influence on the behaviors of the woven arches under asymmetrical loading than those under symmetrical loading. The relationships between the ratio and the location of the maximum deflection are demonstrated in **Fig. 4-41**. It can be found the ratio is increasing when the load from springing moving to crown, so the influence of the rigidity of mortise and tenon joint become more and more obvious from springing to crown. At the same time, under asymmetrical load the rigid of mortise and tenon joint has more influence on restrain the deformation of two systems than under symmetrical load. The results are similar to the bare arches.



(a) Under asymmetrical load (b) Under symmetrical load

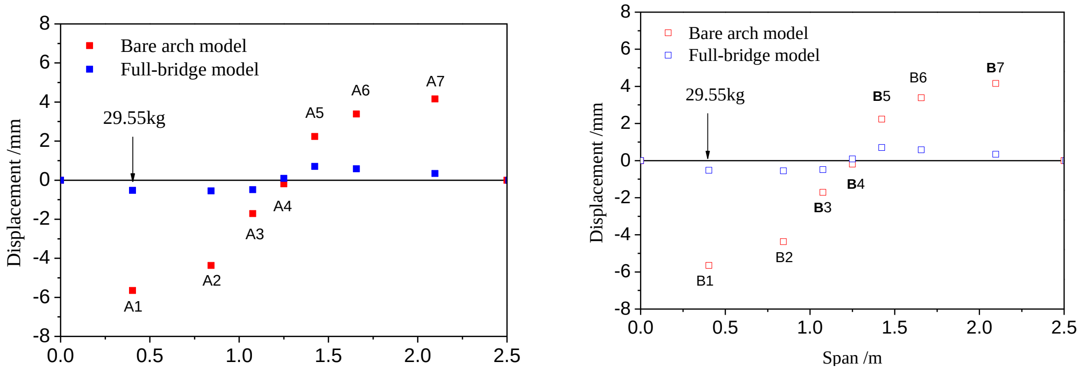
Fig. 4-42 Ratio of maximum deflections of the two models

In conclusion, they have the same tendency of vertical deformation for the two full-bridge models which are with the hinged joint and rigid joint, but the deformation of the model with the hinged joint is greater than the model with the rigid joint, it indicates the rigidity of joint cannot change the deformation tendency of weave arch; Secondly, the difference of maximum deflections is become more and more with the load from arch springing to midspan for weave arch; Thirdly, under asymmetrical load the rigid of mortise and tenon joint has more influence on restrain the deformation of two systems than under symmetrical load.

4.6 Comparison Between Bare-arch and Full-bridge

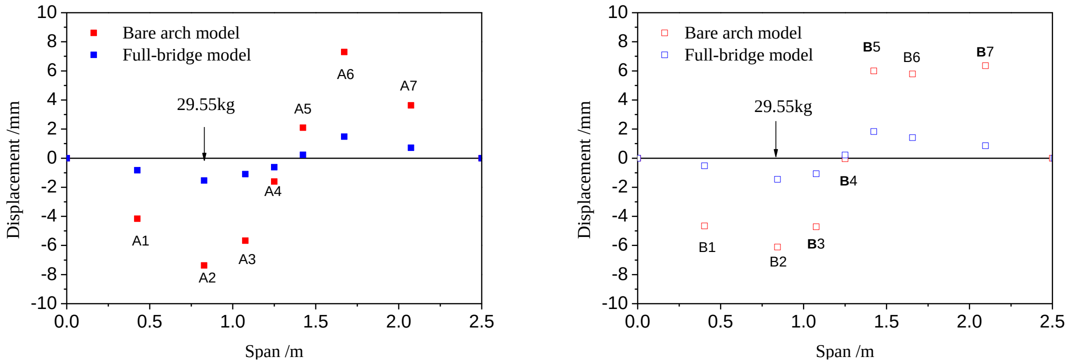
4.6.1 Results of hinged joint models

Fig. 4-42 to **Fig. 4-49** show the vertical displacement of bare-arch and full-bridge with the hinged joint under the same asymmetrical and symmetrical loading. It shows the bare and full-bridge have the similar tendency of deformation. At the same time, the branch points of the positive and negative vertical displacement of two systems are basically identical under asymmetrical load, indicate the spandrel structure cannot change the tendency of deformation of woven arch. However, it also can be found the deformation of bare arch model is obviously greater than the full-bridge model.



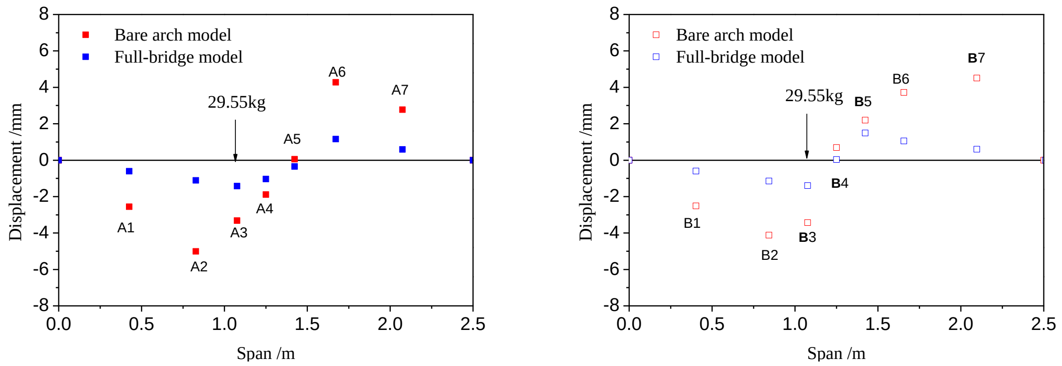
(a) 1st system (b) 2nd system

Fig. 4-43 Displacement under load case 1



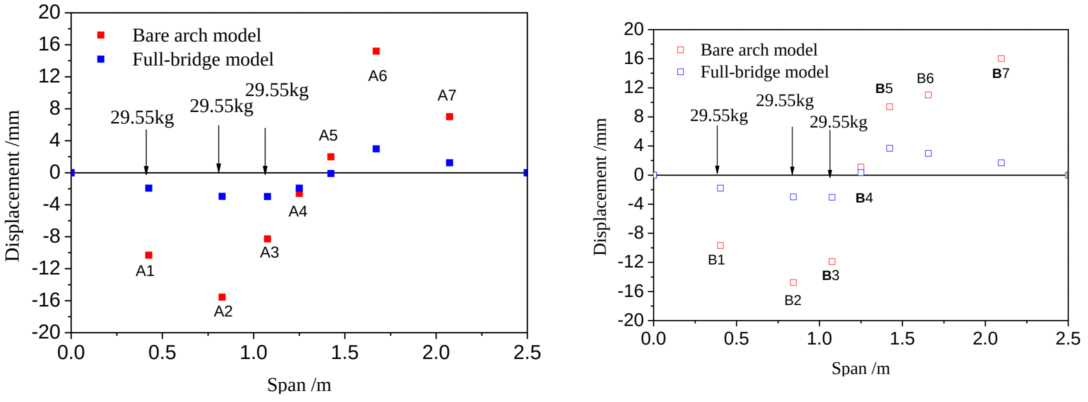
(a) 1st system (b) 2nd system

Fig. 4-44 Displacement under load case 2



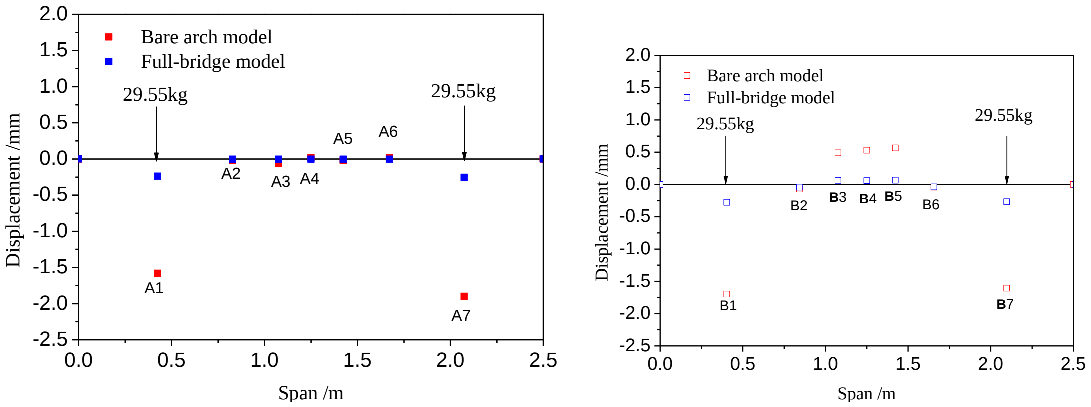
(a) 1st system (b) 2nd system

Fig. 4-45 Displacement under load case 3



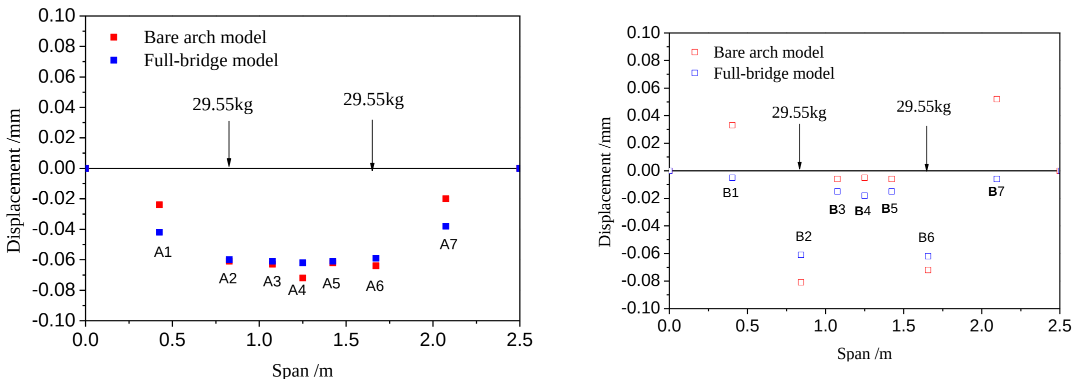
(a) 1st system (b) 2nd system

Fig. 4-46 Displacement under load case 4



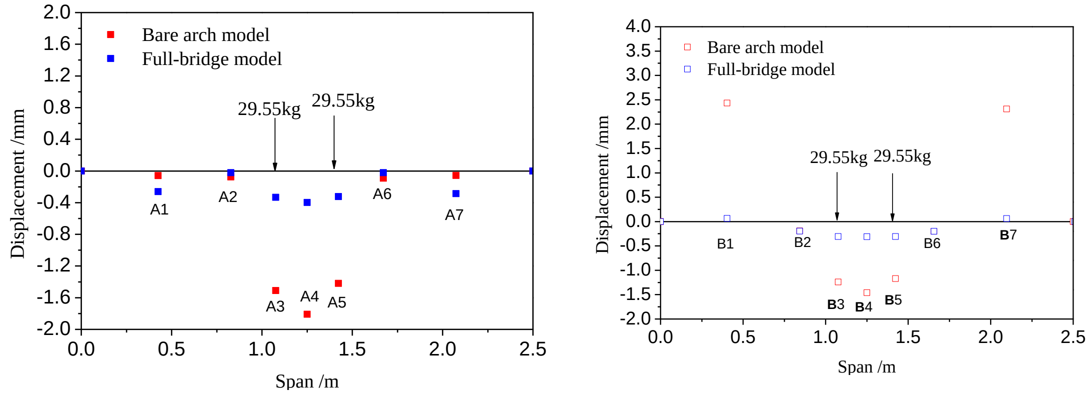
(a) 1st system (b) 2nd system

Fig. 4-47 Displacement under load case 5



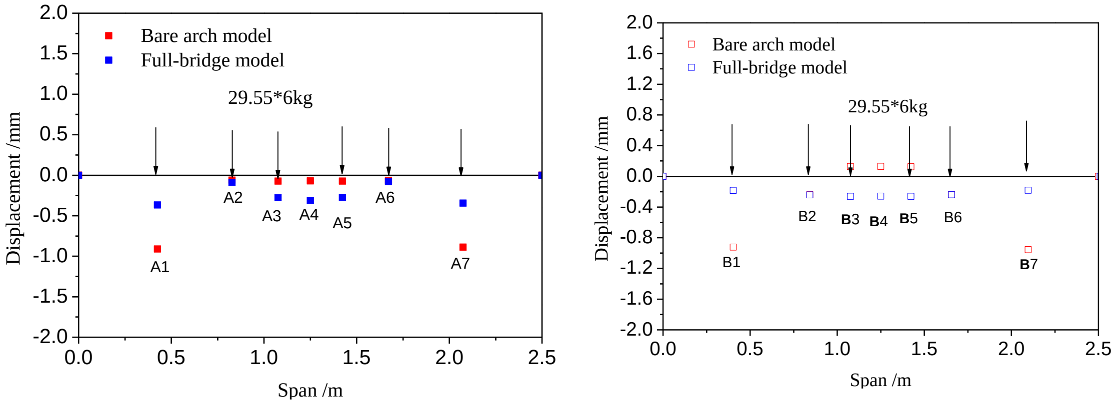
(a) 1st system (b) 2nd system

Fig. 4-48 Displacement under load case 6



(a) 1st system (b) 2nd system

Fig. 4-49 Displacement under load case 7

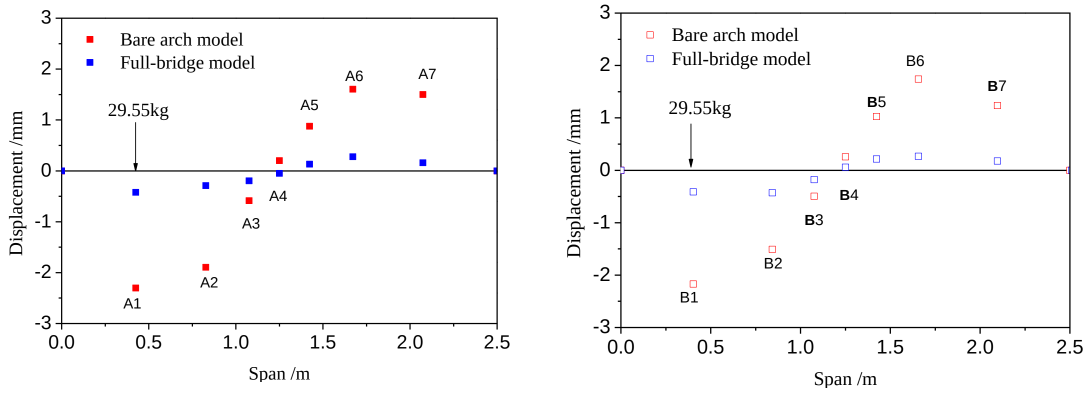


(a) 1st system (b) 2nd system

Fig. 4-50 Displacement under load case 8

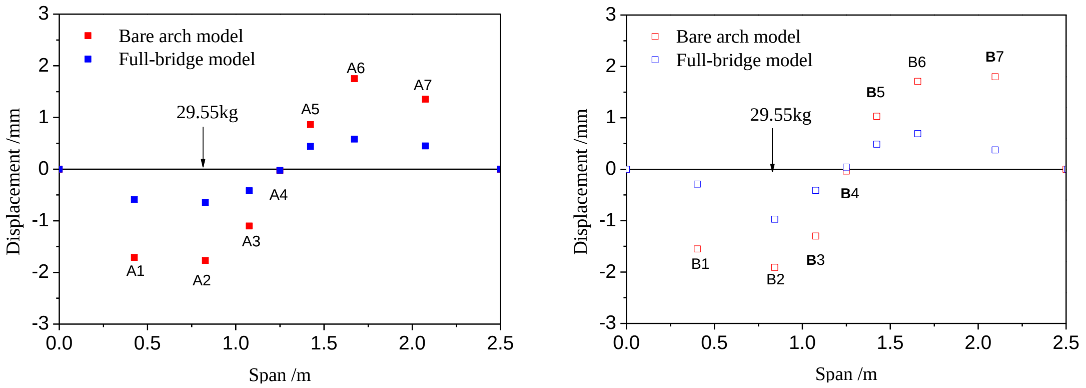
4.6.2 Results of rigid joint models

Fig. 4-50 to **Fig. 4-57** show the vertical displacement of bare-arch and full-bridge with the rigid joint under the same asymmetrical and symmetrical loading. It is similar to the model with hinged joint. They have the similar tendency of deformation, and then, the branch points of the positive and negative vertical displacement of two systems are basically identical under asymmetrical load, indicate the spandrel structure cannot change the tendency of deformation of woven arch. But it also can be found the deformation of bare arch model is obviously greater than the full-bridge model.



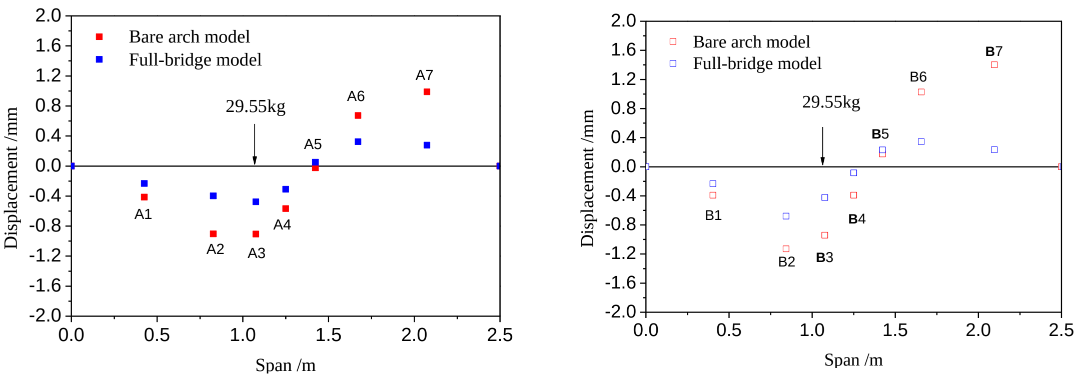
(a) 1st system (b) 2nd system

Fig. 4-51 Displacement under load case 1



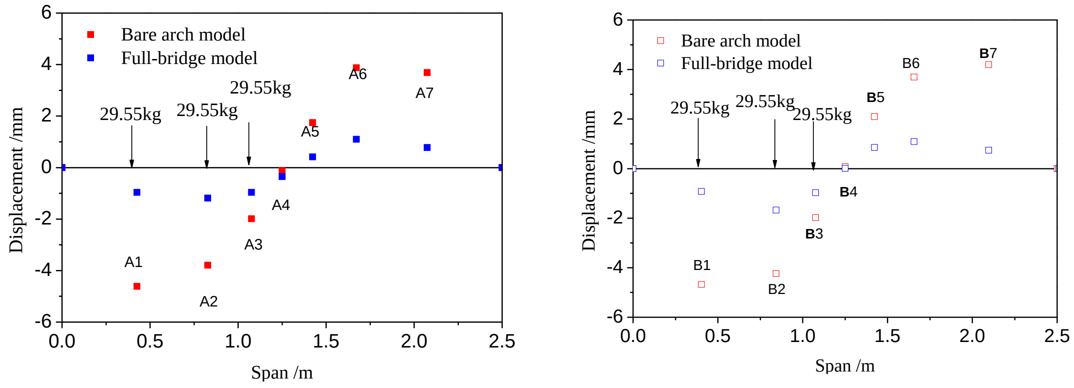
(a) 1st system (b) 2nd system

Fig. 4-52 Displacement under load case 2



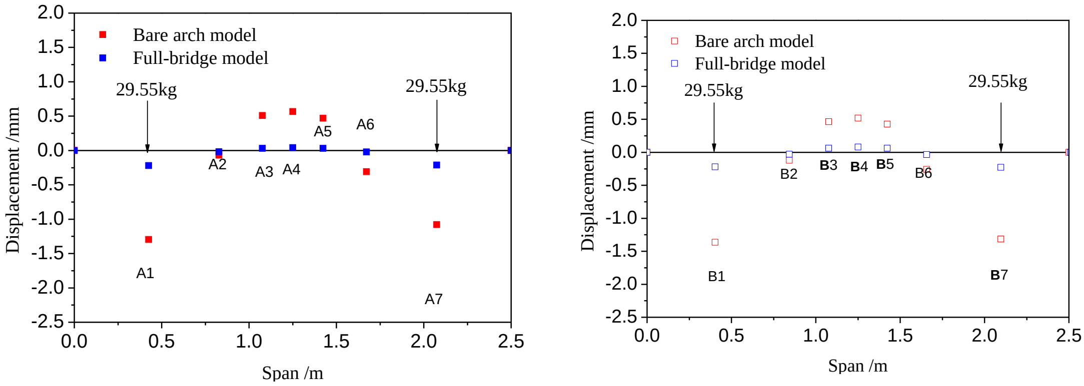
(a) 1st system (b) 2nd system

Fig. 4-53 Displacement under load case 3



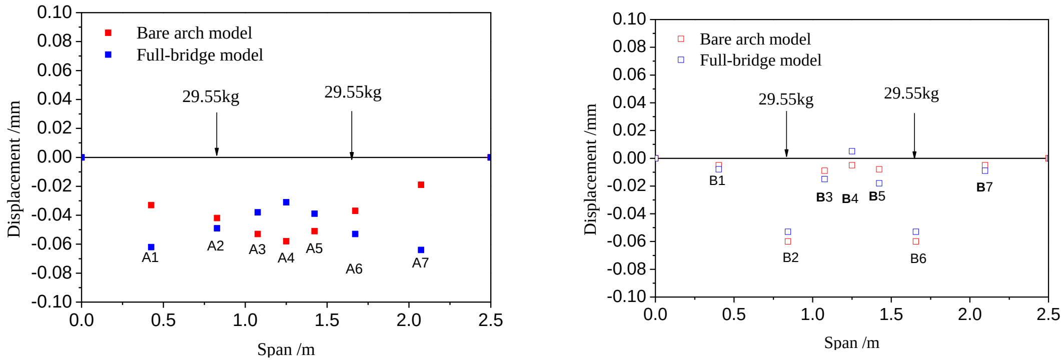
(a) 1st system (b) 2nd system

Fig. 4-54 Displacement under load case 4



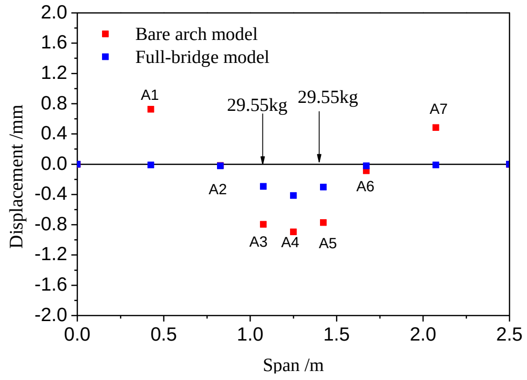
(a) 1st system (b) 2nd system

Fig. 4-55 Displacement under load case 5

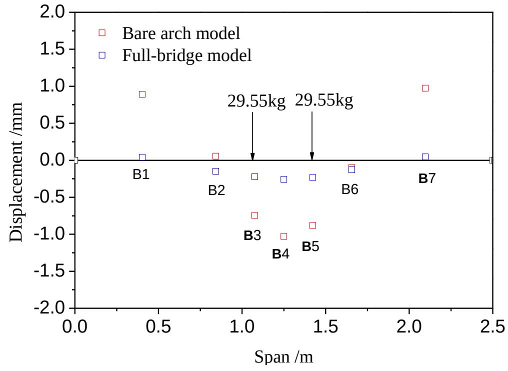


(a) 1st system (b) 2nd system

Fig. 4-56 Displacement under load case 6

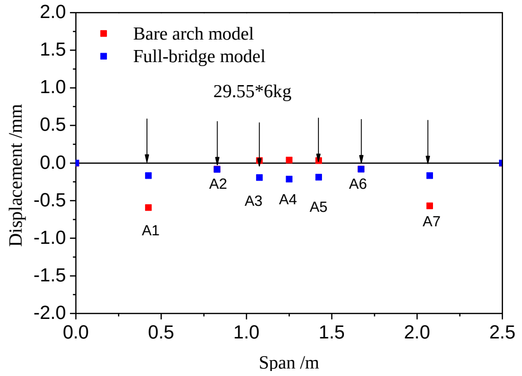


(a) 1st system

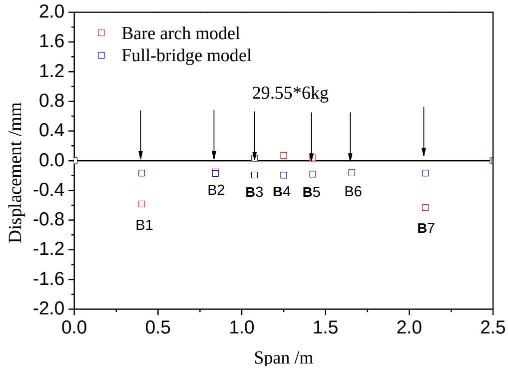


(b) 2nd system

Fig. 4-57 Displacement under load case 7



(a) 1st system



(b) 2nd system

Fig. 4-58 Displacement under load case 8

In conclusion, the spandrel structure cannot change the tendency of deformation of woven arch, but the spandrel structure will participate in bearing the loading of the structure, and then, it will reduce the deformation of woven arch.

4.7 Summary

In this chapter, the really bridge as a case, the structural behavior of woven arch was investigated experimentally and analytically. Four scale models comprise two bare arches and two full-bridges were tested subjected to asymmetrical and symmetrical loading in the lab. The findings obtained in the test study are summarized as follows:

1) In an elastic stage, the deflection of woven is antisymmetric with respect to the midpoint of the bridge under the asymmetrical loading, and the deformation was symmetrical with respect to the midpoint of the bridge under the symmetrical loading follow the arch theory.

2) The deformation tendency of woven arch with hinged joint is similar to woven arch with rigid joint, and the joint rigidity of woven cannot change the deformation tendency. But the woven arch with hinged joint have much greater deformation than the woven arch with rigid joint, the joint rigidity of woven has greater effect on the deformation, and the effect is more and more obvious with the load from arch springing to mid-span.

3) The joint of the transverse beam connect with other system arch rib cannot bear tension, that detachment often occurred at the transverse beam connecting with the arch rib of other system and cause the two systems cannot combine work.

4) The spandrel structure is benefit for wove arch, although it cannot change the tendency of deformation of woven arch, but the spandrel structure will participate in bearing the loading of the structure, and then, it will reduce the deformation of woven arch.

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CHAPTER 5

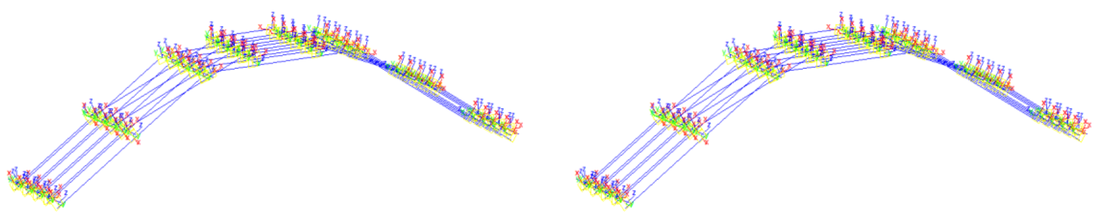
FINITE ELEMENT ANALYSIS OF WOVEN ARCH

5.1 Introduction

For further studying of the mechanical behavior of woven arch, the finite element models of the test models were developed and analyzed in MIDAS CIVIL. In the analysis, beam elements were used to simulate the arch ribs and transverse beams while spring element was applied to simulate the mortise-tennon joint and the transverse beam connect with the arch ribs of other system. More details of the FE method will be described in the next section. The numerical procedure will be verified by the experimental study on woven arch. The objectives of the analysis are to explain the discrepancies of experimental results, and to enhance the understanding of the accuracy of the theoretical assumptions for the problems.

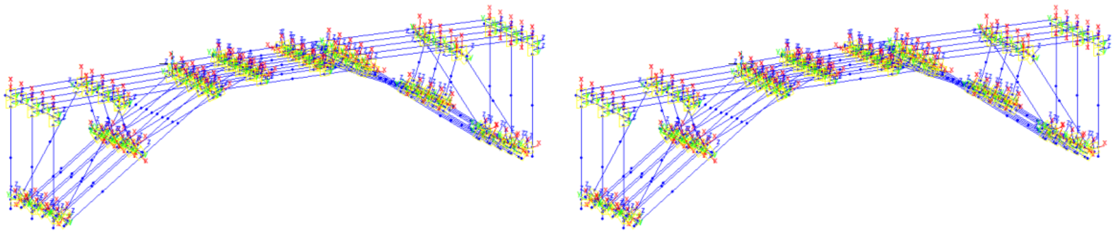
5.2 Description of Finite Element Model

The finite element models of the test models shown in **Fig. 5-1** and **Fig. 5-2** are developed using the MIDAS/CIVIL software. The bare arch consists of a total of 252 nodes, 200 beam elements, 4 types of cross sections, and 252 elastic joints. The full-bridge consists of a total of 1170 nodes, 1143 beam elements, 5 types of cross sections and 210 elastic joints. The acrylate resin was modeled with user-defined materials, which were obtained from tests as follows: the density is 1426 kg/m^3, the axial compressive strength is 111.6 N/mm^2, the elastic modulus is 3160 N/mm^2, and the Poisson ratio is 0.404. **Fig. 5-2** is the FE model of hinged model arch. In the global coordinate system, the X-axis, Y-axis and Z axis are defined in the longitudinal, transverse and vertical direction of the bridge, respectively.



(a) Hinged joint (b) Rigid joint

Fig. 5-1 Models of bare arch



(a) Hinged joint (b) Rigid joint

Fig. 5-2 Models of full-bridge

Connections between transverse beam and arch rib are simulated by elastic link elements whose stiffness is defined with respect to the element's local coordinate system. In the local coordinate system, x-axis is taken along the element length direction as shown in **Fig. 5-3**. The z-axis is defined so that x-z plane becomes the vertical plane, which is perpendicular to X-Y plane of global coordinate system, and then y-axis can be determined by right hand rule. **Fig. 5-4** shows the relationship between element coordinate system and global coordinate system for the connections. SDx, SDy and SDz stand for the translational stiffness in element's local x-direction, y-direction and z-direction, respectively, and SRx, SRy and SRz represent the rotational stiffness around the element's local x-axis, y-axis and z-axis, respectively.

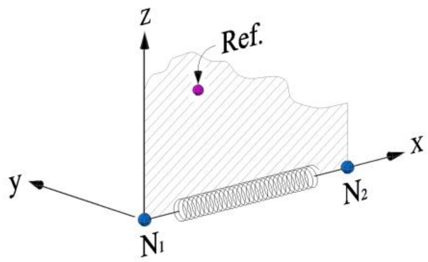


Fig. 5-3 Element's local coordinate system

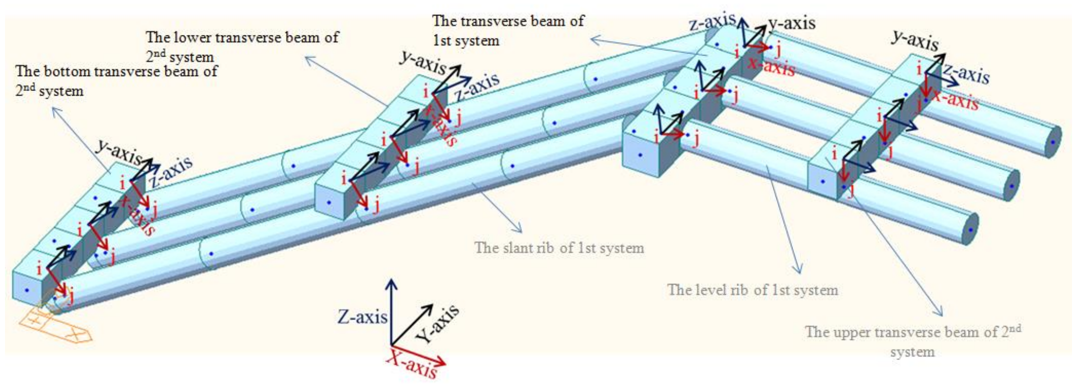


Fig. 5-4 Relationship between element coordinate system and global coordinate system

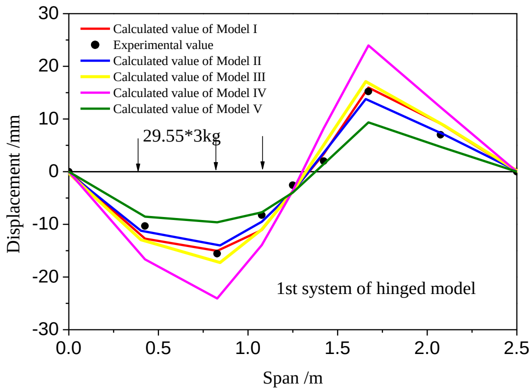
In order to simulate the connection of the two longitudinal systems as described in Section 3.2, two spring elements were adopted. Corresponding to the element coordinate system, one is a compression-only spring element; the other one is a normal spring element to stimulate the friction forces, the friction force is caused by the relative displacement between the members of the two systems along the longitudinal direction.

The spandrel structures, arch ribs, and transverse beams were modeled with beam elements. The arch springing of the first system was secured to the abutment using a L-shaped tongue-and-groove, and the joint was modeled as a hinge joint in which the linear displacements (Dx, Dy, Dz) were constrained, while the angular displacements (Rx, Ry, Rz) were free. An upright column was positioned between the abutment and back wall, and the joint was also modeled as a hinge joint in which the linear displacements (Dx, Dy, Dz) and one angular displacement (Rz) were constrained, but the other two angular displacements (Rx and Ry) were free.

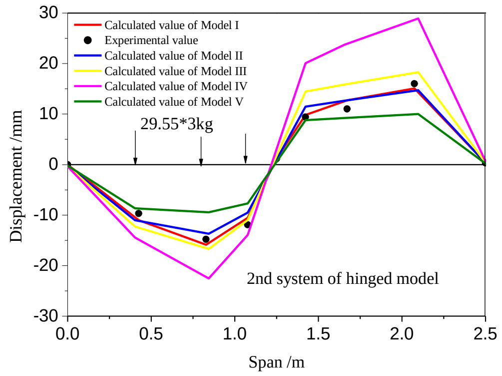
For the hinged model, since only the rotation along y-axis is free, a small stiffness should be taken for it. Through the comparison of the computed results with the test results, SRy was determined to be 900 N·mm/rad in the FE model. Other five degrees of freedom are restrained, and large spring stiffness should be considered. SRx and SRz were taken as 10^6N·mm/rad, while SDx, SDy and SDz, were taken as 10^5N/mm.

For the rigid model, all degrees of freedom are restrained, and large stiffness shall be used. In the FE model, corresponding to the element coordinate system, SRy, SRx and SRz, were taken as 10^6 N·mm/rad; SDx, SDy and SDz, were taken as 10^5N/mm.

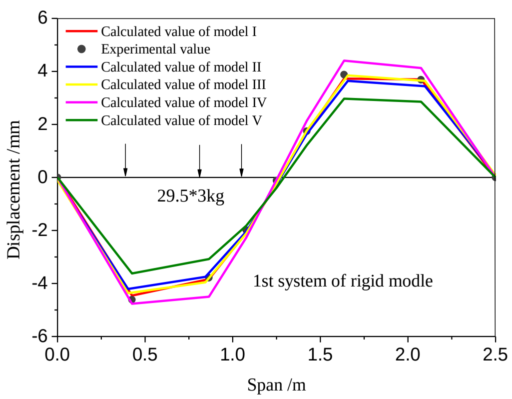
For the two model arches, it can be found from the **Fig. 5-5** that there are little differences between the numerical analysis by FEM and experimental result for connection of the two longitudinal systems with different spring stiffness. So, the spring stiffness of Model I was applied because it is mostly close to the experimental result and is in the effective range between Model II and Model III. Furthermore, In Model I, the compression-only spring element is with a constant linear rigidity of 10^6N/mm and the normal spring element has 6 degrees of freedom. The normal spring element is constrained by a small linear rigidity along the y-axis and the z-axis (the different angles of contact surface induced the different linear rigidity). And also, it is not constrained along the x-axis (SDx=0N/mm) and is constrained by the large rotational rigidity along the x-axis (SRx=10^6N·mm/rad). Moreover, it is not constrained and is allowed for a relative rotation along the y-axis and the z-axis with the small rotational rigidity (the different contact surface angles induced the different rotational rigidity), the detail of stiffness values is shown in **Table 5-1**.



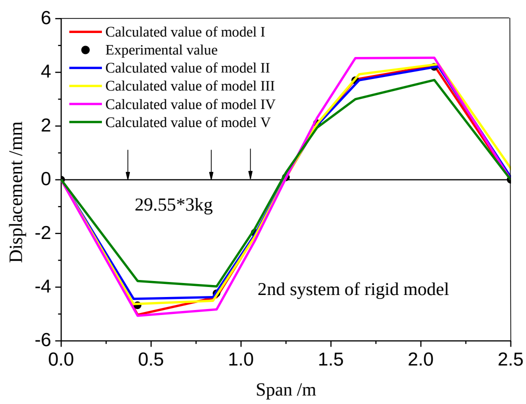
(a) 1st system of hinged model



(b) 2nd system of hinged model



(c) 1st system of rigid model



(d) 2nd system of rigid model

Fig. 5-5 Comparison of stiffness of spring element

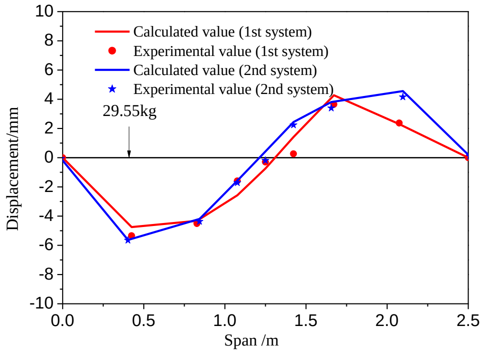
Table 5-1 Stiffness between the two systems

Location	Model	SD_x N/mm	SD_y N/mm	SD_z N/mm	SR_x N·mm/rad	SR_y N·mm/rad	SR_z N·mm/rad
A1 and B1, A7 and B7	I	0	40	40	10^6	400	400
	II	0	60	60	10^7	600	600
	III	0	20	20	10^5	200	200
	IV	0	0	0	10^4	0	0
	V	0	400	400	10^8	4000	4000
A2 and B2, A6 and B6	I	0	60	60	10^6	600	600
	II	0	80	80	10^7	800	800
	III	0	40	40	10^5	400	400
	IV	0	0	0	10^4	0	0
	V	0	600	600	10^8	6000	6000
A3 and B3, A5 and B5	I	0	80	80	10^6	800	800
	II	0	100	100	10^7	1000	1000
	III	0	60	60	10^5	600	600
	IV	0	0	0	10^4	0	0
	V	0	800	800	10^8	8000	8000

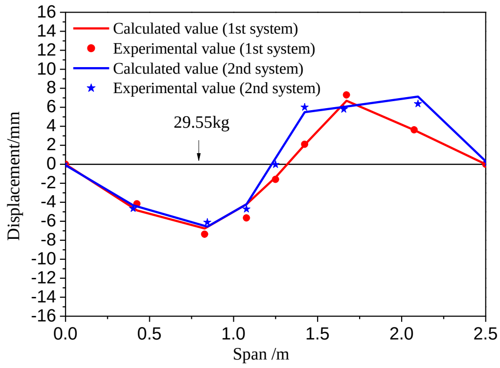
5.3 Finite Element Results and Comparison with Test Results

5.3.1 Bare arch with hinged joint

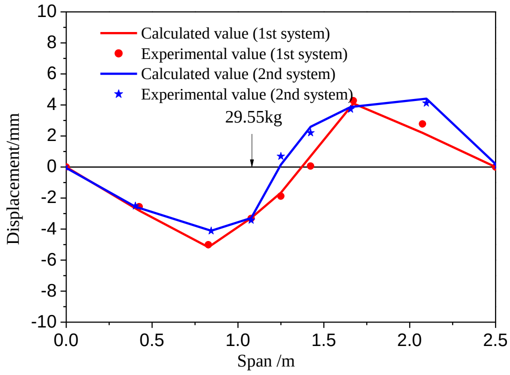
In order to validate the efficiency of the FE models, which are described by the abovementioned method, the analysis results and experimental results of bare arch with hinged joint model are shown in **Fig. 5-6.** It can be seen the results of analysis are very close to those of experimental results at each test load cases, the maximum error value is only 0.699 mm, it is 5.4% of calculated value. It is obvious that the analysis results agree very well with the experimental results, it can be concluded that the FE model can be used to model the behavior of woven arch accurately and efficiently. Further FE analyses will be given in the next sections.



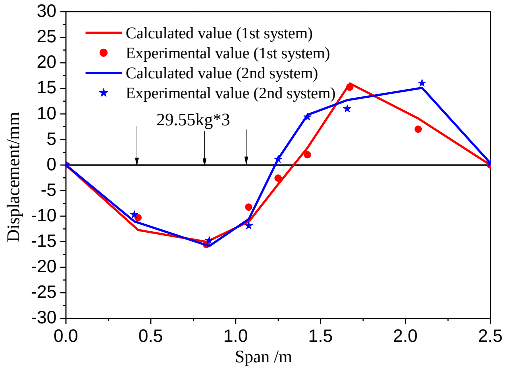
(a) Case 1



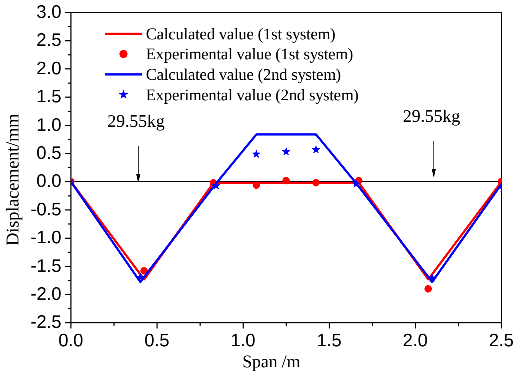
(b) Case 2



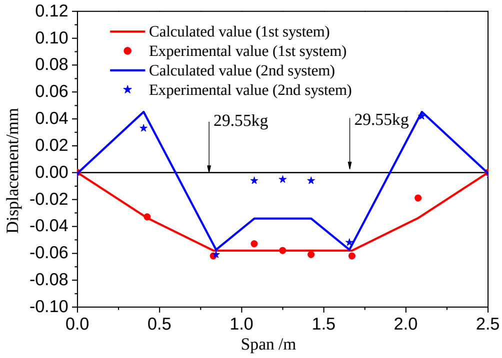
(c) Case 3



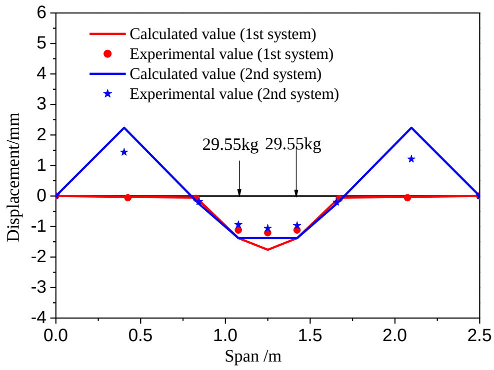
(d) Case 4



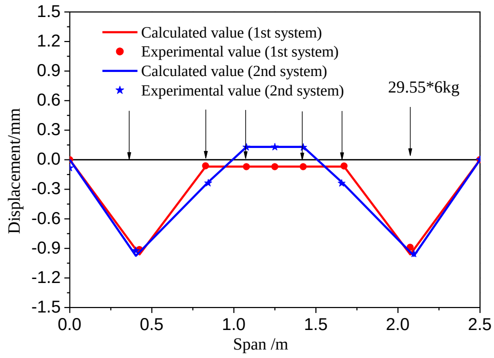
(e) Case 5



(f) Case 6



(g) Case 7

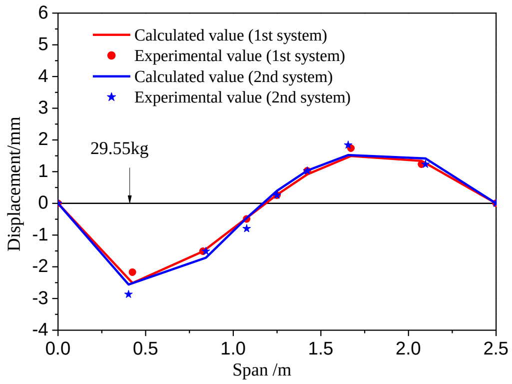


(h) Case 8

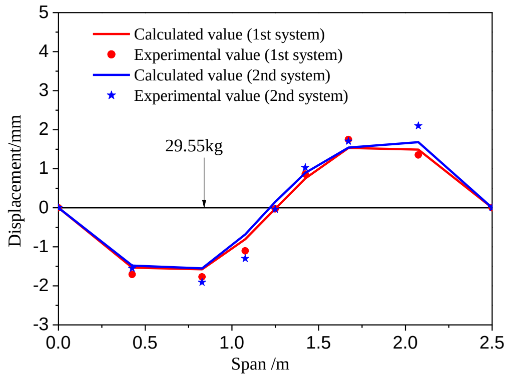
Fig. 5-6 Displacement curves of the two systems of hinged joint model

5.3.2 Bare arch with rigid joint

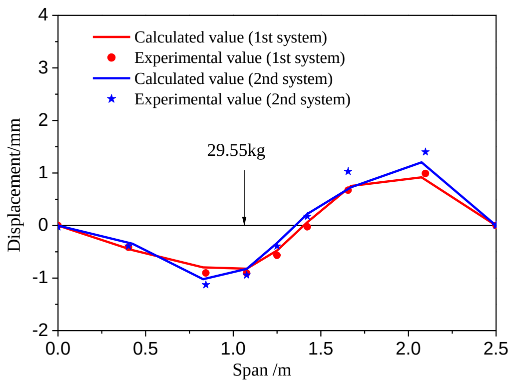
The analysis results and experimental results of bare arch with rigid joint model are shown in **Fig. 5-7**. It can be seen the results of analysis are very close to those of experimental results at each test load cases, the maximum error value is only 0.347 mm, it is 6.6% of calculated value. It is obvious that the analysis results agree very well with the experimental results, it can be concluded that the FE model can be used to model the behavior of woven arch accurately and efficiently. Further FE analyses will be given in the next sections.



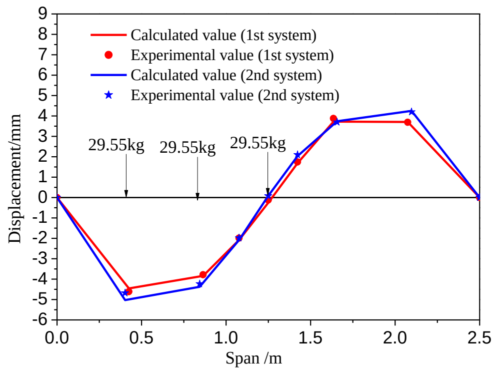
(a) Case 1



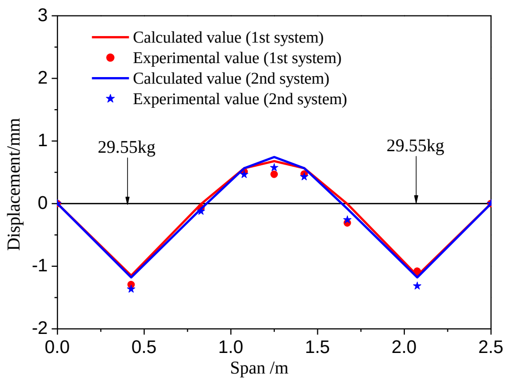
(b) Case 2



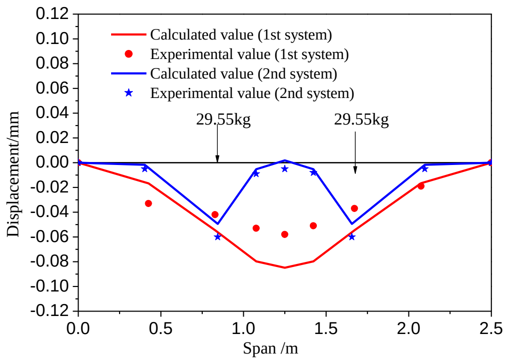
(c) Case 3



(d) Case 4

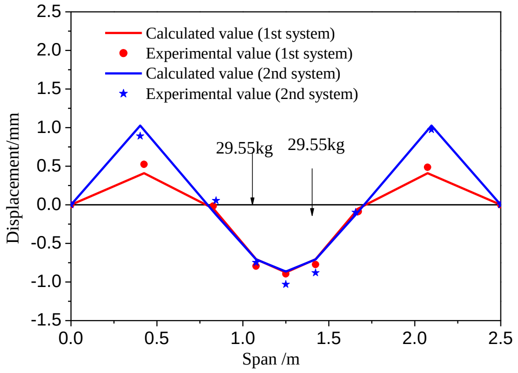


(e) Case 5

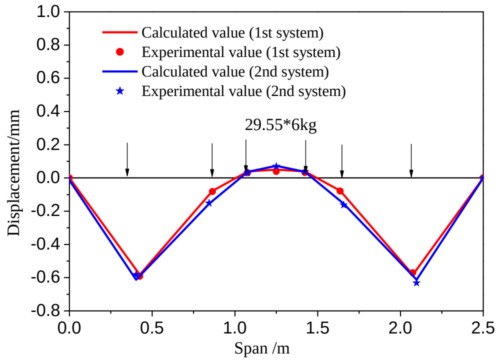


(f) Case 6

Fig. 5-7 Displacement curves of the two systems of rigid joint model



(g) Case 7

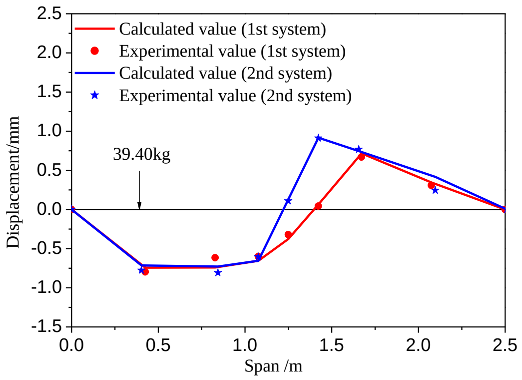


(h) Case 8

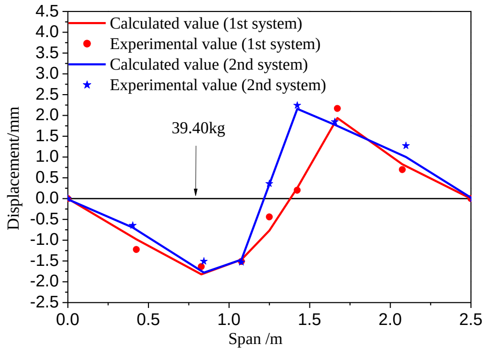
Fig. 5-8 Displacement curves of the two systems of rigid joint model (contd.)

5.3.3 Full-bridge with hinged joint

The analysis results and experimental results of full-bridge with hinged joint model are shown in **Fig. 5-8**. It can be seen the results of analysis are very close to those of experimental results at each test load cases, the maximum error value is only 0.329 mm, it is 6.6% of calculated value. It is obvious that the analysis results agree very well with the experimental results, it can be concluded that the FE model can be used to model the behavior of woven arch accurately and efficiently. Further FE analyses will be given in the next sections.

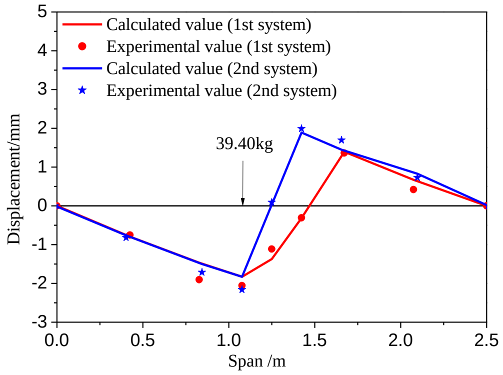


(a) Case 1

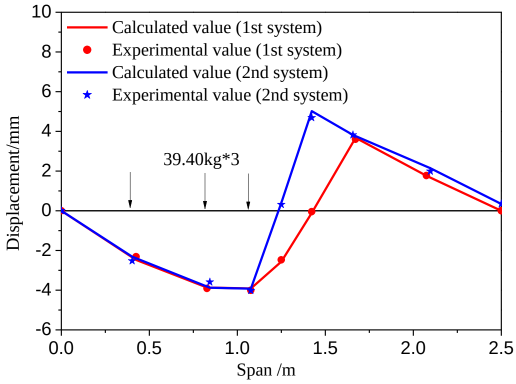


(b) Case 2

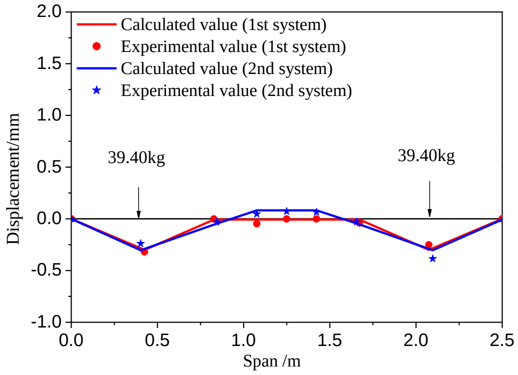
Fig. 5-9 Displacement curves of the two systems of hinged joint model



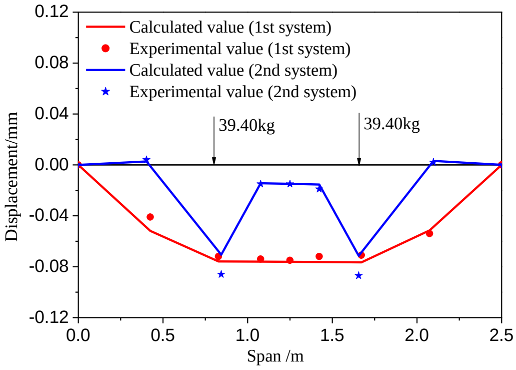
(c) Case 3



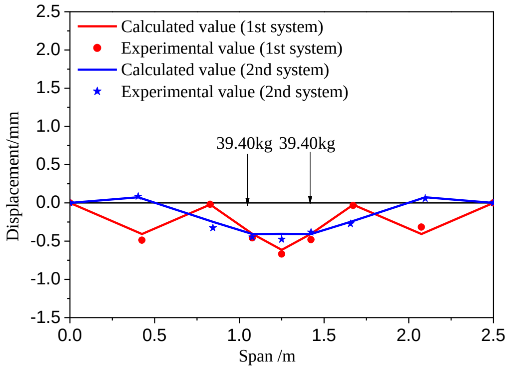
(d) Case 4



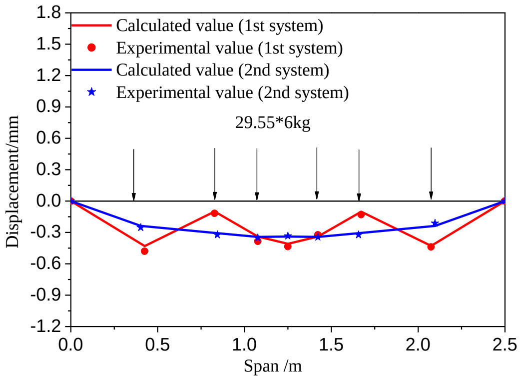
(e) Case 5



(f) Case 6



(g) Case 7

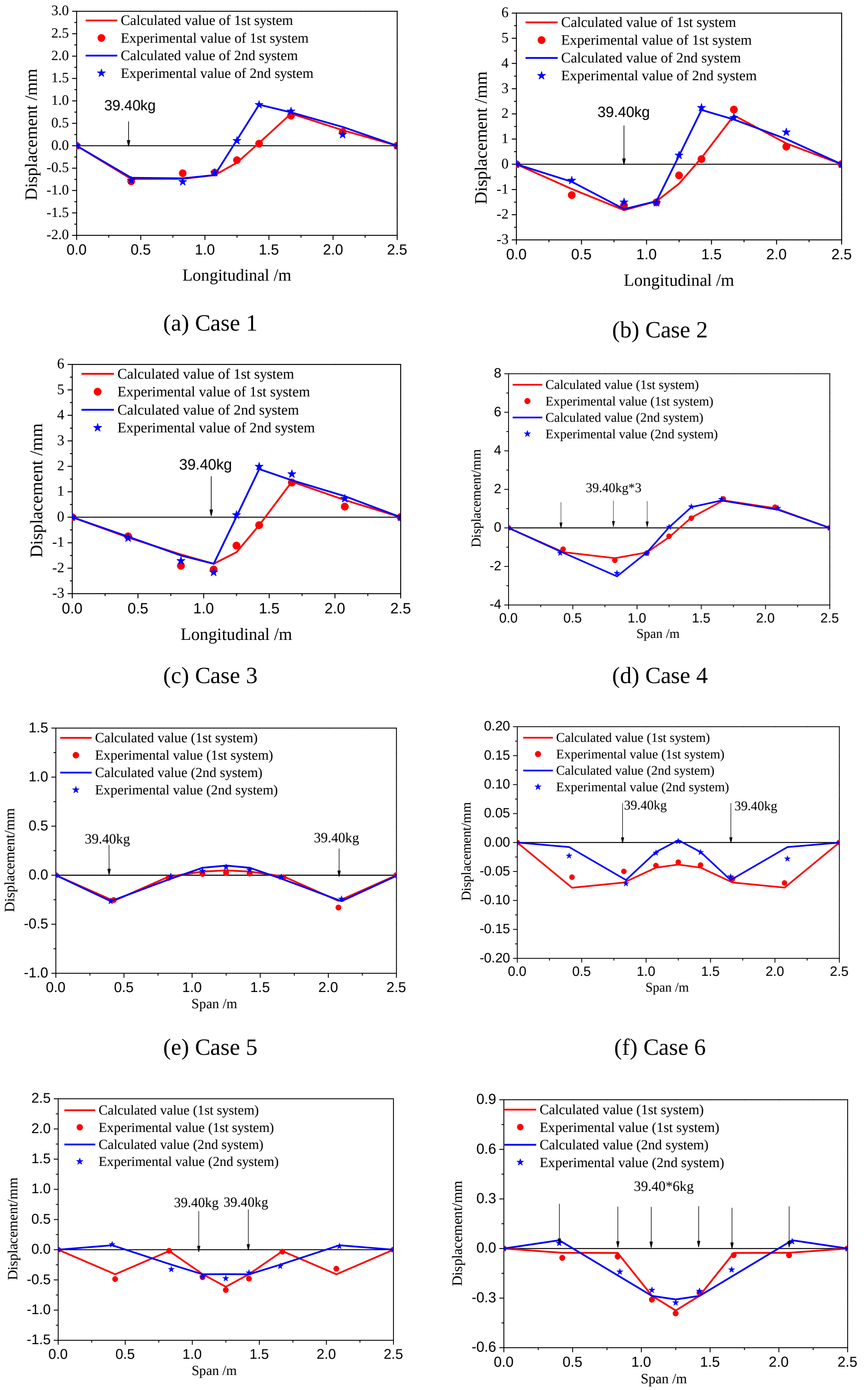


(h) Case 8

Fig. 5-10 Displacement curves of the two systems of hinged joint model (contd.)

5.3.4 Full-bridge with rigid joint

The analysis results and experimental results of full-bridge with rigid joint model are shown in **Fig. 5-9**. It can be seen the results of analysis are very close to those of experimental results at each test load cases, the maximum error value is only 0.169 mm, it is 6.7% of calculated value. It is obvious that the analysis results agree very well with the experimental results, it can be concluded that the FE model can be used to model the behavior of woven arch accurately and efficiently. Further FE analyses will be given in the next sections.



(a) Case 1

(b) Case 2

(c) Case 3

(d) Case 4

(e) Case 5

(f) Case 6

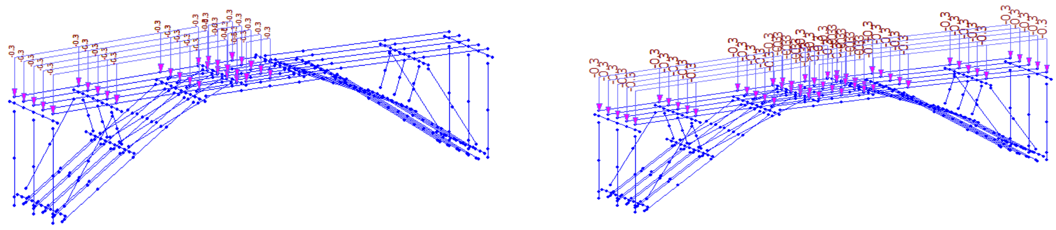
(g) Case 7

(h) Case 8

Fig. 5-11 Displacement curves of the two systems of rigid joint model

5.4. Analysis on Mechanical Behavior of Woven Arch Bridges

In order to investigate the mechanical behavior of woven arch， the asymmetric and symmetric uniform load with the value 3.5 kN/m^2 were applied to the FE model of full-bridges[1]-[4], as shown in **Fig. 5-10**.

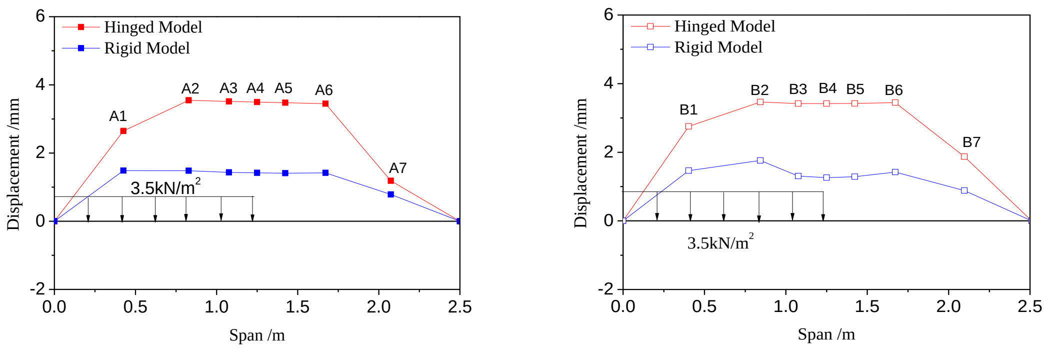


(a) Asymmetric uniform load (b) Symmetric uniform load

Fig. 5-12 Loading diagram

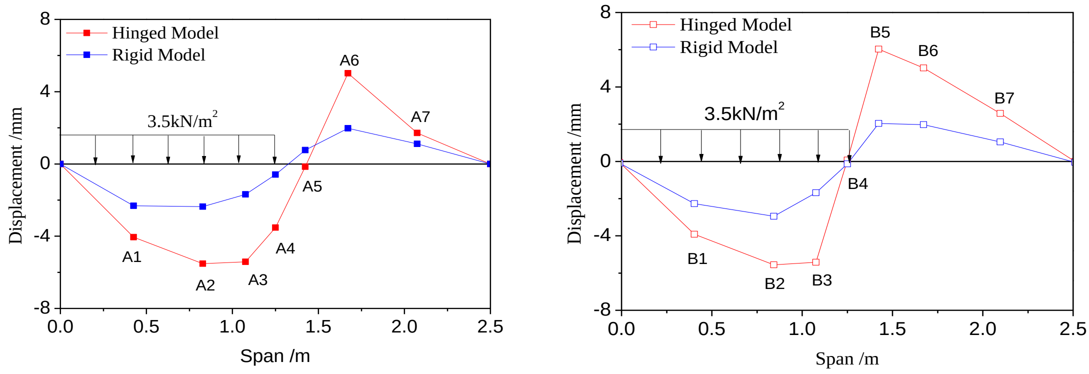
5.4.1 Analysis of structural deformation

It can be seen from **Fig. 5-11** and **Fig. 5-12**, two full-bridge models are all followed by the similar deformation tendency, but the value of model with hinged joint is greater than the model with rigid joint. The horizontal deflections at various testing section are follow by the other side of load, and the vertical deflection is asymmetrical under asymmetrical load.



(a) 1st system (b) 2nd system

Fig. 5-13 Horizontal displacement under asymmetrical pedestrian load



(a) 1st system (b) 2nd system

Fig. 5-14 Vertical displacement under asymmetrical pedestrian load

Table 5-2 shows the measured maximum deflection of the two systems and their locations under a uniform asymmetric load with the value of 3.5 kN/m^2.

From **Table 5-2**, it can be found that the maximum deflection of the two models occurred at the same position under asymmetric load. However, the deflection values of the hinged model are obviously greater than that of the rigid model. For the first system, the ratio of the maximum deflections is 2.419 between the hinged joint and the rigid joint along horizontal direction. The ratio of the maximum upward and downward deflections is 2.592 and 2.355 along vertical direction. For the second system, the ratio of the maximum deflections is 1.998 between the hinged joint and the rigid joint along horizontal direction. The ratio of the maximum upward and downward deflections is 3.022 and 1.891 along vertical direction.

The maximum upward and downward displacement is 5.104 mm and 5.557 mm for the first system of hinged model, respectively. The maximum upward and downward displacement is 6.029 mm and 5.559 mm for the second system of hinged model, respectively. The value is larger than the required value by the General Code for Design of Highway Bridges and Culverts (1/1000 of calculation span length, which is 2.5 mm) [1] - [4].

But for the rigid joint model, the maximum upward and downward displacement of the first system is 1.969 mm and 2.36 mm, respectively. The value is small than the required value by the General Code for Design of Highway Bridges and Culverts (1/1000 of calculation span length, which is 2.5 mm).

Table 5-2 Value and location of the maximum deflection under asymmetrical loading

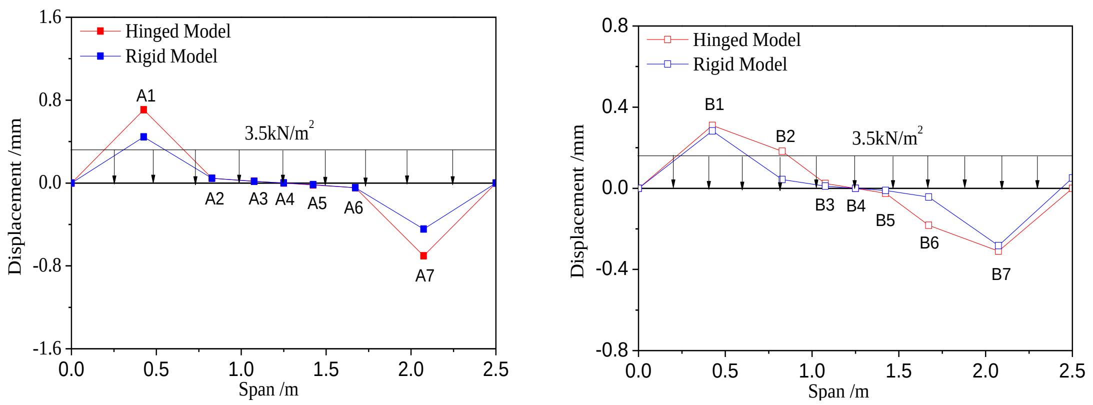
(a) 1st system

Model	DX		DZ			
	Value	Location	Value	Location	Value	Location
Hinged joint	3.578	A2	5.104	A6	-5.557	A2
Rigid joint	1.479	A2	1.969	A6	-2.36	A2
Ratio (%)	2.419		2.592		2.355	

(b) 2nd system

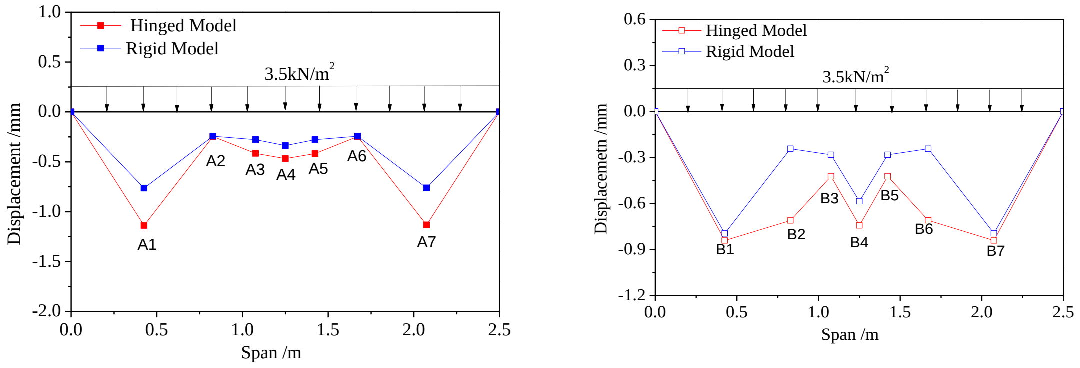
Model	DX		DZ			
	Value	Location	Value	Location	Value	Location
Hinged joint	3.522	B2	6.029	B5	-5.559	B2
Rigid joint	1.762	B2	1.995	B5	-2.94	B2
Ratio (%)	1.998		3.022		1.891	

Fig. 5-13 and **Fig. 5-14** show the deformation curves of two full-bridge models under symmetrical pedestrian loading. It can be seen that they have the similar deformation tendency, the horizontal deflection is antisymmetric with respect to the midpoint of the bridge, the vertical deflection is symmetrical with respect to the midpoint of the bridge.



(a) 1st system (b) 2nd system

Fig. 5-15 Horizontal displacement under symmetrical pedestrian load



(a) 1st system (b) 2nd system

Fig. 5-16 Vertical displacement under symmetrical pedestrian load

Table 5-3 shows the measured maximum deflection of the two systems and their locations under a uniform symmetric load with the value of 3.5 kN/m^2.

From **Table 5-3**, it can be found that the maximum deflection of the two models occurred at the same position under symmetric load. However, the deflection values of the hinged model are obviously greater than that of the rigid model. For the first system, the ratio of the maximum deflections is 1.587 between the hinged joint and the rigid joint along horizontal direction. The ratio of the maximum downward deflections is 1.49 along vertical direction. For the second system, the ratio of the maximum deflections is 1.092 between the hinged joint and the rigid joint along horizontal direction. The ratio of the maximum downward deflections is 1.058 along vertical direction.

The maximum downward displacement is 1.137 mm and 0.842 mm for the two systems of hinged model, respectively. The value is smaller than the required value by the General Code for Design of Highway Bridges and Culverts (1/1000 of calculation span length, which is 2.5 mm).

Table 5-3 Value and location of the maximum deflection under symmetrical loading

(a) 1st system

Model	DX				DZ	
	Value	Location	Value	Location	Value	Location
Hinged joint	0.706	A1	-0.706	A7	-1.137	A1
Rigid joint	0.445	A1	-0.445	A7	-0.763	A1
Ratio (%)	1.587		1.587		1.49	

Table 5-4 Value and location of the maximum deflection under symmetrical loading (contd.)

(b) 2nd system

Model	DX				DZ	
	Value	Location	Value	Location	Value	Location
Hinged joint	0.309	B1	-0.309	B7	-0.842	B1
Rigid joint	0.283	B1	-0.283	B7	-0.796	B1
Ratio (%)	1.092		1.092		1.058	

From the abovementioned results, it can be obtained the ratio of maximum value, as shown in **Table 5-4.** The ratio is between in 1.998~3.022 under asymmetrical load, and the ratio is between in 1.058~1.587 under symmetrical load.

Table 5-5 Ratio of maximum of the models bridges under uniform load

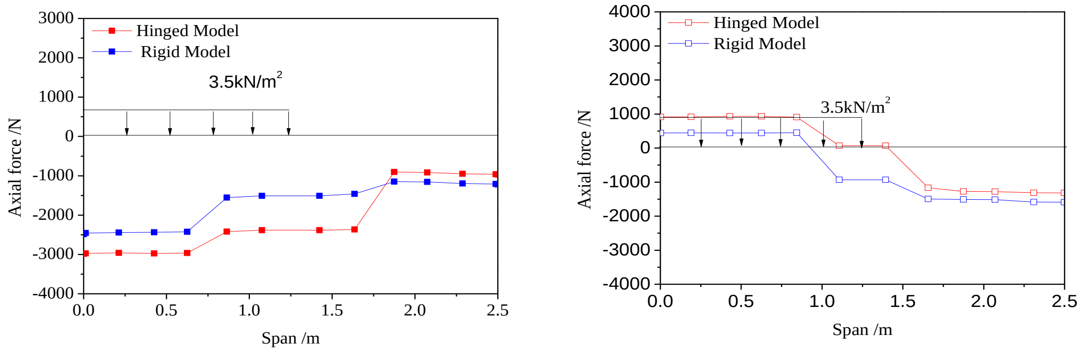
System	Asymmetrical uniform load			
	Horizontal direction		Vertical direction	
	Maximum upward	Maximum downward	Maximum upward	Maximum downward
1st system	2.419		2.592	2.355
2nd system	1.998		3.022	1.891
System	Symmetrical uniform load			
	Horizontal direction		Vertical direction	
	Maximum upward	Maximum downward	Maximum upward	Maximum downward
1st system	1.587	1.587		1.490
2nd system	1.092	1.092		1.058

From the abovementioned results of deformation, it can be found that the woven arches with the different joint have the similar deformation tendency, but the deflection of woven arch with hinged joint is greater than woven arch with rigid joint, the mortise-tenon joint simplified as hinged joint is better conservative calculation for simplified calculate. The deformation of woven arch under asymmetrical load is greater than under symmetrical load, the symmetrical load should be as control load.

5.4.2Analysis of internal force

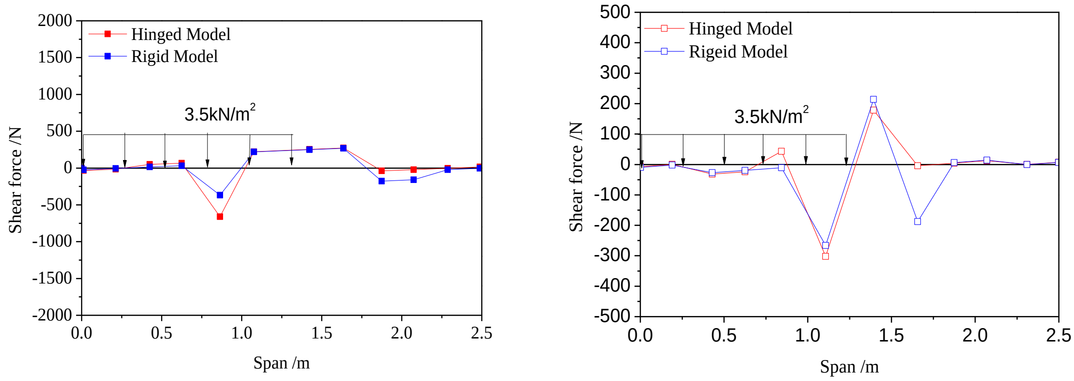
The axial force diagram of woven arch models bridges under asymmetrical pedestrian load as shown in **Fig. 5-15** (the positive value is tension and the negative value is pressure force). It can be seen the axial force of the first system is become smaller and smaller from the arch springing of load side to the other side. The axial force of the second system from the arch springing of load side to the other side is tension force change into compression force and the value of axial force is become more and more. And then, two systems were mainly subjected to compression, and the first system is greater than the second system at the same location.

The shearing force diagram of woven arch models bridge under asymmetrical pedestrian load as shown in **Fig. 5-16**. The distribution of two models bridge is similar. For the first system, the maximum shearing force is existing at the end of the level arch rib of the first system in the load side. For the second system, the maximum shearing force is existing at the end of the level arch rib of the second system.



(a) 1st system (b) 2nd system

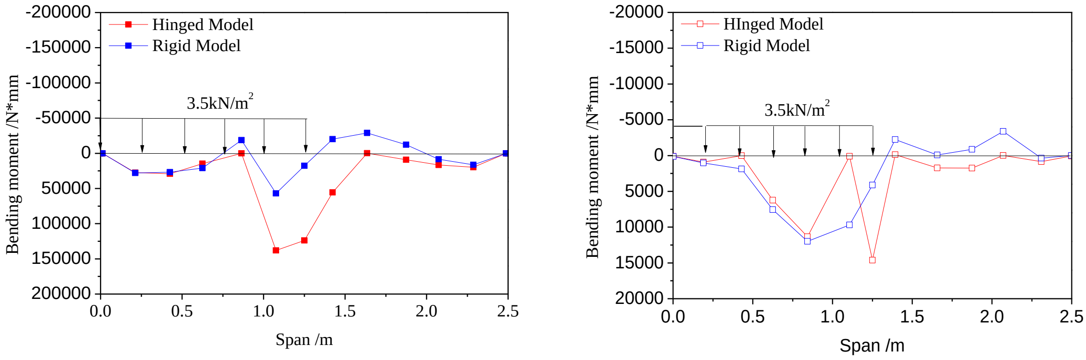
Fig. 5-17 Axial force diagram of models under asymmetrical pedestrian load



(a) 1st system (b) 2nd system

Fig. 5-18 Shearing force diagram of models under asymmetrical pedestrian load

The bending moment diagram of woven arch models bridge under asymmetrical pedestrian load as shown in **Fig. 5-17**. The distribution of two models bridge is similar. For the first system, the maximum bending moment is existing at the level arch rib of the first system connect to the upper transverse beam of the second system. For the second system, the maximum bending moment is existing at the upper slant rib of the second system connect to the transverse beam of the first system.



(a) 1st system (b) 2nd system

Fig. 5-19 Bending moment diagram of models under asymmetrical pedestrian load

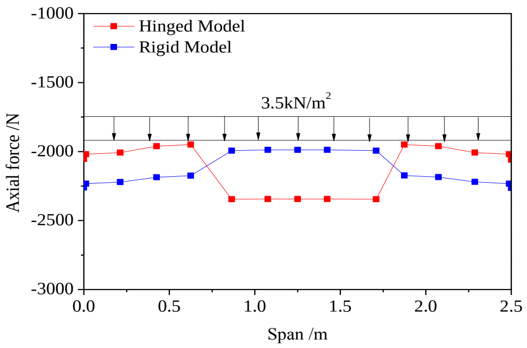
From the abovementioned results, it can be obtained the ratio of internal force, as shown in **Table 5-5.** The results show the internal force of the first system is greater than the second system for woven arch bridge. At the same time, the maximum axial force is 2075N and 2484N for the two models, respectively. The maximum axial compression strength is all smaller than the measured compressive strength of 111.6 MPa.

Table 5-6 Ratio of maximum internal force under asymmetrical pedestrian load

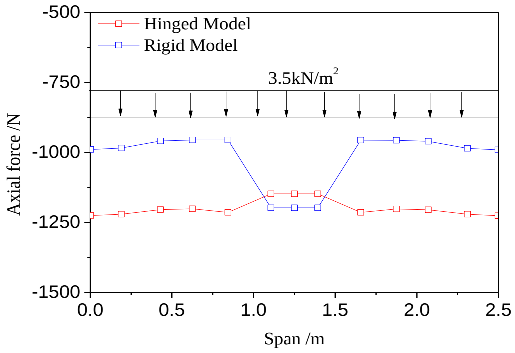
Model	Maximum axial force (N)		Maximum shearing force (N)		Maximum bending moment (N·mm)	
	1st system	2nd system	1st system	2nd system	1st system	2nd system
Hinged joint	-2745	-1194	-1230	-266	137340	14624
Rigid joint	-2484	-1589	-1618	-266	57040	11997
Ratio (%)	1.105	0.751	0.760	1.000	2.408	1.219

The axial force diagram of woven arch models bridges under symmetrical pedestrian load as shown in **Fig. 5-18** (the positive value is tension and the negative value is pressure force). All members of two systems were subjected to compression, and the first system is greater than the second system at the same location. But it is different to the load case of asymmetrical load, the rigidity of joint has the great influence on the distribution of axial force. The axial force of vault is great than the arch springing for the first system with hinged joint, vice versa. The axial force of vault is smaller than the arch springing for the second system with rigid joint, vice versa.

The shearing force diagram of woven arch models bridge under symmetrical pedestrian load as shown in **Fig. 5-19**. The distribution of two models bridge is similar, and the rigidity of joint has small influence on the distribution.

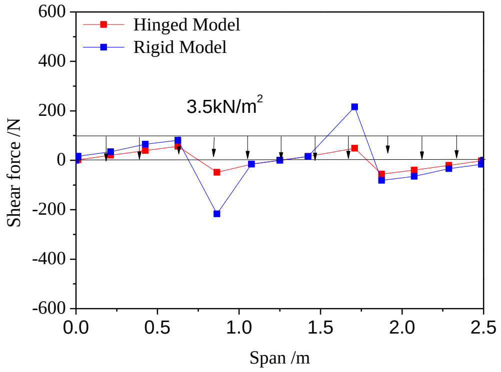


(a) 1st system

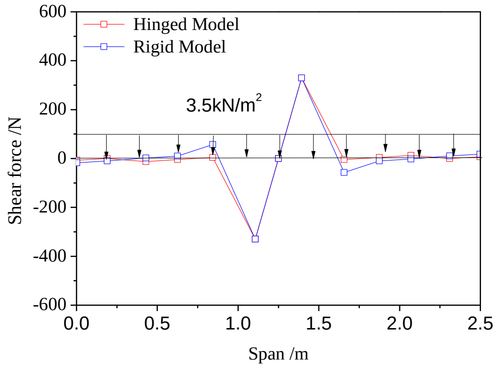


(b) 2nd system

Fig. 5-20 Axial force diagram of models under symmetrical pedestrian load



(a) 1st system



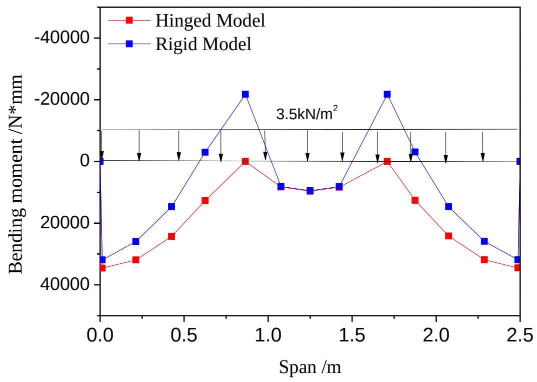
(b) 2nd system

Fig. 5-21 Shearing force diagram of models under symmetrical pedestrian load

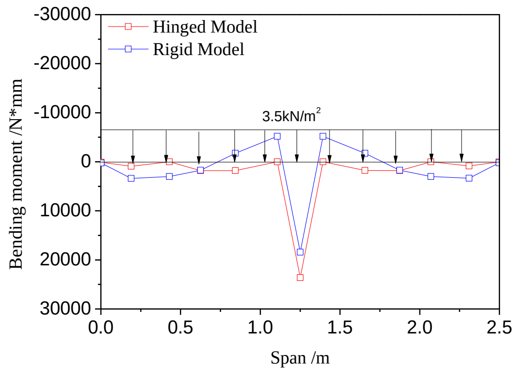
The bending moment diagram of woven arch models bridge under symmetrical pedestrian load as shown in **Fig. 5-20**. The distribution of two models bridge is similar.

Table 5-6 shows the comparison results of internal force of two models. The ratio of the maximum axial force of two systems for two models is vary from 0.908 to 1.238 under symmetrical load. The ratio of the maximum bending moment of two systems for two models is 1.083 and 1.281, respectively. The ratio of the maximum shear force of two systems for two models is very close.

At the same time, the maximum axial force is 2344N and 2261N for the two models, respectively. The maximum axial compression strength is all smaller than the measured compressive strength of 111.6 MPa.



(a) 1st system



(b) 2nd system

Fig. 5-22 Bending moment diagram of models under symmetrical pedestrian load

Table 5-7 Ratio of maximum internal force under symmetrical pedestrian load

Model	Maximum axial force (N)			
	1st system		2nd system	
	Arch springing	Arch vault	Arch springing	Arch vault
Hinged joint	-2054	-2344	-1226	-1148
Rigid joint	-2261	-1988	-990	-1198
Ratio (%)	0.908	1.179	1.238	0.958
Model	Maximum shearing force (N)		Maximum bending moment (N·mm)	
	1st system	2nd system	1st system	2nd system
Hinged joint	-2291	330	34609	23604
Rigid joint	-2114	330	31946	18425
Ratio (%)	1.084	1.000	1.083	1.281

From abovementioned results, it can be seen that distribution trend of internal force of two woven arch models is similar, but they are different value. Under asymmetrical load, there is a small tensile force at load side of the second system. Under symmetrical load, the two systems of woven arch were mainly subjected to compression.

5.5 Argument for Woven Arch Bridge is Arch Structure

According to the description in Chapter one, the academic name is not defined and still being argued. for a long time, some scholars consider that the level arch ribs of first system of Min-zhe Timber Arch Bridge exist larger bending moment, and therefore they can't be identified as arch bridge. In order to investigate whether the woven arch is an arch structure, comparison study of woven arch with a two-hinge arch is carried out by FEM in this section.

5.5.1 FE model for two-hinged arch

A FE model of two-hinged arch with the same span and rise as the woven model bare arch was built, as shown in **Fig. 5-21**. Its arch axis is formed in computer aided design (CAD) software by use of spline curve fitting the nodes and the intersection of two systems of the woven arch, as shown in **Fig. 5-22** (the thick line is the fitted curve) [5]. The cross-section has the same flexural and compressive stiffness as the woven arch (the sum of the two systems members). The two-hinged arch model has the same material properties as the acrylate resin.

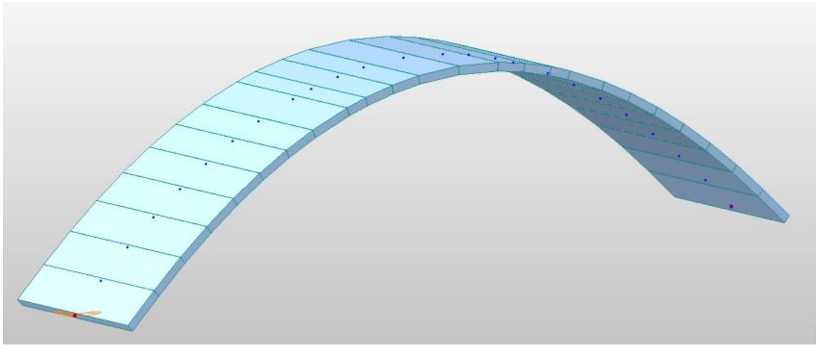


Fig. 5-23 FE model of two-hinge arch

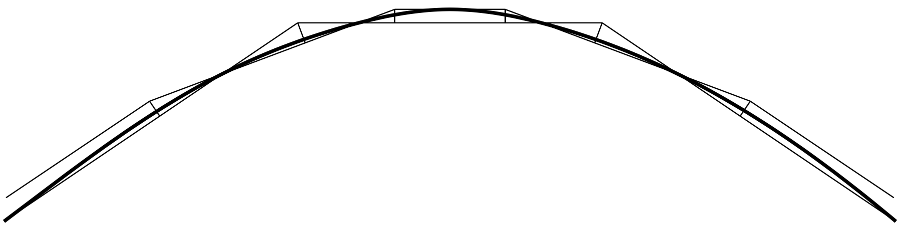


Fig. 5-24 Fitted arch axis of two-hinged arch

5.5.2 Comparison of structural behavior with two-hinged arch

The mechanical behavior of the two-hinged arch is analyzed. The computed results compared with the woven arch models with rigid joint under the same load Cases 1 to 8 are shown in **Table 5-7** and **Fig. 5-23**, where the forces of the model arches are obtained from the arithmetic sum of the forces of the two systems.

Table 5-8 Horizontal thrust at arch springing

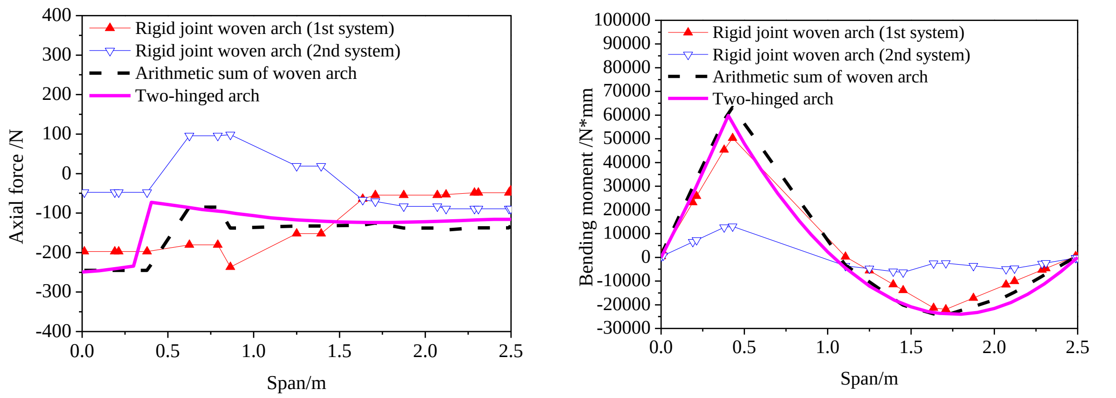
Load case	Two-hinged arch (N)	Woven arch with rigid joint (N)
Case 1	114.93	132.75
Case 2	201.19	220.72
Case 3	226.76	253.35
Case 4	542.88	602.32
Case 5	229.87	269.80
Case 6	402.38	431.07
Case 7	453.51	502.28
Case 8	1085.76	1226.53

Table 5-7 shows that the woven arch has the horizontal thrusts similar to that of the two-hinged arch under vertical loads although it is bigger than that of two-hinged arch. It also can be found the horizontal thrust becomes bigger and bigger as the load moves from arch spring to crown with the same load value. This tendency is also similar to the two-hinged arch.

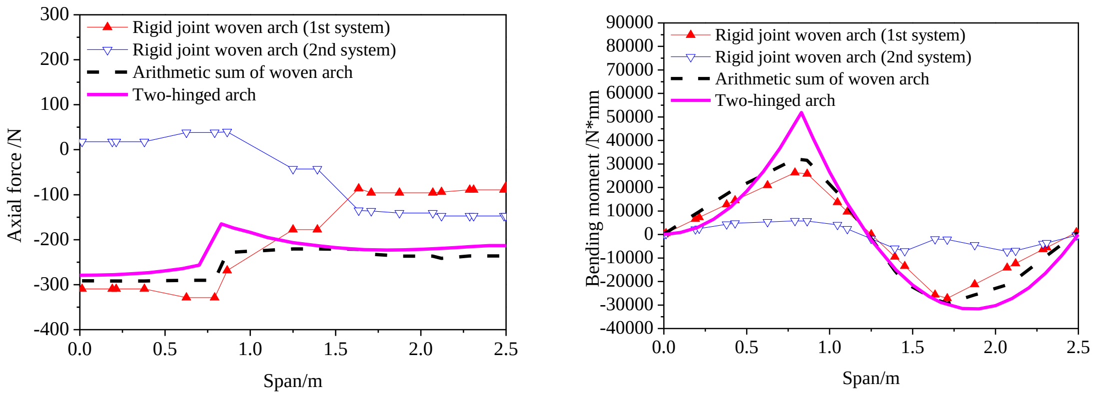
Fig. 5-23 demonstrates that the woven arch bears the similar compression forces as the two-hinged arch, and the arithmetic sum of axial forces in two systems of woven arch is very close to the two-hinged arch regardless of symmetrical or asymmetrical loads. At the same time, in general, the compression force of the first system is larger than that of the second system.

Under asymmetric load, the local bending moments of the second system and the first system are very small, and similar to that of two-hinged arch, respectively; the arithmetic sum of bending moments in two systems of woven arch is very close to the two-hinged arch. The bending moment of the woven arch is smaller than that of two-hinged arch. Under symmetric load, the local bending moment of the second system is also very small; but the arithmetic sum of bending moments in two systems of woven arch is not very close to that of the two-hinged arch except Case 5 due to the large difference in the local bending moment between the first system and two-hinged arch. Especially for load case 6, the bending moment of woven arches is close to zero. It shows the load case 6 is close to a uniform one for woven arch.

It can be thought that the mechanical behavior of woven arch is similar to that of the two-hinged arch, and the first system mainly bears the applied load in the woven arch.

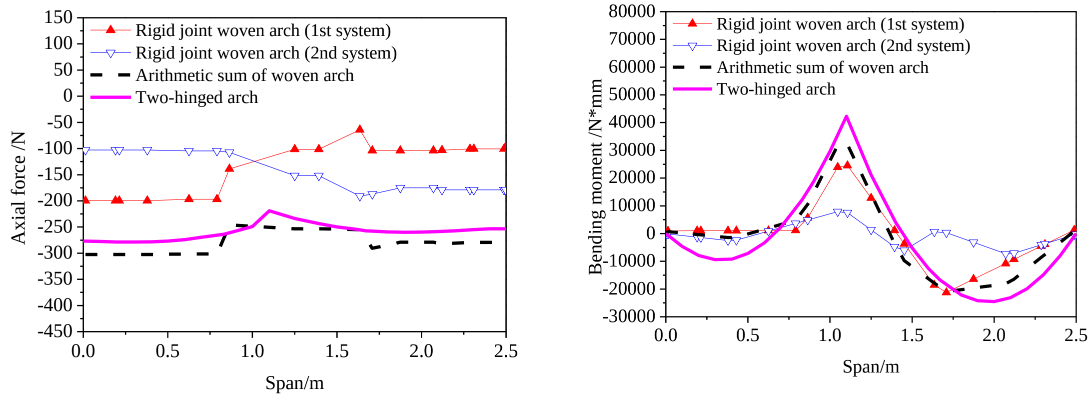


(a) Case 1

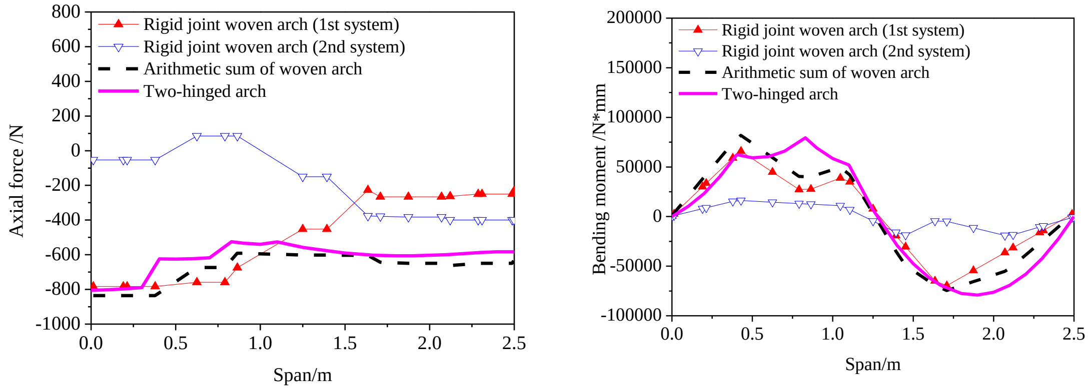


(b) Case 2

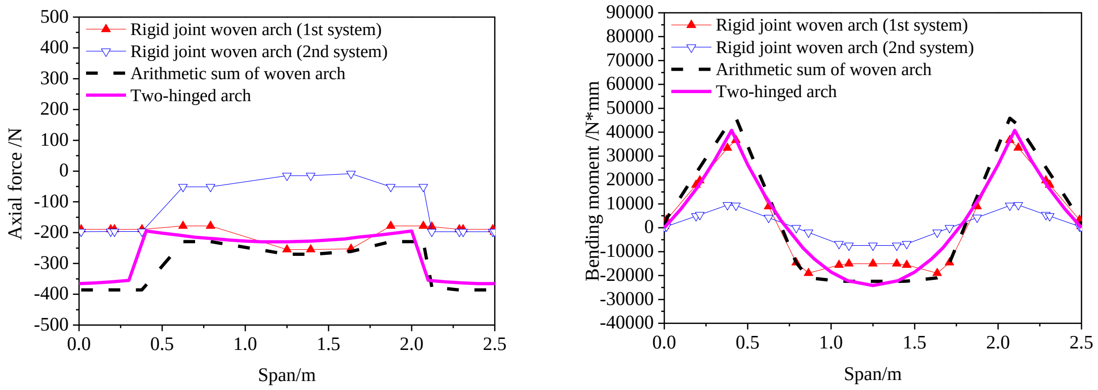
Fig. 5-25 Comparison of internal force with two-hinged arch



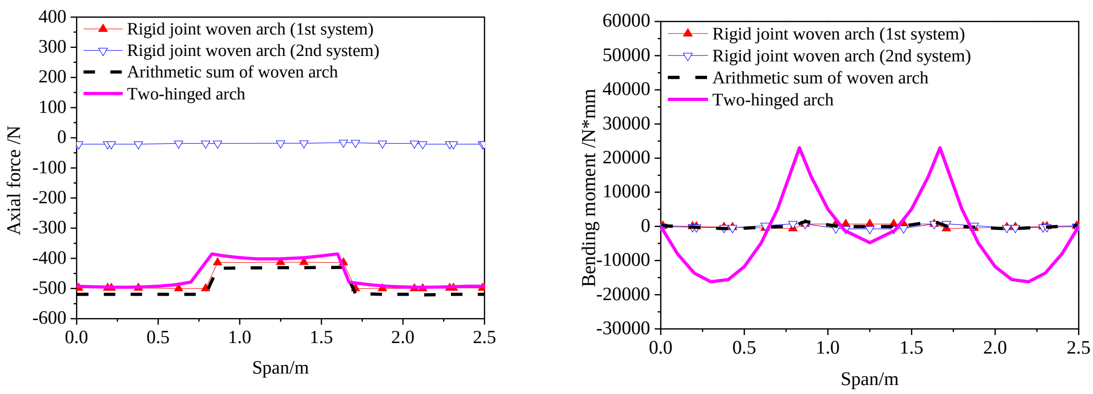
(c) Case 3



(d) Case 4

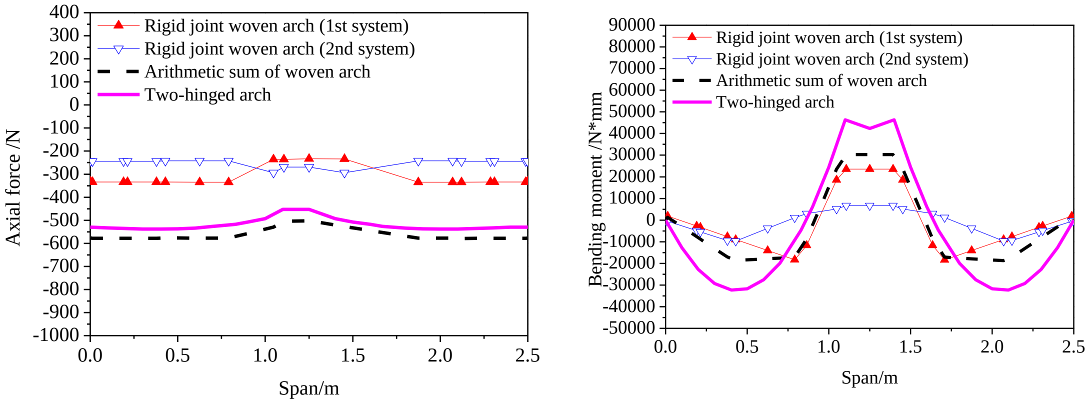


(e) Case 5

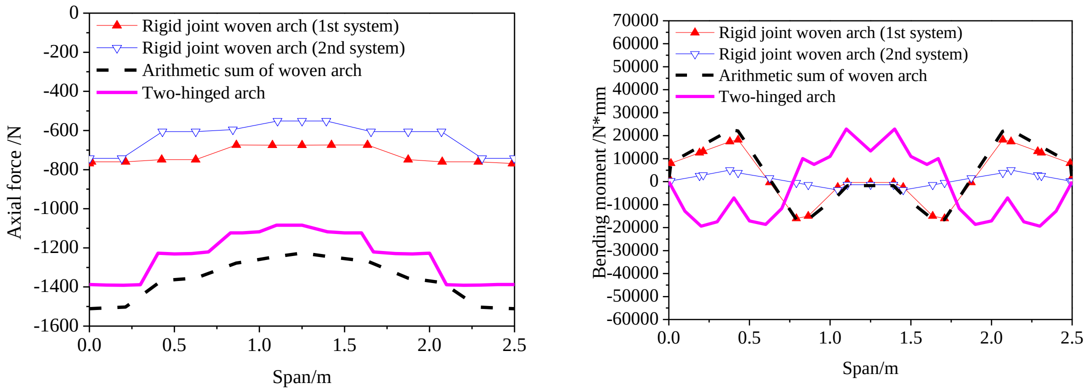


(f) Case 6

Fig. 5-26 Comparison of internal force with two-hinged arch (contd.)



(g) Case 7



(h) Case 8

Fig. 5-27 Comparison of internal force with two-hinged arch (contd.)

By analysis and comparison on the structure of above two models, structure mechanics of woven arch is extremely similar to two-hinged arch. The two systems with mechanics characteristic of arch can force together, and the bending moment at nodes is smaller than two-hinged arch. Therefore, the paper considers that Min-zhe Timber Arch Bridge as same as Bianhe Rainbow Bridge belongs to arch structure. So, the past names with "Beam"(such as "combined beam arch", "combined beam timber arch bridge", woven timber arch beam bridge" and so on) regarded as arch-beam or combined beam-arch structure easily lead to misunderstanding and confusion, and should not be used again. At the same time, the name "Chinese timber arch bridge" including "Bianhe Rainbow Bridge" and "Min-zhe Timber Arch Bridge" should be uniformly accepted by officials and academics.

5.6 Discussion on Origin of Timber Arch Bridges from Structural Behavior

According to the description in Chapter one, there are three different opinions on the origin of the Chinese timber arch bridges. One considers the Bianhe Rainbow Bridge as the original; the other maintains that the Min-Zhe Timber Arch Bridge is the original one, while the third opinion states that the two branches developed independently. In this section, the comparison analysis on mechanics behavior of two branches of woven bridge had been carried out by finite element method. The purpose is to discussion on origin of Chinese timber arch bridge from structural behavior.

5.6.1 Brief introduction of three opinions

Opinion A: Bianhe Rainbow Bridge is the original

In the History of Technique of Archaian Bridges in China published in 1986, the author conjectured that the Chinese timber arch bridge originated from the Bianhe Rainbow Bridge, and the extant Min-zhe Timber Arch Bridge was introduced after the ancient Bianhe Rainbow Bridge when the capital of the Northern Song Dynasty moved from Dongjing to Lin'an (now Hangzhou, Zhejiang Province) in the South Song Dynasty to start a new period. The differences between the Min-zhe Timber Arch Bridge and the Bianhe Rainbow Bridge stemmed from differences in local geographical conditions and characteristics of architecture. The Min-zhe Timber Arch Bridge is a combination of the Bianhe Rainbow Bridge and local wooden craftsmanship [6].

This conjecture has been accepted by many researchers [7]-[11]. In addition, experts and scholars brought forth further arguments as follows:

1) Many historical records have shown that the Bianhe Rainbow Bridge appeared earlier than the Min-zhe Timber Arch Bridge. The former had been built in the Song Dynasty, while archaeological discovery found no evidences to prove that the Min-zhe Timber Arch Bridge had existed before the South Song Dynasty (1126 - 1279) [11].

2) Most families with strong backgrounds in traditional construction technologies come from the north of China. Therefore, the timber bridge technology must have

spread from north to south through these families [11].

3) The cradle of the Bianhe Rainbow Bridge was in the capital of China in the Song Dynasty, which had better economy and advanced technology. At the same time, the Fujian and Zhejiang provinces were major areas in the Song Dynasty, planting and producing tea for the imperial group. The economy, technology, and information exchanges were relatively frequent between the north of China and Fujian and Zhejiang provinces at the south of China in those days. Therefore, it was possible that merchants and craftsmen spread advanced technology from the capital to other places [11].

Opinion B: Min-zhe Timber Arch Bridge is the original

Some other researchers [12]-[17] conjectured that the Chinese timber arch bridges originated from the Min-zhe Timber Arch Bridge based on the following investigations:

1) A piece of tile made in the Tang Dynasty (618 - 907) was found on the roof of a covering house in one of the extant Min-zhe bridges, the Santiao Bridge located in Taishun County of Zhejiang Province. From this fact, some researchers inferred that the Santiao Bridge had been built in the Tang Dynasty (618 - 907 AD), much earlier than the time the first Bianhe Rainbow Bridge was built [12].

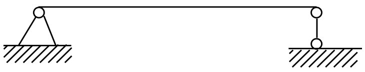
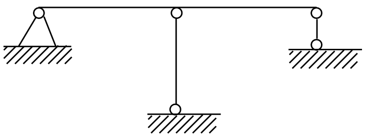
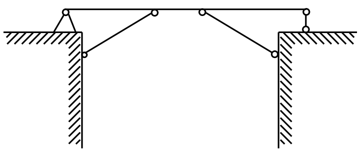
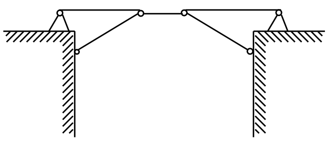
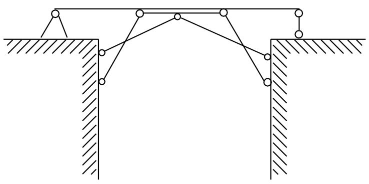
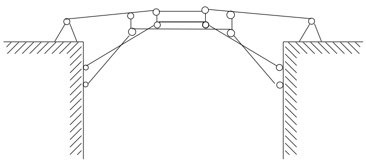
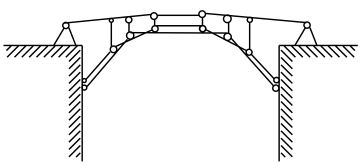
2) Historical records and field surveys show that a series of wooden construction bridges had been built in Fujian and Zhejiang Province. These bridges include simple beam bridges, timber beam bridges with columns, timber beam bridges with inclined races, secondary beam-braced timber bridges, timber bridges with combined braces, and woven timber arch bridges shown in **Table 5-8**, forming a complete construction development system in timber structural bridges [12]-[17]. Theses bridge types consists of whole chains of woven timber arch bridges and may indicate that the Min-zhe Timber Arch Bridge must have developed solely from local timber bridges.

Opinion C: The two kinds of timber arch bridges developed independently

The third opinion is that the two types of bridges perhaps originated and developed independently [11] [18]. Researchers supporting this opinion consider that there were no technology exchanges and communication between the builders due to inconvenience in transportation and communication as well as long and frequent wars.

In addition, there are no historical records due to the wars. The other reason is that these two kinds of bridges differ in appearance and in structural forms.

Table 5-9 A series of timber bridges in Fujian and Zhejiang provinces.

No.	Type	Simplified plane schemes	Bridge name, location	Photo
1	Simple beam bridge		Hua Bridge, Pingnan county of Fujian province	
2	Timber beam bridge with column		Guangtong Bridge, Pingnan county of Fujian province	
3	Timber beam bridge with inclined braces		Jichuan Bridge, Pingnan county of Fujian province	
4	Secondary beam braced timber bridge		Shengxian Bridge, Shouning county of Fujian province	
5	Timber bridge with combined braces		Meishuban Bridge, Xinchang county of Zhejiang Province	
6	Double secondary beam braced timber bridge		Xingrong Bridge, Shuncang county of Fujian province	
7	Min-zhe Timber Arch Bridge		Yingfeng Bridge, Pingnan county of Fujian province	

5.6.2 Discussion on the origin of Chinese timber arch bridges

(1) Discussion on opinion A: Bianhe Rainbow Bridge is the original

From the comparison of the two types of the Chinese timber arch bridges, it can be found that the Min-zhe Timber Arch Bridge with floor system and covering house is more functional than the Bianhe Rainbow Bridge. The road slope of the bridge deck of the Min-zhe Timber Arch Bridge is small and easy for passengers and carriages to pass through; the covering house can provide relaxing and public space for passengers and villagers. In the structural details, the spandrel structure, the X-bracings, as well as the inserted wood blocks among the logs in the Min-zhe Timber Arch Bridge take part in carrying loads and enhancing the integrity and stability of the arch structure. The covering house can add dead load to the structure to improve the structure's resisting capacity to the uplift load. Therefore, it can be concluded that the Min-zhe Timber Arch Bridge is better in traffic function and more reasonable in structure than the ancient Bianhe Rainbow Bridge.

From a reasonable consideration of technological development, an advanced bridge structure generally evolves from experiences with a primitive one. In this sense, it is more reasonable to consider that the Min-zhe Timber Arch Bridge developed from the Bianhe Rainbow Bridge.

Furthermore, the reasons for opinion A seem more reasonable from the historic background and general knowledge than those for opinions B and C, which will be discussed in the following sections.

Consequently, the authors suggest that this opinion, that is, that the Bianhe Rainbow Bridge is the original bridge, could be the prevailing statement, unless new and further research results prove otherwise.

(2) On opinion B: The Min-zhe Timber Arch Bridge is the original

As for opinion B, which asserts that the Min-zhe Timber Arch Bridge is the original, some doubts are raised as follows:

This opinion mainly stands on a piece of tile made in the Tang Dynasty found in Santiao Bridge. Except for a member or a piece of tile, no other proof and available historical record, such as folk story or bridge stone tablet record, can show that one of the Min-zhe Timber Arch Bridges was built earlier than the Bianhe Rainbow Bridge. The evidence is inconclusive, as we all know that timber structures need frequent maintenance, repair, and rebuilding. In those times, it was customary to use not only the original members of the building but also members from other buildings. Thus, it is possible that the tile made in Tang Dynasty was obtained from other buildings.

The complete system of timber bridges listed in **Table 5-8** is the other main argument for opinion B. However, there is no sound evidence to show that the series of the bridge structures developed in that order. From the present investigation, we found few pieces of evidence that the development sequence of the series bridge structures does not agree with the opinion. For example, according to opinion B, the double three-member timber arch bridge as shown in the sixth row of **Table 5-8**, should be built earlier than most of the Ming-zhe timber arch bridges, which have three members in the first system and five members in the second system as shown in the seventh row of **Table 5-8.** However, the field survey by the authors[18)] reveals that there are only six bridges with the double three members in service and they were all built after 1800 (Qing Dynasty (1644-1911)), while there are 130 Min-zhe Timber Arch Bridges in service and about half of them were built before 1800. Therefore, we maintain that the origin of these double three-member timber arch bridges should be later than Min-zhe Timber Arch Bridges, and this type of bridge is a simplified structure of the general Min-zhe Timber Arch Bridge.

Even though the development shown in **Table 5-8** is correct, the authors think that the table cannot support the opinion since the relationship between the Bianhe Rainbow Bridge and Min-zhe Timber Arch Bridge is still unclear.

(3) On opinion C: The two branches of timber arch bridges developed independently

The third opinion is a compromise between the other two opinions. It is possible for ancient bridges to evolve similarly but independently in various continents of the world. However, it is quite difficult to imagine that the two types of the Chinese timber arch bridge have evolved independently with so unique but similar structures, in two regions close to each other in a nation.

The analysis results show that the Min-zhe Timber Arch Bridge has better traffic performance than the Bianhe Rainbow Bridge. The covering house of the Min-zhe Timber Arch Bridge can additionally serve as a public space where passengers and villagers can relax. The spandrel structures, X-bracings, as well as the inserted wood blocks among the logs in the Min-zhe Timber Arch Bridge take part in carrying loads and enhancing the integrity and stability of the arch structure. The covering house adds a dead load to the structure to improve the structure's resisting capacity to the uplift load.

Therefore, based on a reasonable consideration of technological development, the authors take the more reasonable conclusion that the Min-zhe Timber Arch Bridge developed from the Bianhe Rainbow Bridge. In other words, we support opinion A unless new and further research results can prove otherwise [13].

5.7 Summary

The mechanical behaviors of woven timber arch bridge were investigated by finite element analyses under different symmetrical or asymmetrical loading cases. The findings obtained in the present study are summarized as follows:

(1) The woven arch under either symmetrical or asymmetrical loading, it would have vertical and longitudinal displacement, and the vertical displacement was greater than the longitudinal displacement. Moreover, the vertical deformation under asymmetrical loading was greater than its counterpart under symmetrical loading.

(2) The two systems were mainly subjected to compression, and the first system was the main structure to sustain the compression.

(3) The rigidity of joint does not change the deformation tendency of wove arch, but the deflection of woven arch with hinged joint is great than the woven arch with rigid joint. The mortise-tenon joint simplified as hinged joint is better conservative calculation for simplified calculate.

(4) The maximum stress of arch ribs under either half- span or full-span pedestrian loading were much lower than the measured compressive strength of 111.6 MPa. However, the vertical displacement under asymmetrical loading was much larger than the required value by the General Code for Design of Highway Bridges and Culverts (1/1000 of calculation span length). Thus, the structural deformation may be the main

factor for the design of Min-Zhe woven timber arch bridges, and sectional stress should also be considered.

(5) The further analysis shows that the spandrel structure is benefit for wove arch, and the internal force of full-bridge is smaller than the bare arch in the same load value, presenting the spandrel structure will participate in bearing the loading of the structure.

(6) The structure mechanics of woven is extremely similar to two-hinged arch. The sum of axial force of two systems is similar to the two-hinged arch, and the bending moment at nodes is smaller than two-hinged arch.

(7) According to the comparison results which are described in Chapter 2, the Min-zhe Timber Arch Bridge has better traffic performance than the Bianhe Rainbow Bridge. And then, the analysis results on this chapter, the spandrel structures, X-bracings, as well as the inserted wood blocks among the logs in the Min-zhe Timber Arch Bridge take part in carrying loads and enhancing the integrity and stability of the arch structure. The covering house adds a dead load to the structure to improve the structure’s resisting capacity to the uplift load. Based on a reasonable consideration of technological development, the author made a more reasonable conclusion that the Min-zhe Timber Arch Bridge developed from the Bianhe Rainbow Bridge.

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CHAPTER 6

EXPERIMENTAL STUDY ON AN EXISTING MIN-ZHE TIMBER ARCH BRIDGE

6.1 Introduction

In this chapter, in order to investigate structural behavior of the Min-zhe timber arch briges by modern bridge engineering method, an existing single Min-zhe Timber Arch Bridge, Xi’nan Bridge, which has been [illegible] described in Chapter 4, is taken as the case study. Field testing of the bridge is first introduced, and then its behaviors are analyzed by both the finite element method using a general computer software and the procedure proposed in Chapter 5.

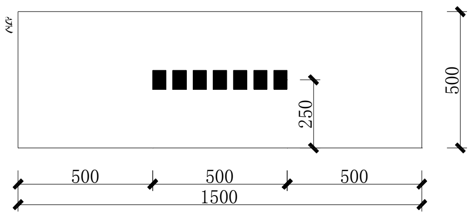
Xi’nan Bridge shown in **Fig. 4-1**, is located in Xi’nan village, Nanyang town, Shouning county, Fujian province. It is a single span Min-zhe Timber Arch Bridge with a covering house, which has 9 rooms, 40 columns, a single eaves and double pitched roofs. The field measurement result shows that it has a length of 20.3 m, a width of 5 m and a clear span of 15.33 m. The clear rise of the arch is 3.4 m with a span-rise ratio of 1 to 4.5. The bridge was taken as a prototype for the experimental models in Chapter 4.

The superstructure of Xi’nan bridge, including a main arch ring, spandrel structure and the covering house are made of Chinese firs woods. The two abutments of the bridge are built with block stones. It was re-constructed with traditional construction technology by some experienced craftworkers in 1966. Under the careful protection by local government and local people, the bridge is in a good condition. No obvious damage, corrosion and weathering were found in the whole structure and components.

6.2 Field Testing

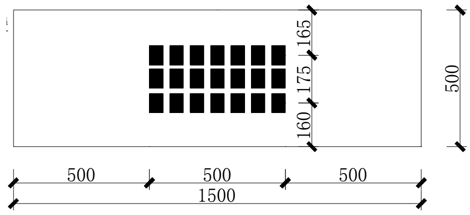
6.2.1 Test process

Two load cases were employed, including a uniform symmetrical load case and an asymmetrical concentrated load case [1], as illustrated in **Fig. 6-1**.

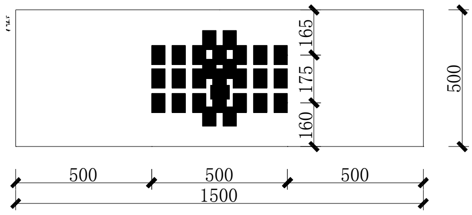


(a) Uniform symmetrical load (0.5t)

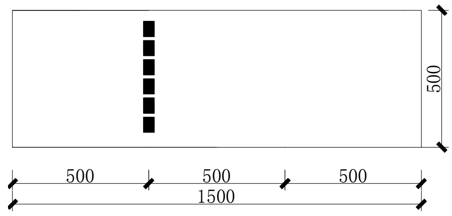
Fig. 6-1 Load cases



(b) Uniform symmetrical load (1.5t)



(c) Uniform symmetrical load (2t)



(d) Asymmetrical concentrated load

Fig. 6-2 Load cases (contd.)

A uniform symmetrical load case with three steps was loaded at the deck system from No.2 transverse beam to No.2' transverse beam, as shown in **Table 1** and **Figs. 6-1(a)-(c).** An asymmetrical concentrated load was loaded at the deck transverse beam No.2, as shown in **Fig. 6-1(d).**

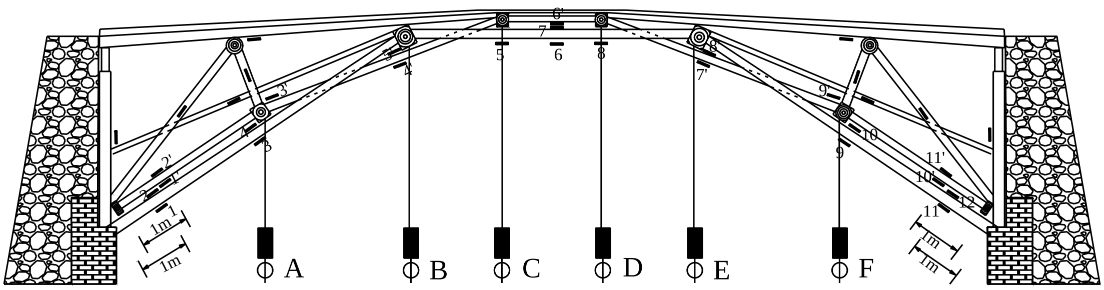
Table 6-1 Number and location of transverse beam

Transverse beam No.	Description
1 (1')	Deck transverse beam closed to the left (right) spring, supported by two groups spandrel columns, one to the spring, the other to the 2nd system in the left (right)
2 (2')	Transverse beam of 1st system in the left (right)
3 (3')	Upper transverse beam of 2nd system in the left (right)
4 (4')	Lower transverse beam of 2nd system in the left (right)

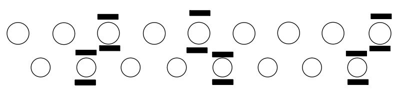
Six centesimal meters were used to measure the vertical displacements of the six transverse beams of the two systems along the center line of the bridge, as shown in **Table 2** and **Fig. 6-2**. A total of 93 strain gauges and rosettes were positioned in the whole bridge, including 36 in the first system, 33 in the second system, 4 in X-bracing, 10 in spandrel column, 4 in springing column and 6 in deck longitudinal beam, as shown in **Fig. 6-2(b)**. A commercially available data acquisition system DH3816, running on a personal computer, as shown in **Fig. 6-3**, was used to record the readings of the centesimal meters and resistance strain gauges. A total of 99 channels were used for each test, in which 6 channels were used for centesimal meters and 93 channels for strain gauges.

Table 6-2 Number and location of the centesimal meters

The centesimal meters number	Measuring point location (The transverse beam number)
A	Lower transverse beam of 2nd system in the left (4)
B	Transverse beam of 1st system in the left (2)
C	Upper transverse beam of 2nd system in the left (3)
D	Upper transverse beam of 2nd system in the right (3’)
E	Transverse beam of 1st system in the right (2’)
F	Lower transverse beam of 2nd system in the right (4’)



(a) Centesimal meters distribution in longitudinal

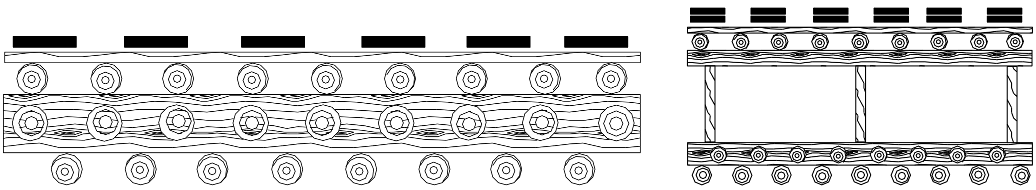


(b) Strain gauge distribution in transverse section

Fig. 6-3 Monitoring point arrangement of Xi’nan Bridge

Fig. 6-4 Data acquisition system

The loading was conducted by sandbags. The locations of sandbags in transverse directions are shown in **Fig. 6-4**, and their weights are listed in **Table 6-3**. In the test, each sandbag was weighted before it was placed on the bridge. For each load case, two to four loading steps were tested. Before the formal test, preliminary test with three load cases was carried out to check the setup and instrumentation. In each load case, testing loads were applied twice. Measurements were taken after the test loads were applied for twenty minutes to obtain steady data. One more measurement was taken after the loads were removed from the bridge. Some photos of loading test are shown in **Fig. 6-5**.



(a) Load case A1-(2) (b) Load case A2-(1)

Fig. 6-5 Test load arrangement in transverse directions

Table 6-3 Testing load

Asymmetrical			Symmetrical		
Load case	Location (Number of transverse beam)	Load value (kN)	Load case	Location (Number of transverse beam)	Load value (kN)
A1-(2)	2	9.6	S1-(2-2’)	2,2’	19.2
A2-(1)	1	9.6	S2-(1-1’)	1,1’	19.2
A3-(3)	3	9.6	S3-(3-3’)	3,3’	19.2

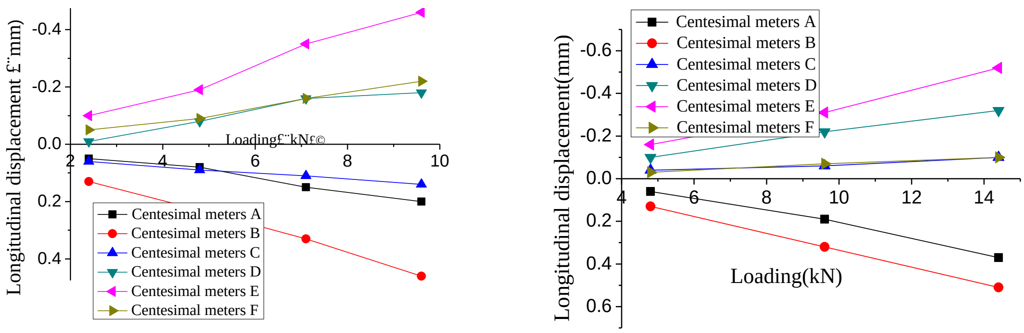
(a) Uniform symmetrical load　　(b) Asymmetrical concentrated load

Fig. 6-6 Load testing on the bridge

6.2.2 Test results

As the Xi'nan Bridge has been in the list of heritage of the local county since 2003, the test loads had been limited in a small value. Therefore, the test results of strains of the structural members are very small, the results of strains are not been presented and the vertical displacement is the main test result, which will be discussed in this paper.

The vertical load-deformation curves under load case A1-(2) and load A2-(1) with four load levels and three load levels are shown in **Fig. 6-6**, respectively, It can be seen that the relationship of deflection and load is almost linear. The test results of all load cases are summarized in **Table 6-4**. It is obvious that the deflection value of the bridge subjected to the asymmetrical concentrated load is larger than that subjected to the symmetrical concentrated load.



a) Load case A1-(2)　　b) Load case A2-(1)

Fig. 6-7 Load-deformation curves

Table 6-4 Test results of deflection (unit: mm)

Transverse beam's number	Centesimal meter's number	A1-(2)	A2-(1)	A3-(3)	S1-(2-2')	S2-(1-1')	S3-(3-3')
		0	0	0	0	0	0
4	A	0.2	0.19	0	0.06	0.03	0
2	B	0.43	0.32	0.28	0.23	0.19	0.23
3	C	0.14	-0.06	0.88	0.08	-0.19	1.29
3'	D	-0.18	-0.22	0.35	-0.08	-0.23	1.22
2'	E	-0.46	-0.31	-0.2	-0.09	-0.09	-0.07
4'	F	-0.22	-0.07	0	-0.36	-0.14	-0.04
		0	0	0	0	0	0

6.3 Finite Element Analysis

6.3.1 Description of finite element model

A three-dimensional finite element model was developed to analyze the Xi'nan Bridge by using Midas/Civil, a popular finite element analysis software. The arch rib, transverse beam, spandrel structure, column and longitudinal beam of deck system were modeled by beam element with two nodes, each node has three translational and three rotational DOFs. The mortise-tenon joints of two systems were simulated by spring elements. The connection between the transverse beams in the first system (second) and the longitudinal members of the second (first) system was modeled by compression-only spring element in vertical direction and shearing-only spring element in longitudinal direction. The arch springing of the first system was modeled as hinges in which the translational displacements (Dx, Dy, Dz) are constrained, while the rotations (Rx, Ry, Rz) are free [2]-[5]. The arch springing of the second system connected with the bottom transverse beam, the bottom transverse beam connected with the column of abutment and the arch ribs of the first system were modeled with the spring elements. As a result, the model has a total of 646 nodes, 528 beam elements, 5 types of cross sections, and 424 elastic joints. **Fig. 6-7** shows the full three-dimensional view of the finite element model.

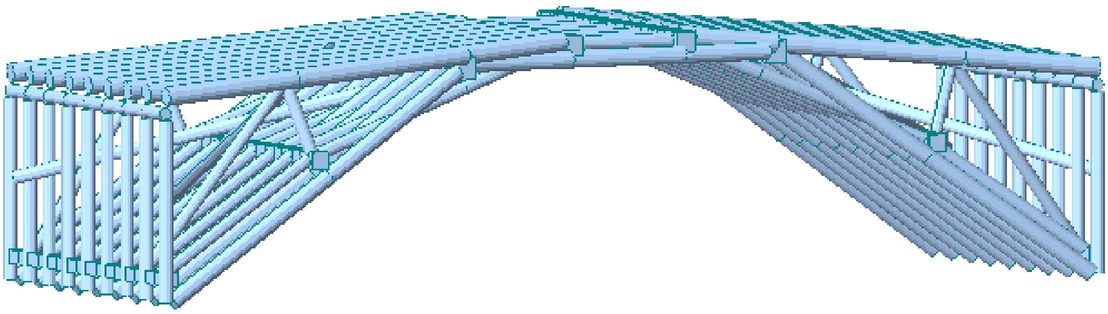


Fig. 6-8 Finite element model of the Xi'nan Bridge

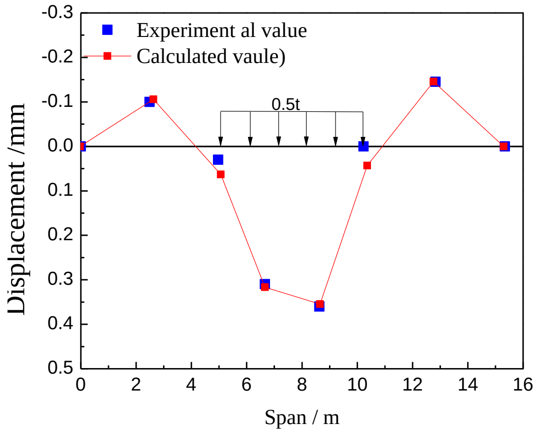
In this calculation, the wood was modeled with user-defined materials. Material properties are shown in **Table 6-5**. The density is taken as 2950 kg/m^3 and the elastic modulus is taken as 9300 MPa based on the actual test values. The other parameters are calculated by 《*the design specifications of timber structure in China*》, which the axial compressive strength is taken as 10 MPa, bending strength is 11 MPa, and the Poisson ratio is 0.25 [6][7].

Table 6-5 Material properties

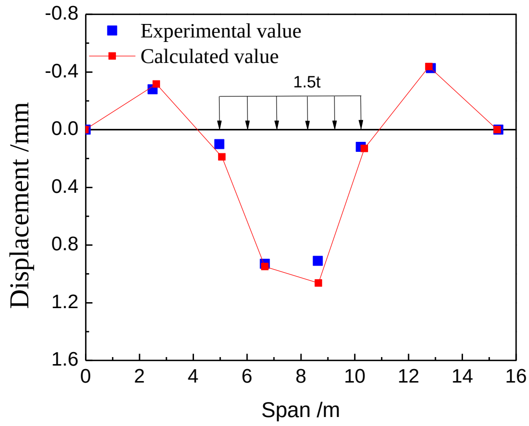
Density	Poisson ratio	Elastic modulus	Axial compressive strength	Bending strength
2950 kg/m^3	0.25	9300 MPa	10 MPa	11 MPa

6.3.2 Finite element results and comparison with test results

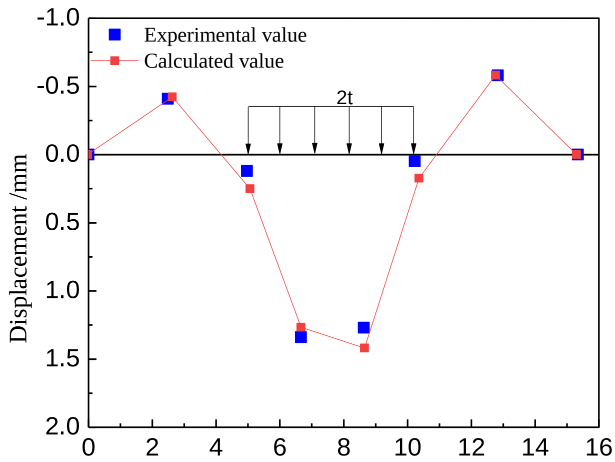
Fig. 6-8 shows the comparison results of field test and FE analysis for the deflections of real bridge under case 1. It can be found that the computed results and the test ones are basically consistent. However, since the wood material property shows larger discreteness and the structure of real bridge is not a strict symmetric structure made by the primitive construction method, test results indicated some difference from the calculation results by an ideal structure. The maximum deflection of experiment is 0.35 mm, 1.06 mm and 1.42 mm for three steps of case 1, respectively. The maximum deflection of calculation is 0.36 mm, 0.93 mm and 1.34 mm for three steps of case 1, respectively. The maximum of relatively error values is 12.26%.



(a) P=0.5t



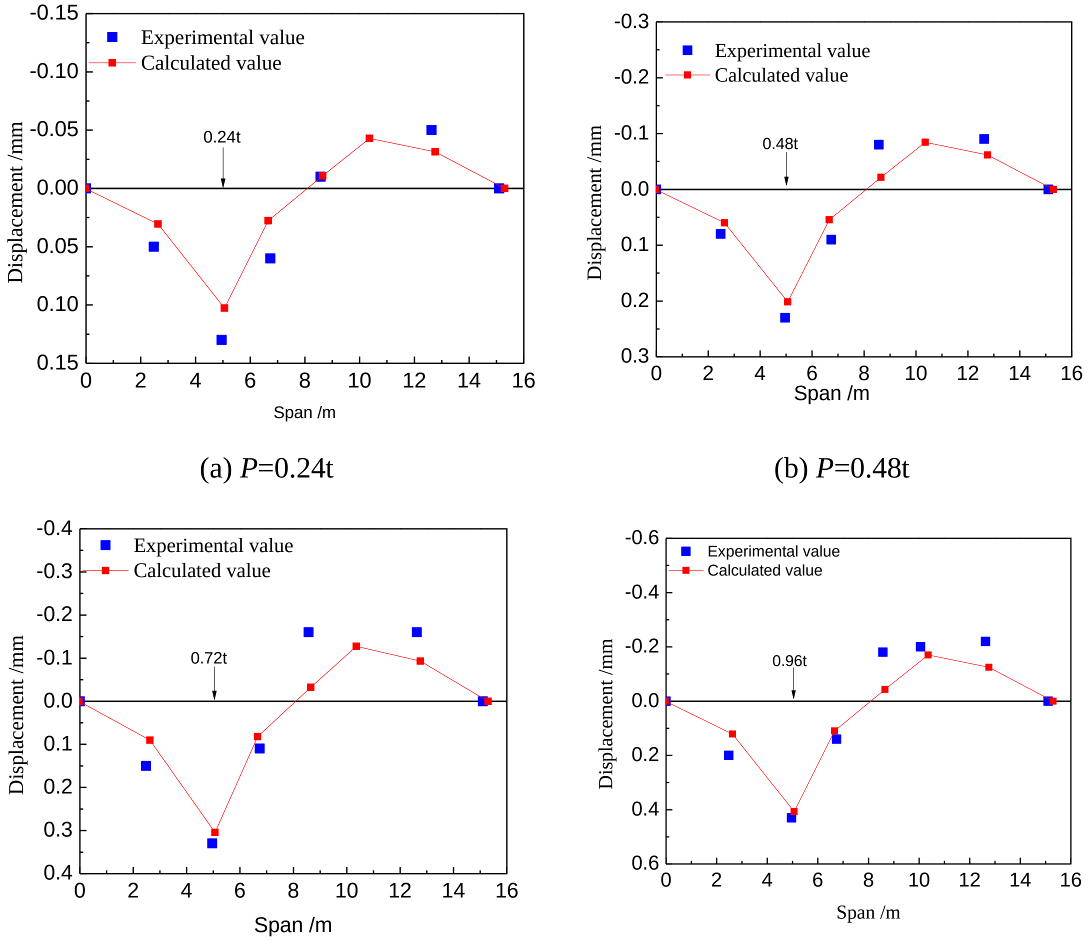
(b) P=1.5t



(c) P=2t

Fig. 6-9 Comparison of experimental value with calculated value under load case 1

Fig. 6-9 shows the comparison results of field test and FE analysis for the deflections of real bridge under case 2. The maximum deflection of experiment is 0.10 mm, 0.20 mm, 0.30 mm and 0.41 mm for four steps of case 2, respectively. The maximum deflection of calculation is 0.13 mm, 0.23 mm, 0.33 mm and 0.43 mm for four steps of case 2, respectively. In some symmetrical loading cases, relatively large error can be observed. It might be caused by the very small displacements under load case 2, which turn small absolute error values into large percentage errors. However, the **Figs. 6-8** and **6-9** show the very good agreements between tested and computed results in general. Therefore, the FE model verified by the test can be used to analyze the woven arches accurately and efficiently.



(a) *P*=0.24t (b) *P*=0.48t

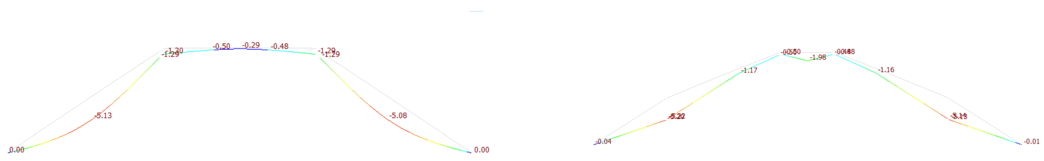
(c) *P*=0.72t (d) *P*=0.96t

Fig. 6-10 Comparison of experimental value with calculated value under load case 2

6.3.3 Analysis on mechanical behavior of Min-zhe Timber Arch Bridges

6.3.3.1 Symmetrical loading

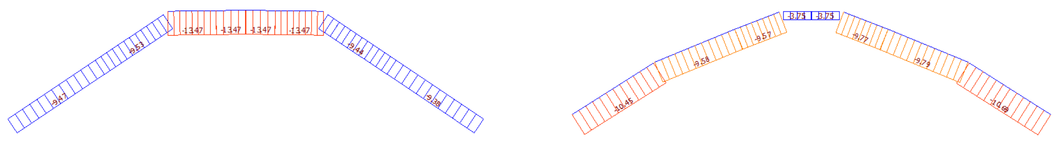
According to the 《*Highway bridge design general specification*》, the load standard value of pedestrian bridge is 3.5 kN/m^2 . The displacement of two systems under symmetrical loading with the value of 3.5 kN/m^2 as shown in **Fig. 6-10**. The maximum displacement of 1st and 2nd system is 5.13 mm and 5.22 mm, respectively.



(a) 1st system (b) 2nd system

Fig. 6-11 Displacement of two systems under symmetrical loading

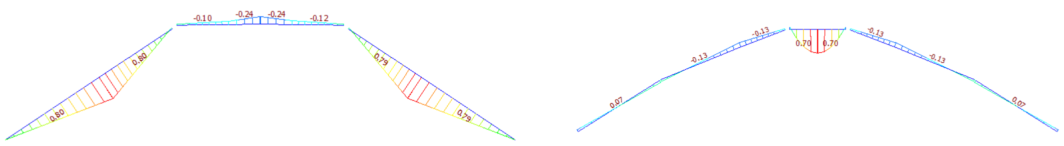
Axial force of two systems under symmetrical loading as shown in **Fig. 6-11.** Two systems of main arch structure are mainly subjected to the compression. The maximum axial force of 1st and 2nd system is 13.47 kN and 10.69 kN, respectively.



(a) 1st system (b) 2nd system

Fig. 6-12 Axial force of two systems under symmetrical loading

Bending moment of two systems under symmetrical loading as shown in **Fig. 6-12.** There are lager local bending moments at the slant arch rib of 1st system and the level arch rib of 2nd system. The maximum bending moment of 1st system is 0.80 kN·m.



(a) 1st system (b) 2nd system

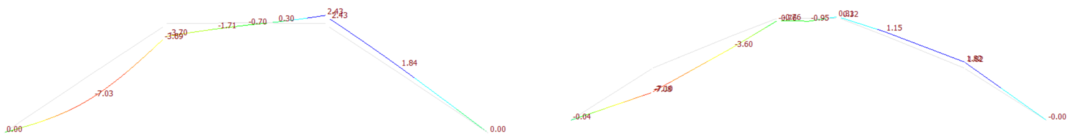
Fig. 6-13 Bending moment of two systems under symmetrical loading

Table 6-6 Displacement and internal force of two systems under symmetrical loading

1st system			
Longitudinal Coordinate (m)	Vertical displacement (mm)	Axial force (kN)	Bending moment (kN·m)
0.00	0	-9.47	0.00
2.79	-5.13	-9.47	0.80
2.79	-5.13	-9.53	0.80
4.98	-1.29	-9.53	-0.04
5.11	-1.30	-13.47	-0.03
6.66	-0.50	-13.47	-0.10
6.66	-0.50	-13.47	-0.10
7.61	-0.29	-13.47	-0.24
7.61	-0.29	-13.47	-0.24
8.55	-0.48	-13.47	-0.12
8.55	-0.48	-13.47	-0.12
10.10	-1.29	-13.47	-0.03
10.24	-1.29	-9.44	-0.04
12.43	-5.08	-9.44	0.79
12.43	-5.08	-9.38	0.79
15.33	0.00	-9.38	0.00
2nd system			
Longitudinal Coordinate (m)	Vertical displacement (mm)	Axial force (kN)	Bending moment (kN·m)
0.03	-0.04	-10.45	-0.06
2.61	-5.20	-10.45	0.07
2.65	-5.22	-9.58	0.06
5.18	-1.17	-9.58	-0.13
5.18	-1.17	-9.57	-0.13
6.59	-0.50	-9.57	-0.04
6.73	-0.50	-3.75	-0.06
7.61	-1.98	-3.74	0.70
7.61	-1.98	-3.74	0.70
8.49	-0.48	-3.75	-0.07
8.63	-0.48	-9.77	-0.04
10.04	-1.16	-9.77	-0.13
10.04	-1.16	-9.79	-0.13
12.57	-5.14	-9.79	0.06
12.61	-5.13	-10.69	0.07
15.33	-0.01	-10.69	-0.06

6.3.3.2 Asymmetrical loading

The displacement of two systems under asymmetrical loading with the value of 3.5 kN/m^2 as shown in **Fig. 6-12**. The maximum down and up displacement is 7.03 mm 2.43 mm at the load side and the other side, respectively.



(a) 1st system (b) 2nd system

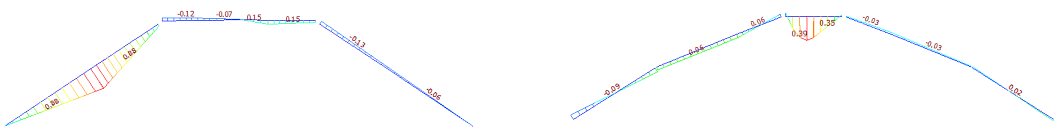
Fig. 6-14 Displacement of two systems under asymmetrical loading

Axial force of two systems under asymmetrical loading as shown in **Fig. 6-13.** The maximum axial force is 10.42 kN, the position is located at the slant arch rib of 1st system. The arch rib of the other side is subjected to the tension, but the value is small.

(a) 1st system (b) 2nd system

Fig. 6-15 Axial force of two systems under asymmetrical loading

Bending moment of two systems under asymmetrical loading as shown in **Fig. 6-14.** There are lager local bending moments at the slant arch rib of 1st system and the level arch rib of 2nd system. The maximum bending moment of 1st system is 0.88 kN·m.



(a) 1st system (b) 2nd system

Fig. 6-16 Bending moment of two systems under asymmetrical loading

Table 6-7 Displacement and internal force of two systems under asymmetrical loading

1st system			
Longitudinal Coordinate (m)	Vertical displacement (mm)	Axial force (kN)	Bending moment (kN·m)
0.00	0	-10.35	0.00
2.79	-7.03	-10.35	0.88
2.79	-7.03	-10.41	0.88
4.98	-3.69	-10.41	0.08
5.11	-3.70	-6.81	-0.12
6.66	-1.71	-6.81	-0.07
6.66	-1.71	-6.75	-0.07
7.61	-0.70	-6.75	-0.03
7.61	-0.70	-6.75	-0.03
8.55	0.30	-6.75	0.15
8.55	0.30	-6.69	0.15
10.10	2.43	-6.69	0.07
10.24	2.43	1.02	-0.13
12.43	1.84	1.02	-0.06
12.43	1.84	1.02	-0.06
15.33	0.00	1.02	0.00
2nd system			
Longitudinal Coordinate (m)	Vertical displacement (mm)	Axial force (kN)	Bending moment (kN·m)
0.03	-0.04	-9.88	-0.09
2.61	-7.08	-9.88	0.07
2.65	-7.10	-8.91	0.05
5.18	-3.60	-8.91	0.06
5.18	-3.60	-8.92	0.06
6.59	-0.76	-8.92	-0.05
6.73	-0.76	-1.85	-0.06
7.61	-0.95	-1.84	0.35
7.61	-0.95	-1.84	0.35
8.49	0.31	-1.84	-0.02
8.63	0.32	-0.82	-0.02
10.04	1.15	-0.82	-0.03
10.04	1.15	-0.82	-0.03
12.57	1.82	-0.82	-0.01
12.61	1.82	-0.74	-0.02
15.18	0.00	-0.74	0.02

It can be found from the above results that the maximum compressive stress and tensile stress of Xi'nan bridge are all far less than the measured compressive strength and tensile stress. The maximum displacement is very small, about 1/2000 of calculation span length. Thus, the Xi'nan bridge is still in good situation.

6.4 Summary

1) An existing Min-zhe Timber Arch Bridge has been tested and analyzed. The results from finite element method reasonably match the test ones. The finite element model can basically reflect the behaviors of the analyzed bridge.
2) Under the design load with the value of 3.5 kN/m^2, the displacement of Min-zhe Timber Arch Bridge is very small, about 1/2000 of calculation span length.
3) Under the design load with the value of 3.5 kN/m^2, two systems of main arch structure are mainly subjected to the compression under design load, and the first system is larger than the second system. Min-zhe Timber Arch Bridge is mainly subjected to the first system.
4) Under the design load with the value of 3.5 kN/m^2, the maximum compression stress and tensile stress of Min-zhe Timber Arch Bridge are all far less than the compressive strength and tensile stress.

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CHAPTER 7

SIMPLIFIED CALCULATION AND ANALYSIS OF CHINESE TIMBER ARCH BRIDGES

7.1 Introduction

Chinese timber arch bridge can be further divided into two branches: one is exemplified by the non-extant ancient Bianhe Rainbow Bridge, and the other by the extant Min-zhe Timber Arch Bridge, which had been introduced in the Chapter 2. The Bianhe Rainbow Bridge had been discovered earlier than Min-zhe Timber Arch Bridge, the research work had been carried out earlier, too. The simplified calculation model of Bianhe Rainbow Bridge had been proposed by some experts. In this chapter, the manual calculation model of Bianhe Rainbow Bridge will been introduced and comparatively validated by Structural Mechanics Solver Method and Finite Element Method, and then, according to the research results of Chapter 4 and Chapter 5, it had been proved that the manual calculation model of Bianhe Rainbow Bridge do not applicable for Min-zhe Timber Arch Bridge; finally, the simplified calculation model of Min-zhe Timber Arch Bridge have been proposed through research on the mechanism of combine work of two systems of Min-zhe Timber Arch Bridge.

7.2 Simplified Calculation Model of Bianhe Rainbow Bridge

7.2.1 Introduction of manual calculation model of Bianhe Rainbow Bridge[1]

7.2.1.1 Planar simplified model of Bianhe Rainbow Bridge

The ancient Bianhe Rainbow Bridge shown in famous painting of "Chhing-Ming Shang Ho Thu" (Festival of Pure Brightness on the River (**Fig. 2-1**), had been as a case in Chinese Timber Arch-Bridge. According to the description, the bridge with span of 18.5 m and rise to span ratio of 3.68. According to the detailed introduction of Bianhe Rainbow Bridge in Chapter 3, we know the crossbeams and arch ribs are connected by ropes, so the joint of Bianhe Rainbow Bridge can bear both compression and tension, but not bending moment. Therefore, the connection of arch ribs of the same system and the connection of arch ribs with the transverse beam can be imitated by hinge joints and half hinge joints, respectively, as shown in **Fig. 7-1**. When the two systems are analyzed respectively, we can find the first system is an unstable system with one degree of freedom and the second system is also an unstable system with two degree of freedoms, as shown in **Fig. 7-2**. Whereas, if the two systems are assembled together, with the half hinge imitating the connection between the transverse beam and its lower arch ribs, we analyze the two systems as a whole like the structure turns to double statically indeterminate structure with high stability, the planar simplified schematic diagram of Bianhe Rainbow bridge, as shown in **Fig. 7-3**

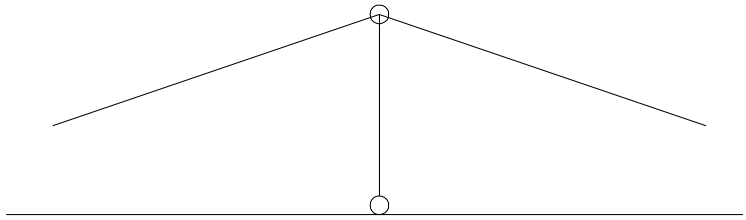
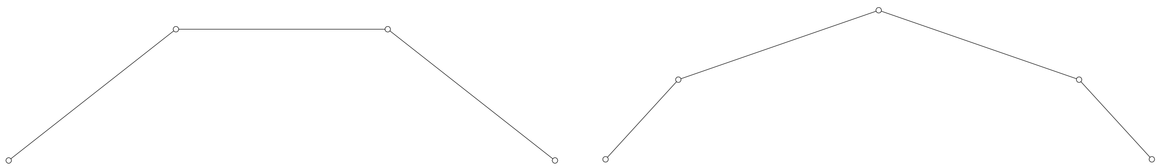


Fig. 7-1 Planar simplification of connection constructions



(a) 1st system (b) 2nd system

Fig. 7-2 Simplified model of two systems of Bianhe Rainbow Bridge

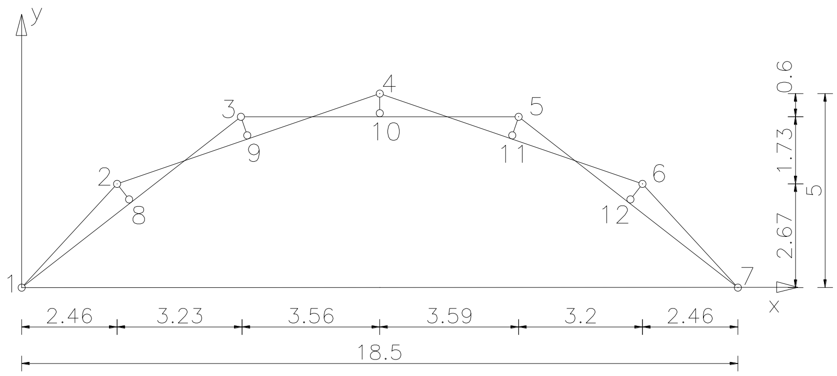


Fig. 7-3 Planar simplified schematic diagram of Bianhe Rainbow bridge

7.2.1.2 Manual Computation Results of Bianhe Rainbow Bridge

Based on the planar simplified model shown in **Fig. 7-3**, the influence lines of axial force of arch ribs and transverse beams, influence lines of bending moment in key cross-sections, and influence lines of support reactions can be calculated by manual computation method. Some of manual computation results are shown in **Fig. 7-4** to **Fig. 7-9** (Positive value shows the tension force, negative value shows the pressure force for influence line of axial force line, and positive value shows the tension, negative value shows the pressure for influence line of bending moment line).

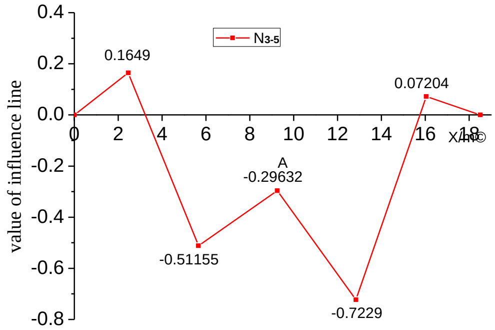


Fig. 7-4 Influence line of axial force of crown rib of the first system (N3-5)

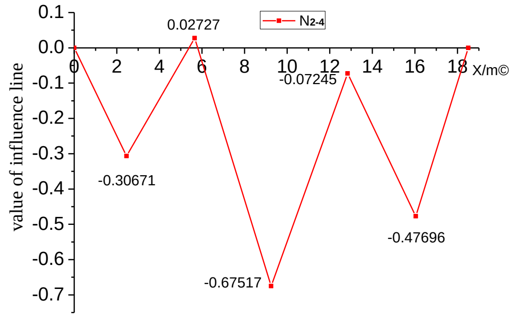


Fig. 7-5 Influence line of axial force of upper inclined rib of the second system (N2-4)

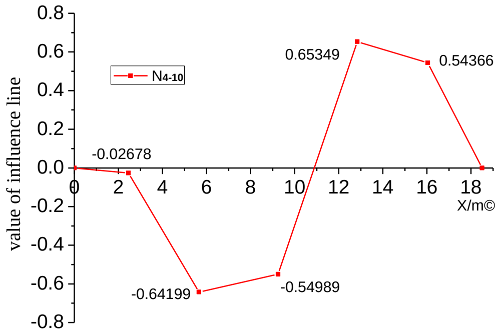


Fig. 7-6 Influence line of axial force of crown transverse beam (N4-10)

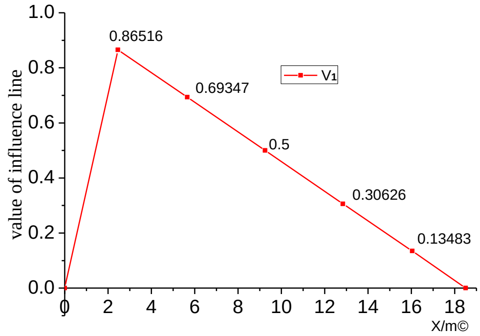


Fig. 7-7 Influence line of Vertical support reaction (V1)

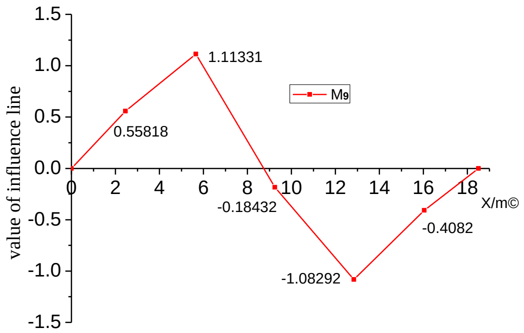


Fig. 7-8 Influence line of bending moment in section 9 (M9)

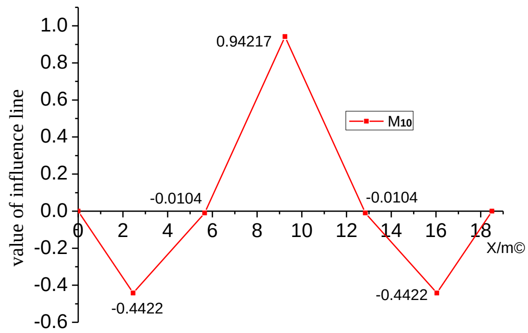
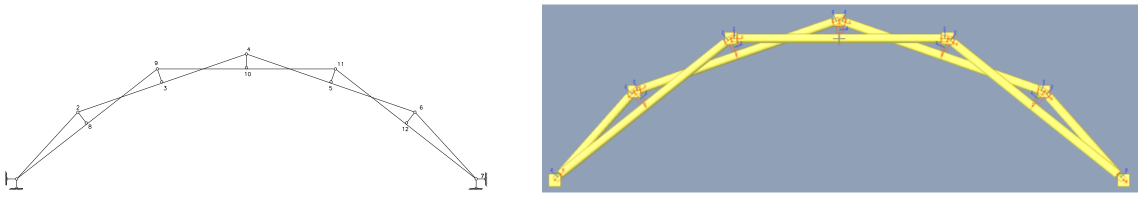


Fig. 7-9 Influence line of bending moment in section 10 (M10)

7.2.2 Verification on manual calculation model of Bianhe Rainbow Bridge

7.2.2.1 Calculation models

According to the structure size of the planar simplified schematic diagram of Bianhe Rainbow bridge, which is shown in **Fig. 7-3**, the calculation model of structural mechanics solver method is set up with 12 nodes and 17 elements in total, as shown in **Fig. 7-10 (a)**. Planar model is set up by the finite element software of Midas/Civil, with 22 nodes and 12 elements in total, as shown in **Fig. 7-10 (b)**. In this model, the hinge joints are simulated by spring elements which can transfer axial force and shear but not bending moments, and the crossbeam is also simulated by spring elements with certain stiffness. China fir is chosen as model material and using the self-defined isotropic material to simulate China fir. According to the "*Code for design of timber structures*"[2][3], strength grade of China fir belongs to TC11A, and the elastic modulus is 9×10^6 kN/m^2, the design value of parallel-to-grain compressive strength is 10 MPa, the design value of bending strength is 11 MPa, the volume-weight is 3.68 kN/m^3, the Poisson's ration is 0.25. The arch rib adopts solid circular cross section, with a diameter of 0.29 m, and the tensile stiffness of 0.59×10^6 kN·m , the bending stiffness of 3.12×10^3 kN·m.



(a) Planar model of SM solver (b) Planar model of finite element

Fig. 7-10 Planar model

Likewise, apply unit force of 1 kN to the nodes from 1 to 7 in turn and calculate the axial force and bending moment under each unit force of each element. The axial force and bending moment under unit force of each element can be got from the SM solver and the model of finite element.

7.2.2.2 Comparative analysis of calculation results

The influence lines of axial force and bending moment are drawn by the results obtained from two methods mentioned above and are compared with manual computation result worked out by Huancheng Tang. Hence the 1/4 section and vault section which are representative section to arch bridge are chosen, the influence lines of axial force and bending moment in these sections are compared and analyzed. **Fig. 7-11** to **Fig. 7-17** show the comparison result of three methods.

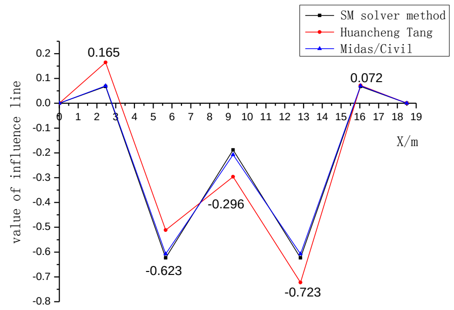


Fig. 7-11 Influence line of axial force in level arch rib of the first system

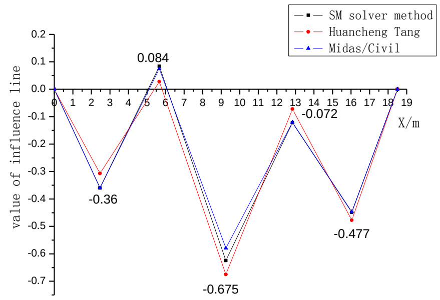


Fig. 7-12 Influence line of axial force in upper slant rib of the second system

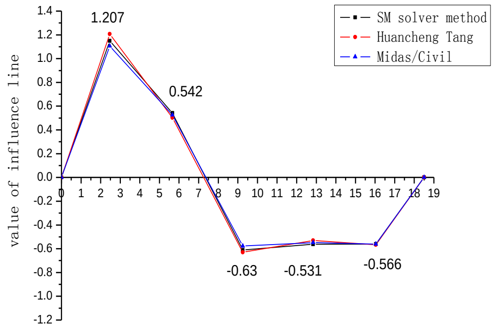


Fig. 7-13 influence line of bending moment in slant rib of the first system

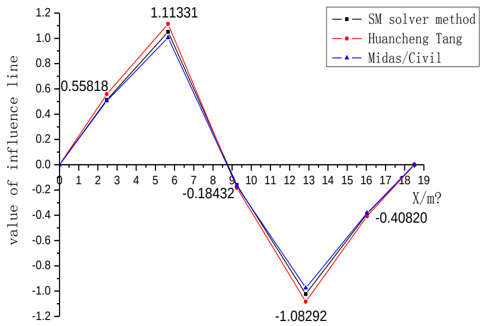


Fig. 7-14 Influence line of bending moment in 1/4 span section

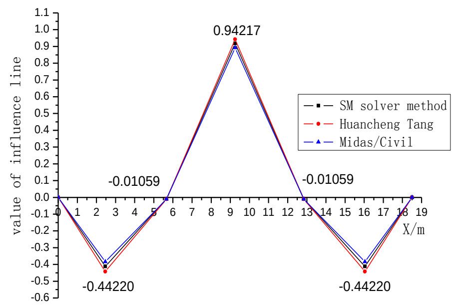


Fig. 7-15 Influence line of bending moment in crown section

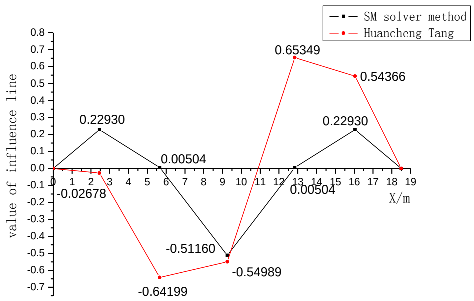


Fig. 7-16 Influence line of axial force in crown transverse beam

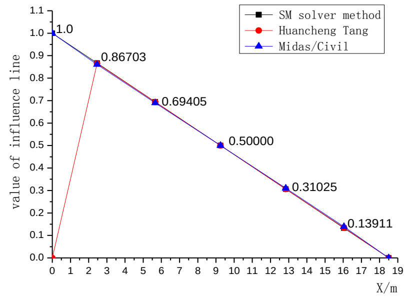


Fig. 7-17 Influence line of Vertical support reaction

Fig. 7-11 and **Fig. 7-12** show the influence line of axial force of the Bianhe Rainbow bridge, it can be found that arch ribs both in the first system and the second system bear axial force mainly. Only when the single load focuses on the crossbeam above the arch rib, it produces small tension in the arch rib. The influence lines of axial force in arch ribs worked out by three different methods have the same route and tendency, and the values calculated by SM solver and Midas/Civil coincide basically. And then, two systems are given priority to with compression, only loads in local areas, the small tension force will produce.

Fig. 7-13 and **Fig. 7-15** show the influence line of bending moment of the Bianhe Rainbow bridge. It can be found the shape of influence of bending moment in crown section is similar to that of the two-hinged arch, as well as a quarter of span section. It indicates that the mechanical behavior of main arch structure with dual systems accords with the two-hinged arches.

Though most results worked out by three different methods are similar, there are still some differences. As **Fig. 7-16** shown, the tendency of influence lines in crown transverse beam worked out by SM solver method and manual computation method are exactly different. Through mechanical analysis, the simplified model of Bianhe Rainbow Bridge is a completely symmetrical structure, so the axial force influence line of crown transverse beam should also be symmetrical. While as the **Fig. 7-16** show, the manual computation result is out of regulation, we may reasonably conclude that the manual computation result of crown transverse beam worked out by Huancheng Tang should be wrong. Another difference is shown in **Fig. 7-17**, when unit load focuses on end support, the support reaction in the same end support should be 1. But the result calculated out by Huancheng Tang is 0, which may be miscalculation or drawing error.

Fig. 7-18 shows the axial force of the main arch structure under full load, which are obtain from finite element method, which can be found clearly that both the first system and the second system only bear pressure. And the axial force in the second system is bigger than the first system. **Fig. 7-19** indicates that the arch rib will produce some bending moment, and the value in sections under crossbeams is bigger than somewhere else. However, the bending moment is smaller than axial force on the whole, which conforms to the mechanical characteristics of the arch. Obviously, the bending moment in the second system is smaller than in the first system. When it comes to stress as shown in **Fig. 7-20**, we find that only compressive stress is exist, and the stress in the first system is bigger than in the second system. Because of the first system and the second system weaving into a unity, they limit deformation and displacement of each other until both deformation and internal force reach a balance, and at last a new internal force is formed in the dual system. Therefore, it can be concluded that the first system plays a more important role than the second system in resisting the load, and the second system help the first system make the main arch structure much more stability. The analysis results are similar to the results of woven arch, which are present in Chapter in 5.

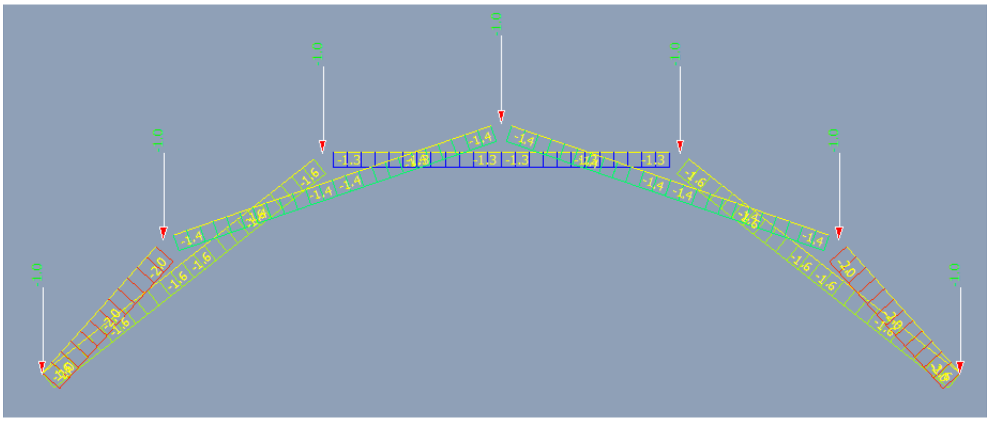


Fig. 7-18 Axial force of the main arch structure

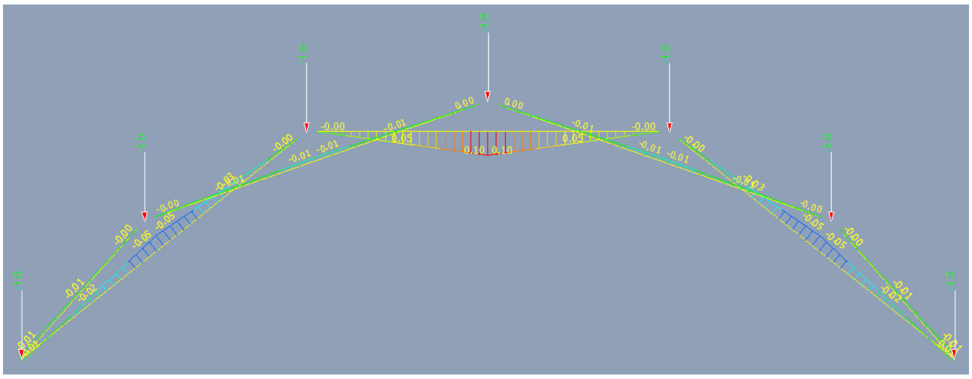


Fig. 7-19 Bending moment of the main arch structure

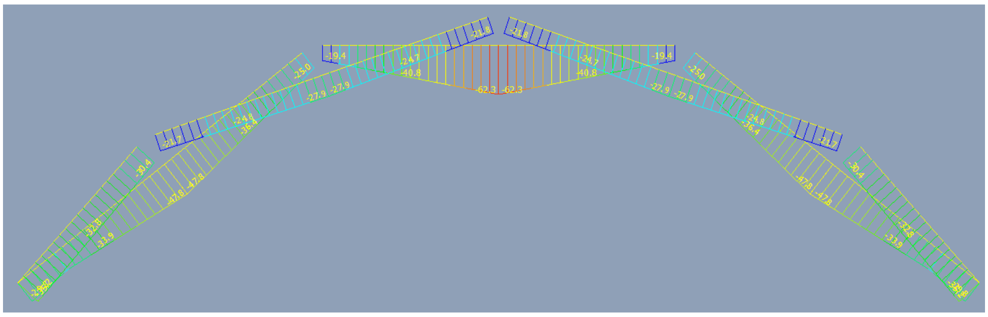


Fig. 7-20 Stress in the main arch structure

From the results shown in above, most of influence lines worked out by three methods have the same tendency with little difference in data in addition to some errors in manual capitation results. The three methods can all be used to calculate the planar simplified model of Bianhe Rainbow Bridge through mutual test and verify. It can be concluded that the finite element method of Midas/Civil and SM solver method are feasible to calculate the structure behavior of timber arch bridge. Finite element method not only solve the difficulty in calculate the statically indeterminate structure by manual computation, but also simulate the connection of arch rib and crossbeam more truly than SM solver method via varying stiffness of spring elements.

7.3 Simplified Calculation Model of Min-zhe Timber Arch Bridge

7.3.1 Introduction of manual calculation model of Min-zhe Timber Arch Bridge by Mr. Tang

The author considers the planar simplified schematic diagram of Min-zhe Timber Arch Bridge can be obtain from the planar simplified schematic diagram of Bianhe Rainbow Bridge in Chinese Timber Arch Bridge. According to the author's viewpoint and the structure size of scale model of Xi'nan Bridge, the planar simplified schematic diagram of Min-zhe Timber Arch Bridge, as shown in **Fig. 7-21**.

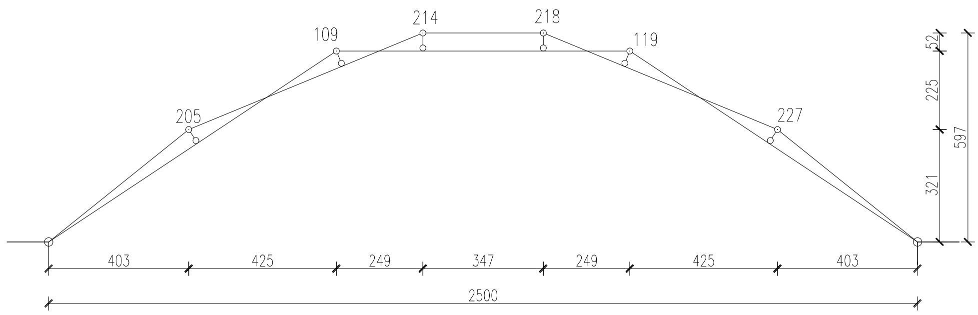


Fig. 7-21 Planar simplified schematic diagram of Min-zhe Timber Arch Bridge

7.3.2 Verification on manual calculation model of Min-zhe Timber Arch Bridge by Mr. Tang

The same modeling method as shown in **Fig. 7-10(b)** had be used to establish the finite element model for planar simplified schematic diagram of Min-zhe Timber Arch Bridge shown in **Fig. 7-22**.

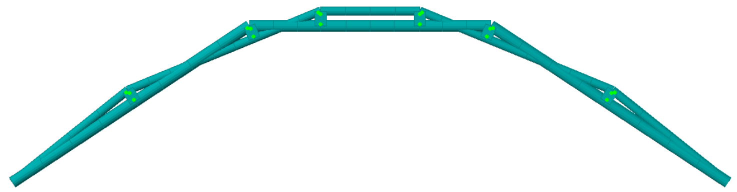


Fig. 7-22 Planar simplified model without detachment of Min-zhe Timber Arch Bridge

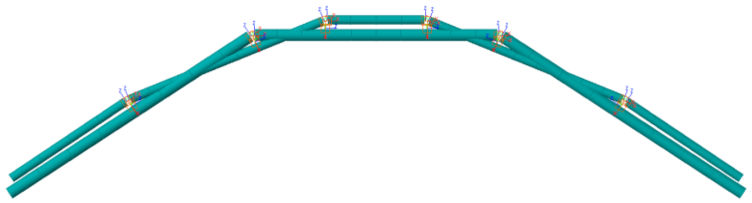


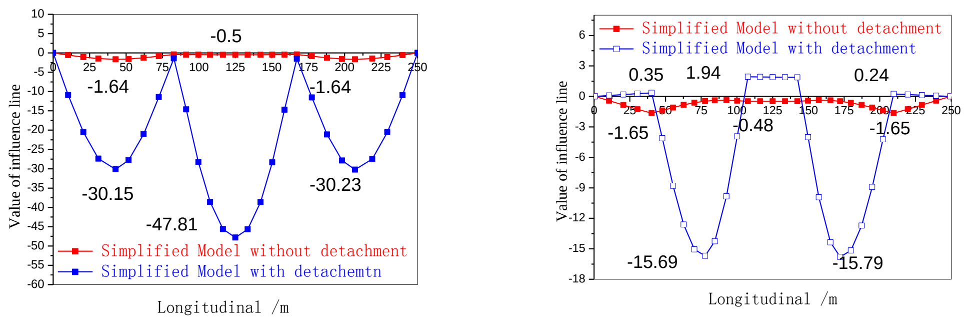
Fig. 7-23 Planar simplified model with detachment of Min-zhe Timber Arch Bridge

The other planar model with detachment of finite element of Min-zhe Timber Arch Bridge was established as shown in **Fig. 7-23**, which is used the same modeling method as mention in Chapter 5, in this model, the connection of arch ribs of the same system were simulated with spring elements, the connection between the transverse beams and arch ribs of the other system was modeled by compression-only spring elements with a linear rigidity. The arch springing was modeled as a hinge joint in which the linear displacements Dx is constrained, while the angular displacement Ry is free.

The two models under the load with the value of 0.24 t/m, the value of joint load as shown in **Table 7-1**, the calculate results as shown in **Fig. 7-24** to **Fig. 7-26** and **Table 7-2**.

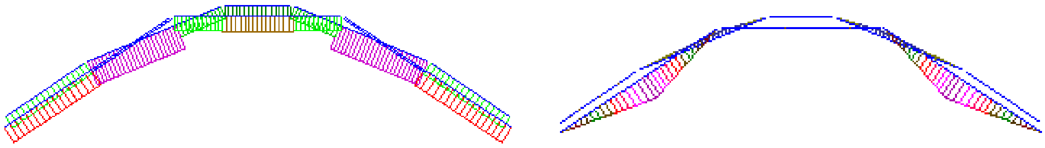
Table 7-1 Load values

Node	205	109	214	218	119	227
Length of bearing strength (cm)	41.4	33.69	29.77	29.77	33.69	41.4
Load (N)	-389.49	-316.96	-280.08	-280.08	-316.96	-389.49



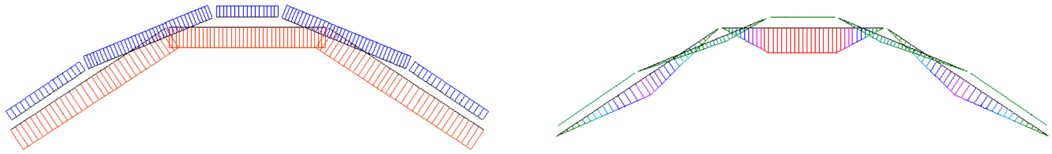
(a) 1st system (b) 2nd system

Fig. 7-24 Comparison diagram of deformation curve



(a) Axial force (b) Bending moment

Fig. 7-25 Internal force diagram of simplified model without detachment



(a) Axial force (b) Bending moment

Fig. 7-26 Internal force diagram of simplified model with detachment

Table 7-2 Comparison of internal force and stress

Internal force	Model	1st system		2nd system		
		1-1	1-2	2-1	2-2	2-3
Axial force/F (N)	Simplified model without detachment	-1015	-912	-739	-1444	-539
	Simplified model with detachment	-2353	-2080	1051	1334	1173
Bending moment/M (N·mm)	Simplified model without detachment	8340	549	9.6	-1763	0
	Simplified model with detachment	174887	244437	-32	56894	1

Form the **Fig. 7-24,** it can be found the vertical displacement of simplified model without detachment is less than that of the simplified model with detachment, and the transformation tendency of two systems of simplified model without detachment is consistent, it shows two systems of simplified model without detachment can collaborative deformation, because the connection between the transverse beams and arch ribs of the other system is connect with the bind joint, the bind joint can bear both compression and tension. But for the simplified model with detachment, from the results shown in Chapter 4, we can find that detachment occurred between the two systems, because the contact constraint cannot bear tension, the transformation tendency of two systems of the simplified model with detachment is different.

Table 7-2 shows the result of comparison of internal force and stress, it can be found that the internal force of the simplified model without detachment is less than those of the simplified model with detachment, the maximum of axial force of the first system is reduce by 57%, and the bending moment reduce by 96.6%; the bending moment of the second system is reducing by 97%.

Fig. 7-25 shows two systems arch ribs of the simplified model without detachment are under pressure, the maximum axial force is existing in the upper slant rib of the second system, the maximum bending moment is existing in the slant rib of the first system. However, **Fig. 7-26** shows the first system arch ribs of the simplified model with detachment are under pressure, the second system arch rib are under tension, the maximum axial force is existing in the slant rib of the first system, the maximum bending moment is existing in the slant rib of the first system.

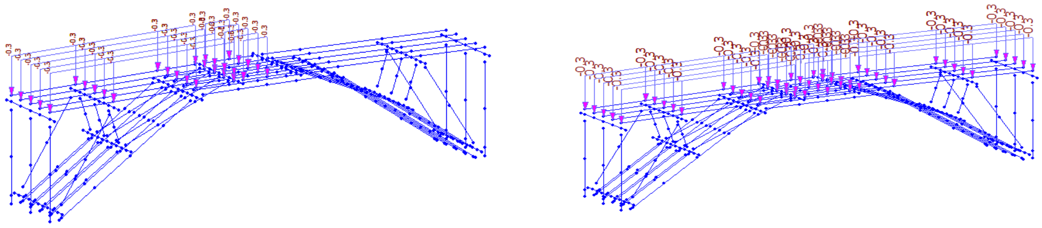
The analysis results show the deformation and internal force of the simplified model with detachment are all larger than those of the simplified model without detachment, and internal force distribution of two models arch are different, so the simplified calculation model of Bianhe Rainbow Bridge is not suitable for Min-zhe Timber Arch Bridge.

7.3.3 Simplified calculation model of Min-zhe Timber Arch Bridge

According to the results, the mortise-tenon joint simplified as hinged joint is conservative calculation for simplified calculation, which is presented in Chapter 4 and Chapter 5. In this section, the mortise and tenon joint of Min-zhe Timber Arch Bridge is reduced to hinge joint, the research work on combine works performance of Min-zhe Timber Arch Bridge which had been carried out, and then, the planar simplified calculation model had been proposed.

7.3.3.1 Effect of the detachment of the arch ribs from the transverse beams on the load transfer performance of the woven arch

In order to analysis on the effect of the detachment of the arch ribs from the transverse beams on the load transfer performance of the Min-zhe Timber Arch bridge, the finite element model which is described in the section 3 of Chapter 5, had been under the half-span and full-span uniform load with the value of 1.5 kN/m^2, 2.5 kN/m^2, 3.5 kN/m^2, respectively, the load schematic diagram as shown in **Fig. 7-27**.



(a) Asymmetrical uniform load　　　　(b) Symmetrical uniform load

Fig. 7-27 Load schematic diagram

In this model, the connections between the transverse beams and arch ribs of the other system are modeled by compression-only spring elements with a linear rigidity, so the calculation results of the spring element can be shown the condition of combine work of two systems, if the value of spring pressure is 0, it shows two systems had not connected pressure, and cannot transmit the load and combine work, vice versa, if the value of spring pressure is negative value, it shows two systems had connect pressure, and can transmit the load and combine work.

For this model arch, the first system has five parallel members, the slant rib of the second system has four parallel members and the level rib of the second has five parallel members. According to the symmetry of structure, the analysis focuses on three rows of the first system, two rows slant ribs and three rows level ribs of the second system.

The model arch under the asymmetrical load with the value from 1.5 kN/m^2 to 3.5 kN/m^2, and the results are shown in **Table 7-3** to **Table 7-6**.

Table 7-3 Calculation result for transverse beam of 1st system connecting with the slant rib of 2nd system

Load value (kN/m^2)	Load side (N)		The other side of load (N)	
	1st row	2nd row	1st row	2nd row
1.5	-2.36	-1.22	0	0
2.5	-9.74	-8.07	0	0
3.5	-17.12	-14.93	0	0

Table 7-4 Calculation result for bottom transverse beam of 2nd system connecting with the slant rib of 1st system

Load value (kN/m^2)	Load side (N)			The other side of load (N)		
	1st row	2nd row	3th row	1st row	2nd row	3rd row
1.5	-371.38	-143.73	-42.07	-170.43	-115.34	-209.04
2.5	-457.8	-149.87	-49.02	-160.63	-139.18	-274.91
3.5	-544.22	-156.02	-56.08	-150.83	-163.01	-340.79

Table 7-5 Calculation result for lower transverse beam of 2nd system connecting with the slant rib of 1st system

Load value (kN/m^2)	Load side (N)			The other side of load (N)		
	1st row	2nd row	3th row	1st row	2nd row	3rd row
1.5	0	-1.94	-6.18	0	0	0
2.5	0	-6.91	-12.41	0	0	0
3.5	0	-11.87	-18.65	0	0	0

Table 7-6 Calculation result for upper transverse beam of 2nd system connecting with the level rib of 1st system

Load value (kN/m^2)	Load side (N)			The other side of load (N)		
	1st row	2nd row	3th row	1st row	2nd row	3rd row
1.5	-73.74	-73.4	-73.04	0	0	0
2.5	-122.9	-122.81	-122.34	0	0	0
3.5	-172.06	-172.23	-171.63	0	0	0

Table 7-3 shows when the model of arch under asymmetrical load, the transverse beam of the first system and the upper slant rib of the second system can combine work at the load side, but the pressure value of all the spring element in the same location at the other side are all 0, which shows the transverse beam of the first system and the upper slant rib of the second system cannot combine work at the other side.

Table 7-4 shows when the model of arch is under asymmetrical load, the bottom transverse beam of the second system and the slant rib of the first system can combine work at both sides.

Table 7-5 shows when the model of arch is under asymmetrical load, part of the lower transverse beam of the second system and the slant rib of the firs system can combine work at the load side, but the pressure value of all the spring element in the same location at the other side are all 0, which shows the transverse beam of the second system and the slant rib of the firs system cannot combine work at the other side.

Table 7-6 shows when the model of arch is under asymmetrical load, the upper transverse beam of the second system and the level rib of the first system can combine work at the load side, but the pressure value of all the spring element in the same location at the other side are all 0, which shows the two systems cannot combine work in the same location at the other side.

From the above analysis, when the model of arch is under asymmetrical load, the transverse beam of the first system and the upper slant rib of the second system, the bottom transverse beam of the second system and the slant rib of the first system can combine work completely, the lower transverse beam of the second system and the slant rib of the first system only part can combine work at the load side. Except that the bottom transverse beam of the second system and the slant rib of the first system can combine work, the others cannot combine work at the other side.

Under the symmetrical load with the value from 1.5 kN/m^2 to 3.5 kN/m^2, and the results are shown in **Table 7-7** to **Table 7-10**.

Table 7-7 Transverse beam of 1st system connecting with slant rib of 2nd system

Load value (kN/m^2)	1st row (N)	2nd row (N)	3rd row (N)
1.5	0	0	0
2.5	0	0	0
3.5	0	0	0

Table 7-8 Bottom transverse beam 2nd system connecting with slant rib of 1st system

Load value (kN/m^2)	1st row (N)	2nd row (N)	3rd row (N)
1.5	-393.63	-167.08	-234.13
2.5	-532.37	-224.17	-313.53
3.5	-671.04	-280.91	-392.05

Table 7-9 Lower transverse beam 2nd system connecting with slant rib of 1st system

Load value (kN/m^2)	1st row (N)	2nd row (N)	3rd row (N)
1.5	0	0	0
2.5	0	0	0
3.5	0	0	0

Table 7-10 Upper transverse beam of 2nd system connecting with level rib of 1st system

Load value (kN/m^2)	1st row (N)	2nd row (N)	3rd row (N)
1.5	-1.33	0	0
2.5	-3.31	-0.57	0
3.5	-5.22	-1.76	-0.43

From the above results, when the model of arch is under symmetrical load, the transverse beam of the first system and the upper slant rib of the second system, the lower transverse beam of the second system and the slant rib of the first system cannot combine work of both sides, with the load increasing, the behavior of combine work of the upper transverse beam of the second system and the level rib of the first system is more and more better, and the bottom transverse beam of the second system and the slant rib of the first system can combine work completely.

The summary table of combine work of two systems is shown in **Table 7-11**. Under the load, the behavior of combine work of two systems is the worst, which is at the location of the lower transverse beam of the second system and the slant rib of the first system cannot combine work of both sides; Secondly, it is the transverse beam of the first system connect with the upper arch rib of the second system, the behavior of combine work of two systems is best, which is at the location of the bottom transverse beam of 2nd system connect with slant rib of 1st system; Thirdly, it is the upper transverse beam of 2nd system connect with slant rib of 1st system. At the same time, the behavior of combine work of two systems is better under the asymmetrical load than under the symmetrical load, because the deformation is small under the symmetrical load, and each system can bear the deformation by itself.

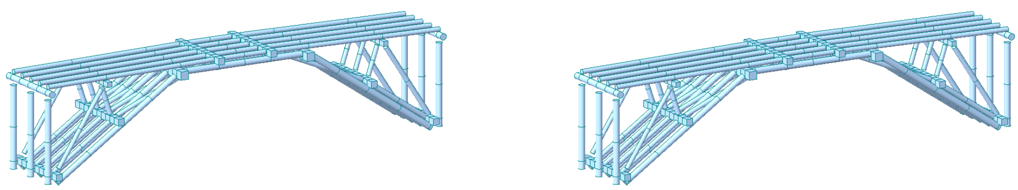
Table 7-11 Summary table of combine work of two systems

Locations	Loading (kN/m^2)	Asymmetric loading		Symmetric loading
		Load side	Non-load side	Both sides
Lower transverse beams of 2nd system	1.5	×○○○×	×××××	×××××
	2.5	×○○○×	×××××	×××××
	3.5	×○○○×	×××××	×××××
Transverse beams of 1st system	1.5	○○○○	××××	××××
	2.5	○○○○	××××	××××
	3.5	○○○○	××××	××××
Upper transverse beams of 2nd system	1.5	○○○○○	×××××	○× × ×○
	2.5	○○○○○	×××××	○○×○○
	3.5	○○○○○	×××××	○○○○○

Note: "×" represents the detachment of the transverse beams from the arch ribs of the other system, resulting in poorer load transfer capability. "○" represents that transverse beams and arch ribs of the other system had not separate, and the two systems of woven arches have better load transfer capability.

7.3.3.2 Influence degree analysis on combine work

Two finite element models with the same size are established, as shown in **Fig. 7-28**. One model (referred to as full bridge with detachment space model) is verified by the tests in the Chapter 5 in which the connection between the transverse beams and arch ribs of the other system is modeled by compression-only spring elements with a linear rigidity. This kind of spring elements can simulate the detachment phenomenon of two systems. The other (referred to as full bridge without detachment space model) is the model in which the connection between the transverse beams and arch ribs of the other system is modeled by tension and compression spring elements. The spring elements cannot simulate the detachment phenomenon of two systems.

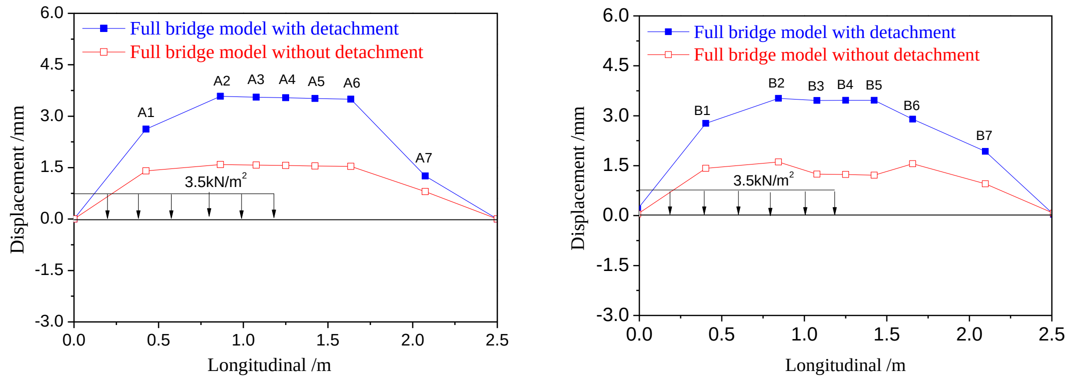


(a) Full bridge model with detachment of woven arch

(b) Full bridge model without detachment of woven arch

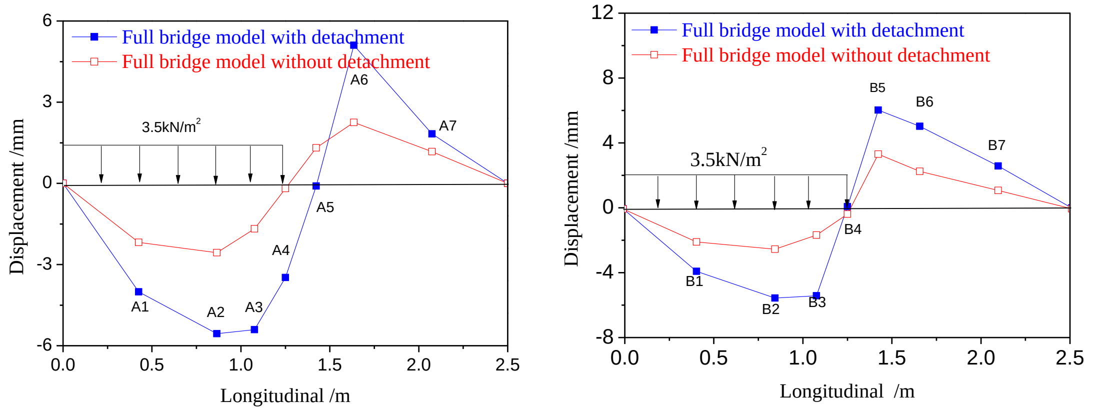
Fig. 7-28 Finite element model

The two models were tested under asymmetrical and symmetrical load with the value of 1.5 kN/m^2, 2.5 kN/m^2, 3.5 kN/m^2, respectively. **Fig. 7-29 and Fig. 7-30** show the displacement of two systems under asymmetrical load with the value of 3.5 kN/m^2. It can be seen that the tendency of deformation of two systems are similar, but the value of deformation is different.



(a) 1st system (b) 2nd system

Fig. 7-29 Horizontal displacement of two systems under asymmetrical load



(a) 1st system (b) 2nd system

Fig. 7-30 Vertical displacement of two systems under asymmetrical load

Table 7-12 shows the maximum deflection and location results of the two models under asymmetrical load with the load value of 1.5 kN/m^2-3.5 kN/m^2. It can be found that the maximum deflection point of the first system always exists at the measuring point A2 when two models are under different load values, and then the maximum deflection point of the second system always exists at the measuring point B2 when two models under different load value. However, compared with the results, the horizontal displacement of the first system of full bridge without detachment space model decreased by 56% and the horizontal displacement of the second system of full bridge without detachment space model decreased by 54% compare with the full bridge model with detachment.

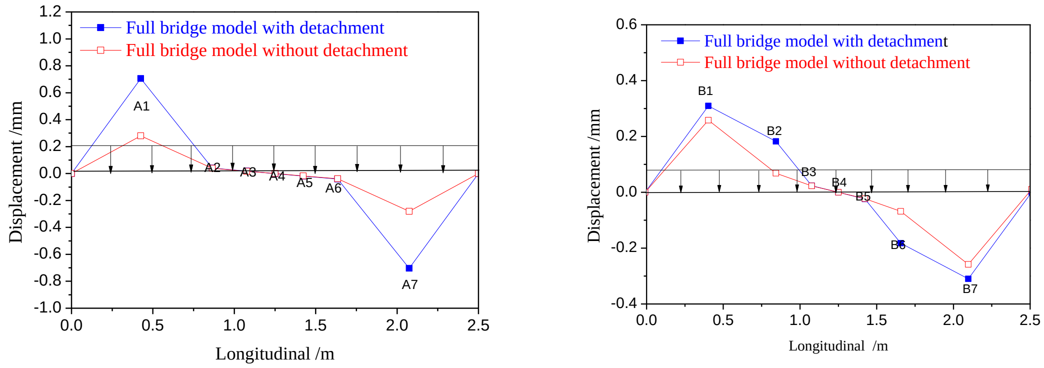
Table 7-12 Maximum horizontal displacements and their locations under asymmetrical load (Unit: mm)

System	Load value (kN/m^2)	Maximum deflection location	Horizontal displacement		
			Full bridge model with detachment	Full bridge model without detachment	Ratio (%)
1st system	1.5	A2	1.518	0.672	56
	2.5	A2	2.548	1.129	56
	3.5	A2	3.578	1.589	56
2nd system	1.5	B2	1.456	0.664	54
	2.5	B2	2.489	1.137	54
	3.5	B2	3.522	1.612	54

Table 7-13 Maximum vertical displacements and their locations under asymmetrical load (Unit: mm)

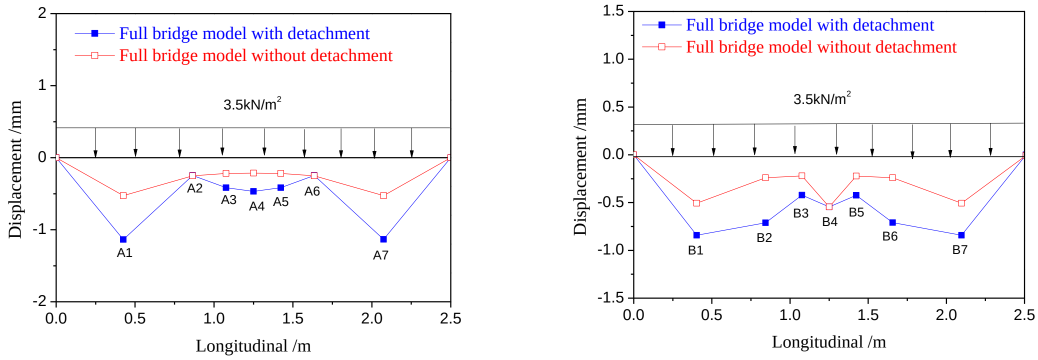
System	Load value (kN /m^2)	Maximum deflection location	Vertical displacement (Negative)		
			Full bridge model with detachment	Full bridge model without detachment	Ratio (%)
1st system	1.5	A2	-2.398	-1.119	53
	2.5	A2	-3.978	-1.846	54
	3.5	A2	-5.557	-2.564	54
2nd system	1.5	B2	-2.425	-1.123	54
	2.5	B2	-3.975	-1.831	54
	3.5	B2	-5.582	-2.556	54
System	Load value (kN /m^2)	Maximum deflection location	Vertical displacement (positive)		
			Full bridge model with detachment	Full bridge model without detachment	Ratio (%)
1st system	1.5	A6	2.113	0.902	57
	2.5	A6	3.609	1.564	57
	3.5	A6	5.104	2.253	56
2nd system	1.5	B5	1.938	0.896	54
	2.5	B5	4.007	2.105	47
	3.5	B5	6.029	3.311	45

Table 7-13 shows the maximum deflection and location results of the two models under symmetrical load with the load value of 1.5 kN/m^2-3.5 kN/m^2. It can be found that the maximum deflection point of vertical displacement of the first system always exists at the measuring point A2 and A6. And then, the maximum deflection point of the second system always exists at the measuring point B2 and B6 when two models under different load value. However, compare with the results of the full bridge model with detachment, the negative maximum deflection and positive maximum deflection of the first system of full bridge without detachment space model decreased by 54% and 57%, respectively. The negative maximum deflection and positive maximum deflection of the second system of full bridge without detachment space model decreased by 54% and 45%-57%, respectively.



(a) 1st system (b) 2nd system

Fig. 7-31 Horizontal displacement of two systems under symmetrical load



(a) 1st system (b) 2nd system

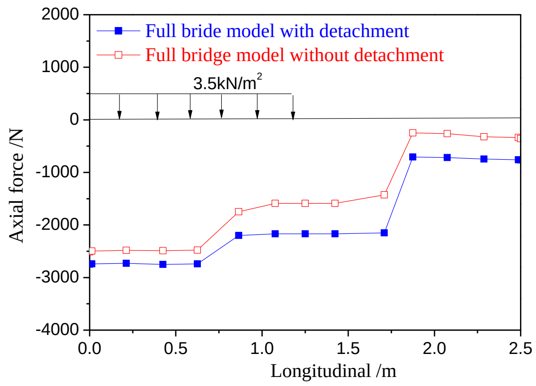
Fig. 7-32 Vertical displacement of two systems under symmetrical load

Fig. 7-31 and **Fig. 7-32** show the displacement of two systems under symmetrical load with the value of 3.5 kN/m^2. It can be seen that the tendency of deformation of two systems is similar, but the value of deformation is different.

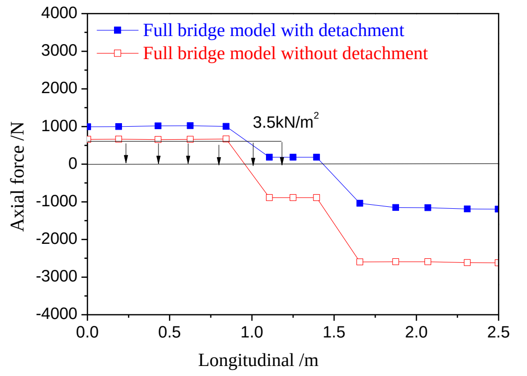
Table 7-14 shows the maximum deflection and location results of the two models are under symmetrical load with the load value of 1.5 kN/m^2-3.5 kN/m^2. It can be found that the maximum deflection point of vertical displacement of the first system always exists at the measuring point A1. And then, the maximum deflection point of the second system always exists at the measuring point B1 when two models are under different load values. However, compared with the results of the full bridge model with detachment, the horizontal displacement maximum deflection of the first system of full bridge model without detachment decreases by 60%-67%. The vertical displacement maximum deflection of the first system of Full bridge model without detachment decreases by 54%-61%. The horizontal displacement maximum deflection of the second system of full bridge model without detachment decreases by 13%-15%. The vertical displacement maximum deflection of the second system of full bridge model without detachment decreases by 40%.

Table 7-14 Maximum horizontal displacements and their locations under symmetrical load (Unit: mm)

System	Load value (kN /m^2)	Maximum deflection location	Horizontal displacement (Negative)		
			Full bridge model with detachment	Full bridge model without detachment	Ratio (%)
1st system	1.5	A1	-0.812	-0.314	61
	2.5		-0.975	-0.421	57
	3.5		-1.138	-0.528	54
2nd system	1.5	B1	-0.503	-0.302	40
	2.5		-0.672	-0.404	40
	3.5		-0.842	-0.507	40
System	Load value (kN /m^2)	Maximum deflection location	Horizontal displacement (Positive)		
			Full bridge model with detachment	Full bridge model without detachment	Ratio (%)
1st system	1.5	A1	0.511	0.167	67
	2.5		0.609	0.223	63
	3.5		0.706	0.28	60
2nd system	1.5	B1	0.178	0.154	13
	2.5		0.243	0.206	15
	3.5		0.309	0.258	17



(a) 1st system



(b) 2nd system

Fig. 7-33 Axial force of two systems under asymmetrical load

Table 7-15 Maximum axial force of two systems under asymmetrical load (Unit: N)

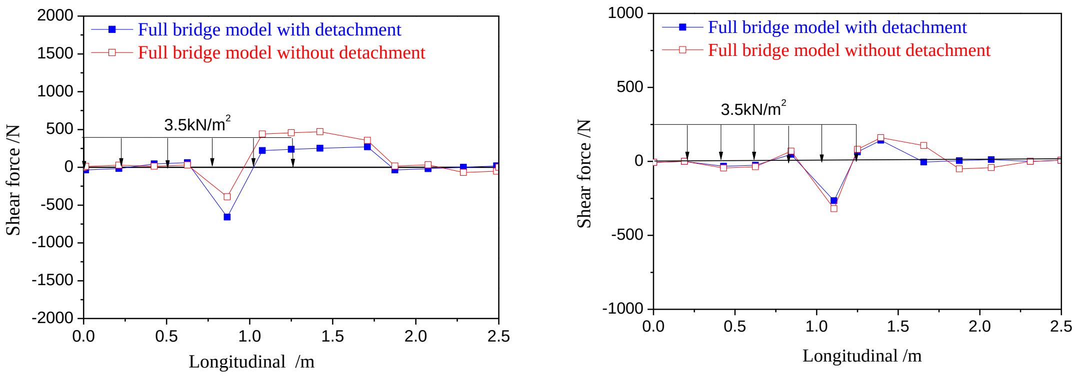
Load value (kN/m^2)	1st system			2nd system		
	Full bridge model with detachment	Full bridge model without detachment	Ratio (%)	Full bridge model with detachment	Full bridge model without detachment	Ratio (%)
1.5	-1612	-1271	21	-705	-1102	-56
2.5	-2179	-1705	22	-950	-1602	-67
3.5	-2745	-2107	23	-1194	-2111	-79

Fig. 7-33 shows the axial force of two systems of two models under the asymmetrical load. Their distributions are similar.

Table 7-15 shows the maximum axial force of two systems under the asymmetrical load with the value of 1.5 kN/m^2-3.5 kN/m^2. The results of full bridge model without detachment compared with the full bridge model with detachment, the maximum axial force of the first system decreases by 22%. The maximum axial force of the second system increases by 56%-79%.

Fig. 7-34 shows the shear diagram under asymmetrical load with the value of 3.5kN/m^2. The variation tendency of two models is similar.

Table 7-16 shows the maximum shear value under the asymmetrical load with the value of 1.5 kN/m^2-3.5 kN/m^2. The result of Full bridge model without detachment compared with the full bridge model with detachment, the maximum shear force of the first system increase by 24%-29%, but the second system is remaining unchanged.



(a) 1st system (b) 2nd system

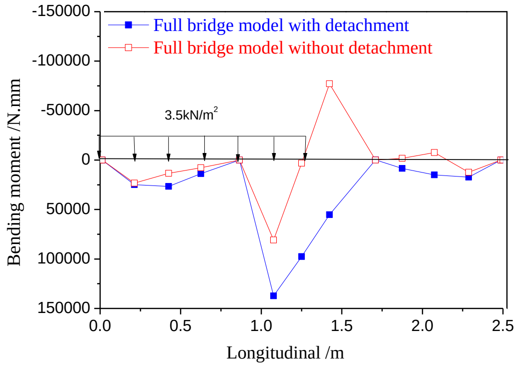
Fig. 7-34 Shear force diagram of two systems under asymmetrical load

Table 7-16 Maximum shear force of two systems under asymmetrical load (Unit: N)

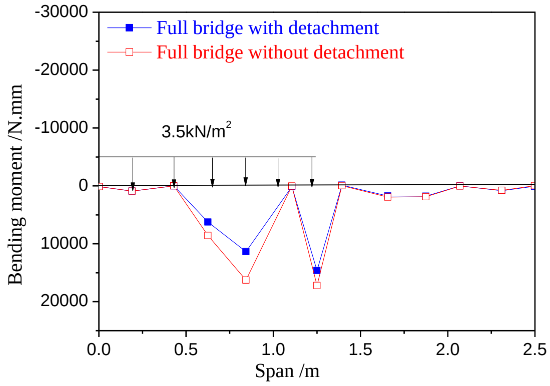
Load value (kN/m^2)	1st system			2nd system		
	Full bridge model with detachment	Full bridge model without detachment	Ratio (%)	Full bridge model with detachment	Full bridge model without detachment	Ratio (%)
1.5	-854	-1062	24	-159	-159	0
2.5	-1042	-1308	26	-213	-213	0
3.5	-1230	-1582	29	-266	-267	0

Fig. 7-35 shows the bending moment diagram of two systems under the asymmetrical load with the value of 3.5 kN/m^2. **Table 7-17** shows the maximum value of bending moment and the ratio of two models. Comparing with the full bridge model with detachment, it can be found that the maximum of the first system decreases by 54%,and the second system remains unchanged in the full bridge model without detachment.

Fig. 7-36 shows the axial force of two systems under the symmetrical load with the value of 3.5 kN/m^2, the distribution of two models is similar. **Table 7-18** shows the maximum axial force value of two systems under symmetrical load with the value of 1.5 kN/m^2-3.5 kN/m^2. Comparing with the full bridge model with detachment, the maximum axial force of the first system decreases by 0~16%, whereas that of the second system increases by 11%.



(a) 1st system

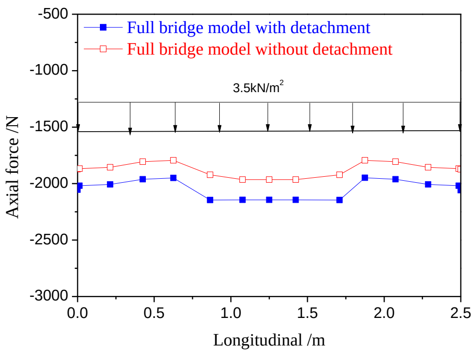


(b) 2nd system

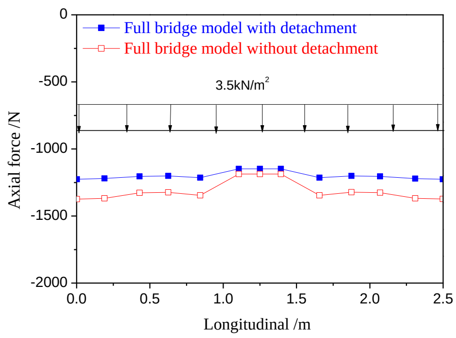
Fig. 7-35 Bending moment diagram of two systems under asymmetrical load

Table 7-17 Maximum bending moment of two systems under asymmetrical load (Unit: N·mm)

Load value (kN/m^2)	1st system			2nd system		
	Full bridge model with detachment	Full bridge model without detachment	Ratio (%)	Full bridge model with detachment	Full bridge model without detachment	Ratio (%)
1.5	61659	28647	54	9493	9499	0
2.5	99499	46180	54	12059	12061	0
3.5	137340	63626	54	14624	14629	0



(a) 1st system



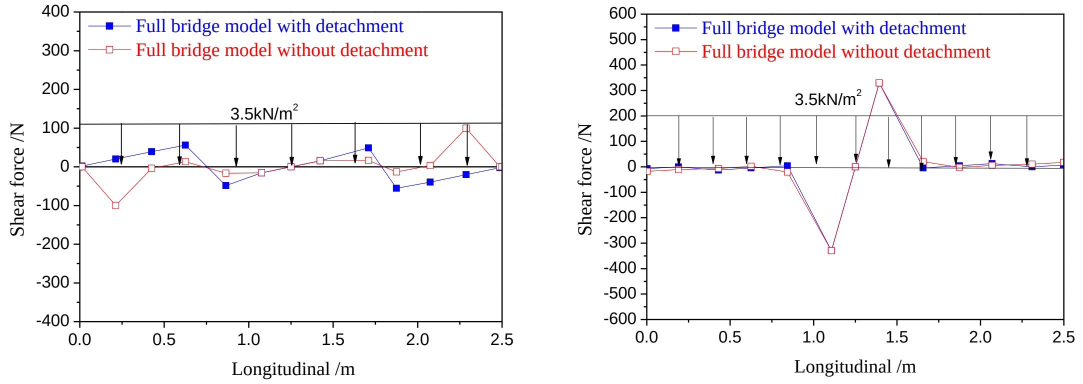
(b) 2nd system

Fig. 7-36 Axial force of two systems under symmetrical load

Table 7-18 Maximum axial force of two systems under symmetrical load (Unit: N)

Load value (kN/m^2)	1st system			2nd system		
	Full bridge model with detachment	Full bridge model without detachment	Ratio (%)	Full bridge model with detachment	Full bridge model without detachment	Ratio (%)
1.5	-1260	-1255	0	-717	-790	10
2.5	-1701	-1559	8	-967	-1076	11
3.5	-2344	-1965	16	-1225	-1373	12

Fig. 7-37 shows the shear force diagram of two systems are under symmetrical load with the value of 3.5 kN/m^2. The distribution of two models is similar. **Table 7-19** shows the maximum shear force of two systems under the symmetrical load with the load value of 1.5 kN/m^2-3.5 kN/m^2. Comparing with the full bridge model with detachment, the maximum shear force of the first system decreases by 53%, but the second system remains unchanged in the full bridge model without detachment.

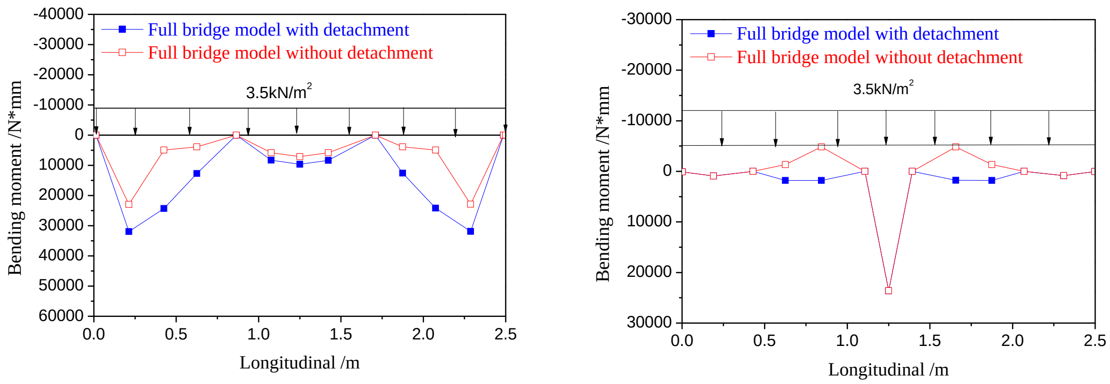


(a) 1st system (b) 2nd system

Fig. 7-37 Shear force diagram of two systems under symmetrical load

Table 7-19 Maximum shear force of two systems (Unit: N)

Load value (kN/m^2)	1st system			2nd system		
	Full bridge model with detachment	Full bridge model without detachment	Ratio (%)	Full bridge model with detachment	Full bridge model without detachment	Ratio (%)
1.5	-1367	-642	53	-186	-186	0
2.5	-1830	-860	53	-258	-258	0
3.5	-2291	-1079	53	-330	-330	0



(a) 1st system (b) 2nd system

Fig. 7-38 Bending moment diagram of two systems under symmetrical load

Table 7-20 Bending moment of two systems under symmetrical load (Unit: N·mm)

Load value (kN/m^2)	1st system			2nd system		
	Full bridge model with detachment	Full bridge model without detachment	Ratio (%)	Full bridge model with detachment	Full bridge model without detachment	Ratio (%)
1.5	20645	21567	4	13339	13342	0
2.5	27640	28517	3	18469	18473	0
3.5	34608	35348	2	23604	23605	0

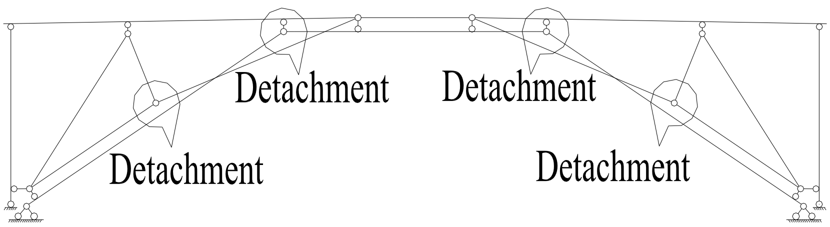
Fig. 7-38 shows the bending moment diagram of two systems under the symmetrical load with the value of 3.5 kN/m^2. The distribution of bending moment diagram is symmetrical, the maximum bending moment of the first system is existing at the slant rib, and the maximum bending moment of the second system exists at the level rib. **Table 7-20** shows the maximum bending moment of two models under the symmetrical load. It can be found the maximum bending moment value is similar.

In conclusion, firstly, the deformation tendency and maximum deflection point of two models are similar under the uniform asymmetrical and symmetrical load, but the maximum deflection has bigger difference. The full bridge model without detachment compared with the full bridge model with detachment under the asymmetrical and symmetrical load, the maximum deflection decreases by 45%-57% and 13%-67%, respectively. Secondly, the variation of tendency of internal force is similar, but there are some differences for the maximum value compared with two models. The maximum axial force, shear force and bending moment of the first system of full bridge model without detachment decrease by 22%, 24% and 54%, respectively, comparing with the full bridge model with detachment under asymmetrical load. However, the maximum axial force of the second system increases by 56%-79%, and the shear force and bending moment have not the difference. So, the results indicate that if two systems of woven arch cannot work together, the deformation and internal force will have big differences. The arch rib connected with the transverse beam cannot be simplified into half-hinged ones.

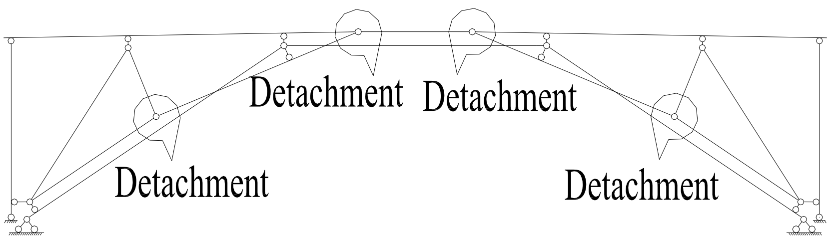
7.3.3.3. Discussion on the planar simplified calculation model of Min-zhe Timber Arch Bridge

The main structures of Min-Zhe Timber Arch Bridges are two longitudinal polygonal arch systems consisting of straight logs. The two systems with different polygonal sides are interlaced to form an integral structure by some transverse beams. Its structure is neither the general two-dimensional plane structure nor three-dimensional space structure. In order to make an initial structural design and reveal the mechanical behavior based on the manual calculation method with structural mechanics, it is very important to propose a simplified model.

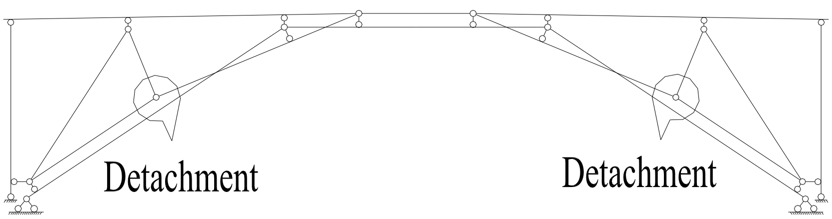
Based on the above research results, three simplified calculation models in which the occurrence of detachment are different are proposed for Min-Zhe Timber Arch Bridges, which are schematically shown in **Fig. 7-39**.



(a) Planner simplified calculation assumed model I



(b) Planner simplified calculation assumed model II



(c) Planner simplified calculation assumed model III

Fig. 7-39 Planner simplified calculation assumed model

Since the Chinese woven timber arch bridges have the two types of arch system in different vertical planes, 3D FE models should be used to simulate the accurate behavior. However, the design calculation becomes simpler and easier if 2D model can be used.

In order to investigate the applicability of the simplified models, three FE models corresponding to assumed models I-III in **Fig. 7-39** were built. For these simplified models, the axial and flexural stiffness of each component are the same as sum of corresponding component of full bridge model with detachment. For example, there are five and four arches in the 1st and 2nd systems of full bridge model with detachment, respectively. The axial and flexural stiffness of the 1st and 2nd systems in the simplified models are the same as their total, respectively. Their material properties are assumed to be the same as the acrylate resin.

In these three 2D FE models, the connection between the transverse beam with the arch rib of the other system except the joints which can be detached is simulated by the normal spring element, which can transfer not only the compression force but also tensile force. There are no spring elements at the joints which can be detached, and they are always separate. The boundary conditions of these three simplified models are the same as the full bridge model with detachment. The 2D FE models of simplified assumed model II under the same load value with the full bridge model with detachment is shown in **Fig. 7-40**.

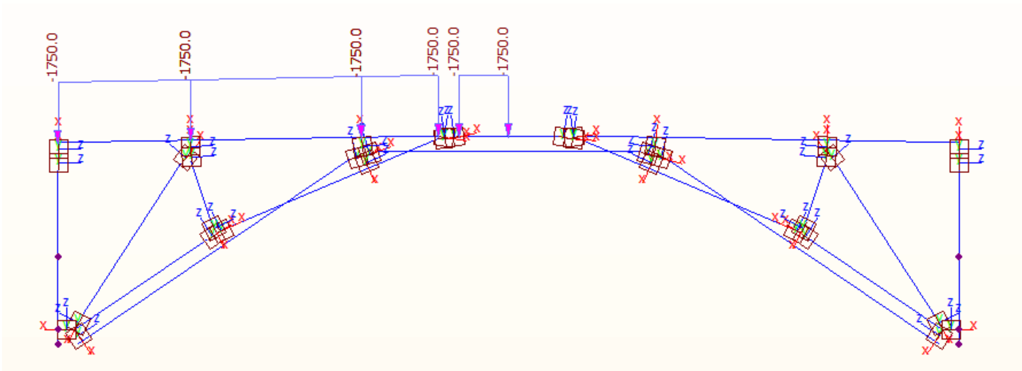
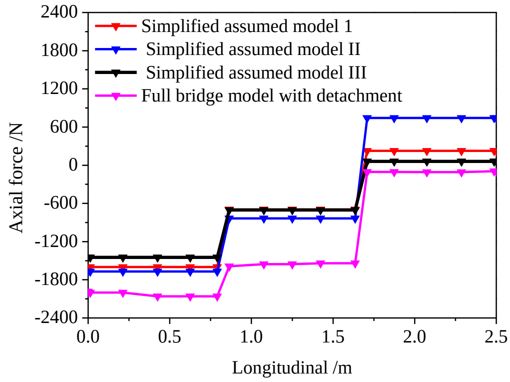
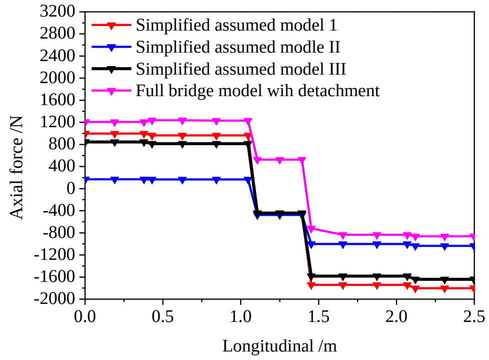


Fig. 7-40 FE model of simplified assumed model II

The computed internal forces of these three simplified models are compared with those of Full bridge model with detachment mode in **Figs. 7-41** to **Fig. 7-43**, where the forces of the full bridge model with detachment are the arithmetic sum of the forces in each system. The maximum internal forces are summarized in **Table 7-21.**

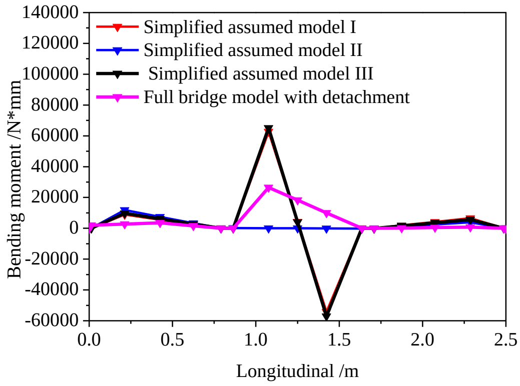


(a) 1st system

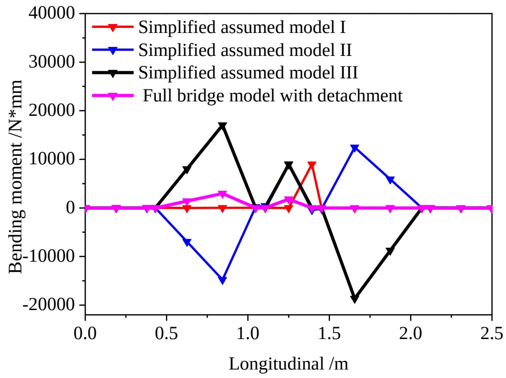


(b) 2nd system

Fig. 7-41 Comparison of axial force under asymmetrical load

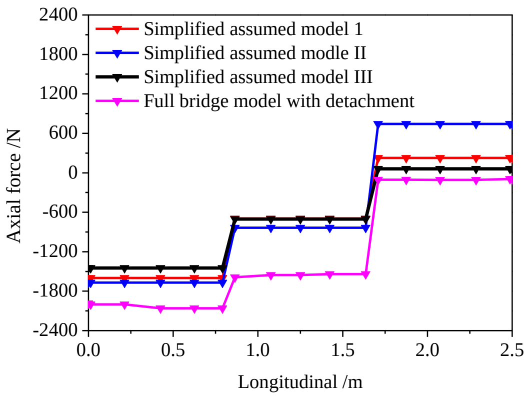


(a) 1st system

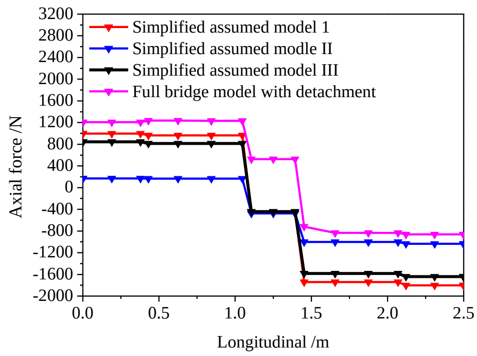


(b) 2nd system

Fig. 7-42 Comparison of bending moment under asymmetrical load



(a) 1st system



(b) 2nd system

Fig. 7-43 Comparison of axial force under asymmetrical load

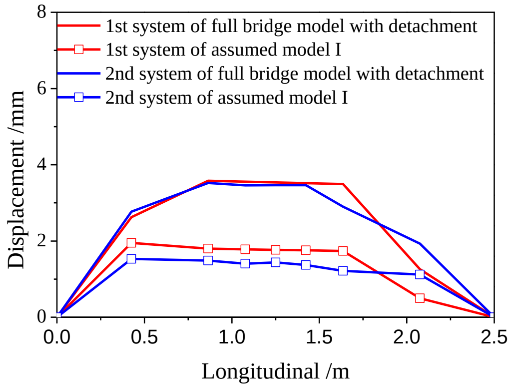
Table 7-21 Comparison of the maximum of internal forces under asymmetrical load

Model	System	Axial force (N)		Bending moment (N·mm)
		Compression	Tension	
Assumed model I	1st system	1601	226	62723
	2nd system	1802	997	-18665
Assumed model II	1st system	1934	586	15830
	2nd system	1035	170	-14774
Assumed model III	1st system	1449	61	65073
	2nd system	1642	846	-18665
Full bridge model with detachment	1st system	2061	-	26556
	2nd system	862	1236	3842

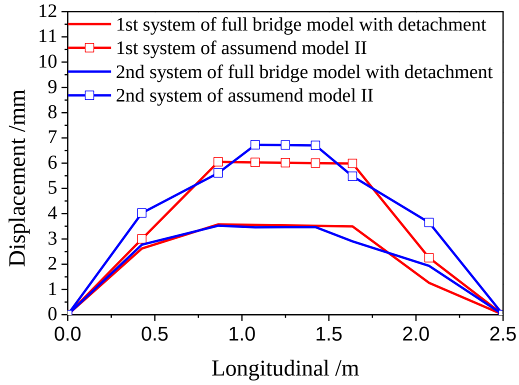
Comparison of the horizontal and vertical displacements of simplified models with those of full bridge model with detachment is shown in **Figs. 7-44** to **Fig. 7-47**, respectively.

Table 7-22 to **7-24** show the maximum deflection and location of two systems for two models under asymmetrical and symmetrical uniform pedestrian load. The tables show the results of model I compare with the full bridge model with detachment. Under asymmetrical pedestrian load, the horizontal displacement, the negative maximum deflection and the positive maximum deflection of the first system reduced by 46%, 47% and 51%, respectively. The horizontal displacement, the negative maximum deflection and the positive maximum deflection of the second system reduced by 57%, 59% and 78%, respectively. Under symmetrical pedestrian load, the horizontal and vertical displacement maximum deflection of the first system reduced by 36% and 39%, respectively, and the horizontal and vertical displacement maximum deflection of the second system reduced by 75% and 70%, respectively.

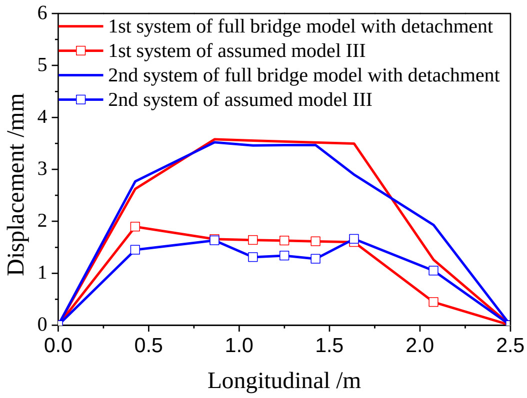
It can be found, the result of simplified assumed model I is smaller than the full bridge model with detachment, so it is not suitable for the Min-zhe Timber Arch Bridge.



(a) Assumed model I

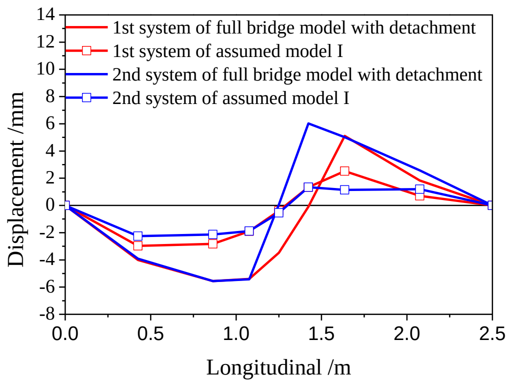


(b) Assumed model II

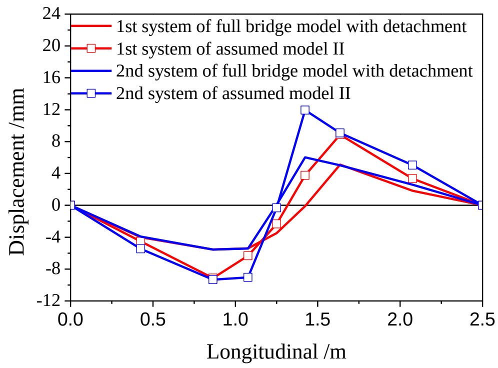


(c) Assumed model III

Fig. 7-44 Comparison of horizontal displacements of simplified models under asymmetrical load

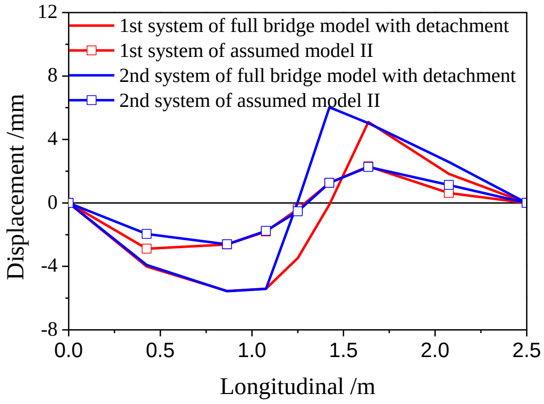


(a) Assumed model I



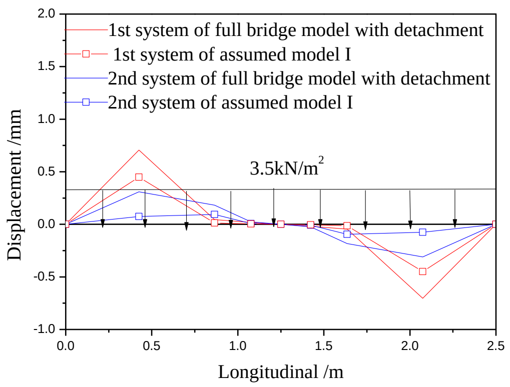
(b) Assumed model II

Fig. 7-45 Comparison of vertical displacements of simplified models under asymmetrical load

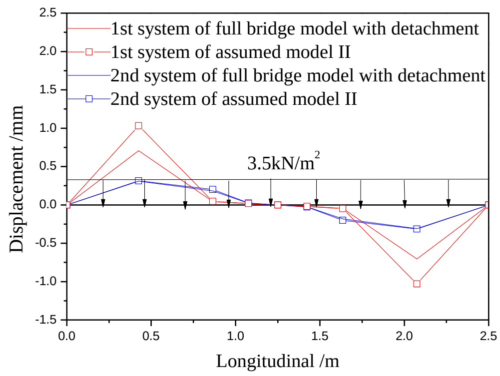


(c) Assumed model III

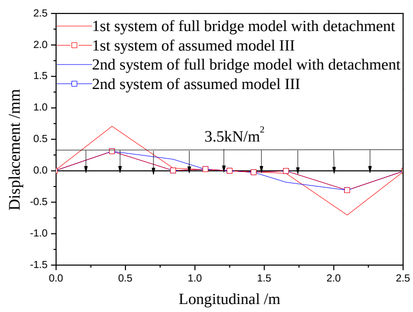
Fig. 7-46 Comparison of vertical displacements of simplified models under asymmetrical load (contd.)



(a) Assumed model I

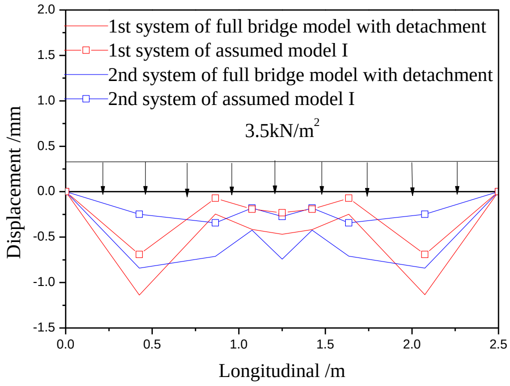


(b) Assumed model II

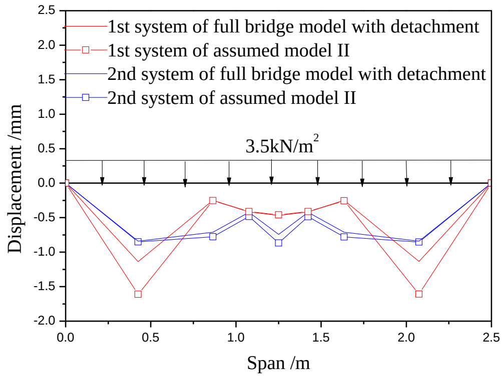


(c) Assumed model III

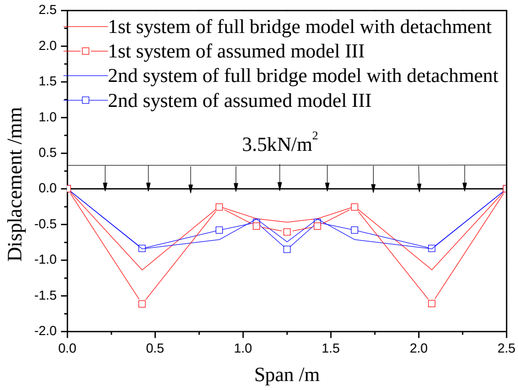
Fig. 7-47 Comparison of horizontal displacements of simplified models under symmetrical load



(a) Assumed model I



(b) Assumed model II



(c) Assumed model III

Fig. 7-48 Comparison of vertical displacements of simplified models under symmetrical load

Table 7-22 Value and location of the maximum deflection under asymmetrical loading (1st system)

Direction	Full bridge model with detachment	Assumed model I	Full bridge model with detachment	Assumed model I	Ratio (%)
	Value		Location		
Horizontal	3.578	1.949	A2	A1	46
Vertical	-5.557	-2.967	A2	A1	47
	5.104	2.523	A6	A5	51

Table 7-23 Value and location of the maximum deflection under asymmetrical loading (2nd system)

Direction	Full bridge model with detachment	Assumed model I	Full bridge model with detachment	Assumed model I	Ratio (%)
	Value		Location		
Horizontal	3.522	1.530	A2	A1	57
Vertical	-5.559	-2.255	A2	A1	59
	6.029	1.339	A5	A5	78

Table 7-24 Value and location of the maximum deflection under symmetrical loading

System	Displacement direction	Full bridge model with detachment		Assumed model I		Ratio (%)
		Value	Location	Value	Location	
1st system	Horizontal	0.706	A1	0.449	A1	36
	Vertical	-1.138	A1	-0.691	A1	39
2nd system	Horizontal	0.309	B1	0.076	B1	75
	Vertical	-0.842	B1	-0.249	B1	70

Table 7-25 Value and location of the maximum deflection under asymmetrical loading (1st system)

Displacement direction	Full bridge model with detachment		Assumed model II		Ratio (%)
	Value	Location	Value	Location	
Horizontal	3.578	A2	6.048	A2	-69
Vertical	-5.557	A2	-9.139	A2	-64
	5.104	A6	8.870	A6	-74

Table 7-26 Value and location of the maximum deflection under asymmetrical loading (2ndt system)

Displacement direction	Full bridge model with detachment		Assumed model II		Ratio (%)
	Value	Location	Value	Location	
Horizontal	3.522	A2	6.727	A2	-91
Vertical	-5.559	A2	-9.320	A2	-68
	6.029	A5	11.951	A5	-98

Table 7-27 Value and location of the maximum deflection under symmetrical loading

System	Displacement direction	Full bridge model with detachment		Assumed model II		Ratio (%)
		Value	Location	Value	Location	
1st system	Horizontal	0.706	A1	1.031	A1	-46
	Vertical	-1.138	A1	-1.612	A1	-42
2nd system	Horizontal	0.309	B1	0.312	B1	-1
	Vertical	-0.842	B1	-0.852	B1	-1

Table 7-25 to **Table 7-27** show the maximum deflection, location and the ratio of maximum value of two systems between in two models under asymmetrical and

symmetrical uniform pedestrian load. Under asymmetrical pedestrian load, the result of full bridge model with detachment is obviously smaller than that of the assumed model II, the horizontal displacement, the negative maximum deflection and the positive maximum deflection of the first system reduced by 69%, 64% and 74%, respectively. The horizontal displacement, the negative maximum deflection and the positive maximum deflection of the second system reduced by 91%, 68% and 98%, respectively. Under symmetrical pedestrian load, the horizontal and vertical displacement maximum deflection of the first system reduced by 46% and 42%, respectively, the horizontal and vertical displacement maximum deflection of the second system remain unchanged.

Because the result of simplified assumed model II is larger than the full bridge model with detachment, so it is suitable for the Min-zhe Timber Arch Bridge, and the results are conservative than those of the full bridge model with detachment.

Table 7-28 to **Table 7-30** show the maximum deflection, location and the ratio of maximum value of two systems between in two models under asymmetrical and symmetrical uniform pedestrian load. Under asymmetrical pedestrian load, the result of full bridge model with detachment is obviously larger than that of the assumed model III. For the horizontal displacement, the negative maximum deflection and the positive maximum deflection of the first system reduced by 47%, 48% and 55%, respectively. The horizontal displacement, the negative maximum deflection and the positive maximum deflection of the second system reduced by 54%, 53% and 62%, respectively. Under symmetrical pedestrian load, the horizontal and vertical displacement maximum deflection of the first system reduced by 46% and 42%, respectively; the horizontal and vertical displacement maximum deflection of the second system remain unchanged.

Table 7-28 Value and location of the maximum deflection under asymmetrical loading (1st system)

Direction	Full bridge model with detachment	Assumed model III	Full bridge model with detachment	Assumed model III	Ratio (%)
	Value		Location		
Horizontal	3.578	1.898	A2	A1	47
Vertical	-5.557	-2.889	A2	A1	48
	5.104	2.301	A6	A6	55

Table 7-29 Value and location of the maximum deflection under asymmetrical loading (2ndt system)

Direction	Full bridge model with detachment	Assumed model III	Full bridge model with detachment	Assumed model III	Ratio
	Value		Location		
Horizontal	3.522	1.631	A2	A1	54%
Vertical	-5.559	-2.608	A2	A1	53%
	6.029	2.261	A5	A6	62%

Table 7-30 Value and location of the maximum deflection under symmetrical loading

System	Displacement direction	Full bridge model with detachment		Assumed model III		Ratio (%)
		Value	Location	Value	Location	
1st system	Horizontal	0.706	A1	1.031	A1	-46
	Vertical	-1.138	A1	-1.612	A1	-42
2nd system	Horizontal	0.309	B1	0.309	B1	0
	Vertical	-0.842	B1	-0.835	B1	1

Because the result of simplified assumed model III is also smaller than that of the full bridge model with detachment, so it is not suitable for the Min-zhe Timber Arch Bridge.

It can be found from **Fig. 7-41** to **Fig. 7-43** and **Table 7-21**, the maximum compressive axial forces of assumed model II are the closest to those of the full bridge model with detachment although the distribution and maximum of other internal forces are not close. The errors are 6.1% and 16.7% for the maximum compressive force of 1st and 2nd systems, respectively. Arch is the compressive axial force dominant structure. Therefore, the accuracy of compressive axial force is more important than those of tensile axial force and bending moment. From this point of view, assumed model II can be thought as the best model among three simplified models. At the same time, as shown in **Fig. 7-44** to **Fig. 7-47**, the displacements of assumed models I and III are obviously smaller than those of the full bridge model with detachment while the displacements of assumed model II are larger than those of the full bridge model with detachment. In other words, assumed model II can provide conservative calculation side results of displacement for design. Based on these results, the authors think that the simplified assumed model II can be used for the preliminary analyses.

7.4 Summary

(1) The transverse beam and arch ribs are connected by ropes in Bianhe Rainbow Bridge, the joint can bear both compression and tension, but cannot bear bending moment, so the connect of arch ribs of the same system can imitated by hinge joints, and the arch ribs connect with transverse beam can imitated by half-hinge joints. The planar simplified calculation model as shown in **Fig. 7-3**, which is proposal by Mr. Tang, suiting for Bianhe Rainbow Bridge.

(2) The transverse beam and arch ribs are connected by mortise and tenon joint in Min-zhe timber arc bridge, the joint can bear compression, smaller bending moment, but not tension, the two systems cannot combine with work sometime.

(3) Detachment is most likely to occur at the contact position between two systems. The load transfer performance of upper transverse beams of the 2nd system is the best, followed by that the transverse beams of the 1st system, and the lower transverse beam of the 2nd system is the worst.

(4) The mechanical behavior of Min-Zhe Timber Arch Bridges is highly affected by the different load transfer performance of two systems. Thus, some contact positions of two systems cannot transfer load, which should be taken into account in the design and calculation of Min-Zhe Timber Arch Bridges. The arch rib connect with the transverse beam cannot all directly simplify into half-hinged for the planar simplified calculation model of Min-zhe Timber Arch Bridge.

(5) The proposed simplified model can provide conservative calculation results for Min-Zhe Timber Arch Bridges, in which the mortise and tenon joints are simplified as the hinge; and only the transverse beam of the 1st system can transfer the load to the 2nd systems arch ribs.

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CHAPTER 8

CONCLUSIONS AND FUTURE RESEARCH

8.1 Concluding Remarks

The purpose of this research is to reveal the mechanical behavior and superiority in structure of the Chinese timber arch bridge, to provide scientific evidence for Chinese timber arch bridge applying as the world cultural heritage, and to give theoretical support for the inheritance of "*the traditional construction technology of the Chinese timber arch bridge*". The main findings obtained in this dissertation are summarized as follows.

(1) According to the present situation, location, and structural details, Chinese timber arch bridge can be further divided into two types, one is the ancient Bianhe Rainbow Bridge, while the other is the Min-zhe Timber Arch Bridge. No ancient Bianhe Rainbow Bridge survived, but many ancient Min-zhe Timber Arch Bridges did. The Bianhe Rainbow Bridge and the Min-zhe Timber Arch Bridge have the same woven timber structure, but there are some differences between them not only in appearance but also in structural details. The Min-zhe Timber Arch Bridge gives a more reasonable design than the Bianhe Rainbow Bridge. The Min-zhe Timber Arch Bridge is not only the essence of architecture in China, but also a part of the precious cultural heritage handed down from the ancient people, because it includes abundant intangible cultural heritage. It is the paragon in the history of bridge and architecture in the world, which is a combination of science, technology, architectural art and architectural culture.

(2) Because of incomplete main technical parameters, mistakes made in all kind of references, the main technical parameters of Chinese timber arch bridge have been defined according to the modern bridge design theory by author. Based on the mass collection information about the Chinese timber arch bridge, an investigation is carried out by field survey on the current situations of the bridges, the main arch ring structures including the longitudinal two systems and the cross-section, the major structural parameters such as the length, span as well as the rise-to-span ratio. The main structural parameters have been analyzed from the view of bridge engineering, Chinese timber arch bridge has a long and consistent construction history. All the extant Chinese timber arch bridge are located in the in mountainous areas in the northeast Fujian Province and southeast Zhejiang Province. The field survey results can be summarized as follows:

1) There are 130 timber arch bridges in use today, and most of them were built in the

Qing Dynasty (accounting for 53.9%).

2) The extant Min-zhe Timber Arch Bridges are managed by the department of cultural relic and local government. 22 timber arch bridges have been listed in the world cultural heritage tentative list in China in 2012. 17 Min-zhe Timber Arch Bridges were listed in the national preservation list of cultural relics.

3) Among 130 timber arch bridges, 123 of which are single-span bridges, only 7 of which are multi-span bridges. The length of the multi-span is between 53 m to 115 m, while six of them have a length over 60 m; while for the single-span bridges, only one single span bridge is over 60 m. Among them, 108 bridges have a span between 20 m and 50 m, accounting for 83.1% of the total.

4) The spans are mainly in 10 m-30 m, and the concentrated area of span distribution is 20 m-30 m, accounting for 42.3%. The longest span is 37.6m. The width of bridges is in 4 m-6 m, mostly in 4 m-5 m. The rise-span ratios are from 1/3 to 1/7, usually in 1/5-1/7, and similar to the other arch bridges in China.

5) The diameters of arch ribs of two systems are between 18 cm and 40 cm, and the first system is always bigger than the second system. There is a tendency that the diameter of the logs becomes bigger with the increase of span length. However, the relationship between the diameter and span is not so clear and definite.

(3) Taking the real bridge as a case, the structural behavior of woven arch was investigated experimentally and analytically. Four scale models comprising two bare arches and two full-bridges were tested subjected to asymmetrical and symmetrical loading in the lab. The findings obtained in the test study are summarized as follows:

1) In an elastic stage, the deflection of woven is antisymmetric with respect to the midpoint of the bridge under the asymmetrical loading, and the deformation was symmetrical with respect to the midpoint of the bridge under the symmetrical loading follow the arch theory.

2) The deformation tendency of woven arch with hinged joint is similar to woven arch with rigid joint, and the joint rigidity of woven cannot change the deformation tendency. But the woven arch with hinged joint have much greater deformation than the woven arch with rigid joint, and the joint rigidity of woven has greater effect on the deformation. The effect is more and more obviously with the load from arch springing to midspan.

3) The joint of the transverse beam connecting with other system arch rib cannot bear tension, and that detachment often occurs at the transverse beam connecting with the arch rib of other system and causes the two systems which cannot combine work.

4) The spandrel structure is beneficial for wove arch. Although it cannot change the tendency of deformation of woven arch, the spandrel structure will participate in bearing the loading of the structure, which will reduce the deformation of woven arch.

(4) The mechanical behaviors of woven timber arch bridge are investigated by finite element analyses under different symmetrical or asymmetrical loading cases. The findings obtained in the present study are summarized as follows:

1) The woven arch under either symmetrical or asymmetrical loading, would have vertical and longitudinal displacement, and the vertical displacement is greater than the longitudinal displacement. Moreover, the vertical deformation under asymmetrical loading is greater than its counterpart under symmetrical loading.

2) The two systems were mainly subjected to compression, and the first system is the main structure to sustain the compression.

3) The rigidity of joint should not change the deformation tendency of wove arch, but the deflection of woven arch with hinged joint is greater than the woven arch with rigid joint. The mortise-tenon joint simplified as hinged joint is a better conservative calculation for simplified calculation.

4) The maximum stress of arch ribs under either half- span or full-span pedestrian loading is much lower than the measured compressive strength of 111.6 MPa. However, the vertical displacement under asymmetrical loading is much larger than the required value by the General Code for Design of Highway Bridges and Culverts (1/1000 of calculation span length). Thus, the structural deformation may be the main factor for the design of Min-Zhe woven timber arch bridges, and sectional stress should also be considered.

5) The further analysis shows the spandrel structure is beneficial for wove arch, and the internal force of full-bridge is smaller than the bare arch in the same load value, and the spandrel structure will participate in bearing the loading of the structure.

6) The structure mechanics of woven is extremely similar to two-hinged arch. The sum of axial force of two systems is similar to the two-hinged arch, and the bending moment at

nodes is smaller than two-hinged arch.

7) According to the comparison results, the Min-zhe Timber Arch Bridge has better traffic performance than the Bianhe Rainbow Bridge. And then, the analysis results show the spandrel structures, X-bracings, as well as the inserted wood blocks among the logs in the Min-zhe Timber Arch Bridge take part in carrying loads and enhancing the integrity and stability of the arch structure. The covering house adds a dead load to the structure to improve the structure's resisting capacity to the uplift load. Based on a reasonable consideration of technological development, the author takes a more reasonable conclusion that the Min-zhe Timber Arch Bridge develops from the Bianhe Rainbow Bridge.

(5) An existing Min-zhe Timber Arch Bridge has been tested and analyzed. The results from finite element method reasonably match the test ones. The results show two systems of main arch structure are mainly subjected to the compression, and the first system is larger than the second system. Min-zhe Timber Arch Bridge is mainly subjected to the first system. Under the design load with the value of 3.5 kN/m^2, the maximum compression stress and tensile stress of Xi'nan bridge are all far less than the compressive strength and tensile stress. At the same time, the maximum displacement is very smaller, about 1/2000 of calculation span length. Thus, the Xi'nan bridge is still in good situation.

(6) The manual calculation model of Bianhe Rainbow Bridge will be introduced and comparatively validated by Structural Mechanics Solver Method and Finite Element Method. According to the research results of Chapter 4 and Chapter 5, it is shown that the manual calculation model of Bianhe Rainbow Bridge is not applicable for Min-zhe Timber Arch Bridge. The simplified calculation model of Min-zhe Timber Arch Bridge have been proposed through the research on the mechanism of combine work of two systems of Min-zhe Timber Arch Bridge. The findings on the simplified model are summarized as follows:

1) The transverse beam and arch ribs are connected by ropes in Bianhe Rainbow Bridge, and the joint can bear both compression and tension, but cannot bear bending moment, so the connect of arch ribs of the same system can be imitated by hinge joints, and the arch ribs connected with transverse beam can imitated by half-hinge joints. The planar simplified calculation model shown in Fig. 7-3, which is proposed by Mr. Tang, is suitable

for Bianhe Rainbow Bridge.

2) The transverse beam and arch ribs are connected by mortise and tenon joint in Min-zhe Timber Arch Bridge. The joint can bear compression, smaller bending moment, but not tension. The two systems cannot combine work in some moment.

3) Detachment is most likely to occur at the contact position between two systems. The load transfer performance of upper transverse beams of the 2nd system is the best, followed by that the transverse beams of the 1st system, and the lower transverse beam of the 2nd system is the worst.

4) The mechanical behavior of Min-zhe Timber Arch Bridges is highly affected by the different load transfer performance of two systems. Thus, some contact positions of two systems cannot transfer load, which should be taken into account in the design and calculation of Min-zhe Timber Arch Bridges. The arch rib connected with the transverse beam cannot all directly be simplified into half-hinged for the planar simplified calculation model of Min-zhe Timber Arch Bridge.

5) The proposed simplified model can provide conservative calculation results for Min-Zhe timber arch bridges, in which the mortise and tenon joints are simplified as the hinge; and only the transverse beam of the 1st system can transfer the load to the 2nd systems arch ribs.

8.2 Recommendations for Future Research

The study in this dissertation has certain deficiencies and need enhancement through future work. Some ideas for enhancement are as follows:

(1) This study focused on the mechanical behavior of Chinese woven arch in an elastic stage, and the study on the load bearing capacity of woven arch will be studied in the future.

(2) The mortise and tenon joints were simplified as hinged joints and rigid joints. The stiffness of mortise and tenon joints should be conducted in the future.

(3) This study emphasized on the static mechanical behavior of Chinese woven arch. The dynamics mechanical behavior of Chinese woven arch also needs to be studied.

(4) The research work had not considered the effect of out-of-plane, hence, the further research work should be carried out in the future.

APPENDIX I

List of field-surveyed 130 bridges

No.	Name	Number of spans	Length	Width	Span	Rise	Rise-span ratio	Number of arch rib	
								1st system	2nd system
1	Wanan Bridge	6	96.6	4.7		2.8		9	8
2	Qiansheng Bridge	2	62.7	4.9	27	4.2	0.16	9	8
3	Longjing Bridge	1	27.5	4.9	22.2	3.57	0.16	9	8
4	Guangfu Bridge	1	32	5	10.5	4.45	0.42	9	8
5	Guangli Bridge	1	30.5	4.5	20.6	3.67	0.18	9	8
6	Longjin Bridge	1	33.5	4.5	23	3.64	0.16	9	8
7	Jinzao Bridge	1	39.5	4.78	31.4	4.63	0.15	9	8
8	Qingyan Bridge	1	26.4	4.5	21.8	3.39	0.16	9	8
9	Huifeng Bridge	1	32.2	4.5	23.5	4.26	0.18	9	8
10	Yingfegn Bridge	1	29	4.3	13.5	3.61	0.27	7	6
11	Xili Bridge	1	37.8	4.3	20	3.56	0.18	9	8
12	Zhangkou Bridge	1	26	3.8	18.5	2.45	0.13	9	8
13	Baixiang Bridge	1	38	4.5	35	5.72	0.16	9	8
14	Shuanglong Bridge	3	66	4.5	19.9			9	8
15	Shijin Bridge	1	12	4.2	6			9	8
16	Luanfeng Bridge	1	47.6	4.9	37.6			9	8
17	Yangxitou Bridge	1	49	5	36.6			9	8
18	Feiyun Bridge	1	29.2	5.3	18.5			9	8
19	Shengping Bridge	1	25.5	5.6	23.4			9	8

No.	Name	Number of spans	Length	Width	Span	Rise	Rise-span ratio	Number of arch rib	
20	Xiangong Bridge	1	27	5.1	24.5			9	8
21	Dengyun Bridge	1	33.8	4.2	30.8			9	8
22	Zhangkeng Bridge	1	40	5	33.4			9	8
23	Changlaixi Bridge	1	39.2	5.2	32			9	8
24	Liren Bridge	1	26.4	5.6	21			9	8
25	Wenming Bridge	1	23.5	4.6	16.7			9	8
26	Dabao Bridge	1	44.3	4.6	33.1			9	8
27	Xiaodongshang Bridge	1	21.4	4.6	16.4			9	8
28	Yangmeizhou Bridge	1	42.5	4.2	35.7			9	8
29	single Bridge	1	20.1	4.1	16.3			7	6
30	Fushou Bridge	1	40.7	4.7	32.8			9	8
31	Shouchun Bridge	1	19.6	4.2	12.4			7	6
32	Huilan Bridge	1	26	5.2	17.2			9	8
33	Hongjun Bridge	1	42	5.1	32.6			9	8
34	Puji Bridge	1	25	5	16.4			9	8
35	Sanxian Bridge	1	24.6	5.32	17.93	2.1	0.12	7	6
36	Denglong Bridge	1	33.45	4.8	25.42	3.84	0.15	9	8
37	Louxia Bridge	1	22.15	4.2	17.4	3.3	0.19	9	8
38	Zhuling Bridge	1	34.6	4.48	24.7	4.02	0.16	9	8

No.	Name	Number of spans	Length	Width	Span	Rise	Rise-span ratio	Number of arch rib	
39	Qixian Bridge	1	24.16	5	15.24	2.44	0.16	7	6
40	Changfeng Bridge	1	20.38	4.2	14.58	2.55	0.17	9	8
41	Houlong Bridge	1	34.25	4.8	30.2	4.8	0.16	9	8
42	Tangxi Bridge	1	41.25	4.8	34.55	5.84	0.17	9	8
43	Jigu Bridge	1	17.9	4.05	12.12	1.96	0.16	7	6
44	Yangkeng Bridge	1	21.4	4.39	15.69	3.77	0.24	9	8
45	Yuting Bridge	1	28.75	4.63	22.94	3.71	0.16	9	8
46	Zhetou Bridge	1	16.55	4.2	15.4	2.63	0.17	7	6
47	Lanxi Bridge	1	36.35	5.05	25.29	3.71	0.15	9	8
48	Xuzhou Bridge	1	35.15	4.6	29.13	5.22	0.18	9	8
49	Tiandi Bridge	1	40.5	5.38	30.77	5.29	0.17	9	8
50	Tingxia Bridge	1	29.4	5.02	27.22	4.07	0.15	9	8
51	Shuyin Bridge	1	24.4	4.06	15.3	2.46	0.16	7	6
52	Shuanghong Bridge	1	35	4.6	27	4	0.15	9	8
53	Guisi Bridge	1	21.8	4.9	15.22	1.5	0.10	9	8
54	Dongyuan Bridge	1	40.8	6.83	14.48	2.07	0.14	9	8
55	Laoren Bridge	1	30.15	5.81	24.27	4.92	0.20	9	8
56	Linqing Bridge	1	15.45	3.42	10.92	1.5	0.14	5	4
57	Sanxi Bridge	1	32	5.4	21.1			9	8

No.	Name	Number of spans	Length	Width	Span	Rise	Rise-span ratio	Number of arch rib	
58	Yuanji Bridge	1	31.42	5.23	30.47	4.33	0.14	9	8
59	Longjin Bridge	1	27.23	4.28	21.58	3.44	0.16	7	6
60	Kengping Bridge	1	24.14	4.3	21.38	2.69	0.13	8	7
61	Taishan Bridge	1	24.14	4.2	17.93	2.89	0.16	9	8
62	Tangli Bridge	1	28.18	4.75	23.74	3.87	0.16	7	6
63	Jiaoxi Bridge	1	24.35	4.29	19.03	2.72	0.14	7	6
64	Helong Bridge	2	53	4.35	12.5 14.7	2.45		9	8
65	Wentang Bridge	1	11.6	4				7	6
66	Duoting Bridge	1	32.3	4.7	20.3			7	6
67	Yanghou Bridge	1	35.04	5.3	25.96	4.59	0.18	9	8
68	Houshan Bridge	1	33	5.43	29.91	5.16	0.17	9	8
69	Longtan Bridge	1	31	5	23			9	8
70	Luoling Bridge	1	39.52	4.06	26	3.66	0.14	9	8
71	Jjiaolong Bridge	1	24.06	5.25	13.04	3.21	0.25	9	8
72	Chixi Bridge	1	33.5	5	24			9	8
73	Xiaban Bridge	1	26	4.5	21	3.5	0.17	9	8
74	Xianen Bridge	1	45.17	4.3	24.5			9	8
75	Desheng Bridge	1	36.8	5	25.23	4.57	0.18	9	8
76	Houjian Bridge	1	31.47	4.45	22.94	4.34	0.19	9	8

No.	Name	Number of spans	Length	Width	Span	Rise	Rise-span ratio	Number of arch rib	
77	Jielong Bridge	1	47.12	4.89	31.04	5.24	0.17	9	8
78	Chenglong Bridge	1	59	4.2	18	3	0.17	9	8
79	Lanxia Bridge	1	50	4.21	16.06	2.72	0.17	9	8
80	Xinglong Bridge	1	47.75	5	19.76	3.17	0.16	9	8
81	Huayang Bridge	1	99	4.2	18			7	6
82	Xidong Bridge	1	41.7	5.6	25.18	4.55	0.18	9	8
83	Beijian Bridge	1	51	4.73	30.39	5.43	0.18	9	8
84	Xianju Bridge	1	40.47	5.76	34.31	6.22	0.18	7	6
85	Xuezha Bridge	1	33.56	5.12	27.25	6.01	0.22	9	8
86	Santiao Bridge	1	28.18	4.66	21.39	3.48	0.16	7	6
87	Wenxing Bridge	1	40.15	5.47	30.5	5.18	0.17	9	8
88	Tongle Bridge	1	34.4	5.2	23			9	8
89	Wuyanling Bridge	1	26	5	18			9	8
90	Nanxi New Bridge	1	19	3.2	5.9			9	8
91	Buxia Bridge	1	38	5	23			9	8
92	Fuqing Bridge	1	44.1	4.8				9	8
93	Qionghua Bridge	1	20.9	4.8	23.4	3.3	0.14	9	8
94	Lianchuandadi Bridge	1	41.3	4.8	29.9	4.9	0.16	9	8
95	Jielong Bridge	1	37.6	4.6	30.7	4.5	0.15	9	8

No.	Name	Number of spans	Length	Width	Span	Rise	Rise-span ratio	Number of arch rib	
96	Dongkeng shang	1	24.5	4.2	18.2	2.26	0.12	7	6
97	Dongkeng xia Bridge	1	29.2	4.8	21.8	9.5	0.44	7	6
98	Meiqi Bridge	1	32.6	4.5	24.8	4.3	0.17	7	6
99	Dachikeng Bridge	1	35	4.9	29.1	5.27	0.18	9	8
100	Beixi Bridge	1	21	4.1	13.9	1.76	0.13	7	6
101	Yongzhen Bridge	1	36.5	3.8	23.6	4.7	0.20	8	7
102	Yongping Bridge	1	20.1	4.2	14.4	2.34	0.16	7	6
103	Chatang Bridge	1	40.6	4.9	26.7	12.3	0.46	9	8
104	Lingjiao Bridge	1	35.9	4.6	35.5	5	0.14	7	6
105	She Bridge	1	35.7	4.5	28.2	5.05	0.18	7	6
106	Shijiankeng Bridge	1	22.1	4.6	16.7	2.46	0.15	7	6
107	Changtan Bridge	1	24.9	4.6	19.6	4.4	0.22	7	6
108	Jingning County New	3	69.2	5.6	15.7	2.8	0.18	9	8
109	Rulong Bridge	1	28.2	5.08	18.56	2.23	0.12	7	6
110	Lanxi Bridge	1	46.9	4.9	34.3	5.87	0.17	9	8
111	Houkeng Bridge	1	36.2	4.29	25.56	4.32	0.17	9	8
112	Yonggui Bridge	1	26.4	5.4	21	4.27	0.20	11	10
113	Shuangmen Bridge	1	15.4	4.4	10.4	1.64	0.16	7	6
114	Niao Bridge	1	28.9	3.6	14.4	2.35	0.16	7	6

No.	Name	Number of spans	Length	Width	Span	Rise	Rise-span ratio	Number of arch rib	
115	Zhuping Bridge	1	37.1	4.55	18.2	3.14	0.17	7	6
116	Huangshui Long Bridge	1	54.3	4.9	17.5	3.66	0.21	9	8
117	Bantinglu Bridge	1	28.8	4.9	18.8	4.01	0.21	9	8
118	Mengyu Bridge	1	36.1	4.56	28.4	4.39	0.15	9	8
119	Wenchang Bridge	1	15.8	5.3	12.6	2.33	0.18	7	6
120	Mengzhou Bridge	3	115	5.9	22.9	4.09	0.18	9	8
121	Futian Bridge	1	16.4	4.4	9.1	1.45	0.16	9	8
122	Jiajin Bridge	1	49.4	5.25	27.9	5.75	0.21	9	8
123	Baishanzu Bridge	1	25.72	4.46	17	2.4	0.14	9	8
124	Fuliang Bridge	3	76.8	5.5	22	3.06	0.14	9	8
125	Hexing Bridge	1	25.8	4	21.08	4.81	0.23	7	6
126	Shunde Bridge	1	35	4.5	26.31	4.04	0.15	8	7
127	Huairen Bridge	1	35.6	4.4	25.8	11	0.43	9	8
128	Wohong Bridge	1	25	4	13.23	2.02	0.15	7	6
129	Gongqi Bridge	1	22.7	4.1	12.4	2.4	0.19	7	6
130	Zhongshan Bridge	1	29.8	4	19.15	3.2	0.17	7	6

APPENDIX II

Photograph of field surveyed 130 bridges

1	Wan'an Bridge	
		
2	Qiancheng Bridge	
		
3	Longjing Bridge	
		
4	Guangfu Bridge	
		
5	Guangli Bridge	
		

<table>
<tr><td rowspan="2">6</td><td colspan="2">Longjin Bridge</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">7</td><td colspan="2">Jinzao Bridge</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">8</td><td colspan="2">Qingyan Bridge</td></tr>
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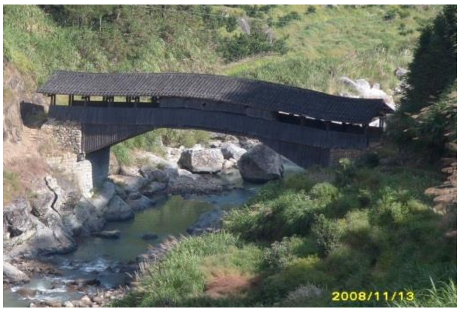
<tr><td rowspan="2">9</td><td colspan="2">Huifeng Bridge</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">10</td><td colspan="2">Yingfegn Bridge</td></tr>
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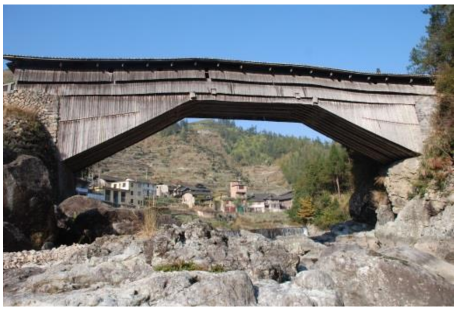
11	Xili Bridge	
		
12	Zhangkou Bridge	
		
13	Baixiang Bridge	
		
14	Shuanglong Bridge	
		
15	Shijin Bridge	
		

16	Luanfeng Bridge	
		
17	Yangxitou Bridge	
		
18	Feiyun Bridge	
		
19	Shengping Bridge	
		
20	Xiangong Bridge	
		

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<tr><td rowspan="2">21</td><td colspan="2">Dengyun Bridge</td></tr>
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<tr><td rowspan="2">22</td><td colspan="2">Zhangkeng Bridge</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">23</td><td colspan="2">Changlaixi Bridge</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">24</td><td colspan="2">Liren Bridge</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">25</td><td colspan="2">Wenming Bridge</td></tr>
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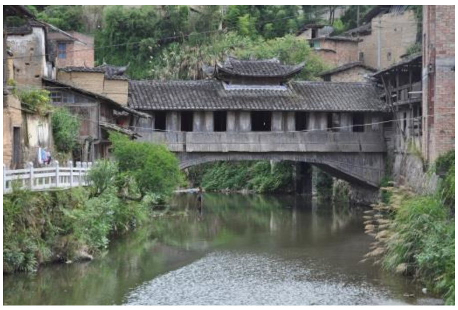
26	Dabao Bridge	
		
27	Xiaodongshang Bridge	
		
28	Yangmeizhou Bridge	
		
29	Single Bridge	
		
30	Fushou Bridge	
		

31	Shouchun Bridge	
		
32	Huilan Bridge	
		
33	Hongjun Bridge	
		
34	Puji Bridge	
		
35	Sanxian Bridge	
		

36	Denglong Bridge	
		
37	Louxia Bridge	
		
38	Zhuling Bridge	
		
39	Qixian Bridge	
		
40	Changfeng Bridge	
		

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<tr><td rowspan="2">41</td><td colspan="2">Houlong Bridge</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">42</td><td colspan="2">Tangxi Bridge</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">43</td><td colspan="2">Jigu Bridge</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">44</td><td colspan="2">Yangkeng Bridge</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">45</td><td colspan="2">Yuting Bridge</td></tr>
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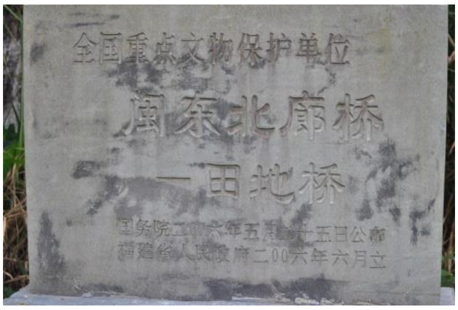
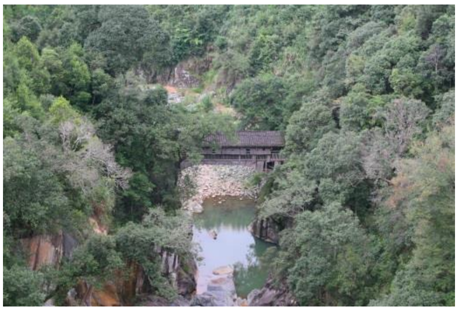
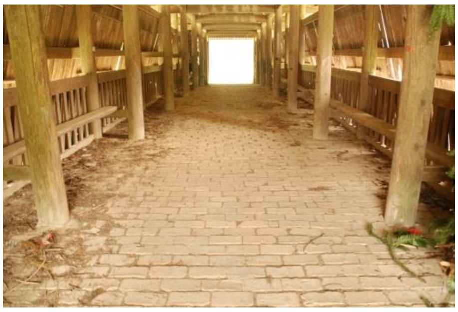
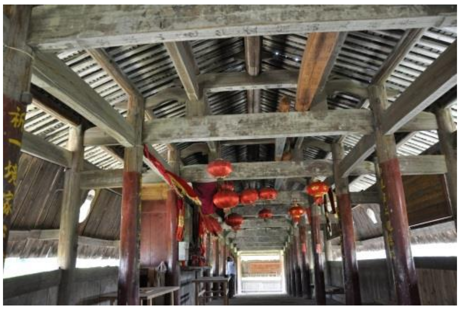
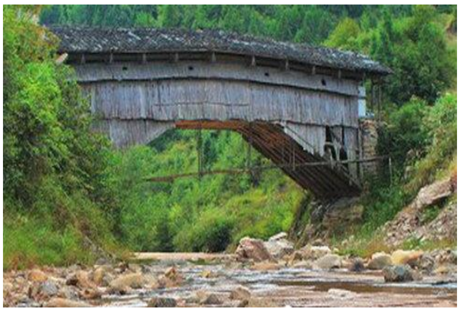
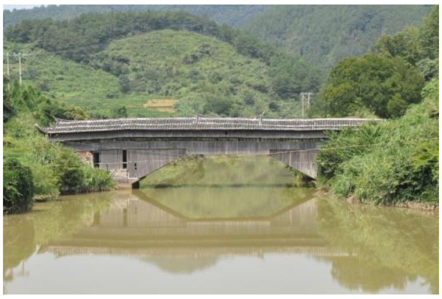
46	Zhetou Bridge	
		
47	Lanxi Bridge	
		
48	Xuzhou Bridge	
		
49	Tiandi Bridge	
		
50	Tingxia Bridge	
		

51	Shuyin Bridge	
		
52	Shuanghong Bridge	
		
53	Guisi Bridge	
		
54	Dongyuan Bridge	
		
55	Laoren Bridge	
		

56	Linqing Bridge	
		
57	Sanxi Bridge	
		
58	Yuanji Bridge	
		
59	Longjin Bridge	
		
60	Kengping Bridge	
		

61	Taishan Bridge	
		
62	Tangli Bridge	
		
63	Jiaoxi Bridge	
		
64	Helong Bridge	
		
65	Wentang Bridge	
		

66	Duoting Bridge	
		
67	Yanghou Bridge	
		
68	Houshan Bridge	
		
69	Longtan Bridge	
		
70	Luoling Bridge	
		

71	Jiaolong Bridge	
		
72	Chixi Bridge	
		
73	Xiaban Bridge	
		
74	Xianen Bridge	
		
75	Desheng Bridge	
		

76	Houjian Bridge	
		
77	Jielong Bridge	
		
78	Chenglong Bridge	
		
79	Lanxia Bridge	
		
80	Xinglong Bridge	
		

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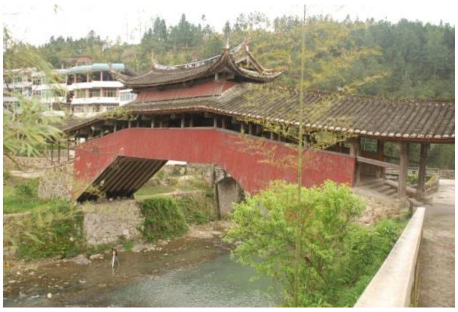
<tr><td></td><td></td></tr>
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<tr><td></td><td></td></tr>
<tr><td rowspan="2">84</td><td colspan="2">Xianju Bridge</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">85</td><td colspan="2">Xuezha Bridge</td></tr>
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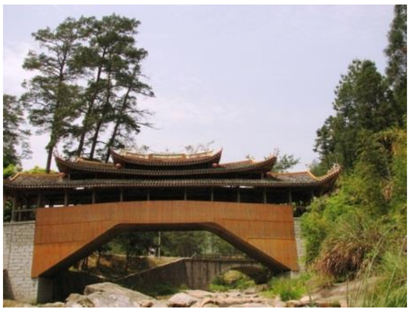
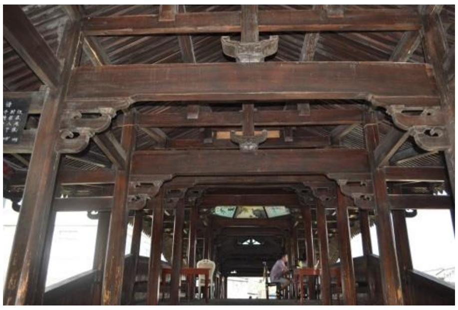
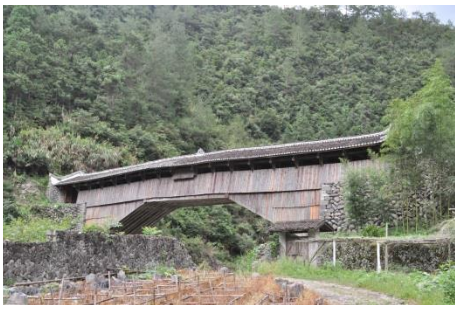
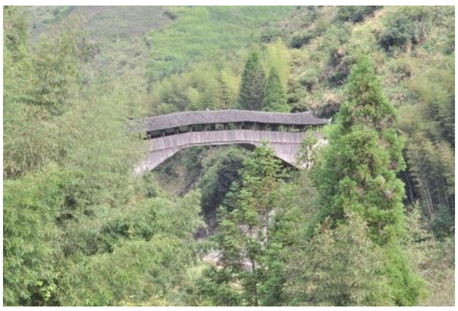
86	Santiao Bridge	
		
87	Wenxing Bridge	
		
88	Tongle Bridge	
		
89	Wuyanling Bridge	
		
90	Nanxi New Bridge	
		

91	Buxia Bridge	
		
92	Fuqing Bridge	
	The photoes had not be obtained.	
93	Qionghua Bridge	
		
94	Lianchuandadi Bridge	
		
95	Jielong Bridge	
		

96	Dongkengshang Bridge	
		
97	Dongkengxia Bridge	
		
98	Meiqi Bridge	
		
99	Dachikeng Bridge	
		
100	Beixi Bridge	
		

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<tr><td rowspan="2">101</td><td colspan="2">Yongzhen Bridge</td></tr>
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<tr><td rowspan="2">103</td><td colspan="2">Chatang Bridge</td></tr>
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<tr><td></td><td></td></tr>
<tr><td rowspan="2">105</td><td colspan="2">She Bridge</td></tr>
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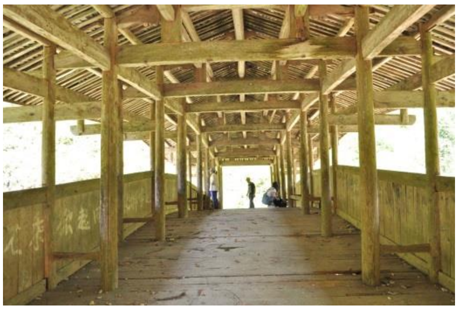
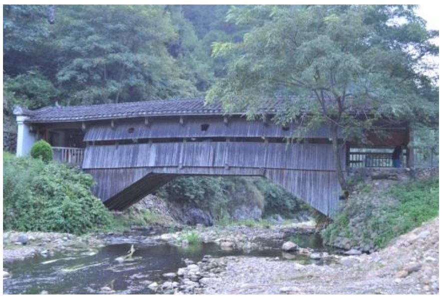
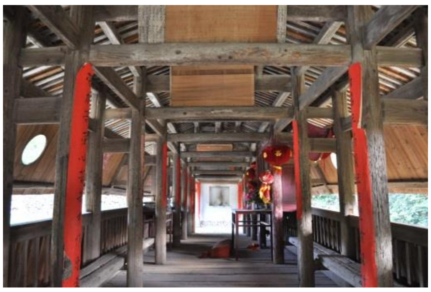
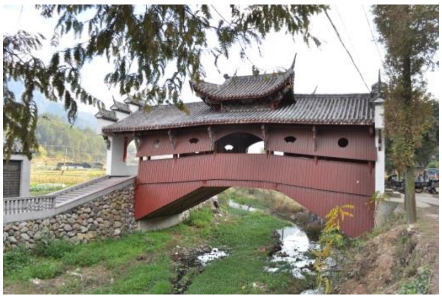
106	Shijiankeng Bridge	
		
107	Changtan Bridge	
		
108	Jingning County New Bridge	
		
109	Rulong Bridge	
		
110	Lanxi Bridge	
		

111	Houkeng Bridge	
		
112	Yonggui Bridge	
		
113	Shuangmen Bridge	
		
114	Niao Bridge	
		
115	Zhuping Bridge	
		

116	Huangshui Long Bridge	
		
117	Bantinglu Bridge	
		
118	Mengyu Bridge	
		
119	Wenchang Bridge	
		
120	Mengzhou Bridge	
		

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<tr><td rowspan="2">122</td><td colspan="2">Jiajin Bridge</td></tr>
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<tr><td rowspan="2">123</td><td colspan="2">Baishanzu Bridge</td></tr>
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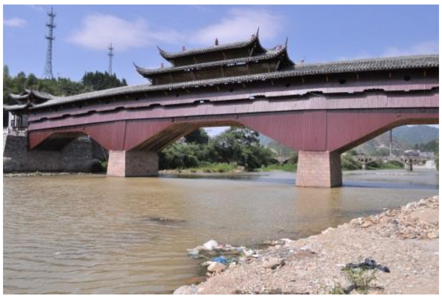
<tr><td></td><td></td></tr>
<tr><td rowspan="2">125</td><td colspan="2">Hexing Bridge</td></tr>
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126	Shunde Bridge	
		
127	Huairen Bridge	
	The photoes of Wohong Bridge could not be obtained since the shooting location is very difficult for the filming work.	
128	Wohong Bridge	
		
129	Gongqi Bridge	
		
130	Zhongshan Bridge