Design of Concrete Bridges

混凝土桥梁设计

Shouxin WU
武守信

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CONTENTS

PREFACE

Concrete is a widely used construction material in China, and indeed in the world. The application of prestressing techniques for bridges has extended the spanning capability of concrete bridges, and has made concrete bridges more competitive with steel bridges for long span crossings. In China, prestressed concrete bridges represent over 75% of all bridges on highways and railways. Hence, a course on design and analysis of concrete bridges offered in the civil engineering program is necessary at undergraduate and graduate levels.

This book is written for senior level undergraduate or first-year graduate students in civil engineering. It is also suitable for practicing bridge engineers to use as a reference book in design. The text is the outgrowth of the author's lecture notes developed in teaching the international class on design of concrete bridges at Southwest Jiaotong University, China since 2012 and the research and consulting experience in the area of concrete bridges over the years. The objective is to provide fundamental theories and approaches for design and analysis of reinforced and prestressed concrete bridges, based on China’s up-to-date railway and highway design codes and specifications. The emphasis is on the understanding of the structural behavior and performance of reinforced and prestressed concrete structures, with developing proficiency in practical methods of design.

The text is organized into 9 chapters. Chapter 1 introduces bridge types with a history of bridge engineering and advancement of bridges in China. Chapter 2 describes the material properties of concrete and steel. Chapter 3 discusses the various loads that act on bridges. Chapter 4 reviews the design philosophies and methods, including the traditional allowable stress design and the probability-based limit state design. Chapter 5 presents the influence line method for determining the maximum force effects in bridge girder when vehicles move in the span direction and the transverse load distribution when the vehicles move in the transverse direction. Chapters 6 and 7 are design chapters for reinforced and prestressed concrete girder bridges, respectively. Since China's railway bridges have been designed on the foundation of the allowable stress design method, review of the allowable stress design method is presented in this chapter. Chapter 8 gives an overview of continuous prestressed concrete bridges with emphasis on the secondary forces and the transformation of structural system during construction. Chapter 9 reviews the various construction methods for concrete girder bridges.

A reference list is attached to the end of each chapter. The reference lists are far from exhaustive but gives the major source materials used in preparing the manuscript. In addition to the references provided in the text, other valuable source materials include the journal articles, reports, books, and manuals published online of in print by universities and technological institutes in China and other countries, such as the FHWA, AASHTO, AREMA, ASCE, ACI, PCI, ASTM, ICE, and BSI. However, inadvertent missing of references could not be avoided, especially for some pictures or graphs. Contributions from all these institutes and all authors, mentioned or anonymous, are greatly acknowledged.

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Shouxin Wu
Southwest Jiaotong University, Chengdu
October, 2020

Chapter 1 *Introduction*

1.1 Significance of bridges

Bridges are key parts of a transportation system. A bridge usually controls the load-carrying capacity and traffic volume of a transportation network. If a bridge collapses, the whole transportation system will fail to work. If the width of a bridge does not meet the need to carry the number of lanes required by the traffic volume, the flow of traffic in the whole transportation system will be constricted by the bridge; if the strength of a bridge is not sufficient to support the maximum loads required for the roadway, load limits have to be posted, and overloaded vehicles have to be rerouted.

From an engineer' point of view, the bridge stands out from other types of structures in that the bridge is generally subjected to moving loads, i.e., moving vehicles or pedestrians, which means that the directions, magnitudes, and positions of the loads carried by a bridge are varying with time. The resulting dynamic responses of bridge structures differ saliently from the responses of other civil structures. Vibrations of bridges and fatigue of materials due to cyclic loading affect seriously on the serviceability and strength of bridges.

Failure of bridges almost always results in substantial injury and loss of life. In the history of bridges, the failure of bridges deeply shocked not only the engineering world but also the general public. Also, the bridge collapse has significant impact on the road-users and the local economy. For this reason, structural safety of a bridge is the primary concern of bridge engineers working on the bridge project, from the beginning of conceptual design to the final construction and maintenance.

Building bridges is a great challenge to all the engineers and workers involved, generally more so than building other structures, in spite of the fact that for most bridge systems the actions or effects of the forces involved are more easily determined than for other load-carrying structures. Ever increasing span lengths, widths, and loads generate the need for new design, new materials, and new construction method which are used for the first time to build the bridge as specified. Consequently, many bridges had failed since the knowledge available at the time of the design and construction was later proven to be inadequate. Failure may happen during construction or in service (Figure 1.1 and Figure 1.2). The causes of bridge failure may be structural overload, deterioration of structural members due to corrosion or fatigue, scour of the foundation soils, and many others. Therefore, engineers involved in design, construction, and maintenance of a bridge should always carry out their duties properly to assure the structural integrity and safety of the bridge for the intended lifetime.

Figure 1.1 Failure of a bridge during construction.

Figure 1.2 Failure of a bridge in service.

1.2 Structural types of concrete bridges

Concrete bridges can be classified based on their load-carrying mechanisms by which gravitational and lateral loads are transferred from the deck to the foundations. The method used in the structural analysis of a bridge is mainly dependent on its structural type. Also, for certain range of span lengths, only certain structural types of bridges are suitable and economically viable. Thus concrete bridges are usually classified into girder bridges, arch bridges, and cable-stayed bridges. This classification is not strict and absolute, since each type of these bridges may have more than one subtype or variant. In practice, some bridge combines the features of more than one bridge type, thus it does not fall into any category of the bridge types mentioned above.

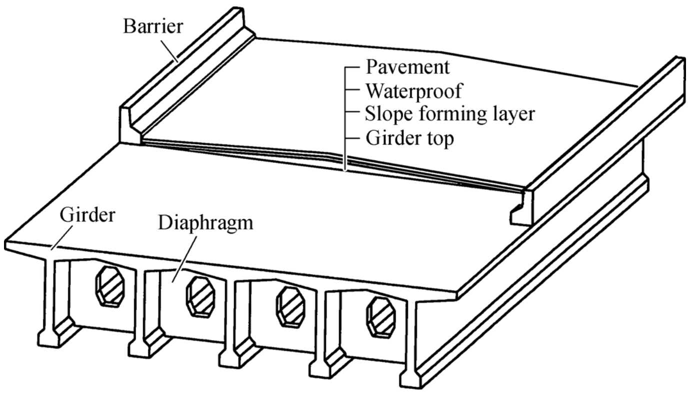
1.2.1 Girder bridges

The girder bridge is also called the slab-on-stringer bridge or the beam bridge. A girder bridge consists mainly of a deck, a set of girders that support the deck slab, and several diaphragms that transversely connect the girders together (Figure 1.3(a)). All the girders are supported on abutments (for single-span bridges) or piers (for multi-span bridges). In a girder bridge, loads are transferred from deck to girders, and then to abutments or piers. The girder is the main load-resisting component which carries the vertical loads by its bending and shearing resistance, while the deck slab is designed to bend in the direction perpendicular to the plane of bending of the girders. Generally, the deck is built from reinforced concrete, while the girder can be made of steel, reinforced concrete, prestressed concrete, or combination of concrete and steel.

The girder bridge is the most common bridge type which includes simply-supported girder bridges, continuous girder bridges, rigid-frame girder bridges, and continuous rigid-frame girder bridges (Figure 1.3(b), (c), (d), and (e)). The popular cross-sections of the girders include the solid slab or voided slab, the I-shape, the T-shape, U-shape, and the box-shape (Figure 1.4). Except for the solid slab girders which are usually made from reinforced concrete, the girder with other cross-sections can be made of reinforced concrete, prestressed concrete, steel or other structural materials (e.g. composite materials).

The principal advantages of the girder bridges are that (a) the structural form is simple and straightforward, (b) the girder bridge is suitable for a uniform and standardized design. Standardization and uniformity minimize the need for designing and casting structural members of different sizes for different bridge projects, thus reducing the construction cost and period in repairing or replacing deteriorated structures.

Girder bridges are primarily for short- to medium-span lengths, say, for the span length less than 75 m. The simply supported girder bridges are most suitable for short-span lengths, whereas continuous and continuous rigid-frame girder bridges are the better choices for medium-and longer-span bridges. Currently, the span-length of the continuous rigid-frame girder bridge in China has reached more than 200 m. When the span length becomes excessive, other type of bridges become viable alternatives.



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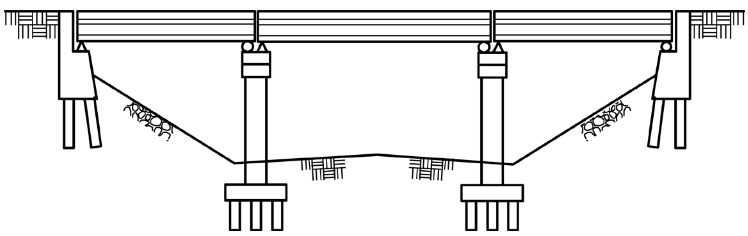

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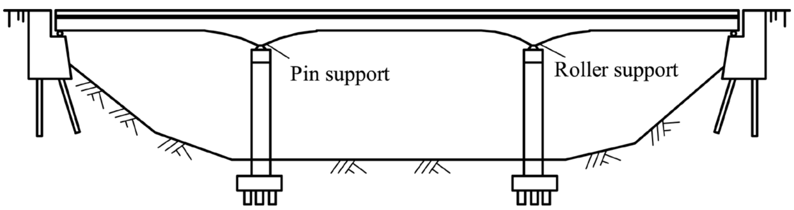

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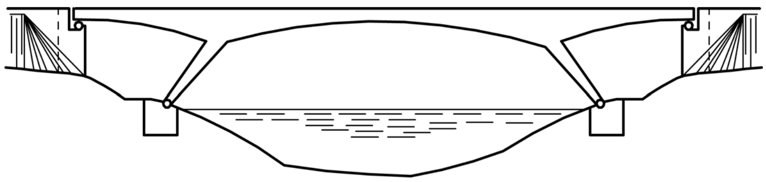

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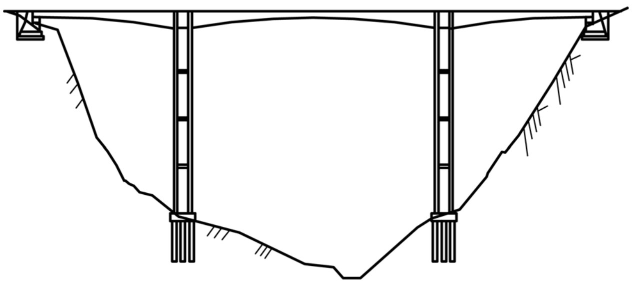

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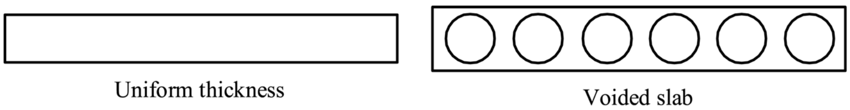
Figure 1.3 Girder bridges: (a) deck configuration; (b) simply-supported; (c) continuous; (d) rigid-frame; (e) continuous rigid-frame.



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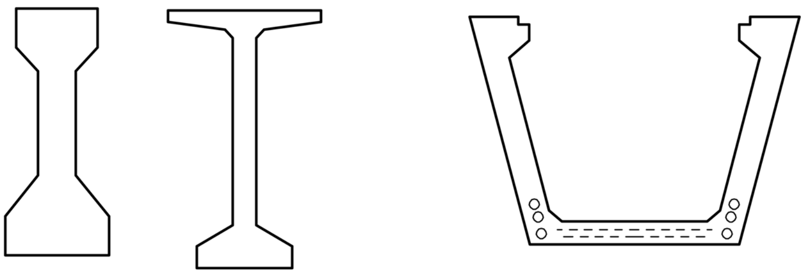

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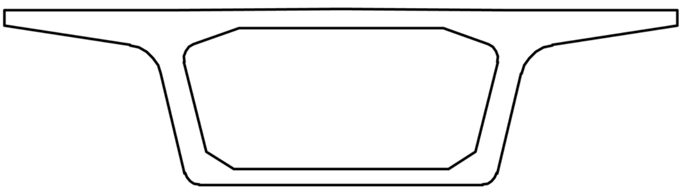

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Figure 1.4 Cross-sections of girder bridges: (a) slab (solid or voided); (b) I-shape; (c) T-shape;(d) U-shape; (e) box-shape.

1.2.2 Arch bridges

The arch bridge is a bridge type whose main load-resisting structures or members are curved arches (Figure 1.5). The common feature of all the arch bridges is that the gravitational loads are transmitted to the supports primarily by axial compressive forces in the arch. This makes such brittle materials as rock, brick, or concrete, which are strong in compression but weak in tension, suitable for construction of the arch. In modern arch bridges, the arch can be made up of a truss of various forms. At each end of the arch, horizontal thrust as well as the vertical force is exerted on the support. Arch bridges are usually divided into three types according to the relative position of the deck with respect to the arch: deck arch bridges, through arch bridges, and tied-arch bridges.

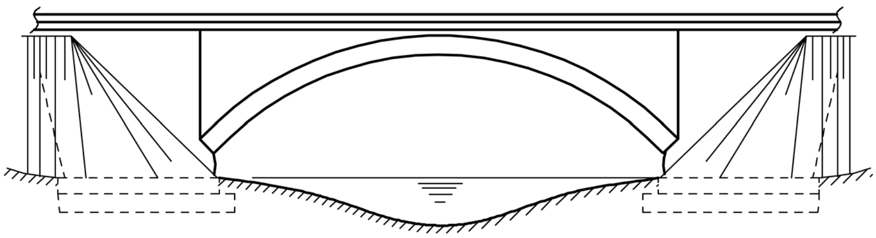
The deck arch bridge is a typical arch bridge whose main structure–arch–is below the deck line. This type of bridge consists of an arch, a deck, which is completely above the arch, and columns or solid fill in the spandrel to transfer the roads from the deck to the arch. If the spandrel is filled with solids, as in a masonry or stone arch bridge, the bridge is called a closed-spandrel arch bridge (Figure 1.5(a)); if the deck is supported by columns rising from the arch, the bridge is termed as an open-spandrel arch bridge (Figure 1.5(b)).

The half-through arch bridge is a type of arch bridge whose deck passes through the arch, i.e., the top of the arch is above the deck, while the springings of the arch are below the deck. As a result, the central part of the deck is supported by the arch via cables or tie bars, whereas the side part of the deck, which is close to the springings, is supported below by the columns resting on the arch (Figure 1.5(c)).

The tied-arch bridge is also known as the bowstring arch bridge. In this type of arch bridge, the thrust at the ends of an arch is resisted by tie-rods connecting the two ends of the arch. The deck is suspended from the arch and the loads are thus transferred from the deck to the arch through tension hangers. Because the tie-rods are at the deck level and the traffic loads pass through completely between and the arch and deck slab, a tied-arch bridge is also a through arch bridge (Figure 1.5(d)).

The distinctive features of the arch bridge are that (a) the arch is predominantly a compression structure and thus favors concrete or rock as construction materials; as a result, a masonry arch bridges can be designed such that the arch is always under compression as it carries all the vertical loads above; (b) this type of bridge is most suitable for crossing a deep valley with the arch foundations located on the dry rock slopes, so that the vertical settling and horizontal sliding of the arch ends can be restrained by the foundations. In modern practices, the arch are usually built from plain concrete, reinforced concrete, and steel trusses, with cross-sections being of I-shape, T-shape, or box-shape.

The arch bridge is the oldest type of bridges ever built and is also one of the most popular type of bridges. Some stone arch bridges built more than 2,000 years ago are still in service (Figure 1.6). In China, the oldest existing arch bridge is the Zhaozhou Bridge (or called Anji Bridge) (Figure 1.7) built in 605 AD. With a span length of 37 m, the Zhaozhou Bridge is the world's first wholly stone open-spandrel segmental arch bridge.



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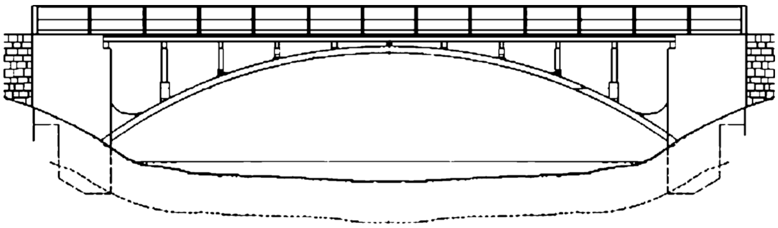

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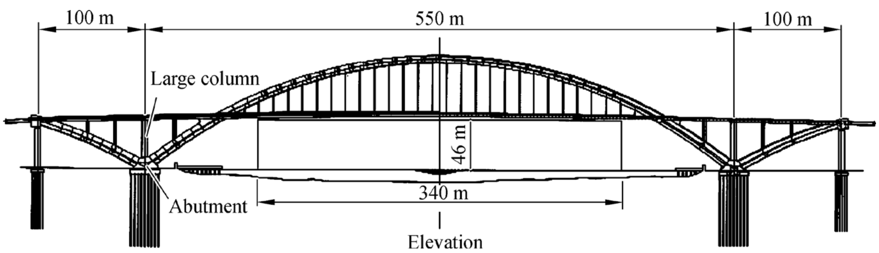

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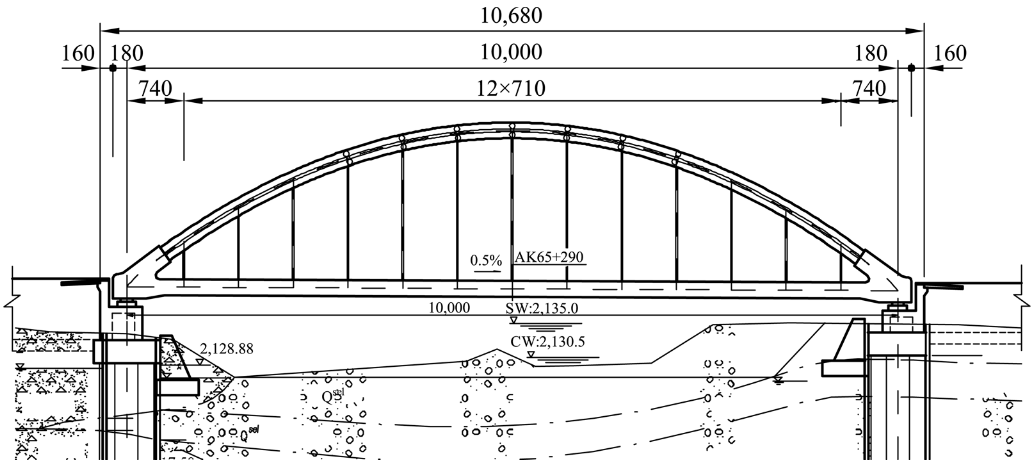

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Figure 1.5 Various types of arch bridges: (a) closed spandrel arch; (b) open spandrel arch; (c) half-through arch; (d) tied-arch.

Figure 1.6 An ancient roman arch bridge.

Figure 1.7 The Anji Bridge, an ancient arch bridge, Zhao county, China.

1.2.3 Cable-stayed bridges

A cable-stayed bridge consists of one or two towers or pylons, a stiffening girder, and multiple stay cables that radiate from the towers and are anchored at several intermediate points on the stiffening girder (Figure 1.8). The traffic loads on the deck are transferred by the stiffening girder to the stay cables, and subsequently to the towers by the cables through tension. This structural system results in compressive axial forces in the stiffening girder and in the pylons which are in equilibrium with tensile forces in the cables. In other words, the traffic loads are mainly transferred by axial forces rather than by bending, which can substantially reduce the depth of the stiffening girder, and in turn reduce the self-weight of the girder. Thus, the cable-stayed bridges are suitable for crossing long distance.

The cable-stayed-bridge has a large variety of geometrical configurations. The layout of the stay cables, the type of stiffening girder, and the style of the towers can be easily adjusted to suit the design requirements. In the transverse direction to the longitudinal axis of the bridge, the cables may lie in either a single or a double plane, may be symmetrically or asymmetrically placed, and may lie in oblique or vertical planes (Figure 1.9). In the longitudinal direction, there are basically three cable configurations in general use: the fan type, the harp type, and modified fan type (Figure 1.10). All these configurations or types are applicable to either the single-or double planar cable systems.

The cable-stayed bridges can be built with steel, concrete, or both. The stay cables are usually made from high strength steel, while the stiffening girders are made up of either prestressed concrete or steel or both. Some cable-stayed bridges have been arranged with a steel stiffening girder in the main span and concrete girder in the side spans so that the weight of the longer main span is balanced by the heavier section in the side spans. The towers are normally constructed of cellular sections and are fabricated of structural steel or reinforced concrete or prestressed concrete.

The cable-stayed bridges have proven more economic, for mediate span lengths, i.e. 100-350 m, than either the suspension or arch bridges. However, the cable-stayed bridges with span lengths of more than 1,000 m have been successfully built and in service. Today, the cable-stayed bridge has become a competitive choice for major crossings within a wide range of span lengths.

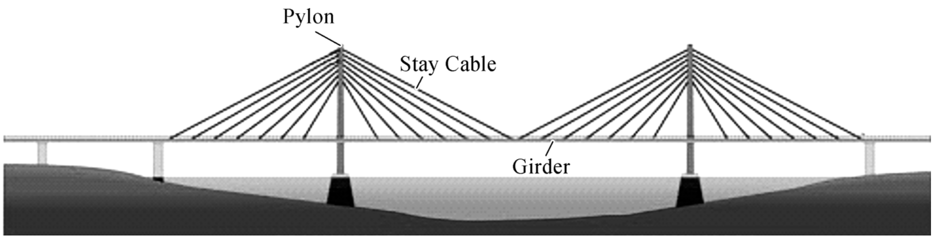
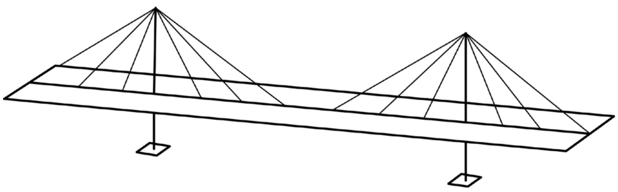


Figure 1.8 A typical cable-stayed bridge.



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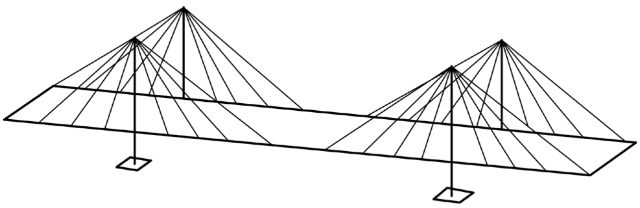

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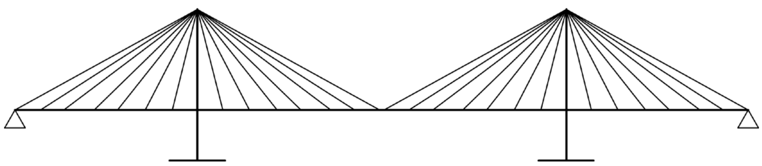
Figure 1.9 Transverse layouts of stay cables: (a) single plane; (b) double plane.



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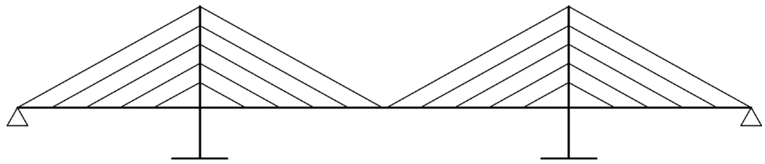

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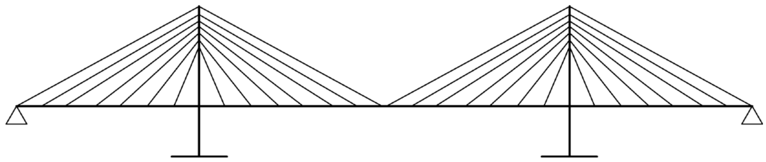

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Figure 1.10 Longitudinal layouts of stay cables: (a) fan pattern; (b) harp pattern; (c) modified fan pattern.

1.3 Historic development of bridge building

The earliest written record of bridges seems to be a bridge built across the Euphrates around 600 BC. The bridge connected the palaces of ancient Babylon on either side of the river, and had multiple spans of wooden beams made from cedar, cypress and palm, supported on a hundred stone piers, forming a carriageway of 11 m wide and 182 m long. In China, records exist from the time of Emperor Yao in around 2300 BC on the traditions of bridge building. It is believed that ancient China was the birthplace of the floating bridge, which is a collection of boats about 9 m long, connected together to cross a river, with a walkway or deck attached on top (Figure 1.11). The other bridge forms in ancient China were the timber beam bridges, cantilever bridges, and rope suspension bridges. Timber beam bridges were often supported on rows of timber piles driven into the riverbed. The cantilever bridges were built by extending beams out from the piers on both sides of a stream. A primitive cantilever bridge with interdigitating timber members in China's southwestern provinces is shown in Figure 1.12. In later centuries development of bridges in China was dominated by stone arch bridges.

Figure 1.11　A floating bridge.

Figure 1.12　A primitive cantilever bridge made of wood.

Stone arch bridges are the earliest bridges built that represent the bridge-building skill in ancient times. Many stone arch bridges were built by engineers of the Roman empire, some of which are still in service after more than 2,000 years. Romans excelled in building stone arches since stone was abundantly available, while timber was rather scarce and had to be used economically. One of the most spectacular arch bridge built by the early Roman engineers is the Pont du Gard Aqueduct in France (Figure 1.13) which is part a bridge and part an aqueduct, built about 19 BC to carry water. It consists of three tiers of arches, reaching to a height of 47.2 m above the river. The bottom tier consists of six arches varying in width from 15.5 m to 24.4 m, the largest spanning the river. The middle tier has eleven arches of the same dimensions as those of the bottom, to reach across the widening valley. The topmost tier consists of thirty-five 4.6-m arches, extending 270 m across the river.

In China, the oldest stone arch bridge, the Anji Bridge (also called Zhaozhou Bridge)(Figure 1.6), located in Hebei Province, was built in Sui Dynasty (A.D.

595 to 605) . It has a single span length of 37.02 m with two small arches in each of its spandrels. Another stone arch bridge , Baodai Bridge (Figure 1.14), located in Suzhou City, was built in the Tang Dynasty (A.D. 618 to 907) and has thin arch rib and light piers to adapt to the low load-bearing capacity of the soft foundation soil. With a length of 316.8 m, the Baodai Bridge is the longest old stone arch bridge in China.

Figure 1.13 The Pont du Gard Aqueduct, France.

Figure 1.14 The Baodai Bridge, China.

Although the ancient people built bridges, and even built great bridges, such as the cantilever bridges and the arch bridges, they lacked understanding of structural mechanics of bridges. The curves of their arches were always semicircular in form, and the sizes of the cross-section of arches and beams were determined by only empirical rules, without the use of any theory. The only building materials for bridges in ancient times were stone and timber, which are available in nature.

The Renaissance period from the 14th through the 16th centuries brought advances in both the art and science, and gave birth to the modern science. Several renowned scientists lived in this period, such as Leonardo da Vinci (1452-1519) and Galileo Galilei (1564-1642). Although many new scientific theories were developed during this period, relatively little advancement was made in construction. Leonardo da Vinci developed new ideas on the mechanics of bridges, introduced the concept of the moment of a force, and considered the strength of beams. Galileo, regarded as the founder of structural mechanics, proposed the theory of structural mechanics which formed the basis of structural engineering and material strength. Galileo discussed fundamental principles of stress analysis for beams and framed structures, and examined how the properties, shape, and size of a member would affect its breaking strength.

The post-renaissance period saw the birth of many great scientists such as Robert Hooke (1635-1703), Isaac Newton (1642-1727), Daniel Bernoulli (1700-1782), and Leonard Euler (1707-1783). Robert Hooke (1635-1703) proposed the arch theory in 1670 and the famous Hooke's law. Later, the arch theory was expounded upon by Thomas Young (1773-1829), who, 130 years later, defined the modulus of elasticity. It was Hooke who first obtained the correct linear distribution of both compressive and tensile stresses across the cross section of a beam, and found that planar cross-sections before bending remained plane after bending, a fundamental assumption of beam theory.

The advent of cement and concrete in the late 19th century brought about the birth of reinforced and prestressed concrete bridges. Francois Hennebique, a French engineer, developed the T-shaped cross-section for reinforced concrete members. His disciple, the Swiss engineer Robert Maillart Robert Maillart (1872-1940) built several famous reinforced concrete arch bridges. Eugene Freysinnet, another French engineer, proposed the prestressing technology for construction of bridges and provided to bridge industry one of the most efficient methods for constructing bridge deck. The Walnut Lane Memorial Bridge (Figure 1.15) located in Philadelphia, Pennsylvania, the United States of America (USA), completed in 1951, was the first major prestressed concrete bridges built in the USA. This three-span prestressed girder bridge, each spanning 49 m, revolutionized the prestressed concrete in the world. Since then, the prestressed concrete has gradually used in construction of bridges of short to medium or even long spans. With advances of prestressing technology and high-strength steel and concrete, prestressed concrete bridges have becomes popular around the world. The lower cost of concrete relative to steel and invention of the cantilever or the segmental method of construction has made the presstressed concrete the preferred type for short and medium spans, and competitive with steel bridges in long-spans.

Figure 1.15 The first major prestressed concrete bridge in USA – the Walnut Lane Memorial Bridge.

Concurrent with the advances of prestresed concrete bridges were the evolution of the cable-stayed bridges. The modern cable-stay bridges were pioneered by German engineers Fritz Leonhardt, Rene Walter, and Jörge Schlaich, after the World War II. A cable-stayed bridge can use steel girders or prestressed concrete girder to stiffen the deck. In many modern cable-stay bridges, prestressed concrete box girders are usually used as decks. The first modern cable-stayed bridge was built in 1955 at Strömsund, Sweden, with steel deck and span length of 74 m+183 m+74 m (Figure 1.16). Later, several other cable-stayed bridges were built in Europe and USA, with steel or prestressed concrete girders supporting the decks. The cable-stayed bridges fill the void between continuous girder bridges and suspension bridges. In the late 19th century and early 21st centrury , many long-span cable-stayed bridges were built throughout the world, and significant advances were achieved in the construction technology and spanning capabilities of this type of bridges. The Sutong Yangtze River Bridge, a cable-stayed bridge with prestressed concrete deck, located in Jiangsu Province of China, has a main span of 1,088 m which was the longest in main span length among all the cable-stayed bridges in the world up to 2012 (Figure 1.17).

Figure 1.16 The first modern cable-stayed bridge–Strömsund Bridge, Sweden.

Figure 1.17 The Sutong Yangtze River Bridge, China.

The historic development of concrete bridges accompanied the evolution of structural theory and development of new materials and advances of construction technology. In modern times, rapid improvement of computer hardware and development of computer aided design technology makes design and analysis of long-span and complex bridges easier and more efficient than before. Many great girder, arch, and cable-stayed bridges of record-breaking span lengths have been built worldwide, especially in Asia. They are standing as symbols of structure engineering achievements. Nevertheless, construction of a bridge, especially a long-span bridge, is still a formidable task. Bridge engineers are still faced with the challenge of building longer, stronger, and reliable bridges crossing ocean or arduous mountainous terrains in the future.

1.4 Advancement of bridges in China

China has a long history of bridge construction. From 1100 BC to 220 AD, the period from Shang Dynasty to the Eastern Han Dynasty, the Chinese built lots of girder bridges and arch bridges with timber and stone. The girder bridge usually consists of one or several timber beams supported on the stone piers or abutments, but there were some short span bridges made up of stone beams. The arch bridges are always made from stone. Although there were thousands of bridges built in ancient times of China according to historic records, very few of them have survived until today.

The oldest bridge that survives today in China is the Anji Bridge (or Zhaozhou Bridge) built in 605 AD. It is a single-span stone arch bridge (Figure 1.7) comprising 28 arch ribs bonded together transversely and having a span length of 37.02 m and a rise of 7.23 m above the springing line.

The longest ancient stone beam bridge is the Anping Bridge (Figure 1.18) across a sea bay in Jinjiang, Fujian Province. Completed in 1151 AD, the Anping Bridge consists of 362 spans with the longest span length of 8.6 m. Each span has 5 to 8 stone beams, each beam being 5 m to 11 m long with rectangular cross-section 0.6 m to 1 m wide and 0.5 m to 1 m deep. The total length of the Anping Bridge is 2,255 m.

Another famous ancient Chinese bridge is the Lugou Bridge (Figure 1.19), located in Beijing. It is a multi-span stone arch bridge consisting of

11 semicircular stone arches, each spanning 11.4 m to 13.45 m. The whole bridge is 212.2 m long, 9.3 m wide.

Figure 1.18 The Anping Bridge-the longest ancient stone beam bridge, China.

Figure 1.19 The Lugou Bridge-an ancient multi-span stone arch bridge, China.

After the 1950s, the China's booming economy and rapid development of highways and railways created the need for a great amount of new bridges to be built. The first prestressed concrete highway bridge, with a span length of 20 m, was completed in China in 1956. One year later, the Wuhan Yangtze River Bridge (Figure 1.20), the first bridge across the Yangtze River, was built. It is a double-deck steel truss bridge, carrying two railroad tracks on the lower deck and highway traffic on the upper deck. The bridge has nine main spans, each being 128 m long, and the total length of the bridge is 1,155 m. The steel used in the trusses are produced in China and the structural components are manufactured in

China's bridge factories. The Wuhan Yangtze River Bridge is a mile stone in the history of modern bridges in China. Following the success of this bridge, another steel truss bridge, the Nanjing Yangtze River Bridge (Figure 1.21), which has longer span lengths, was completed in 1968. Since then, hundreds of bridges have been built crossing the Yangtze River.

Figure 1.20 The Wuhan Yangtze River Bridge, China.

Figure 1.21 The Nanjing Yangtze River Bridge, China.

Beginning from 1960s, cantilever construction technology was adopted to erect T-shape rigid frame prestressed concrete bridges. During the 1970s, more prestressed concrete continuous bridges were constructed. In this period, Chinese engineer developed new erection techniques such as the lift-push launching method, the traveling formwork method, the span-by-span erecting method, and other novel construction method for various types of bridges. By using these methods, two reinforced concrete cable-stayed bridges were constructed in 1975, which marked the beginning of the construction of modern cable-stayed bridges in China.

Construction of long-span bridges started from 1980s. Since then, many great long-span bridges have completed in China.

The Luzhou Yangtze River Bridge (Figure 1.22), located in Sichuan Province, is 1,252.5 m in total length with main span of 170 m (105 m+3×170 m+105 m). The prestressed T-shape rigid-frame bridge was completed in 1982, and the design loads are Truck-20 and Trailer-100.

The Luoxi Bridge (Figure 1.23), located in Guangdong Province, is 1,916 m in total length with main span of 180 m (65 m+125 m+180 m+110 m). The prestressed T-shape rigid-frame bridge was completed in 1988, and the design loads are Truck-20 and Trailer-100.

The Wanxian Yangtze River Bridge (Figure 1.24), located in Wanzhou, Chongqing City, is 856.12 m in total length with main span of 420 m. The reinforced concrete steel-pipe-frame box-rib arch bridge was completed in 1997, and it ranks the first among the similar bridges in the world. The design loads are Truck-super 20 and Trailer-120.

The Wuhu Yangtzi River Bridge (Figure 1.25), located in Wuhu City, Anhui Province, is 6,078.4 m in total length and 312 m in main span length (180 m+312 m+180 m). The double-pylon double-plane cable-stayed bridge with steel truss and reinforced concrete composite girder was completed in 2000. The design loads are Truck-super-20 and Trailer-120.

Figure 1.22 The Luzhou Yangtze River Bridge.

Figure 1.23　The Luoxi Bridge.

Figure 1.24　The Wanxian Yangtze River Bridge.

Figure 1.25　The Wuhu Yangtzi River Bridge.

The Sutong Yangtze River Bridge (Figure 1.26) , located in Jiangsu Province, connecting Nantong and Changshu. With a main span of 1,088 m (3,570 ft), it held the longest main span in the world between 2008 and 2012. Its two side spans are 300 m long each.The bridge received the 2010 Outstanding Civil Engineering Achievement award (OCEA) from ASCE. Two towers of the bridge are 306 m high and thus the second tallest in the world. The bridge was opened to traffic on May 25, 2008.

Up to 2014, 590,000 highway bridges with a total length of 250,000 km have been built in China, among which 165 long-span bridges are across the Yangtze River with structural types of rigid frame, arch, cable-stayed, and suspension. Since the 1990s, 72 long-span bridges with main span lengths of more than 400 m each have been completed in China, among which three sea-crossing bridges of more than 20,000 m long each, were built after the year 2005.

Driven by urbanization, increasing traffic, and demand for infrastructure, China is in great need of new bridges. Large progress was made in the construction of extra longe-span bridges crossing ocean over the last two decades. The world's longest sea bridge, the Hong Kong-Zhuhai-Macau Bridge (Figure 1.27), was completed in 2017 and open to traffic in 2018 after seven years of construction. Spanning 55 kilometers, the bridge-tunnel project consists of several steel box girder bridges in non-navigable spans and three cable-stayed bridges with maximum span length of 1,150 m in the navigable spans, one undersea tunnel, and three artificial islands. The grand bridge links the two special administrative regions of Hong Kong and Macau with the mainland of China, cutting travel time from Hong Kong to Zhuhai down to 30 minutes from 3 hours and linking up to 60 million people into a metropolis-style economy.

Chinese bridge builders have come a long way since they built the first modern prestressed concrete bridge. The progress in the construction of bridges represents the advances of civil engineering in China. In the next decade, China's investment in the construction of infrastructure continues to increase. Chinese bridge engineers have more opportunities than before to design and construct longer, record-breaking bridges, crossing wider and deeper rivers, gorges, and sea channels.

Figure 1.26 The Sutong Yangtze River Bridge, China.

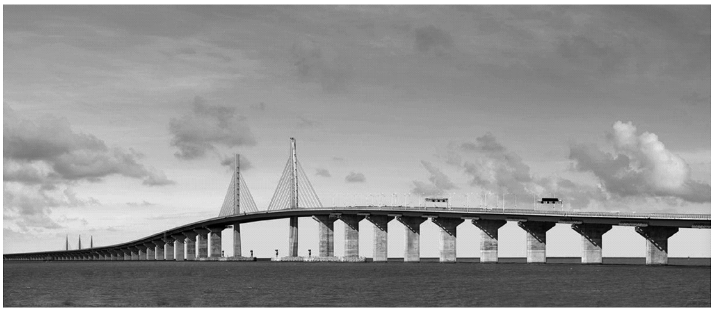

Figure 1.27 The Hong Kong-Zhuhai-Macau Bridge.

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