

Development and Features of Ancient and Modern Bridges in China

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Abstract. China has a long history and rich culture, and built and developed bridges very early compared with other countries in the world. With the rise and fall of China, Chinese bridges have also shown a certain rise and fall. By analyzing and studying the technology and development of Chinese bridges from ancient times to the present, and with the comparative analysis of some world bridges, this paper obtains some brilliant design concepts and valuable technologies to find out the future development path of Chinese bridge engineers. Most ancient bridges in China are divided into wooden and stone bridges according to materials, with various structures. Many designs and skills, such as the design and selection of arches through catenary, can still be used today. Modern bridges are divided into the beam, arch, suspension, and cable-stayed, according to mechanical and structural characteristics. Beam and arch bridges are suitable for small and medium-sized bridges, cable-stayed bridges for medium-sized bridges, and suspension bridges for large ones.

Keywords: Ancient Bridge; Modern Bridge; China; Bridge Development.

1. Introduction

Bridges are overhead structures for pedestrians, vehicles, channels, and pipelines to cross rivers, valleys or other traffic lines. The bridge is not only a functional structure but also the product of engineering technology and humanities. Many bridges have become fascinating cultural landscapes with distinctive characteristics of the times and are essential components of the world's architectural art.

With the development of bridges worldwide, bridge engineering has developed into a systematic discipline integrating theoretical analysis, design, construction control and management, which belongs to an important branch of civil engineering. Over the past 5000 years, with the progress of Chinese civilization, Chinese bridges have experienced the development of ancient and modern bridges. The world recognizes the brilliance of ancient Chinese bridges, such as the Zhaozhou Bridge, Luoyang Bridge and Lugou Bridge. The backwardness of modern Chinese bridges and the resurgence of modern Chinese bridges at the end of the 20th century are also indisputable facts.

This study focuses on Chinese bridges and discusses the development of typical ancient and modern bridges.

2. Development and features of bridges in ancient China

China is an ancient civilization with a long cultural history, and many ancient Chinese bridges have been preserved to this day. These ancient bridges include beams, arch, cable, floating, and other types. Most of them are made of stone and wood. Among them, the construction types of stone bridges are more diverse, and representative, and their integrity and fidelity are also brilliant.

2.1 Ancient Wooden Bridge

Chinese ancient bridge technology has never lagged behind the world. The early literature records can be traced back to the 13th century BC. The literature records that the bridge is a wooden bridge. In this regard, China is at the world's advanced level regarding history and relics. In 1986, two ancient bridge sites were found in Xianyang City, Shanxi Province. During the excavation of the site of No. 1 bridge, a total of 112 wooden piles were cleared out in 16 rows, with a spacing of 3 to 6 meters.

The diameter of the remaining wooden bridge columns is about 40 cm. According to these bridge piles, columns, and river channel sites, the bridge is estimated to be about 500 meters long. According to the carbon isotope dating data, this bridge was built at the end of the Warring States period or after Qin moved its capital to Xianyang [2]. So far, scholars believe that this ancient bridge is the largest and oldest large wooden structure bridge known in the world

2.2 Ancient Stone Bridge

Natural stone is the earliest building material endowed by nature with high strength and durability. Stone bridges are also the majority of ancient bridges built for thousands of years. The Zhaozhou Bridge, designed and constructed by Chun Li, a stonemason in the Sui Dynasty, is nearly 1400 years old. It is the oldest and most magnificent stone arch bridge in the world. Zhaozhou Bridge only uses a single-hole stone arch to cross the river. The stone arch span is 37.7 meters, connecting the north and South Bridge blocks, with a total length of 50.82 meters[3]. Taking such a huge span was an unprecedented initiative at that time. In addition, superb is that two small stone arches are built on the two shoulders of the giant stone arch, which changes the traditional architectural style filled with sand and stone on the big arch ring in the past, and creates the world's first new bridge type of "open-spandrel arch". This is a great scientific invention.

In Europe, during the 14th century, a similar open-spandrel arch bridge appeared on the river in France, more than 700 years later than the Zhaozhou Bridge, and the bridge was destroyed in 1809. The famous stone bridges in China include Lugou Bridge, which was first built in A.D. 1189 and completed in A.D. 1192. Luoyang Bridge, first built in 1053 A.D., was completed in 1059 A.D [3]. and lasted seven years. It is the earliest existing cross sea beam stone bridge in China. Guangji Bridge was built in 1170 A.D. and completed in 1226 A.D. and took 57 years to complete. It is the earliest switch movable stone bridge in the history of China and the world. These four bridges were built in the Sui, Tang, Song and Yuan Dynasties, which was also the peak period of the development of ancient bridges in China.

2.3 Ancient Cable Bridge

In ancient China, there was also a praiseworthy bridge, the cable bridge, which was first recorded in the Qin and Han Dynasties. Many bridge experts believed that the cable bridge was the first in China. Currently, the earliest verified cable bridge is the Gan bridge in Yizhou (now Chengdu), Sichuan Province. It was written by Bing Li, in the Qin Dynasty, and was completed in 251 BC[3].

More than 2200 years ago. The iron cable bridge has been built since the early Han Dynasty. The Fanhe bridge, built on the ancient plank road in Baocheng County, Shanxi Province, by Kuai fan, a great general of the Western Han Dynasty, was completed in 206 BC

Jihong bridge in Yongping County, Yunnan Province, crosses the Lancang River. It is the oldest, broadest and most iron cable bridge in China. The net span of the bridge is 57.3 meters, the total length is 113.4 meters, and the bridge width is about 4.1 meters. There are 16 cables at the bottom of the bridge and two railing cables on the left and right.

Luding railway cable bridge in Sichuan, which crosses the Dadu River and is located on the main road between Sichuan and Tibet, is the most well-made existing railway cable bridge. Luding railway cable bridge was first built in the 44th year of Kangxi in the Qing Dynasty, in 1705, and completed the following year. The clear span of the bridge is 100 meters, and the board is paved on it. There are 9 bottom cables in total, each iron cable is about 128 meters long, and there are two railing cables on both sides.

In the history of bridges abroad, according to Joseph Needham, the famous author of the history of science and technology, the ancient cable bridge in South America was spread by the Chinese in the pre-Columbian era in the 7th century BC. In Poland, the West's first temporary iron cable bridge appeared in 1734. And in 1741, Britain built the first permanent iron cable bridge in Europe, the Tees River Bridge. It spans 21.34 meters and has been used for 61 years. However, all these attempts were

inspired by two books sent back by Western missionaries from China. In terms of iron cable bridges, Europe is 1800 years behind China.

3. Comparison between china and other countries ancient bridges

Beam bridges, arch bridges, cable bridges and other types are mostly stone and wood. Among them, the construction types of stone bridges are more diverse, and representative, and their integrity and fidelity are beyond the reach of wooden bridges. Based on this, this paper selects three classical stone bridges in ancient China, Zhaozhou Bridge in Zhao County, Hebei Province, Luoyang Bridge in Quanzhou, Fujian Province and Lugou Bridge in Fengtai District, Beijing, as the research objects[3].

Compared with the construction time, material, purpose and appearance of the Zhaozhou Bridge, Luoyang Bridge and Lugou Bridge, this paper specially selects the relatively similar Pont du Gard (Roman Aqueduct) and Mehmed Paša Sokolovic Bridge in Višegrad as representatives for comparative research.

3.1 Structure Features Of Ancient Bridges

3.1.1. Pont du Gard (Roman Aqueduct)

In the 1st century BC, in order to solve the local water problem, the ancient Roman Empire built a 275-meter long and 50-meter high giant ancient Roman Viaduct in southern France. The bridge body is divided into three layers, and all of them are made of stone. The upper layer is 3 meters wide, divided into 35 small arches, and is equipped with a headrace about 1 meter wide and 1.5 meters deep. The middle layer is 4.5m wide and divided into 11 arches. The bottom floor is 6.4m wide, divided into 6 arches, and is a sidewalk (Table 1). As an imperial landmark building as famous as the Colosseum in ancient Rome, the Gade bridge has stood up after more than 2000 years of earthquakes, floods and wars, which can be said to be a miracle in the history of bridge architecture.

3.1.2. Mehmed Paša Sokolovic Bridge in Višegrad

Table 1. Structure features of different bridges

Bridge name	Structure features
Pont du Gard (Roman Aqueduct)	This bridge occupies a place in the history of bridges and hydraulic engineering. The overall design of the bridge body is divided into three layers. Although they are all joint arches, the system of layers is different. Thirty-five small arches are specially built in the upper layer to compress the area of the joint arch as much as possible to reduce the wind stress in windy weather; In the middle layer, considering the impact on the cross-section of the bridge during flooding, many large-span bridge arches have been deliberately set up; In the bottom layer, the original intention of strengthening the bridge body is to adopt the design of the main arch crossing the river and partial arch support.
Mehmed Paša Sokolovic Bridge in Višegrad	this bridge is a typical representative of the multi-arch stone arch bridge, was built in the way of longitudinal masonry in the form of the pointed arch. From the perspective of its joint plane, it was a non-hinged stone arch bridge, a relatively advanced technology at that time.
Zhaozhou Bridge	First, the bridge adopts the single-hole stone arch system with a span of 37 meters to reduce the resistance of the bridge body to the water flow and extend the service life of the bridge. Secondly, the bridge arch adopts the flat arc system to facilitate the traffic of pedestrians and reduce the difficulty of construction and the use of raw materials. Finally, Zhaozhou Bridge created the shape of an open-shouldered stone arch bridge in the history of bridge construction in the world. On both sides of its large arch, there are two arches on each side of the arch. It reduces the weight of the bridge, saves materials and can also play a role in flood diversion and discharge.
Luoyang Bridge	The proudest scientific and technological achievements of Luoyang Bridge are reflected in the two construction technologies of "raft foundation" and "Oyster house solid foundation". The former aims at the problem that building a bridge on soft soil foundation is difficult. First, many stones are set along the middle line of the bridge to form a solid stone embankment at the bottom of the river, and then the bridge is built on it. The latter is further to strengthen the connection between the bridge foundation and pier, innovatively plant a large number of oysters under the bridge, and use the characteristics of strong adhesion and rapid reproduction of oysters to cement the bridge foundation and pier into an artificial rock that can withstand the impact of seawater.
Lugou Bridge	In terms of the design of the bridge body, the arch design with 11 arches is adopted. The biggest advantage of this shape is that the pier can disperse the load of any arch borne by the bridge body as a whole, extending the service life of the bridge. The pier design is also very distinctive, its pier is shaped like a ship and its head is northward to kill the water potential. The front end of the pier head is reinforced.

Mehmed Paša Sokolovic Bridge in Višegrad crosses the river in eastern Bosnia and Herzegovina. It was ordered by the Prime Minister of the Ottoman Empire Mehmed bash Sokolovic, at the end of the 16th century[3]. As the pinnacle of the monumental architecture of the Ottoman Empire, it is 179.50 meters long and has 11 stone arches, each with a span of 11 ~ 15 meters. There are 4 arches on the proper entrance slope, which is located on the left bank of the river[3]. It is one of the best architects and engineers of the Renaissance in Turkey and Italy - the representative masterpiece of Mehmed Paša Sokolovic.

3.2 Comparison Of Ancient Bridges

3.2.1. Comparison Of Design

There are significant differences between the two. First, ancient Chinese bridges pay more attention to detailed design, while ancient European bridges appear simple. Second, the overall layout of ancient Chinese stone bridges reflects a traditional culture - "the beauty of mountains and rivers", and attaches great importance to the perfect combination of artificial buildings and the natural environment. Third, the mellow and symmetrical beauty of ancient Chinese bridges with oriental characteristics and the artistic design of ancient European bridges pay attention to the sense of hierarchy and line

3.2.2. Comparison Of Technology And Structure

It can be found that the ancient bridges in China are not inferior to those in the world. Whether it is the Zhaozhou Bridge, which pioneered the open-shouldered stone arch bridge system, or the Luoyang Bridge, which pioneered the two new technologies of "raft foundation" and "Oyster house foundation consolidation" in the process of bridge construction, it is a classic in the history of bridge architecture

4. Development and features of bridges in modern China

In ancient times, China's bridge technology was not inferior to those in the world. In modern times, with the industrial revolution in western society, China's bridge technology began to lag behind the world's advanced level. Since the founding of China, China's bridge technology has started to catch up with or surpass the world's advanced level.

4.1 Backward Period

Since the Ming and Qing Dynasties, China's bridge technology has stagnated and finally lagged due to the closed-door policy implemented by successive rulers. Especially since the western industrial revolution, China's bridge technology has lagged far behind western societies. The industrial revolution in Britain since 1760 created modern science and technology, and the birth of modern steel-making methods promoted the development of steel bridges. In 1850, the first steel box bridge was built in Britain, and in 1857, the first steel truss bridge was built in Germany. In 1883, the Brooklyn Bridge, with a main span of 486 meters, was built in the United States as a highway cable bridge [6]. In 1890, the fourth Bay Bridge in Scotland, with a main span of 520 meters, was built in the United States as a railway cantilever truss bridge, representing the highest steel bridge achievement in the 19th century [7]. At the same time, China has made very few achievements in bridge construction.

From the beginning of the 20th century to the 1950s, with the innovation of technology and materials, as well as the development of theory, bridge construction reached a new height. Many applications of reinforced concrete have led to the rise of reinforced concrete arch bridges, which has promoted the development of arch bridges to a larger span. For example, in 1930, France built a three-hole arch bridge with a span of 186 meters [7]. In 1940, Sweden built a 246-meter Sandu bridge. In 1928, after 20 years of research, France's famous engineer Francine put prestressed concrete technology into practice, which greatly promoted the development of beam bridges.

Compared with the above achievements, the achievements of developed countries in cable-stayed bridges and suspension bridges are also remarkable. As early as 1925, Spain built the world's first cable-stayed bridge with reinforced concrete girders, with a main span of 60.35 meters, while the world's first modern cable-stayed bridge, the Strom Strait Bridge, built in Sweden, with a main span of 182.6 meters [7]. Subsequently, the South span of the cable-stayed bridge became larger and larger, and the scientific and technological content became higher and higher. In terms of suspension bridges, the Brooklyn Bridge in New York, built in 1883, has a span of 483 meters, creating a precedent for modern suspension bridges.

During these hundreds of years, China's productivity fell behind due to the closed-door policy. Before the founding of new China, the vast majority of bridges in China were still wooden and stone bridges, which were in disrepair and dilapidated for many years. Even though some steel truss bridges, suspension bridges and reinforced concrete bridges were built, they were still in a very backward state compared with the bridge construction technology in the world at that time.

4.2 Catch-Up Period

Since the reform and opening up, China's comprehensive national strength and productivity have been rapidly enhanced, and the level of science and technology has quickly been improved, which has provided sufficient impetus for the development of bridges in China and made bridge engineering in china develop unprecedentedly [8]. It has made remarkable achievements in concrete beam bridges, arch bridges, cable-stayed bridges and suspension bridges, reaching the world's advanced or leading level.

4.2.1. Modern Arch Bridge

The arch bridge refers to the bridge with the arch as the main load-bearing component in the vertical dimension. In the 1960s, the application and development of the unsupported construction method of arch bridges greatly improved the competition of concrete arch bridges.

One of the famous stone arch bridges is the Wuchao River Bridge in Fenghuang County, Hunan Province, built in 1991[9]. Its span is 120m. Its arch ring comprises two stone slab arches with a width of 2.5m, and reinforced concrete beams connect the slabs. Another is the Xindanhe bridge on Shanxi Jincheng Henan Jiaozuo expressway, completed in 1999, which holds the world record for a stone arch bridge with a span of 146m, and the arch ring is made of 80 large stones.

The rise of concrete-filled steel tubular arch bridges in the 1990s has further improved the construction capacity of long-span arch bridges. Its feature is to close the steel pipe arch ring with lightweight and high strength, use it as the construction arch, and inject high-strength concrete into the pipe to harden it further to form the main arch ring. Using this method, a 200m West diameter analysis of three mountains in Nanhai, Guangdong Province, was built in 1995 respectively; In 1998, the Yongjiang bridge on the third bank of Guangxi was built, with a main span of 270m. The Bosideng Yangtze River Bridge, completed in 2013, has a span of 530m and is the largest concrete-filled steel tubular arch bridge in the world [10].

Taking concrete-filled steel tubes as the rigid skeleton and outsourcing concrete to form a box arch is a very good design for building a long-span bridge. In addition to the convenience of construction, it avoids the problem of steel tube protection. In addition, this section formed by stages takes full advantage of the excellent bearing potential of concrete-filled steel tubes because the concrete-filled steel tube is first stressed. Theoretically, this structure's late creep deformation is relatively small under the action of load. Based on this idea, China has built the Guangxi Yongning Yongjiang bridge (1=312m, 1996) and the Chongqing Wanxian Yangtze River Bridge (1=420m, 1997). The former was the largest reinforced concrete rib arch bridge in China then, and the latter reached the world's largest reinforced concrete arch bridge then.

4.2.2. Concrete Beam Bridge

A Beam bridge is a bridge in which the main beam in bending is used as the bearing member. In the 1980s, beam bridges constructed by the symmetrically balanced cantilever method developed

rapidly. For example, the Yunnan Liuku Nujiang River Bridge was built in 1991, and the main bridge span is 85m+154m+85m prestressed concrete continuous beams. The main span of the Minjiang River Bridge of Leshan Zigong expressway, completed in 2013, is the prestressed concrete continuous beam bridge with the largest span in China.

The rigid frame is characterized by continuous beams and consolidation of pier beams [10]. In this way, the advantages of the constant beam without expansion joint and smooth driving and the T-shaped rigid frame without support are maintained. At the same time, the disadvantages of the continuous beam and the T-structure are avoided. Therefore, continuous rigid frame bridge develops rapidly in our country.

4.2.3. Cable-Stayed Bridge

A cable-stayed bridge is a bridge in which the main beam is directly pulled on the bridge tower with many cables. Chinese cable-stayed bridges started a little late. For example, The Sichuan Yunyang bridge, with a span of 76m, which was built in 1975, is the first cable-stayed bridge in China [11]. Since the 1990s, cable-stayed bridges have developed rapidly due to the need to cross rivers, and a series of cable-stayed bridges with extra-long spans have been built. According to incomplete statistics, China has built more than 100 cable-stayed bridges, including more than 60 cable-stayed bridges with a span of more than 400m, ranking first in the world.

In addition, Shanghai Nanpu Bridge, completed in 1991, has a span of 423m; Shanghai Yangpu Bridge, completed in 1993, has a span of 602m; Ting Kau Bridge in Hong Kong, completed in 19, has a span of 448m+475m; Fujian Qingzhou Minjiang Bridge, completed in 2001, has a span of 605m and is a steel-concrete composite beam cable-stayed bridge. Chongqing Dafosi Yangtze River Bridge, completed in 2001, has a span of 450m and is a concrete beam cable-stayed bridge. Both the Nanjing Changzheng second bridge with a span of 628m and the Wuhan Junshan Yangtze River Bridge with 460m is cable-stayed bridges with steel beams [11].

Currently, China has built two cable-stayed bridges spanning more than kilometers. Hong Kong stonecutters bridge has a main span of 1019m, and Jiangsu Sutong Yangtze River Highway Bridge has a main span of 1088m [12]. It is the second-longest cable-stayed bridge in the world. Moreover, the Chishi bridge in Chenzhou, which started in March 2010, is a four-tower prestressed concrete cable-stayed bridge with double cable planes, with a main span of 380m. The cable tower is 287m high, completed and opened to traffic in 2016. It has become the concrete cable-stayed bridge with the tallest cable tower in the world.

4.2.4. Suspension Bridge

The suspension bridge is a bridge with cables (or steel chains) suspended through cable towers and anchored on both banks (or both ends of the bridge) as the main load-bearing components of the superstructure.

The construction of modern suspension bridges in China started late, especially in the super long-span suspension bridge. But things are beginning to improve after the mid-1990s with the quick development in civil engineering. The Shantou Bay Bridge in Guangdong Province, completed in 1995, is China's first modern highway suspension bridge [12]. And then Xiling Yangtze River Bridge (l=900m, 1996), Humen Bridge (l=888m, 1997), Hong Kong Tsing Ma Bridge (l=1377m, 1997), Jiangyin Yangtze River Bridge (l=1385m, 1999) and Jiangsu Runyang Yangtze River Bridge (l=1490m, 2005) were completed. Xihoumen Bridge, completed in 2009, has a span of 1650m, ranking second in the world. Hunan Aizhai bridge, which was completed and opened to traffic in 2012, is a single-span suspension bridge with steel truss stiffening beams, with separated towers and beams. Its main span spans Aizhai Grand Canyon, with a span of 1176m. It is the largest steel truss suspension bridge across Canyon in the world.

5. Conclusion and Recommendations

This study focuses on Chinese bridges and discusses the development of typical ancient and modern bridges.

For ancient bridges, limited by technology and materials, people mainly divided them into wooden and stone bridges, and some cable bridges containing iron cables. For wooden bridges, because wood is an organic material and is not corrosion-resistant, it has little research value, but many great works have emerged in stone bridges, such as Zhaozhou Bridge. These bridges reveal the ancestors' ingenious designs on arches and foundations against River Scouring. Among them, cable bridges have brought a lot of inspiration to the development of suspension bridges in the world. Many designs and skills, such as the design and selection of arches through catenary, can still be used today.

Modern bridges are mainly classified according to structure and stress. Through scientific methods, bridges are divided into beam, arch, suspension, and cable-stayed bridges. Among these bridges, beam and arch bridges are suitable for small and medium-sized bridges, cable-stayed bridges for medium-sized bridges, and suspension bridges for large ones. Among them, beam bridges, arch bridges and suspension bridges are closely related to the development of bridges in ancient China.

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