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Section VII
Worldwide Practice

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Bridge Design Practice in China

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63.1 Introduction

63.1.1 Historical Evolution

With a recorded history of about 5000 years, China has a vast territory, topographically higher in the northwest and lower in the southeast. Networked with rivers, China has the well-known valleys of the Yangtze River, the Yellow River, and the Pearl River, which are the cradle of the Chinese nation and culture. Throughout history, the Chinese nation erected thousands of bridges, which form an important part of Chinese culture.

FIGURE 63.1 Anji Bridge.

Ancient Chinese bridges are universally acknowledged and have enjoyed high prestige in world bridge history. They can be classified into four categories: beam, arch, cable suspension, and pontoon bridges.

The earliest reference to the beam bridge in Chinese history is the Ju Bridge dating from the Shang Dynasty (16th to 11th century B.C.). During the Song Dynasty (A.D. 960 to 1279), a large number of stone pier and stone-beam bridges were constructed. In Quanzhou alone, as recorded in ancient books, 110 bridges were erected during the two centuries, including 10 well-known ones. For example, the 362-span Anping Bridge was known for its length of 2223 m, a national record for over 700 years. To elongate the span, either the timber beams or the stone ones were placed horizontally on top of each other, the upper layer cantilevering over the lower one, thus supporting the simple beam in the middle. The extant single-span timber cantilever bridge, the Yinping Bridge built in Qing Dynasty (A.D. 1644 to 1911) has a span of more than 60 m with a covered housing on it.

The oldest arch bridge in China, which still survives and is well preserved, is the Anji Bridge, also known as the Zhaozhou Bridge, at Zhouxian, Hebei Province, built in the Sui Dynasty (Figure 63.1). It is a single segmental stone arch, composed of 28 individual arches bonded transversely, 37.02 m in span and rising 7.23 m above the chord line. Narrower in the upper part and wider in the lower, the bridge averages 9 m in width. The main arch ring is 1.03 m thick with protective arch stones on it. Each of its spandrels is perforated by two small arches, 3.8 and 2.85 m in clear span, respectively, so that flood can be drained and the bridge weight is lightened as well. The Anji Bridge has a segmental deck and the parapets are engraved with dragons and other animals. Its construction started in the 15th year of the reign of Kaithuang (A.D. 595) and was completed in the first year of Day's reign (A.D. 605) of the Sui Dynasty. To date, it has survived for 1393 years. The bridge, exquisite in workmanship, unique in structure, well proportioned and graceful in shape, with its meticulous yet lively engraving, has been regarded as one of the greatest achievements in China. Great attention has been paid to its preservation through successive dynasties. In 1991, the Anji Bridge was named among the world cultural relics.

Stone arches in China vary in accordance with different land transport and different natures between the north and south waterways. In the north, what prevails is the flat-deck bridge with solid spandrels, thick piers, and arch rings, whereas in the south crisscrossed with rivers, the hump-shaped bridge with thin piers and shell arches prevails.

In the southeastern part of China, Jiangsu and Zhejiang Provinces, networked with navigable rivers, boats were the main means of transportation. As bridges were to be built over tidal waters and their foundations laid in soft soil, even the stone arch bridge had to be built with thin piers and shell arches in order that its weight could be reduced as much as possible. The thinnest arch

FIGURE 63.2 Suzhou Baodai Bridge.

ring is merely 1/67 of the span, whereas for an average the depth of the arch ring is 1/20 of the span. The longest surviving combined multispan bridge with shell arches and thin piers is the Baodai Bridge (Figure 63.2) in Suzhou, Jiangsu Province. Built in the Tang Dynasty (A.D. 618 to 907) and having undergone a series of renovations in successive dynasties, the bridge is now 316.8 m long, 4.1 m wide, with 53 spans in all, the three central arches being higher than the rest for boats to pass through. Both ends of the bridge are ornamented with lions or pavilions and towers, all of stone.

Cable suspension bridges vary in kind according to the material of which the cables are made: rattan, bamboo, leather, and iron chain. According to historical records, 285 B.C. saw the Zha Bridge (bamboo cable bridge). Li Bin of the Qin State, who guarded Shu (256 to 251 B.C.), superintended the establishment of seven bridges in Gaizhou (now Chengdu, Sichuan Province), one of which was built of bamboo cables. The Jihong Bridge at Yongping County, Yunnan Province, is the oldest and broadest bridge with the mostly iron chains in China today. Spanning the Lanchang River, it is 113.4 m long, 4.1 m wide, and 57.3 m in clear span. There are 16 bottom chains and a handrail chain on each side. The bridge is situated on the ancient road leading to India and Burma.

The Luding Iron-Chain Bridge (Figure 63.3) in Sichuan Province, the most exquisite of the extant bridges of the same type, spans the Dadu River and has served as an important link between Sichuan Province and Tibet. It is 104 m in clear span, 2.8 m in width, with boards laid on the bottom chains. There are nine bottom chains, each about 128 m long, and 2 handrail chains on each side. On each bank, there is a stone abutment, whose deadweight balances the pulling force of the iron chains. Its erection began in 1705 and was completed in the following year.

According to historical records, a great number of pontoon bridges were built at nine and five different places over the Yangtze and the Yellow Rivers, respectively, in ancient times. In 1989 unearthed in Yongji, Shanxi Province, were four iron oxen, weighing over 10 tons each, and four life-size iron men, all with lively charm, exquisitely cast. They were intended to anchor the iron chains on the east bank of the Pujing Floating Bridge in the Tang Dynasty.

Ancient Chinese bridges, with various structures, exquisite workmanship, and reasonable details are the fruit of practical experience. Calculations and analyses by modern means prove that the great majority is in conformity with scientific principles. Ancient Chinese bridges are of great artistic and scientific value and have made remarkable achievements, from which we can assimilate rich nourishment to give birth to new and future bridges.

Comparatively speaking, the construction of modern bridges in China started late. Before the 1950s, many bridges were invested, designed, and constructed by foreigners. Most highway bridges were made up of wood. After the 1950s, China's bridge construction entered a new era. In 1956, the first prestressed concrete highway bridge was constructed. After 1 year, Wuhan Yangtze River Bridge was erected, which ended the history of the Yangtze River having no bridges. Nanjing Yangtze

FIGURE 63.3 Luding Iron-Chain Bridge.

River bridge was completed in 1969. In the 1960s, China began to adopt cantilever construction technology to construct T-type rigid frame bridges. During the 1970s, more prestressed concrete continuous bridges were constructed. China also began to practice new construction technology such as the lift-push launching method, the traveling formwork method, the span-by-span erecting method, etc. Two reinforced concrete cable-stayed bridges were constructed in 1975, which signified the start of cable-stayed bridge construction in China. Since 1980, China began to develop long-span bridges. One after another, many long-span bridges such as Humen Bridge (prestressed concrete continous rigid frame) in Guangdong Province with a main span of 270 m, Wanxian Yangtze River Bridge (arch reinforced concrete) in Shichuan Province with a main span of 420 m, Yangpu Bridge (cable-stayed) in Shanghai City with a main span of 602 m, etc. have been completed. The Jiangying Yangtze River (suspension) Bridge with a main span of 1385 m is under construction. The first two bridges mentioned above have the longest spans of their respective types in the world. Today, five large-scale and across-sea projects for high-class road arteries along the coast are under planning by the Ministry of Communications of China. From north to south, the road arteries cut across Bohai Strait, Yangtze Seaport, Hangzhou Bay, Pearl Seaport, Lingdingyang Ocean, and Qiongzhou strait. A large number of long-span bridges have to be constructed in these projects. The Lingdingyang long-span bridge project across Pearl Seaport has started.

63.1.2 Bridge Design Techniques

63.1.2.1 Design Specifications and Codes

There are two series of bridge design specifications and codes in China. One is for highway bridges [3] and the other for railway bridges [4]. In addition, there are design guides such as the wind-resistant guide for bridges [6]. Design Specifications for Highway Bridges are mainly for concrete bridges, which are widely constructed in China. Here only these specifications are presented because of space limitations.

The current Design Specifications for Highway Bridges [3], which were issued by the Ministry of Communications of the People's Republic of China in 1989, include six parts. They are the General Design Specification for Bridges, the Design Specification for Masonry Bridges, the Design Specification for Reinforced and Prestressed Concrete Bridges, the Design Specification for Footing and Foundations of Bridges, the Design Specification for Steel and Timber Members of Bridges, and the Seismic Design Specification for Bridges. The design philosophies and loads are provided in the General Design Specification.

In the specifications, two design philosophies are adopted: load and resistance factor design (RFD) theory for reinforced prestressed concrete members and allowable stress design (ASD) theory for steel and timber members.

Three basic requirements for strength, rigidity, and durability need to be checked for all bridge members. For a bridge member that may be subjected to bending, axial tension, or compression, combined bending and axial forces etc. should be checked in accordance with its loading states. To ensure its strength requirement, the rigidity of a bridge is evaluated according to the displacement range at the midspan or cantilever end. By checking the widths of cracks and taking some measurements, the durability of structures may be ensured.

63.1.2.2 Analysis Theories and Methods

The analysis of a bridge structure in terms of service is based on the assumption of linear elastic theory and general mechanics of materials. According to design requirements, the enveloping curves of internal forces and displacements of members of a bridge are calculated. Then, checking for strength, rigidity, and durability is done carefully in accordance with the design specifications. For simple structures, they are usually simplified as plane structures but they can also be analyzed more accurately by 3D-FEM.

For example, simply supported girder bridges are usually simplified in the following way. According to the cross section shape and the construction method, the bridge may be divided into several longitudinal basic members such as T-girders or hollow plate girders or box girders. The internal forces of the basic members caused by dead loads are calculated under an assumption of every basic member carrying the same loads. In order to consider the effect of space structure under live loads, the influence surfaces of internal forces and displacements are approximately simplified as two univariant curves; one is the influence line of internal forces or displacements of a basic member and another is the influence line of the transverse load distribution.

To prove the feasibility and reliability of the approximate method, extensive tests and theoretical studies have been conducted. Several methods to determine the influence lines of transverse load distribution for different structures and construction methods have been developed [5]. In the current practice, the transversely hinge-connected slab (or beam) method, rigid-connected beam method, rigid cross beam method, and lever principle method are used according to structures and construction methods. They may satisfy the design requirement for a lot of bridges. With computer programs, these simplified analysis methods have become very easy.

However, some bridges, such as irregular skewed bridges, curved bridges, and composite bridges, cannot be divided into several longitudinal girders that mainly have behaviors of vertical plane structures. They are not suited to the simplified analysis methods mentioned above. For those complex space structures, the influence surfaces of internal forces and displacements due to dead load are obtained by the static finite-element method and the maximal impact responses of internal forces and displacements caused by live loads can be obtained using dynamic analysis proceedures.

63.1.2.3 Theories and Methods for Long-Span Bridges

Long-span bridges are usually expensive to construct and are flexible in structural nature. In view of the economic and functional requirements, the problems of structural optimization, nonlinear analysis, stability analysis, and construction control become especially important to long-span bridges. Chinese bridge experts who participate in the study and design of China's long-span bridges have put forward many theories and methods to solve the problems mentioned above. In respect to the nonlinear analysis of long-span bridges, they developed an influence area method for geometric nonlinear analysis of live loads, nonlinear adjustment calculation method, and nonlinear construction simulation calculation method, for construction control [8]. Using finite displacement theory, a three-dimensional nonlinear analysis system considering dead load, live load, and construction stage and methods was developed [9]. Stability problems of truss, frame, and arch bridge have been studyed extensively [1]. A stability analysis approach was developed for the wind effect on long-span bridges. Optimization theory and techniques have been applied to all kinds of bridges successfully. The accuracy and efficiency of those methods developed have been verified by practical application.

63.1.2.4 Bridge CAD Techniques

Since the late 1970s, computer technologies have been widely employed for structural analysis in bridge design practice in China. Many special-purpose structural analysis programs for bridge design were developed. With full concern for the special feature of bridge design, for example, the Synthetical Bridge Program [9], provided the capability of construction stage transferring, concrete creep and shrinkage analysis, prestress calculation, etc. To a certain extent, widespread adoption of this program reflected the application status of computational technology in the field of highway bridge design in China during the years from the late 1970s to the early 1980s.

Since the 1980s, the popularization of computer graphics devices, such as the rolled drafting plotter and digitizer, have brought computational application from merely structural analyzing to aided design including both structural analysis and detail drafting. With the development of the highway system, standardized simply supported bridges have spread over China. Based on the microcomputer platform, many researchers and engineers began to develop automated CAD systems integrating structural analysis and detail drafting. The "Automated Medium and Short-Span Bridge CAD System on Micro-computer" cooperatively developed by the membership of China Highway Computer Application Association, for example, has the capabilities to accomplish all processes of simply supported T-beam and plate bridge design. With the aid of this system, only a few primary pieces of information are required to be input, and the computer will automatically produce a set of design documents including both specifications and drawings in a short time. The design efficiency is excellent compared with the traditional manner. Many design institutes and firms employed this system to design medium- and short-span bridges.

During the7th Five Year Plan of China (1985 to 1990), to develop a new highway bridge system, a special task group consisting of more than 40 practical bridge engineers and scholars was formed and organized by the Ministry of Communications. As a national key scientific research project, the allied group invested $2 million of RMB to research and develop the CAD techniques applied in the construction of highway bridges. In 1991, the "Highway Bridge CAD System (JT-HBCADS)" was successfully developed. More than 10 large highway bridge design institutes have installed this system and fulfilled the design of about 10 large bridges such as Nanpu Bridge, Yangpu Bridge, etc.

During the years from 1991 to 1995, the increase in personal computer (PC) hardware performance and software technology has issued a critical challenge to the development of research and application of bridge CAD techniques. Many advanced software development techniques, such as kernel database accessing, object-oriented programming, application visualizing, and rapid application developing, were entirely developed and made available for the personal computer, which brought forth lots of chances that had never appeared before in developing the new generation of integrated and intelligent bridge CAD systems.

With full regard to, and on the basis of, experience and acquaintance with the development of JT-HBCADS and many newly available support software technologies, the developing ideas of integrated bridge CAD system (BICADS) has been brought up, and the new generation BICADS was successfully developed thoroughly under the guidance of this thought. Taking the Windows NT operating system as the platform, the system architectural design of BICADS entirely adopted the kernel database accessing techniques to avoid the difficulties of system maintenance and upgrading the innate and unavoidable weakness caused by the traditional file system. The first version of BICADS consists of five subsystems including the Design Documentation, Pre-Processing of Bridge FEM, Bridge FEM Kernel, Post-Processing of Bridge FEM, and the Preliminary Design of Box Girder Bridges. Several detailed design subsystems of other commonly used bridges can be included by employing a good integrating and expanding mechanism in the main system. Additionally, the research of some fundamental problems in the field of bridge intelligent CAD techniques and the development of bridge experts system tools with graphics processing abilities have already yielded considerable promise. It is predicted that, motivated by the rapid development of computer technologies by the end of this century, a new generation in China's bridge CAD techniques application and research is being opened.

63.1.3 Experimental Research of Dynamic and Seismic Loads

Model Tests for Bridges

To establish the dynamic behavior base line for health monitoring bridge structures, the model tests are usually done just after construction of bridges. Experimental procedures that have been used in the past include (1) impact tests and (2) ambient vibrations. For large bridges, such as Shanghai Yangpu Bridge (cable-stayed bridge) and Shanghai Fengpu Bridge (continuous box-girder bridge), the method of using test vehicles (controlled traffic) for exciting bridges was successfully verified.

Shaking Table Test of Bridge Models

The tests of a simply supported beam and a continuous girder bridge model were performed on the shaking table (made by the MTS Co.). These tests were to evaluate the effect of ductility and seismic isolation on bridges, in which the viaduct of Shanghai Inner Ring Road was regarded as the background of the continuous girder bridge model; meanwhile, the analytical models of bridges and elements were verified.

Ductility Performance and Seismic Retrofitting Techniques for Bridge Piers

Recently, high-strength concrete with cylindrical compressive strength up to 100 MPa or higher can be made with locally obtainable materials, such as ordinary cement, sand, crushed stone, a water-reducing superplasticizer, standard mixing methods, and careful quality control in production. There are many characteristics for high-strength concrete that are beneficial in civil engineering, but, on the other hand, there are some shortcomings to the increasing use of high-strength concrete. For instance, brittle features and less postpeak deformability may cause brittle failure during earthquakes or under other conditions. Much work, theoretical and experimental, has been done by Chinese researchers for ductility design and improving design code of bridges. Through the tests and analyses, some important conclusions may be summarized briefly as follows:

1. Test results indicate that for high-strength concrete columns, very large ductility could be achieved by using lateral confining reinforcement.
2. All retrofitted piers using steel jackets, steel fiber concrete, expoxy concrete, and fiberglass-expoxy performed extremely satisfactorily. Good ductility, energy-dissipation capacity, and stable-deformation behavior were achieved.

Dynamic Behavior Test of Isolation Devices

To meet the requirements of earthquake resistance design of bridge, seismic design of isolated bridge and optimization have been widely used in China. The dynamic properties of elastomeric pad bearings (EP bearings) has been evaluated, including the shear modulus, hysteretic behavior, and sliding friction coefficient of EP bearings and Teflon plate-coated sliding bearings (TPCS bearings). The tests were done on an electro-hydraulic fatigue machine (made by INSTRON Co.) with an auxiliary clamping apparatus. These results may be summarized as follows:

1. At constant shear strain amplitude, the shear modulus of EP bearings increases with the increase in frequency. At constant frequency, the shear modulus obviously decreases with the increase in shear strain amplitude. Sizes and compression have no obvious effect on dynamic shear modulus.
2. At constant compression and sliding displacement amplitude, the hysteretic energy of TPCS bearings increases with the increase in frequency. At constant sliding displacement amplitude and frequency, the increased compression results in an increase in the hysteretic energy of TPCS bearings.
3. The friction coefficient of TPCS bearing decreases with the increase in compression.

Based on experimental research of rubber bearings and steel damping, a system of seismic isolation and energy absorption, composed of curved steel-strip energy absorbers and TPCS bearings, was developed, and then a seismic rubber bearing with curved mild-steel strip, was invented.

Recently, some kinds of improved seismic bearings have come out. A great number of dynamic experiments show that these types of bearings have better hysteretic characteristics than elastomeric laminated bearings. To avoid span failures of bridges upon impact, restricting blocks are usually placed at the end of beams. To compare the behavior of the blocks, three kinds of blocks [4] have been manufactured and an experiment has been conducted on these blocks: (1) " T-type" rubber blocks, (b) "bowl-type" rubber blocks, and (3) cubic reinforced concrete blocks. During the tests, the impact hammer freely fell from a given height and contact forces between the block and high-strength concrete hammer were recorded. The test results show it is very obvious that T-type rubber blocks have the best energy absorption capacity and the impact force of T-type rubber blocks is much lower than that of concrete blocks.

63.1.4 Wind Tunnel Test Techniques

Since the 1980s, with the building of long-span cable-stayed and suspension bridges, China has made great progress in wind engineering. For example, there are three boundary-layer wind tunnels in the National Key Laboratory for Disaster Reduction in Civil Engineering at Tongji University. TJ-1, TJ-2, and TJ-3 BLWTs, which have been put into service only for several years, have working sections of 1.2 m (width), 1.8 m (height); 3 m (width), 2.5 m (height); and 15 m (width), 2 m (height), respectively. The maximum wind speeds of these are 32, 17, and 65 m/s, respectively. Until now, about 30 model tests have been carried out in these wind tunnels. Wind-resistant researches on about 40 cable-stayed bridges and suspension bridges have been carried out mainly at Tongji University, Shanghai, China. More than 10 full-scale aeroelastic bridge model tests have been performed. To meet the requirements of the wind-resistant design of highway bridges with increasing spans, a Chinese Wind Resistant Design Guideline of Highway Bridge was compiled. Some achievements of flutter analysis, buffeting analysis, and wind-induced vibration control have been made and are introduced in the following.

Flutter Analysis

As is well known, the critical flutter velocity is the first factor that controls the design for a long-span bridge, especially located in typhoon areas. Precision of torsional frequency in the calculation is very important. The traditional single-beam model test of bridge deck usually gives estimates of torsional frequencies lower than the actual ones and may make a lower critical flutter velocity estimation. A three-beam model of a bridge deck which was developed by Xiang et al., [6] has been proved to be efficient in improving the precision of torsional frequency to a great extent.

The state-space method for flutter analysis overcomes the shortcomings of Scanlan's method for flutter analysis in which only one vertical mode and one torsional mode can be considered. A multimode flutter phenomenon was found. Participation of more than two modes in flutter make the critical velocity higher than that from Scanlan's method.

Buffeting Analysis

With the increase in span length, bridge structures tend to become more flexible. Excessive buffeting in near-ground turbulent wind, although not destructive, may cause fatigue problems due to high frequency of occurrence and traffic discomfort. Davenport and Scanlan et al., proposed buffeting analysis methods in the 1960s and 1970s, respectively. Since then, refinement studies on these methods have been made. It is possible to establish practical methods for buffeting response spectrum and buffeting-based selection.

Aerodynamic selection of deck cross section shape is important in the preliminary design stage of a long-span bridge. In the past year, this selection aimed mainly at flutter-based selection. The concept of "buffeting-based selection" and the corresponding method were used in the wind-resistant design of the Jiangying Yangtze River Bridge and the Humen Bridge, a suspension bridge with a main span of 888 m.

To investigate the nonlinear response characteristics of long-span bridges, a nonlinear buffeting analysis method in the time domain has been used to analyze the Jiangying Yangtze River Bridge and the Shantou Bay Bridge, etc. Analysis results show that for long-span suspension bridges the aerodynamic and structural nonlinear effects on the buffeting response should be considered.

Wind-Induced Vibration Control

In practice today, the increment of critical flutter velocity of a long-span bridge is usually achieved using aerodynamic measures. The theoretical analysis and experiments indicate that passive TMD may also be an effective device for flutter control. A couple of TMDs with proper parameters can increase the critical flutter velocity of the Humen-Gate Bridge with wind screens on the deck (for improving vehicle moving condition) by 50%, although the efficiency, duration, and reliability of the device for long-time-period use still have some problems to be solved.

The buffeting response increases with wind speed, and may become very strong at high wind speed. Two new methods were proposed for determination of optimal parameters of the TMD system for controlling buffeting response with only the vertical mode and with coupling the vertical and torsional modes, respectively.

63.1.5 Bridge Construction Techniques

63.1.5.1 Constructional Materials

According to the design specifications for bridges in China, the maximum strength of concrete is 60 MPa; the prestressing tendons include hard-drawn steel bars, high-strength steel wires, and high-strength strands, the strengths of which are from 750 to 1860 MPa; the general reinforcement bars are made of A3, 16Mn, etc.; the steel plate is made of A3 or 16Mn or 15MnVN, etc. In normal designs, the concrete used in prestressed bridges should have a strength higher than 40 MPa; the prestressing tendons used in pretensioned slab girders are hard-drawn 45 SiMnV bars with the strength of 750 MPa or steel strands with strength of 1860 MPa; the high tensile strength and low relaxation strands are widely used in post-tensioned concrete bridges. Now a viaduct usually has a lower depth of girders so high-strength concrete over 50 MPa is often adopted. Concrete having a strength of over 60 MPa and tensile wires and strands will be used in bridges in the future.

63.1.5.2 Prestressing Techniques

Prestressing techniques including internal and external prestressing have been used for about 40 years in China. Not only were the full and partial prestressed bridges constructed speedily, but also the preflex prestressed girders and double-prestressed girders have been used in viaducts and separation structures. The high tensile strength and low relaxation strands, the reliable anchorages, such as the OVM system, and the high-tonnage jacks have been widely used in many bridges including continuous girder bridges, T-frame bridges, cable-stayed bridges, and suspension bridges. The design and construction of prestressed concrete structures is a normal process in China. The external prestressing tendons, including unbonded tendons, have been used in new bridges and in the strengthening of many old bridges. Now, several external prestressed long-span composite bridges are being built in China.

63.1.5.3 Precast Techniques of Concrete and Steel Girders

Most simply supported girder bridges are made with fabricated methods in China, and factory production is usually adopted. When the span is shorter than about 22 m, the pretensioned, prestressed voided slab girder is often the best choice, and the high-strength and low-relaxation strands are used as the prestressed reinforcement. When the span is over about 25 m, the post-tensioned T-girder may be used, in which the strands are arranged with curved profiles. In the construction of some bridges and urban viaducts and in precasting yards, steam curing is often used to increase the strength of concrete early and to raise the working efficiency. Usually the weight and length of a precast girder are limited to below about 1200 kN and 50 m to ease transport and erection.

Segmental bridges are usually built using the cantilever casting method, or other casting methods; nevertheless, only a few segmental bridges are constructed with the cantilever erection method. We usually cast in place because it is noticed that the rusting of prestressing strands at the segment joints may cut down the service life of bridges. The high anticorrosive external prestressing tendon or strand cable is not widely adopted yet in post-tensioned segmental bridges.

In China, complete riveting techniques have been replaced by welding and high-strength bolting techniques. Complete welded box and composite girders have been used in urban viaducts, separation structures, and cable-stayed bridges; techniques adopted in shipbuilding, such as computer layout and precision cutting, are being introduced.

63.1.5.4 Cable Fabrication Techniques

About 10 to 20 years ago, the stay cable in China was fabricated mainly on the construction site and consisted of 5-mm-diameter or 7-mm-diameter parallel galvanized steel wires. It was protected with PE casing pipe grouted with cement, or with corrosion paint and three layers of glass fibers coated by epoxy resin. A lot of cable-stayed bridges have been built in the last decade and the cable fabrication techniques have developed rapidly. With the construction of Shanghai Nanpu Bridge in 1988, the first factory, which mechanically produced long-lay spiral parallel wire cables with a hot-extruded PE or PE and PU sheath, was established. Since then, the quality of stay cables has greatly improved, especially in resistance to corrosion. Now the maximum working tension of stay cables is over 10,000 kN and high-quality anchorage has been developed. In recent years, the parallel and spiral strand cables of factory production with maximum working tensions at over 10,000 kN have been frequently used in cable-stayed bridges.

At the same time, the main cables of Santo and Humen (suspension) Bridges were successfully fabricated in China; the parallel wire strand consisted of 127ϕ 5.2-mm zinc-coated steel wires and had a length of over 1600 m; the mean square root error in the length of wires was lower than 1/36,000. Now, Jiangyin Yangtze River Bridge, having the longest span, close to 1400 m, in China, is under construction; its main cables will also be prefabricated.

63.1.5.5 Construction Techniques of Large-Diameter Piles

In China, bored piles are usually adopted for large bridges. When the ground is poor or the rock formation is near the Earth's surface or riverbed, piles have to be built in the rock and they become the bearing piles. Normally, the diameter of bearing piles is about 0.8 to 2.5 m. A large-diameter pile can be adopted to replace the pile group in order to reduce material construction time. Usually this large-diameter pile has a diameter of 2.5 to 7 m, is hollow, and consists of two or three segments. The first segment of the pile is a double-wall steel and concrete composite drive pipe which is driven into a weathered layer as a cofferdam; the second segment is a hollow concrete bearing pile which has a smaller diameter than the first segment, and the pier shaft is connected on the top of this segment; the last segment has a minimum diameter or, similar to the second, it is built in the rock. As a result, construction is easy, and no platform or hollow pile uses up a lot of concrete and steel.

63.1.5.6 Advanced Construction Techniques

With the development of transportation in China, more and more large bridges have been built and new construction techniques have been developed. Continuous curved bridges have been built with the incremental launching method, and the speed of the cantilever casting construction method is about 5 or 6 days per segment. The cable-stayed composite bridges, whose composite girders are composed of prefabricated, wholly welded steel girders and precast reinforced concrete deck slabs, were constructed with the cantilever erection method — for example, the 602-m Shanghai Yangpu Bridge, built in 1993. For prestressed concrete cable-stayed bridges, the tensions of stay cables and alignment of girder can easily achieve their best states by using computer-automated control techniques. The construction method of modern long-span suspension bridges was a new technique in China several years ago, most using PWS (prefabricated parallel wire strand) methods.

The improvement of construction techniques is not only in continuous girder bridges, rigid frame bridges, cable-stayed bridges, and suspension bridges. In a deep valley or flood river, the stiff reinforcement skeleton consisting of steel pipes is used as the reinforcement of a long-span concrete arch ring; after the stiff reinforcement skeleton is erected and closed up at midspan, the concrete is pumped into the steel pipes; then, by using the traveling form, which is supported on the stiff reinforcement skeleton, the concrete is cast and the reinforced concrete box arch ring is formed. Another construction method used in long-span composite arch bridges is the swing method. The two halves of the arch are separately erected on each side of river embankments or hillsides; then, by using jacks, they are rotated around their supports under arch seats and closed at midspan; finally, the concrete is pumped into the pipe arch. In order to keep the balance of a half arch, water containers are usually used as the ballast weights.

The progress of construction techniques has not only been made for superstructures but also for substructures. The height of reinforced, prestressed hollow piers and precast piers used in deep valleys has reached over 80 m. Large-diameter hollow piles and large concrete and steel caissons and double-wall steel and concrete composite cofferdams are adopted in river or sea depths over 50 m.

63.2 Beam Bridges

63.2.1 General Description

Simple in structure, convenient to fabricate and erect, easy to maintain, and with less construction time and low cost, beam structures have found wide application in short- to medium-span bridges. In 1937, over the Qiantang River, in the city of Hangzhou, a railway-highway bipurpose bridge was erected , with a total length of 1453 m, the longest span being 67 m. When completed, it was a remarkable milestone of the beam bridge designed and built by Chinese engineers themselves.

Reinforced concrete beam structures are most commonly used for short- to medium-span bridges. A representative masterpiece is the Rong River Bridge completed in 1964 in the city of Nanning, the capital of Guangxi Zhuangzu Autonomous Region. The bridge, with a main span of 55 m and a cross section of a thin-walled box with continuous cells, designed in accordance with closed thin-walled member theory, is the first of its kind in China.

Prestressed concrete beam bridges are a new type of structure. China began to research and develop their construction in the 1950s. In early 1956, a simply supported prestressed concrete beam railway bridge with a main span of 23.9 m was erected over the Xinyi River along the Longhai Railway. Completed at the same time, the first prestressed concrete highway bridge was the Jingzhou Highway Bridge. The longest simply supported prestressed concrete beam which reaches 62 m in span is the Feiyun River Bridge in Ruan'an, Zhejiang Province, built in 1988. Another example is the 4475.09-m Yellow River Bridge, built in the city of Kaifeng, Henan Province in 1989. Its 77 spans are 50-m simply supported prestressed concrete beams and its continuous deck extends to 450 m. It is also noticeable that the Kaifeng Yellow River Bridge is designed on the basis of partially prestressed concrete theory. Representative of prestressed concrete continuous girder railway bridges, the second Qiantang River Bridge (completed in 1991) boasts its large span and its great length, its main span being 80 m long and continuous over 18 spans. Its erection was an arduous task as the piers were subjected to a wave height of 1.96 m and a tidal pressure of 32 kPa when under construction. The extensive construction of continuous beam bridges has led to the application of the incremental launching method especially to straight and plane curved bridges. In addition, large capacity (500-t) floating crane installation and movable slip forms as well as span erection schemes have also attained remarkable advancement.

Beam bridges are also used widely in overcrossings. In the 1980s, with the growth of urban construction and the development of highway transportation, numerous elevated freeways were built, which provide great traffic capacity and allow high vehicle speed, for instance, Beijing's Second and Third Freeway and East City Freeway, the Intermediate and Outer Freeway in Tianjin, and Guangzhou's Inner and Outer Freeway and viaduct. In Shanghai, the elevated inner beltway was completed in 1996. Subsequently, there has appeared an upsurge of erecting different-sized grade separation structures on urban main streets and express highways. Uutil now, in Beijing alone, 80-odd large overcrossings have been erected, which makes the city rank the first in the whole country in number and scale.

To optimize the bridge configuration, to reduce the peak moment value at supports, and to minimize the constructional depth of girders, V-shaped or Y-shaped piers are developed for prestressed concrete continuous beam, cantilever, or rigid frame bridges. The prominent examples are the Zhongxiao Bridge (1981) in Taiwan Province and the Lijiang Bridge (1987) at Zhishan in the city of Guilin.

63.2.2 Examples of Beam Bridges

Kaifeng Yellow River Bridge

Kaifeng Yellow River Bridge (Figure 63.4) is an extra large highway bridge, located at the northwest part of Kaifeng City, Henan Province. It consists of 108 spans ($77 \times 50 + 31 \times 20$) m, its total length reaching 4475.09 m.

Simply supported prestressed concrete T-girders are adopted for its superstructure. The deck is 18.5 m wide, including 12.3 m for motor vehicle traffic and two sidewalks 3.1 m wide each on both sides. Substructure applies single-row double-column piers, which rest on 2200-mm large-diameter bored pile foundations.

The bridge is of the same type as those built earlier over the Yellow River in Luoyang and Zhengzhou. Kaifeng Bridge has obtained an optimized design scheme, with its construction cost reduced and schedule shortened. The main characteristics of the bridge are as follows:

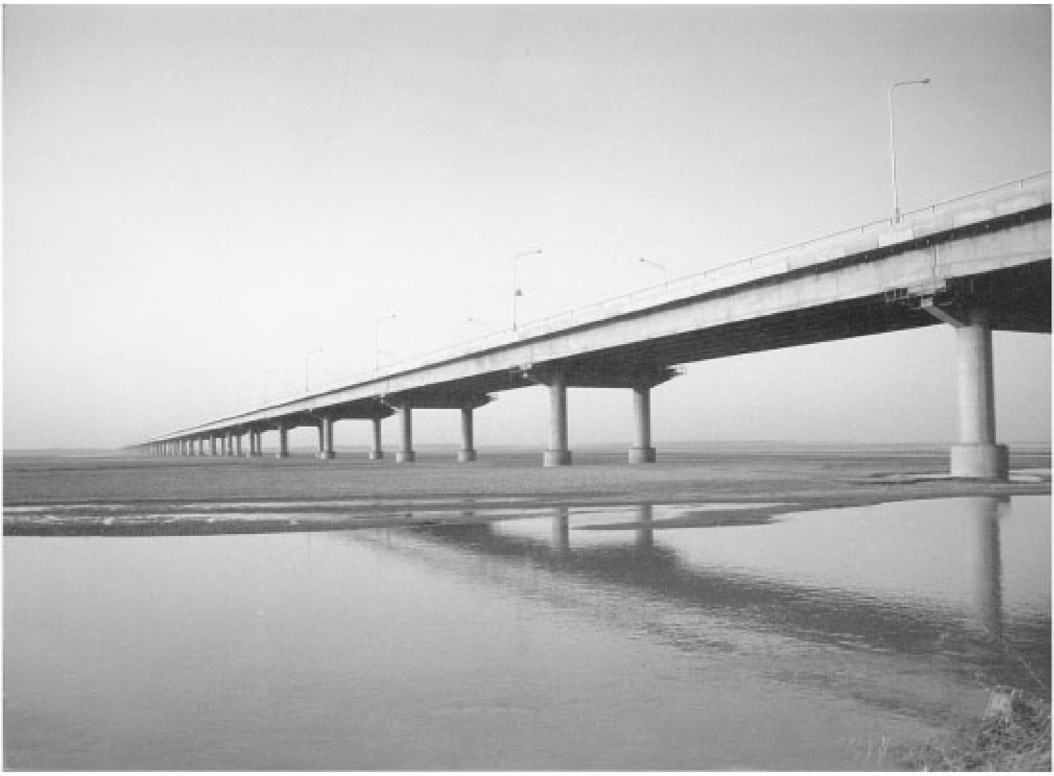

FIGURE 63.4 Kaifeng Yellow River Bridge.

1. Adoption of partial prestress concrete in the design of T-girder;
2. Modification of the beams over central piers as prestressed concrete structure;
3. Increase in the continuous length of the deck reaching 450 m.

The bridge was designed by Highway Planning, Survey and Design Institute of Henan Province, and constructed by Highway Engineering Bureau of Henan Province. It was opened in 1989.

Xuzhuangzi Overcrossing

Xuzhuangzi Overcrossing (Figure 63.5), a long bell-mouth interchange grade crossing on the freeway connecting Beijing-Tianjin and Tangshan, is a main entrance to the city of Tianjin.

The overcrossing has a total length of 4264 m. The superstructure consists of simply supported prestressed concrete T-griders and multispan continuous box girders. The 1.5-m-diameter bored piles and invested trapezoidal piers are adopted for the substructure.

The bridge was designed by the first Highway Survey and Design Institute, Tianjin Municipal Engineering Co. and constructed by the first Highway Co., Ministry of Communications, Kumagai Co., Ltd, Japan. It was opened to traffic in 1992.

Liuku Nu River Bridge

Liuku Nu River Bridge (Figure 63.6), the longest prestressed concrete continuous bridge in China at present, is located in the Nu River Lisu Autonomous Prefecture, Yunnan Province. It has three spans of length (85 + 154 + 85) m. The superstructure is a single-box single-cell girder with two 2.5-m-wide overhangs on both sides. The beam depth at the support is 8.5 m, i.e., $1/18$ of the span, while at the midspan it is only 2.8 m, i.e., $1/55$ of the span. The whole bridge has only two diaphragms at the hammer-headed block.

FIGURE 63.5 Xuzhuangzi Overcrossing.

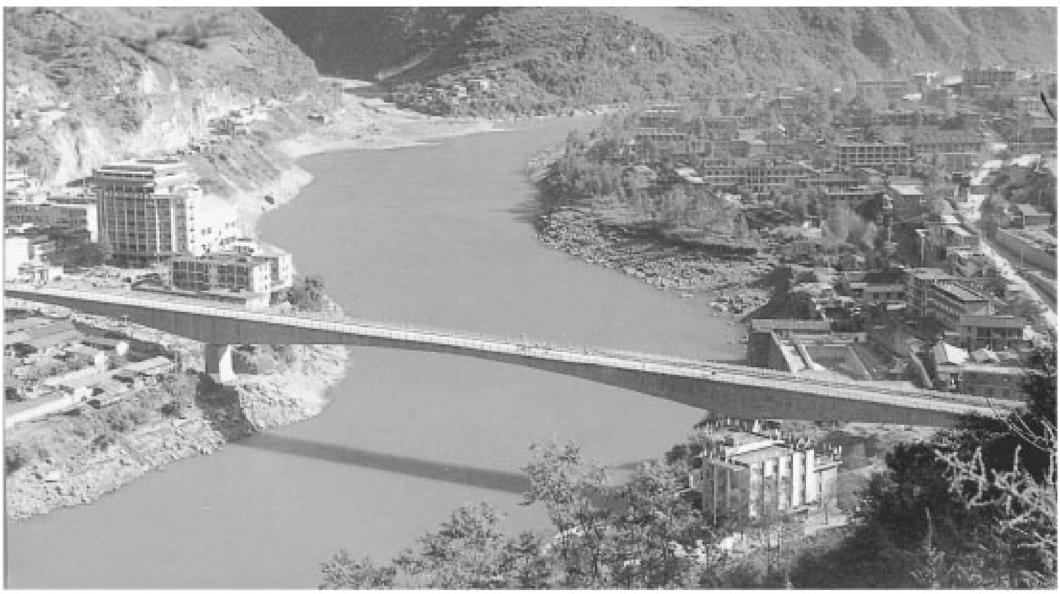

FIGURE 63.6 Liuku Nu River Bridge.

Three-way prestress is employed. A large tonnage strand group anchorage system is applied. With tendons installed only in the top and bottom slabs, no bent-up or bent-down tendon is needed and the widening of the web is avoided, which makes the construction very convenient. Vertical prestress is provided by Grade 4 high-strength rolled screwed rebars with diameter of 32 mm, which also served as the rear anchorage devices of the form traveler during cantilever casting. For the substructure hollow piers supported by bored piles foundation on rock stratum were adopted.

The bridge was completed in 1993, designed by Highway Survey and Design Institute of Yunnan Province and constructed by Chongqing Bridge Engineering Co.

FIGURE 63.7 Second Qiantang River Bridge.

The Second Qiantang River Bridge

The second Qiantang River Bridge, located on Sibao in Hangzhou, Zhejiang Province, is a parallel and separate highway–railway bipurpose bridge (Figure 63.7). The 11.4-m-wide railway bridge carries two tracks, with a total length of 2861.4 m. The highway bridge, which was designed according to freeway standard, is 20 m wide and 1792.8 m long, carrying four-lane traffic. Both main bridges are of prestressed concrete continuous box girders, and the continuous beams reach a total length of 1340 m, i.e., 45 + 65 + 14 × 80 + 65 + 45 m, the longest in China at present.

To obtain the 506 mm expansion magnitude of the main bridge, composite expansion joints were applied in the highway bridge, whereas transition beams and expansion rails were used for the railway bridge. Pot neoprene bearings were specially designed to accommodate the large displacement and to offer sufficient vertical resistance.

Three-way prestress was introduced to the box girder. Strands and group anchorage system were adopted longitudinally, with the maximum stretching force in excess of 2000 kN. The cantilever casting method was used for the main construction of the bridge, while the bored piles foundation was constructed at river sections of rare strong tidal surge with a height of 1.96 m and a pressure reaching 32 kPa. The bridge was designed and constructed by Major Bridge Engineering Bureau, Ministry of Railway. It was completed in November 1991.

63.3 Arch Bridges

63.3.1 General Description

Of all types of bridges in China, the arch bridge takes the leading role in variety and magnitude. Statistics from all the sources available show that close to 60% of highway bridges are arch bridges. China is renowned for its mountains with an abundant supply of stone. Stone has been used as the main construction material for arch bridges. The Wuchao River Bridge in Hunan Province, for instance, with a span of 120 m is the longest stone arch bridge in the world. However, reinforced concrete arch bridges are also widely used in various forms and styles.

Most of the arches used in China fall into the following categories: box arch, two-way curved arch, ribbed arch, trussed arch, and rigid framed arch. The majority of these structures are deck bridges with wide clearance, and it costs less to build such bridges. The box arch is especially suitable for long-span bridges. The longest stone arch ever built in China is the Wu River Bridge in Beiling, Sichuan Province, whose span is as long as 120 m. The Wanxian Yangtze River Bridge in Wanxian, Sichuan Province with a spectacular span of 420 m set a world record in the concrete arch literature. A unique and successful improvement of the reinforced concrete arch, the two-way curved arch structure, which originated in Wuxi, Jiangsu Province, has found wide application all over the country, because of its advantages of saving labor and falsework. The largest span of this type goes to the 150-m-span Qianhe River Bridge in Henan Province, built in 1969. This trussed arch with light deadweight performs effectively on soft subsoil foundations. It has been adopted to improve the composite action between the rib and the spandrel. On the basis of the truss theory, a light and congruous reinforced concrete arch bridge has been gradually developed for short and medium spans. Through prestressing and with the application of cantilevering erection process, a special type of bridge known as a "cantilever composite trussed arch bridge" has come into use. An example of this type is the 330 m-span Jiangjie River Bridge in Guizhou Province. The Yong River Bridge, located in Yunnan Province, is a half-through ribbed arch bridge with a span of 312 m, the longest of its kind. With a simplified spandrel construction, the rigid framed arch bridge has a much better stress distribution on the main rib by means of inclined struts, which transfer to the springing point the force induced by the live load on the critical position. In the city of Wuxi, Jiangsu Province, three such bridges with a span of 100 m each were erected in succession across the Great Canal. Many bridges, quite a number of which are ribbed arch bridges, have been built either with tied-arches or with Langer's girders. The recently completed Wangcang Bridge in Sichuan Province and the Gaoming Bridge in Guangdong Province are both steel pipe arch bridges. The former has a 115-m prestressed tied-arch, while the latter has a 110-m half-through fixed rib arch. A few steel arch bridges and slant-legged rigid frame bridges have also been constructed.

In building arch bridges of short and medium spans, precast ribs are used to serve as temporary falsework. And sometimes a cantilever paving process is used. Large-span arch bridges are segmented transversely and longitudinally. With precast ribs, a bridge can be erected without scaffolding, its components being assembled complemented by cast-in-place concrete. Also, successful experience has been accumulated on arch bridge erection, particularly erection by the method of overall rotation without any auxiliary falsework or support.

Along with the construction of reinforced concrete arch bridges, research on the following topics has been carried out: optimum arch axis locus, redistribution of internal forces between concrete and reinforcement caused by concrete creep, analytical approach to continuous arch, and lateral distribution of load between arch ribs.

63.3.2 Examples of Masonry Arch Bridge

Longmen Bridge

Longmen Bridge (Figure 63.8), 12 km south of Luoyang City, Henan Province, is an entrance of the Longmen Grottoes over Yihe River. It is a 60 + 90 + 60 m three-span stone arch bridge, with a width of 12.6 m. A catenary of 1:8 rise-to-span ratio was chosen as the arch axis. The main arch ring has a constant cross section, with a depth of 1.1 m. Two stone arches of 6 m long each were arranged on either bank providing under crossing traffic. The bridge was constructed on steel truss falsework supported by temporary piers. It was designed and constructed by Highway Engineering Bureau, Communications Department of Henan Province and completed in 1961.

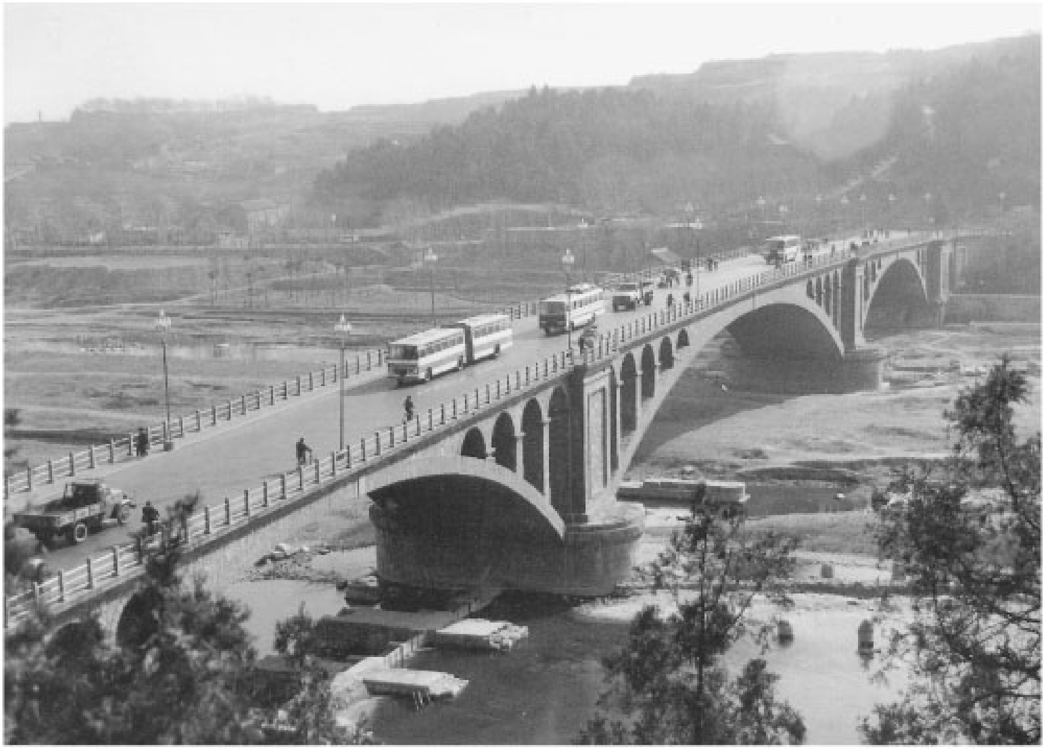

FIGURE 63.8 Longmen Bridge.

Wuchao River Bridge

Wuchao River Bridge (Figure 63.9), a structure on Fenghuang County Highway Route, Hunan Province, spans the valley of the Wuchao River with a total length of 241 m. To use local materials, a masonry arch bridge scheme was adopted. On the basis of the experience accumulated in the last 20 years of construction of masonry arch bridges in China, the bridge has a main span of 120 m, which is a world record for this type of bridge.

The bridge is 8 m wide. There are nine spandrel spans of 13 m each over the main spans; three spans of 13 m each for the south approach; a single span of 15 m for the north approach. The main arch ring is a structure of twin separated arch ribs, connected by eight reinforced concrete floor beams. A catenary of $m = 1.543$ was chosen as the arch axis, with a rise-to-span ratio of 1:5. The arch rib has a variable width and a uniform depth of 1.6 m. It is made up of block stone with a strength of 100 kPa and ballast concrete of 20 Mpa.

The lateral stability of the bridge was checked. Because the masonry volume of its superstructure is only 1.36 m^3/m^2, the structure achieves a slim and graceful aesthetic effect. The bridge was designed and constructed by Communication Bureau of Fenghuang County, Hunan Province. It was completed in 1990.

Heyuan DongRiver Bridge

Heyuan DongRiver Bridge (Figure 63.10) is on the Provincial Route near Heyuan County. It is a 6 × 50 m multispan masonry arch bridge with a width of 7 + 2 × 1 m and a total length of 420.06 m. The rise-to-span ratio of the arch ring is 1:6.

A transversely cantilevered setting method was applied for its arch ring construction. The arch ring was divided into several arch ribs, and each rib was longitudinally divided into several precast

FIGURE 63.9 Wuchao River Bridge.

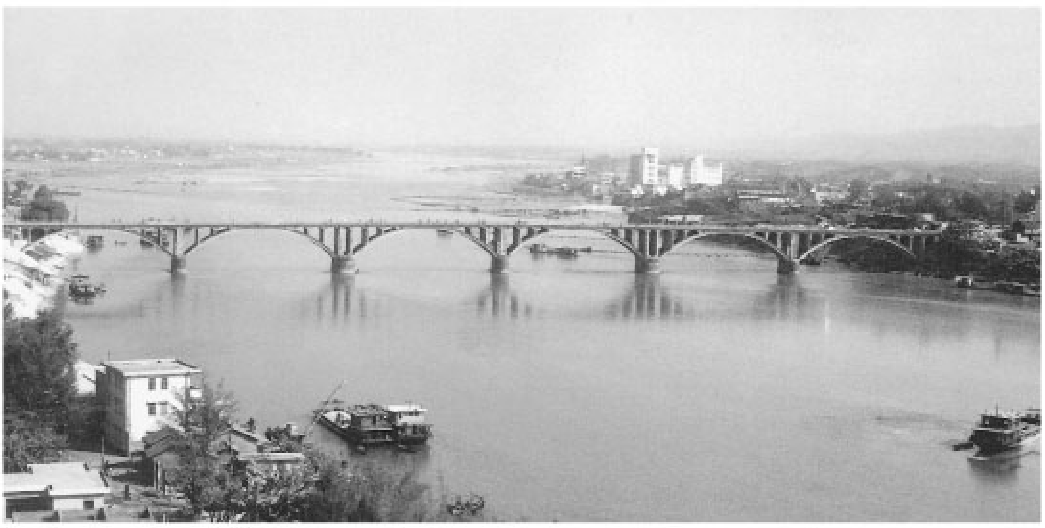

FIGURE 63.10 Heyuan DongRiver Bridge.

concrete hollow blocks. Side ribs were erected by transversely setting with the support of the erected central rib. The bridge was designed by Highway Survey and Design Institute of Guangdong Province and constructed by Highway Engineering Department of Guangdong Province. It was completed in 1972.

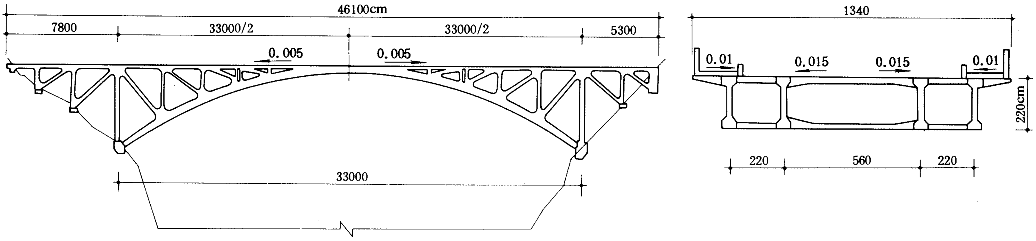

FIGURE 63.11 Jiangjie River Bridge.

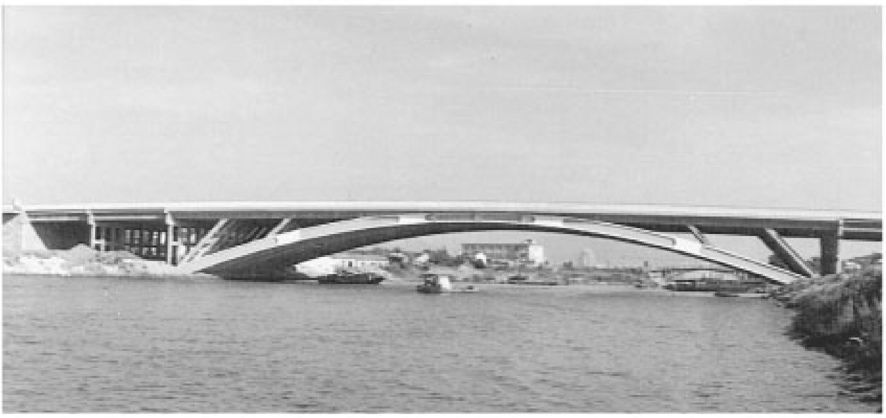

FIGURE 63.12 Jinkui Grand Canal Bridge.

63.3.3 Examples of Prestressed Concrete, Reinforced Concrete, and Arch Bridges

Jiangjie River Bridge

Jiangjie River Bridge (Figure 63.11), located in Weng'an County, Guizhou Province, is a prestressed concrete truss arch bridge crossing Wujiang Valley at a height of 270 m above normal water level. It has a record-breaking main span of 330 m in China. Its side truss spans, 30 + 20 m on one side and 30 + 25 + 20 m for the other, are arranged along the mountain slopes. The total length of the bridge is 461 m.

The most obvious characteristics of the bridge are the use of batholite as the lower chords of the side spans and the anchoring of the prestress bars in tensile diagonals on the batholite. The deck is 13.4 m wide with 9 m for lanes and two pedestrian walkways of 1.5 m each. The arch depth is 2.7 m, L/122, and its width is 10.56 m, L/31.3, with a rise-to-span ratio being 1:6. The bridge was constructed by cantilever assembling. A derrick mast with a hoisting duty of 1200 kN was used. The bridge was designed by Communication Department of Guizhou Province and constructed by Bridge Engineering Co. of Guizhou Province.

Jinkui Grand Canal Bridge

Jinkui Grand Canal Bridge (Figure 63.12), with a main span reaching 100 m, is one of the longest rigid-framed prestressed concrete arch bridges on soft-soil foundation. It crosses the Grand Canal in Wuxi County, Jiangsu Province.

The bridge has a rise-to-span ratio of 1:10. The arch rib is of the I type with a constant cross section, while the solid spandrel segment has a variable cross section. Only two inclined braces are

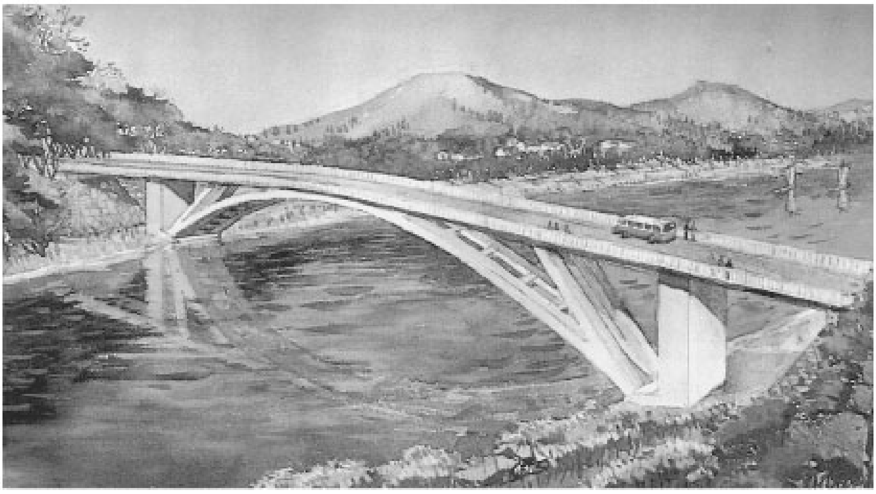

FIGURE 63.13 Taibai Bridge.

arranged on either side to get a aesthetic effect. In order to reduce the deadweight, ribbed slabs are employed for the deck. The substructure includes combined-type thin-wall abutments, which are designed to resist the horizontal thrusts from superstructure by boring piles and slide-resistant slabs working jointly. The bridge was designed by Shanghai Urban Construction College and constructed by Bridge Engineering Co. of Wuxi County. It was completed in 1980.

Taibai Bridge

Taibai Bridge (Figure 63.13), a rigid-framed reinforced concrete arch highway bridge with a span of 130 m, is located in Dexi copper mining area, Jiangxi Province. The bridge was constructed by the swing method. After assembling steel bar skeletons and casting 100 mm bottom slab on simple scaffoldings, 42 25-mm tensile bars were stretched to get the structure separate from the scaffoldings. The whole swing system, with a total weight of 18,100 kN, was supported by a reinforced concrete spherical hinge on abutment foundation. The bridge was designed by Nanchang Non-ferrous Metallurgical Design Institute and constructed by Huachang Engineering Co. It was completed in March 1993.

Wanxian Yangtze River Bridge

The bridge located in Huangniu Kong, 7 km upstream from Wanxian, is an important structure on the No. 318 national highway (Figure 63.14). It is 864.12 m long. A reinforced concrete box arch with a rise-to-span ratio of 1:5 offers a single span of 420 m. Steel pipes are used to form stiffening arch skeletons before the erection of the main arch; there are 14 spans of 30 m prestressed concrete. Simply supported T-girders make up the spandrel structure, while 13 spans of the same girders are for the approaches. The continuous deck is 24 m wide, providing 2 × 7.75 m lanes for motor vehicle traffic and two sidewalks of 3.0 m each. A longitudinal slope of 1% is arranged from the midspan to either side with a radius of vertical curve being 5000 m, while the cross slope is 2%. The bridge was designed by Highway Survey and Design Institute of Sichuan Province and constructed by Highway Engineering Company of Sichuan Province. It was completed in 1997.

63.4 T-Type and Continuous Rigid Frame Bridges

63.4.1 General Description

The prestressed concrete rigid T-frame bridge was primarily developed and built in China in the 1960s. This kind of structure is most suitable to be erected by balanced cantilever construction

FIGURE 63.14 Wanxian Yangtze River Bridge.

process, either by cantilever segmental concreting with suspended formwork or by cantilever erection with segments of precast concrete. The first example of cantilever erection is the Wei River Bridge (completed in 1964) in Wuling, Henan Province, while the Liu River Bridge (completed in 1967) in Liuzhou in Guangxi Zhuangzu Autonomous Region is the first by cantilever casting. The Yangtze River Highway Bridge at Chongqing (completed in 1980), having a main span of 174 m, is regarded as the largest of this kind at present.

From prestressed concrete rigid T-frame bridges were developed multiple prestressed concrete continuous beam and continuous rigid frame bridges, which can have longer spans and offer better traffic conditions. Among others, the Luoxi Bridge in Guangzhou, Guangdong Province (completed in 1988) features a 180-m main span. The Huangshi Yangtze River Bridge in Hubei Province has a main span of 245 m. And the Humen Continuous Rigid Frame Bridge in Guangdong Province (completed in 1997), which has a 270-m main span, is regarded as the largest of this kind in the world.

63.4.2 Examples of T-Type Rigid Frame Bridges

Qingtongxia Yellow River Highway Bridge

Qingtongxia Highway Bridge (Figure 63.15) is 80 km south of Yinchuan, Ningxia. It is 743 m long and 14 m wide. The spans arrangement is 4 × 30 + 60 + 3 × 90 + 60 + 6 × 30 + 20 m. Prestressed concrete T-girders were adopted for the three main spans, while prestressed concrete simply supported beams were used for approaches. The T-frame is a two-cell single-box thin-wall structure, which was built by cantilever casting. The substructure consists of thin-wall hollow box piers, resting on elevated bored pile foundations, the piles having a diameter of 1.5 m. The bridge was designed by Highway Survey and Design Institute of Ningxia Province and constructed by Highway Engineering Bureau of Ningxia Province. It was completed in October 1991.

Huanglingji Bridge

Huanglingji Bridge (Figure 63.16), located in Hanyang County, Hubei Province, is a prestressed concrete truss T-frame highway bridge. It has spans of 7 × 20 + 53 + 90 +53 + 2 × 20 m, with a

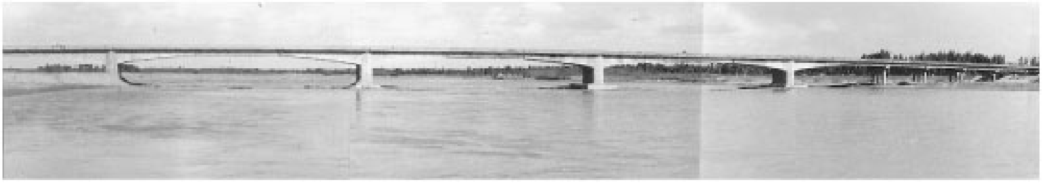

FIGURE 63.15 Qingtongxia Yellow River Highway Bridge.

FIGURE 63.16 Huanglingji Bridge.

total length of 380.19 m. The 90-m-long main span is composed of two cantilever arms of 37 m each and a 16-m-long suspended span.

Caisson foundations and box piers were adopted for the substructure. Its superstructure consists of two trusses, with prestressed concrete simply supported slab on the top, which serves as upper bracing after transverse prestressing has been introduced. Prestressing tendons are used for tensile members, while common rebars for compressive members. Longitudinal prestress tendons are arranged in open channels which makes stretching convenient. The cantilever assembling method was employed. The bridge type featuresa slim configuration and saves construction materials. The bridge was designed at Tongji University in cooperation with Highway Engineering Bureau of Hubei Province. The construction unit was Road and Bridge Co. of Hubei Province. It was completed in 1979.

Hongtang Bridge

Hongtang Bridge (Figure 63.17), the longest highway bridge over Min River, is west of Fuzhou City, Fujian Province. It is 1843 m long and 12 m wide. The main span is a three-hinge connected lower chord supported prestressed concrete truss T-frame, which synthesizes the virtues of cable-stayed bridges, truss bridges, and T-frame bridges.

The bridge was erected by cantilever assembling with cable cranes. On the side shoal 31 spans are of prestressed concrete continuous girders erected by adopting nonglued segmental assembling span by span, a new technology first applied in Chinese bridge construction. Spans on the banks are of simply supported prestressed concrete beams.

The substructure of the bridge is prestressed concrete V-type hollow piers on bored piles foundation for the main span and dual-column bored piles foundation for the side spans. The bridge

FIGURE 63.17 Hongtang Bridge.

was designed by Communication Planning and Design Institute of Fujian Province and constructed by the Second Highway Engineering Co. of Fujian Province. It was completed in December of 1990.

63.4.3 Examples of Continuous Rigid Frame Bridges

Luoxi Bridge

Luoxi bridge (Figure 63.18), the longest prestressed concrete continuous rigid frame bridge in China, spans Pearl River in Guangzhou, Guangdong Province. It is 1916.04 m long and 15.5 m wide. The main bridge has spans of 65 + 125 + 180 + 110 m, providing a navigation clearance of 34 × 120 m.

The single-cell box beam has a variable depth, 10 m (i.e., ⅛ of the main span) at root and 3 m (i.e., ⅙ of the main span) at midspan. Three-way prestresses were introduced. A great tonnage group anchorage system with a post-tension force of 4275 kN for each group, which set a record in China, was employed longitudinally, with the tendons reaching 190 m long.

The superstructure was erected by cantilever casting. As the thickness is only 500 mm, the dual-wall hollow box piers of the main span have rather small thrust-resistant rigidity. Artificial islands were constructed around the piers to safeguard against the collision of passing vessels. The top diameter of each island is 23 and 28 m at bottom, with a height of 20 m. Two types of spans, 16 and 32 m, were chosen for the 1376.24-m-long approach mainly based on economical consideration, thus achieving a rather low construction cost. The bridge was designed by Highway Survey and Design Institute of Guangdong Province. It was constructed by Highway Engineering Department of Guangdong Province and completed in August 1988.

Huangshi Yangtze River Bridge

Huangshi Yangtze River Bridge (Figure 63.19) is located in Huangshi, Hubei Province, with its total length reaching 2580.08 m. A 162.5 + 3 × 245 + 162.5 m prestressed concrete continuous box girder rigid frame bridge was designed for the main bridge. The deck is 20 m wide, providing 15 m for motor vehicle traffic and 2.5 m on both sides for non-motor-vehicle traffic.

The approach along the Huangshi bank is 840.7 m long, consisting of continuous bridges and simply supported T-girder bridges with continuous decks, while the approach along the Xishui bank is 679.21 m, being single supported T-girder bridges with continuous decks.

FIGURE 63.18 Luoxi Bridge.

FIGURE 63.19 Huangshi Yangtze River Bridge.

FIGURE 63.20 Humen Bridge (continuous rigid frame).

A 28-m-diameter double-wall steel cofferdam with 16 3-m-diameter bored piles foundation was employed for piers of the main span, which provided enough capacity to resist impact force of ships. The navigation clearance of the bridge is 200 × 24 m, which allows the navigation of a vessel of 5000 tons. The bridge was designed by Highway Planning and Design Institute affiliated with the Ministry of Communications. It was constructed by China Road and Bridge Corporation and completed in 1996.

Humen Bridge

The Humen Bridge (Figure 63.20), an extra major highway bridge over Pearl River, is on the freeway connecting Guangzhou, Zhuhai and Shenzhen. It is composed of bridges of different types.

A rigid frame bridge (150 + 270 + 150 m) is arranged over the auxiliary navigation channel, with its main span reaching 270 m, a world record of the same type. The superstructure of the bridge consists of two separate bridges, each a single-box, single-cell prestressed concrete continuous rigid frame. The 24-m-wide deck provides 214.25 m for motor vehicle traffic. Adoption of 15.24 mm VSL prestress system makes thinner top slabs and no bottom slabs of the box girder possible, the single-box single-cell thin-wall section offers a greater moment of inertia per unit area, and the depth of main girder at the supports is 14.8 m ($1/18$ of the main span) and 5 m ($1/54$ of the main span) in midspan. The substructure consists of double thin-wall piers resting upon group piles foundations. The symmetrical cantilever casting method is employed for the erection of the superstructure. The bridge was designed by GuangDong Highway Planning and Design Institute and constructed by Highway Engineering Construction Ltd, Guangdong Province. It was opened to traffic in July 1997.

63.5 Steel Bridges

63.5.1 General Description

Steel structures are employed primarily for railway and railway–highway bipurpose bridges. In 1957, in the city of Wuhan, a railway–highway bipurpose bridge was erected over the Yangtze River, another milestone in China's bridge construction history. The bridge has continuous steel trusses with 128 m main spans. The rivet-connected truss is made of grade No. 3 steel. A newly developed cylinder shaft 1.55 m in diameter was initially used in the deep foundation. (Later in 1962, a 5.8-m cylinder shaft foundation was laid in the Ganjiang South Bridge in Nanchang, Jiangxi Province.) In 1968, another such bridge over the Yangtze River — the Nanjing Yangtze River Bridge — came into being. The whole project, including its material, design, and installation, was completed through the

Chinese own efforts. It is a rivet-connected continuous truss bridge with 160-m main spans. The material used is high-quality steel of 16 Mn. In construction, a deep-water foundation was developed. Open caissons were sunk to a depth of 54.87 m, and pretensioned concrete cylinder shafts 3.6 m in diameter were laid, thus forming a new type of compound foundation. And underwater cleaning was performed in a depth of 65 m. China's longest steel highway bridge is the Beige Yellow River Bridge in Shandong Province (1972), its main span being 113 m long. It has a continuous truss of bolt-connected welded members. The foundation is composed of 1.5-m-diameter concrete bored piles, whose penetration depth into subsoil reaches 107 m, the deepest pile ever drilled in China. A new structure of field-bolting welded box girder paved with orthotropic steel deck was first introduced in the North River Highway Bridge at Mafang, Guangdong Province, which was completed in 1980.

Another attractive and gigantic structure standing over the Yangtze River is the Jiujiang railway–highway Bridge completed in 1992. Chinese-made 15 MnVN steel was used and shop-welded steel plates 56 mm thick were bolted on site. The main span reaches 216 m. The continuous steel truss is reinforced by flexible stiffening arch ribs. In laying the foundation, a double-walled sheet piling cofferdam was built, in which a concrete bored pile was cast in place. When erecting the steel beams, double suspended cable frame took the place of a single one, which is another innovation.

Since the 1980s, stell girder or composite girder bridges have been adopted in the construction of long-span or complex-structure city bridges in China. For example, they were applied in Guangzhong Road Flyover and East Yanan Road Viaduct in Shanghai.

63.5.2 Examples of Steel Bridges

Nanjing Yangtze River Bridge

Nanjing Yangtze River Bridge (Figure 63.21) is a highway and railway double-deck continuous steel truss bridge in Nanjing, Jiangsu Province. On the upper deck there are four lanes of highway traffic, which are 15 m wide, plus two sidewalks of 2.25 m wide each, and on the lower deck two tracks for railway. The main bridge is 1576 m long. If approaches are taken into account, the length of the railway bridge reaches 6772 m and the highway bridge is 4588 m long.

Ten spans were arranged for the main bridge, including a side span of 128 m being simply supported steel truss and nine spans of 160 m each being continuous steel trusses, continued every three spans. The main truss is a parallel chord rhombic truss with reinforcing bottom chord. It was erected by cantilever assembling.

Considering the complex geologic conditions at the bridge site, different types of foundations were used: heavy concrete caissons with a depth of penetration reaching 54.87 m for areas with shallow water and deep coverings; a floating-type steel caisson combined with pipe column foundations was used for the first time at sites of deep water. The bridge was designed and constructed by the Major Bridge Engineering Bureau, Ministry of Railways. It was completed in December 1968.

Jiujiang Yangtze River Bridge

Jiujiang Bridge (Figure 63.22), on the border of Hubei Province and Jiangxi Province, is a double-deck highway and railway bipurpose bridge, with the longest truss span, 216 m, in China at present. The four-lane highway is on the upper deck, with a width of 14 m for motor vehicles and two sidewalks of 2 m each on both sides, while the double-track railway is carried on the lower deck.

The main bridge, divided into 11 spans, is all of steel. The three main spans (180 + 216 + 180 m) are combined truss-arch system, which consists of continuous steel truss beams and flexible steel stiffening arches. Two continuous steel truss beams of 3 × 162 m each are for the side span on the northern bank, while a 2 × 126 m continuous steel beam is over the south bank.

The main truss is of parallel chord triangular type with reinforcing bottom chord members, and its depth is 16 m and doubled at the supports. The stiffening arch over main span has a rise of 32 m and those over the side spans have a rise of 24 m. All steel structures are bolted and welded. The

FIGURE 63.21 Nanjing Yangtze River Bridge.

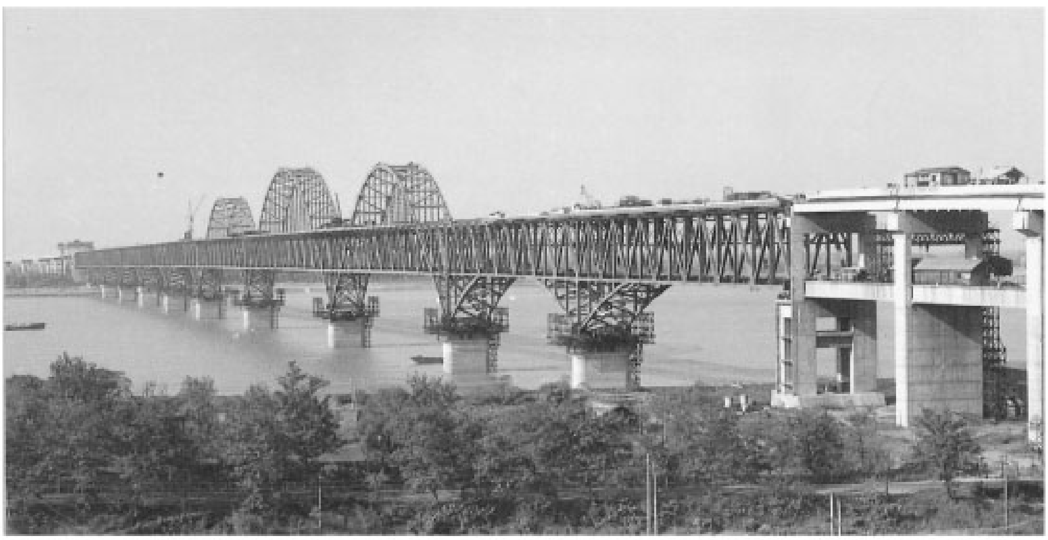

FIGURE 63.22 Jiujiang Yangtze River Bridge.

first-used 15 MnVN steel has a yield strength of 420 MPa. Double layers of suspenders were applied for assembling the truss beams.

There are different types of foundations employed in the bridge: circular reinforced concrete caisson for No. 1 pier in shoal, application of clay slurry lubricating jacket makes the depth of penetration reach 50 m; double-wall steel cofferdam and bored piles foundation in deep water with favorable rock conditions. The bridge was designed and constructed by the Major Bridge Engineering Bureau, Ministry of Railways. It was completed in May 1992.

63.6 Cable-Stayed Bridges

63.6.1 General Description

Cable-stayed bridges were first introduced into China in the early 1960s. Two trial bridges, the Xinwu Bridge with a main span of 54 m in Shanghai and the Tangxi Bridge with a span of 75.8 m in Yuyang, Sichuan Province — are both reinforced concrete cable-stayed bridges and were completed in 1975.

In 1977 the construction of long-span cable-stayed bridges began. The Jinan Bridge across the Yellow River with a main span of 220 m was completed in 1982. In the 1980s, the construction of cable-stayed bridges developed rapidly over a wide area in China. More than 30 bridges of various types were built in different provinces and municipalities. Among them, the Yong River Bridge in Tianjin has a main span of 260 m, and the Dongying Bridge in Shandong Province has span of 288 m, China's first steel cable-stayed bridge. In addition, the Haiying Bridge in Guangzhou has a 35-m-wide deck, single cable plane and double thin-walled pylon piers; the Jiujiang Bridge in Nanhai of Guangdong Province was erected by a floating crane with a capacity of 5000 kN; the Shimen Bridge in Chongqing has an asymmetrical single cable plane arrangement and a 230 m cantilever cast in place; and the attractive-looking Xiang River North Bridge in Changsha, Hunan Province, was completed in 1990 with light traveling formwork. All are representative of this period with their respective features.

At the beginning of the 1990s, with the completion of the Nanpu Bridge in Shanghai in 1991, a new high tide of construction of cable-stayed bridges began to surge in China. Now more then 20 cable-stayed bridges with a span of over 400 m have been completed, and a large number of long-span cable-stayed bridges are under design and construction. The most outstanding is the Yangpu Bridge with a main span of 602 m, a composite deck cable-stayed bridge in Shanghai.

63.6.2 Examples of Cable-Stayed Bridges

Laibin Hongshui River Railway Bridge

Laibin Hongshui River Bridge (Figure 63.23), a structure 398 m long over Hongshui River, is on the second Xianggui Railway Route. The main bridge, having three spans of 48 + 96 + 48 m, is the first prestressed concrete cable-stayed railway bridge built in China, with two pylons and an H-type cable configuration. The main girder, with a box section of two cells dimensioning 4.8 m (width) 3.2 m (depth), is prestressed longitudinally by 245 mm tendons whose $\sigma_p = 1600$ MPa.

The pylons are 29 m high, rigidly connected with main girder by strong box cross beams. Pot neoprene bearings were employed in the bridge. Three groups of parallel cables were installed on either side of each pylon, and each group consists of six bunches of 705-mm steel strands. To guarantee sufficient fatigue strength, key-grooved composite anchorage was specially designed, which also made adjustment and replacement of a cable possible.

The girders over side spans were cast on scaffoldings, while the middle span was constructed by cantilever casting. During the design and construction, special studies and tests were carried out to obtain the characteristics of the structure under railway loads. The bridge was designed by China Academy of Railway Sciences. It was constructed by Liuzhou Railway Bureau and completed in 1981.

Dongying Yellow River Bridge

Dongying Yellow River Bridge (Figure 63.24), the first steel cable-stayed bridge built in China, is on the highway route along the northern coast in Shandong Province. The total length of the bridge is 2817.46 m. The main bridge, a continuous steel cable-stayed bridge, has five spans of 60.5 + 136.5 + 288 + 136.5 + 60.5 m, while the 2135.46-m approaches are 71 spans of pretensioning prestressed concrete box girders, each being 30 m long.

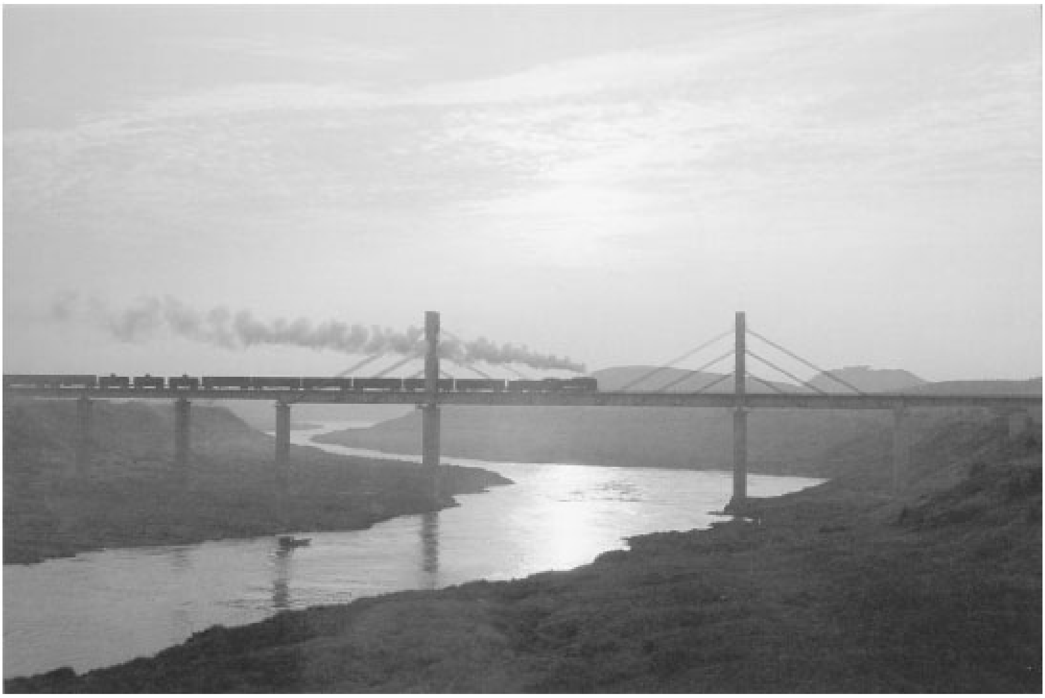

FIGURE 63.23 Laibin Bridge.

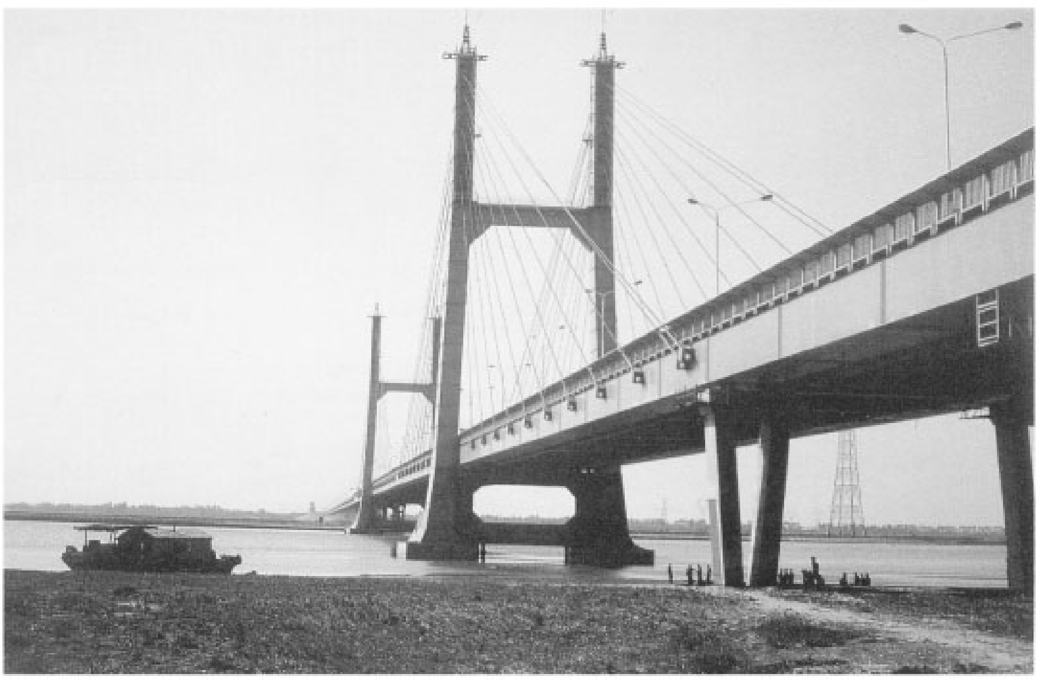

FIGURE 63.24 Dongying Yellow River Bridge.

FIGURE 63.25 Shanghai Yangpu Bridge.

The deck is 19.5 m wide, among which 16 m are for vehicle traffic. Steel box girders with orthotropic plate deck form the main cable-stayed spans. It was erected by cantilever assembling. Each segment for assembling is about 12 m on average and consists of two side boxes, four plate decks, and cross beam. The H-type pylons are 69.7 m high. A fan-type cable configuration was adopted. Ten pairs of cables were installed on either side of each pylon, with an anchorage distance of 12 m on the deck. Each cable consists of 73/127ϕ7 galvanized steel wires with hot-squeezed sheath for protection. Bored piles foundation was employed in the substructure. The pylon rests on separate elevated pile caps which are supported by 22 piles with a diameter of 1.5 m and a length of 96.5 m.

The bridge was designed by Communication Planning and Design Institute of Shandong Province. It was constructed by Communication Engineering Co. of Shandong Province and completed in September 1987.

Yangpu Bridge

Shanghai Yangpu Bridge (Figure 63.25), located in Shanghai Yangpu District, is an important bridge in an urban district, which spans Huangpu River and connects Puxi old district with Pudong Development Zone. It is an essential component of the Inner Ring Elevated Viaduct. The bridge site is 11 km from the Nanpu Bridge, a cable-stayed bridge with 423 m main span completed in 1991.

The overall length of the bridge is 8354 m, including main spans, approach spans, and guide passage spans. The width of the bridge is 30.35 m. The main span is a dual-pylon, space dual-cable

FIGURE 63.26 Wuhan Yangtze River Highway Bridge.

plane, steel–concrete composite structure. As pylons rigidly connected with piers and separate from the girder, the superstructure is a suspended system longitudinally, with displacement-resistant and anti-seismic devices installed transversely.

The 200-m-high diamond-shaped pylons are of reinforced concrete, resting on steel pipe piles foundations. Columnar piers supported by precast concrete piles have found wide application in auxiliary piers, anchor piers, and side piers as well. Steel side box girders and I-type steel cross beams composite with precast reinforced concrete slabs make up the girder over the main span and two side spans. The center-to-center distance between the two main steel side box girders is 25 m, while that between steel cross beams is 4.5 m. For transitional spans, simply supported prestressed concrete T-girders are used. The stayed cables are 256 in number and there are 32 pairs of them on either side of each pylon. The maximum length of stays is 330 m, and 312ϕ7 high-strength parallel wires form the maximum cross section of the stays.

The bridge was designed by Shanghai Municipal Engineering Design Institute in cooperation with Tongji University, Shanghai Urban Construction Design Institute, and Shanghai Urban Construction College. The construction of the bridge was presided over by the Headquarters of Shanghai Huangpujiang Bridge Engineering Construction. It was completed and opened to traffic in 1993.

Wuhan Yangtze River Highway Bridge

The bridge (Figure 63.26) is a 4687.73-m-long structure in Wuhan, Hubei Province. Its cable-stayed bridge consists of prestressed concrete girder with t spans of 180 + 400 + 180 m. The cable-stayed bridge is a suspended system, with its longitudinal displacement restrained by the devices installed at the intersection parts of the girder and the pylons. The deck is 29.4 m wide, carrying six lanes 23 m wide and two pedestrian walks of 1.75 m each.

An open section with two side boxes is adopted, which is 3 m in depth and stiffened by cross beams every 4 m. The H-type reinforced concrete pylons are 94 m high, and a fan-type multicable configuration is adopted. There are a total of 392 cables, which are made up of 7-mm-diameter galvanized parallel steel wires and protected by hot-squeezed PE sheath. The maximum cable force reaches 5000 kN. Double-wall steel cofferdam bored piles foundations are employed. The bridge was designed and constructed by Major Bridge Engineering Bureau, Ministry of Railways. It was completed in 1995.

Huangshan Taiping Lake Bridge

The bridge (Figure 63.27) is a prestressed concrete cable-stayed bridge with a single pylon and a single cable plane. It has two spans of 190 m each. The pylon is 86.6 m high. A fan-type cable configuration with a cable distance of 6 m on the girder was adopted. Four lanes are arranged on

FIGURE 63.27 Huangshan Taiping Lake Bridge.

the deck, which is 18.2 m wide. The main girder is a three-cell prestressed concrete box girder with skew webs. It has a uniform depth of 3.5 m. The thickness of the top slab and the bottom slab are 220 and 200 mm, respectively. Three-way prestress was introduced. The bridge was designed by Lin & Li Consultants Shanghai Ltd., constructed by Major Bridge Engineering Bureau, Ministry of Railways, and opened to traffic in 1996.

63.7 Suspension Bridges

63.7.1 General Description

The construction of modern suspension bridges in China started in the 1960s. Some flexible suspension bridges with spans less than 200 m were built in the mountain areas of southwestern China, the Chaoyang Bridge in Chongqing, Sichuan Province, being the most famous one. However, the Dazi Bridge in Tibet completed in 1984 has a span of 500 m.

The upsurge of transportation engineering construction in the 1990s has led to a new stage of modern suspension bridges. The Shantou Bay Bridge in Shantou, Guangdong Province, was completed in 1995, having a 452 m concrete stiffening girder. The Humen Pearl River Bridge, a steel box girder suspension bridge with a main span of 888 m, was completed in 1997. The Jiangying Yangtze River Bridge with a main span of 1385 m, is now under construction.

63.7.2 Examples of Suspension Bridges

Chaoyang Bridge

Chaoyang Bridge (Figure 63.28), a highway bridge crossing Jialin River, is located in Beipei District, Chongqing. The bridge has three spans with a total length of 233.2 m. A double-chain reinforced girder suspension bridge, over 186 m long, is the main span, and two reinforced concrete slim curved beams are for the two side spans of 21.6 m each. The deck is 8.5 m wide, providing 7 m for motor vehicle traffic.

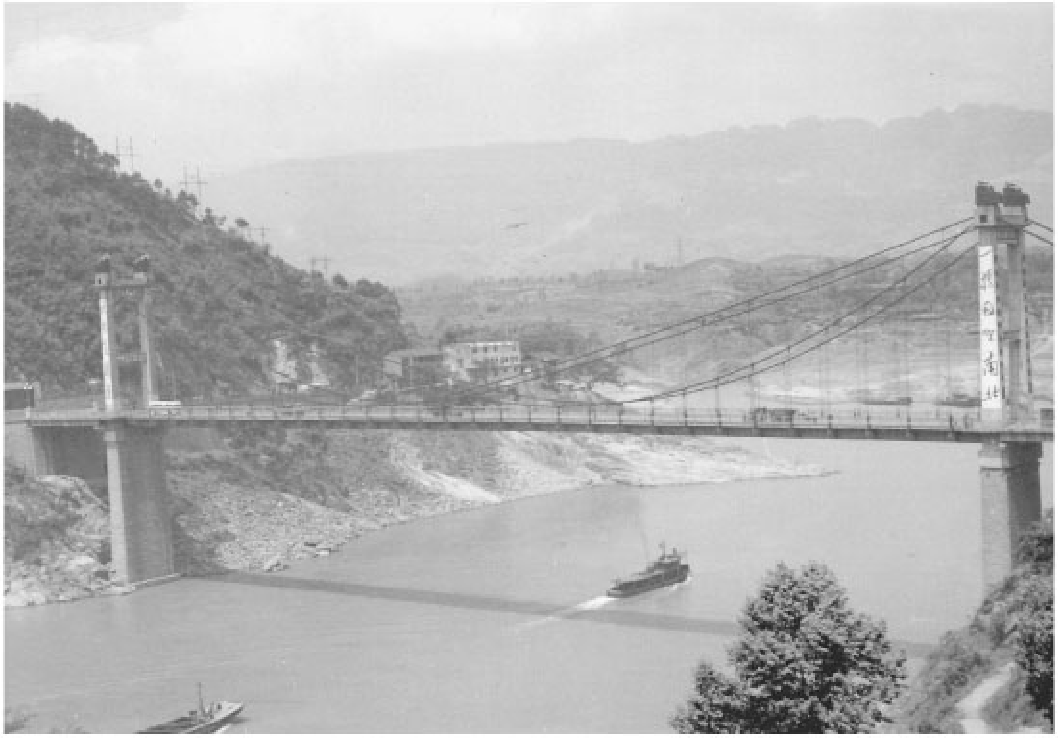

FIGURE 63.28 Chaoyang Bridge.

There are four cables in total and every two make a chain that is installed on either side. Each cable is made up of 19ϕ42 steel ropes; ϕ 42 steel pipe and ϕ42 steel rope are used as upper hanger and lower hanger, respectively. The stiffening girder, with depth of 2.0 m, is a single open-steel box composited with a reinforced concrete deck slab. The 63.8-m-high pylons are reinforced concrete portal frames. A tunnel-type anchorage system was adopted, and the tunnel length reached 15 m. The anchorage slabs are 1.8 m in depth and anchored in rock stratum.

The bridge was designed by Chongqing Communication Research Institute and Chongqing Communication Institute, and was built by Chongqing Bridge Engineering Corporation. The bridge was completed in 1969.

Dazi Bridge

Dazi Bridge (Figure 63.29), a 500-m suspension bridge crossing Lasa River, is located in Dazi, 25 km east of Lasa, Tibet. It is 4.5 m wide, providing only one lane for highway traffic. The main cables are made up of 5-mm-diameter parallel wires and its sag-to-span ratio is 1:5. The main girder is an open welded steel truss with a depth of 1.5 m. A simple orthotropic deck was formed by the composition of the longitudinal girder and steel plates. Four trucks of 200 kN each were used as design loads.

The bridge was designed by Highway Planning, Survey and Design Institute of Tibet Autonomous Region and constructed by Highway Bureau of Tibet Autonomous Region. It was completed in December 1984.

Shantou Bay Bridge

Shantou Bay Bridge (Figure 63.30), a 2420-m-long structure, crosses Shantou Bay in Shantou, Grangdong Province. The main bridge is a prestressed concrete suspension bridge, with a central span of 452 m and two side spans of 154 m each. Four spans of 25 m prestressed concrete T-girders

FIGURE 63.29 Dazi Bridge.

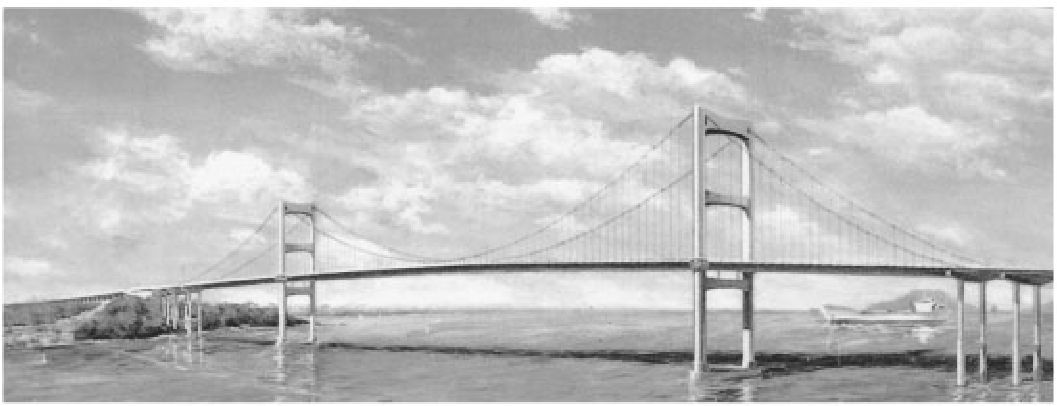

FIGURE 63.30 Shantou Bay Bridge.

connect the main bridge with the bank on either side. The width of the bridge varies from approaches of 27.3 m to the main bridge of 23.8 m.

The stiffening girder is a prestressed concrete flat box with three cells. It is prestressed longitudinally by tendons inside the top slab and those outside the bottom slab. Two prestressed concrete beams, which are specially designed to connect the central span and two side spans, provide a smooth transition of the deck. A pair of flexible steel piers was installed between each beam and the lower cross beam of a pylon, to get the stiffening girder restrained elastically and maintain the structural flexible characteristics.

The pylons are three-layer reinforced concrete rigid frame structures, each resting on two separate caisson foundations connected by a strong bracing beam on the top. The center-to-center distance

FIGURE 63.31 Hong Kong Tsing Ma Bridge.

between the two cable saddles on one pylon is 25.2 m. Roller bearings were employed during the erection of cables, which were fixed to the saddles later.

The main cables have a sag-to-span ratio of 1:10. Each cable consists of 110 bunches of $9\phi.5$-mm parallel wires, which makes its diameter reach approximately 550 to 630 mm. Every 6 m a hanger, which is composed of a pair of $\phi 42$ steel ropes, is installed. The segment assembling scheme was adopted for the girder erection. A 5.7-m-long precast segment, weighing 16,000 kN, was connected with the completed girder by wet joint.

The bridge was designed and constructed by Major Bridge Engineering Bureau, Ministry of Railways. It was open to traffic in 1995.

Hong Kong Tsing Ma Bridge

Tsing Ma Bridge (Figure 63.31), a highway–railway bipurpose suspension bridge on the freeway between the new airport and the urban district, connecting the Tsing Yi Island and Mawan Island in Hong Kong, is the world's longest of its kind. The main span is 1377 m. The design of its main girder was mainly based on consideration of its aerodynamic stability and a truss type was finally adopted: The cross beams are of Vierendeel truss. The whole longitudinal girder can be treated as a composite structure.

There are six lanes of highway traffic on the upper deck and three passages on the lower deck, the central one on lower deck for railway while the other opened to highway traffic under severe weather condition. The main cable is of $80 \times 368 + 11 \times 360$ steel wires, each wire having a diameter of 5.35 mm. The construction of the bridge was started in 1992 and it was opened to traffic in 1997.

Jiangyin Yangtze River Bridge

Jiangyin Yangtze River Bridge (Figure 63.32) is located on the planned North–South Principal Highway System in the coastal area between Jiangyin and Jinjiang in Jiangsu Province. It is a large suspension bridge with a central span of 1385 m, and will be the first bridge with a span in excess of 1000 m designed and built by Chinese engineers. Its total length reaches nearly 3 km. The deck is designed to carry six-lane highway traffic, while median and emergency parking strips are also considered, with two 1.5-m-wide pedestrian walks on the central span.

Flat steel box girder with wind fairing is adopted, whose depth and width are 3 and 37.7 m, respectively. The two main cables, with sag-to-span ratio being 1:10.5, are composed of five galvanized high-strength wires, and will be erected by the PWS method. The bridge provides a navigation clearance 50 m high. The 190-m-high pylons are reinforced concrete structures. The northern pylon, located in the shallow water area outside the north bank, rests on piles foundation constructed by the sand island method, whereas the southern one is on rock stratum of the bank.

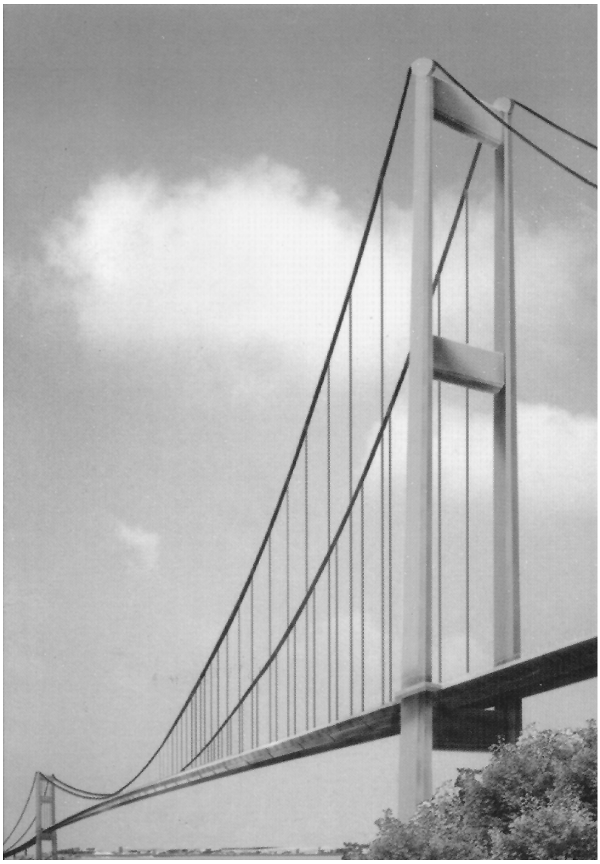

FIGURE 63.32 Jiangyin Yangtze River Bridge.

The south anchorage is of gravity type embedded on rock bed in comparison with the north anchorage gravity-friction type on soft-soil ground. The north anchorage is a massive concrete caisson, measuring 69 by 51 m in plan and 58 m in depth. It is the largest concrete caisson in the world. All the approaches are prestressed concrete beam bridges. A multispan prestressed concrete continuous rigid frame structure was chosen for the northern side span.

The project was designed by Highway Planning and Design Institute, Ministry of Communications in cooperation with Communication Design Institute of Jiangsu Province and Tongji University. It was scheduled to be completed in 1999.

References

1. Guohao Li, *Stability and Vibration of Bridge Structures,* 2nd ed., China Railway Publishing House, 1996.
2. Haifang Xiang, *Bridges in China*, Tongji University Press, A&U Publication Ltd., Hong Kong, 1993.
3. Chinese Design Code for Highway Bridges, People's Communication Press House of China, 1991.
4. Chinese Design Code for Railway Bridges, China Railway Publishing House, 1988.
5. Guohao Li, Computation of Transverse Load Distribution for Highway Bridges, People's Communication Press House of China, 1977.
6. Haifang Xiang, Wind Resistance Design Guideline for Highway Bridges, People's Communication Press House of China, 1996.

7. Yuan Wancheng and Fan Lichu, Study on energy absorption of a new aseismic rubber bearing for bridge, *J. Vibration Shock,* 14(3), 1995 [in Chinese].
8. Rucheng Xiao, Influence matrix method for structural adjustment calculation of internal forces and displacements of concern sections, *Comput. Struct. Mech. Appl.* 9(1), 1992 [in Chinese].
9. Rucheng Xiao, Synthetical bridge nonlinear analysis program system, *China Comp. Appl. Highway Eng.,* 4(1), 1994.