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目　录

Chongqing — Bridge Capital of China

Man-Chung Tang[1] Delan Yin[2]

(1 T. Y. Lin International 2 T. Y. Lin International China)

Abstract: Chongqing has always been a pioneer in bridge engineering in China. It has built all types of bridges. Out of the world's four basic bridge categories, girder, arch, suspension and cable stayed bridges, the world record span of two of them is in Chongqing.

Key words: bridge capital; long span bridges; girder bridges; arch bridges; bridge aesthetics; partially cable-supported girder bridges; Chongqing

1 Rapid Development

The speed of development in China is truly amazing. Take, for instance, expressway construction. The Interstate in the United States started in 1956. It started at a time when the economy in the United States was the strongest in the world. The construction of expressway in China started in 1987. At that time, China was relatively poor and underdeveloped. However, as shown in Fig. 1, in the first 20 years, China built about the same amount of expressway, in length, or mileage, as the United States in its first 20 years of Interstates' construction. Certainly, this means that the total length of expressway in China by the end of 2007 is only the same as that of the United States in 1976, and therefore, China is about 30 years behind. However, if the curves in Fig. 1 can be used to project the future, China will surpass the US in the total length of expressway by 2011. The land area of China is a little smaller than the entire United States, including Alaska and Hawaii. The population of China is about four and a half times of the US.

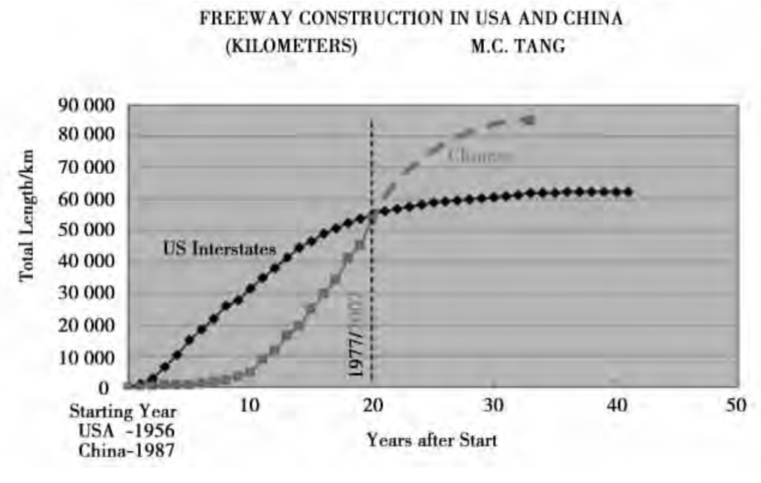

Fig. 1 Comparison of Freeway Construction in the United States and China

Bridge construction in China has been advanced at about the same speed as expressway construction. Obviously, bridges are needed to span the rivers and valleys on expressways. So when China builds expressways and roads, it must also build bridges at the same time.

China not only built a large number of bridges. It also built a variety of bridge types. In general, we can divide all existing bridges in the world into four basic categories: arch bridges, girder bridges, cable-stayed bridges and suspension bridges. China has built them all. The longest spans of these four categories of bridges in China are shown in Fig. 2. Today, in three out of these four categories, girder bridge, arch bridge, and cable-stayed bridge, the world record span length is in China. For the fourth category, suspension bridge, China has completed the second longest span in the world. This is a proof that China now has the technology as well as the experience in building these spectacular structures.

Niujiaotuo

Fengdu

First Shibanpo

Fig. 2 Pioneering Bridges in Chongqing

Besides being on expressways, many bridges are needed in the cities, which have undergone the same speed of new developments in the past 30 years. To illustrate this development, Chongqing is a good example.

2 The City of Chongqing

Chongqing is a city located in the middle part of China. It has a population of about 32 millions, which is slightly more than the entire Canada. It is very hilly and is bisected by several big rivers, such as the Yangtze, the Jialing, the Wujiang, the Fujiang, etc. The metropolitan area of the city has about 6.5 million inhabitants. It is located at the junction of the Yangtze River and the Jialing River. This is the area where many major bridges have been built or under construction because such crossings are needed to overcome the terrain and the river crossings to allow for rapid economic development of the area. This need offers good opportunities in bridge engineering.

In the past 30 years, Chongqing has been a pioneer in innovation and progress in bridge engineering. The Niujiaotou Bridge, completed in 1966 was one of the first major steel bridges in China. The First Shibanpo Bridge, completed in 1981, was one of the major long span prestressed concrete bridges. The Fendu Bridge, completed in 1997 with an extremely low budget, was one of the pioneering suspension bridges in the country.

Today, in the city, there are over 30 major bridges over the Yangtze River and about 14 over the Jialing River, completed, under construction or being designed.

3 World Records

Inside metropolitan Chongqing, the Yangtze River is less than 1 200 m wide, and the Jialing River, about 600 m. There are no large ships on these rivers so the required navigation channels are relatively small. There is no need for any bridge span over 600 m. Consequently, all bridges in Chongqing are in the middle range of span lengths.

Nevertheless, as China has three of the four world records in span length, two of them are in

Chongqing: the 330 m span Second Shibanpo Bridge, which is the world's longest girder bridge span, and the 552 m span Chaotianmen Bridge, which is the world's longest arch bridge span. The Shibanpo Bridge was opened to traffic in 2006. The Chaotianmen Bridge is scheduled to be open to traffic in 2009. Following is a description of these two bridges.

3.1 Twinning of the Shibanpo Bridge

The original Shibanpo Bridge over the Yangtze River was built in 1981. Its main span of 173 m was the longest prestressed concrete box girder bridge span in China at that time. It was designed for a daily traffic of 20 000, which has grown to 80 000 today. Therefore, a twinning of the bridge is needed to relieve the daily traffic jam in this area.

The new bridge is a parallel structure 25 m from the old structure center to center. It carries 3 lanes of one way traffic. The deck width is 19 m. The exiting bridge will then be changed to one way traffic in the other direction.

Due to its proximity to the old bridge, the new bridge must be compatible with the existing structure in its appearance. Most bridge types, such as cable-stayed, arch and suspension bridges were deemed unacceptable for aesthetic reasons. Therefore, the owner decided that the new structure should be a girder bridge, if it is structurally feasible.

Fig. 3

Even though the main span of the original bridge is only 173 m, the Waterway Department requested that the new structure's main span be longer while all other piers must align with the old piers. This is because aligning the new piers with the old ones will significantly enlarge the transverse dimension of the obstruction of the piers in the river. At the navigation channel, this would render the maneuvering in the river very difficult. To widen the navigation channel, the pier at this location must be deleted, which resulted in a 330 m main span.

Fig. 4 shows the history of world record spans of steel and concrete box girder bridges. No matter it is constructed in steel or concrete, the Second Shibanpo Bridge will be a big step beyond the existing maximum span lengths in the world.

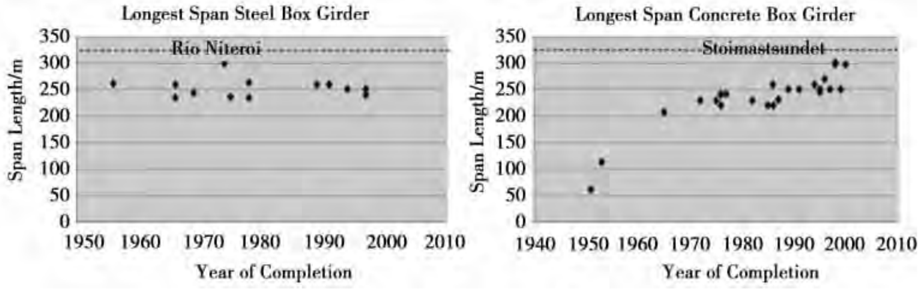

Fig. 4 **Existing Longest Box Girder Bridge Spans Dotted Line indicates a** 330 **m span**

To date, the longest steel box girder bridge span is the 300 m span Rio Niteroi Bridge in Brazil, built in 1974. A longer steel span has never been attempted. As the span gets longer, the thickness of the top and bottom plates becomes thicker. This increases the weight of the box girder and thus increases the cost of the bridge. The bottom plate of a 330 m span would be very thick, so fabrication would also be difficult. Consequently, building the new Shibanpo Bridge in steel is economically not feasible and technically not advisable under current conditions.

Currently, the longest concrete box girder span is the 301 m span Stolmastsunde Bridge in Norway. Norway also built a few concrete box girder bridges with spans close to 300 m. A new bridge with a 330 m span is a big step beyond the world's existing structures.

The Norwegian long span bridges are all hybrid concrete structures with a combination of normal weight concrete and light weight concrete. The light weight aggregate for the construction of these bridges was imported from the United States. It is only logical that the new Shibanpo Bridge shall also use light weight concrete in the middle portion of the main span to reduce shear and bending in the superstructure. During the design of the Benicia Martinez Bridge in California, T. Y. Lin International rigorously tested many different commercially available light weight aggregates in the United States. These tests showed that only extremely few of them could meet all the design requirements. The majority of light weight aggregates do not have the required modulus of elasticity. This probably explains why Norway imported the light weight aggregate from the United States.

It is not economically feasible to import the aggregate from the United States for the new Shibanpo Bridge. On the other hand, light weight concrete is not popular in China for bridge construction. It is also not feasible to carry out an extensive test program to search for a suitable light weight aggregate inside China due to the very tight construction schedule.

In addition, for a span of 330 m, use of light weight concrete in the middle portion of the main span may not offer sufficient reduction in weight to render the new Shibanpo Bridge economically feasible. Therefore, it was decided that instead of light weight concrete, the middle portion of the main span will be a steel box girder.

The length of the steel section is determined by the weight and by the proposed construction method. The entire steel section was fabricated in a factory in Wuhan, about 1 000 km downstream the Yangtze River. The ends of the box girder were closed by temporary bulkheads and towed to the site as a barge. It was then lifted in one piece. After careful comparisons, it was decided that the middle section should be 103 meters. Adding a transition piece at both ends, the total length of the steel box section is 108 m and weighs about 1 400 tons.

The resulting new Shibanpo Bridge is shown in Fig. 5.

Fig. 5　Shibanpo Bridge — A Concrete and Steel Hybrid Structure

Other than the steel section in the middle of the main span, the rest of the bridge is constructed with normal weight concrete.

The bridge was opened to traffic in November 2006.

(Owner of the Second Shibanpo Bridge is Chongqing City Construction Investment Company; Engineer is T. Y. Lin International; Contractor is Chongqing Bridge Construction Company)

3.2 The Chaotianmen Bridge

Slightly downstream of the junction of the Yangtze and Jialing Rivers, connecting the southern district and the northern district of the city, the Chaotianmen Bridge is considered a gateway to the metropolitan Chongqing. It carries 6 lanes of traffic and two pedestrian paths on its upper deck and two tracks of transit on its lower deck. The local people desire a spectacular structure that can befit this important location. After repeated deliberation, they decided on a large truss arch similar to the Sidney Harbor Bridge in Australia.

Navigation at this location requires a main span of 552 m. At that time, the world's longest arch bridge span was the 550 m span Lupu Bridge in Shanghai, China, which has box shaped arch ribs while the longest truss arch was the 530.6 m Bayonne Bridge in New York.

Truss arch has a long and successful history that can be traced back to Gustave Eiffel, who built several iron truss arches in southern Europe in late 1980s. The selected bridge configuration for the Chaotianmen Bridge, one that is similar to the Sidney Harbor Bridge, was originally developed by Gustave Lindenthal for the Hell Gate Bridge in New York City. Successful completion of the Hell Gate Bridge prompted the construction of the 503 m span Sydney Harbor Bridge in Australia, completed in 1932 and the 503.6 m span Bayonne Bridge in New York, completed in 1931. Several bridges with similar configuration but with lesser span length had been completed in various countries in the mean time.

Hell Gate　　Sydney Harbor　　Bayonne

Fig. 6

With a 552 m span, the Chaotianmen Bridge (Fig. 7) is again a big step beyond the present range of truss arch bridges. However, the technology in the design and construction of such a long span truss arch is rather mature. The Chaotianmen Bridge was completed without much difficulty. The bridge is to open to traffic in 2009.

Fig. 7　**Chaotianmen Bridge — During Construction and the Completed Bridge**

(Owner of the Chaotianmen Bridge is Chongqing City Construction Investment Company; Engineer is a joint venture of Chongqing Communications Design & Research Institute and Zhongtie Major Bridge Reconnaissance & Design Institute; Contractor is Second Harbor Engineering Company)

4 Pioneer in Bridge Engineering

Besides the two world record span bridges, Second Shibanpo and Chaotianmen, Chongqing has built about 4 500 bridges. All along, Chongqing has always been China's pioneer in bridge construction [2]:

(1) The first cable-stayed bridge of China, the Yun An Bridge in Yunyang, with a main span of 76 m, was completed in 1975.

(2) The First Shibanpo Bridge, with a main span of 173 m, was the longest girder span in China when it was completed in 1981.

(3) The 122 m span Wushan Linmen Bridge, completed in 1987, and the 200 m span First Wujiang Bridge, completed in 1989, were the world's first arch bridges built by the horizontal swing method.

(4) Today's largest span concrete arch bridge in the world, the 420 m span Wanxian Bridge, was completed in 1997.

(5) The 460 m span Wushan Bridge, opened to traffic in 2005, is the largest concrete filled steel pipe arch in the world.

(6) The Chaoyang Bridge in Beibei, with a main span of 186 m, was the longest span suspension bridge in China, probably in Asia as well, at the time of its completion in 1969.

Currently, the longest span cable-stayed bridge in Chongqing is the Yangtze River Bridge in Fengjie, which has a main span of 460 m. The longest span suspension bridge is the 600 m span Ergongyan Bridge. It was opened to traffic in 1999. And the longest span arch bridge and girder bridge, as mentioned above, are the Chaotianmen Bridge and the Shibanpo Bridge, respectively.

5 Recent Additions

Aesthetics has been getting much more attention in the planning and design of most new bridges in the City. Several of them do deserve mentioning in a discussion about bridges in Chongqing. Following are a few representative structures: Caiyuanba Bridge, Jiayue Bridge, Second Wujiang Bridge and the Twin River Bridges.

5.1 Caiyuanba Bridge

The Caiyuanba Bridge (Fig. 8) is a major artery over the Yangtze River connecting the central district with the rapidly developing southern district of the city. The bridge carries six lanes of street traffic plus two pedestrian paths on its upper deck and two tracks of monorail on its lower deck. The headroom of the monorail and its connection to the approaches require that the girder be 11.5 m deep. A truss is selected for its openness to offer the passengers in the monorail a more comfortable view of the Yangtze valley.

Due to its very central location, aesthetics has been a very important factor in the bridge type study. A half through tied arch was selected for the main spans for its slender appearance and aesthetic appeal. To assure a clean appearance, the arch ribs are steel box sections.

The navigation clearance determined by the Waterway Department requires that the main span of the bridge be 420 m. This happened to be the world's longest span for a dual use (highway and rail) arch bridge at the time of its completion in 2007.

A major problem in bridge construction in Chongqing is the variation of the water level in both the Yangtze River and the Jialing River. At the bridge site, the maximum possible difference in water level can be as high as 39 m. Even the difference between normal high and low water levels is 29 m. The water rushes fast during high water season so all falsework supports must be very sturdy and designed for very high water pressure. To avoid expensive cofferdams, the entire foundation must be completed within one low water season of about 7 months. The superstructure, the arch ribs and the girder are to be erected by high lines. With a capacity of over 300 tons, the highline used for this bridge is the largest highline ever used worldwide.

Fig. 8

(The owner of the Caiyuanba Bridge is the Chongqing City Construction Investment Company; Engineer is a joint venture of Chongqing Communication Design & Research Institute and T. Y. Lin International; Contractor is Zhongtie Major Bridge Construction Company)

5.2 The Second Wujiang Bridge, Fuling

The design of this bridge (Fig. 9) has three basic requirements: it must be aesthetically pleasing, it must be economical and the piers must be sufficiently strong to resist impact force from barges.

Fig. 9

The town of Fuling is rather hilly. There are steep slopes on both sides of the Wujiang River with very little flat land. High leveles are constructed along both banks of the river to keep out high water to maximize useable land. Because the Waterway Department requires that the bridge provide a minimum vertical navigation clearance of 10 m from the highest water level, the elevation of the bridge is quite high above the land on both banks. This results in very steep ramps on both ends of the bridge and very short end spans. The northern end span is only 100 m and the southern end span is 150 m. For a 340 m main span, these end spans are too short to be efficient for a cable-stayed bridge, which was the selected bridge type. But the local condition does not allow a better arrangement. In fact, on the south bank, the topography is so restricted that a three level spiral ramp has to be used to bring the traffic from the bridge to the local streets.

Other bridge types, such as arch and suspension bridges are also feasible for this site. However, an arch bridge would have been too big and too imposing at this location. A suspension bridge would have been too expensive in such span range. A concrete cable-stayed bridge is considered to be the most economical bridge type for a 340 m main span bridge at this location. A cable-stayed bridge was chosen after careful consideration.

Single pole towers with a single plane of cables were selected to achieve a more open appearance. The substructure of a single pole type tower is also deemed sturdier than a portal type tower with two legs. This is advantageous for ship impact.

To solve the problem that the end spans are uneven and too short, a non-symmetrical cable-stayed bridge with two uneven towers is configured. The height of the towers above the deck is proportionate to the length of the end span. The sum of the two side span lengths is 250 m (100 m + 150 m), which is about 74% of the 340 m man span. This is small but it is still acceptable. With a single pole type tower, the tower is obviously in the middle of the roadway. This usually increases the deck width by about two to three meters. However, a single pole tower is easier to build and costs less than a portal tower. Therefore, the cost of the two alternatives is actually very comparable. The single pole tower is good for a single box deck cross section. A portal tower is good for a girder and slab type flexible deck cross section. Construction of the box section is very similar to regular segmental cantilever bridges, which is rather common in China. The local contractors are more familiar with this type of construction.

The bridge has been completed in 2008 but will be opened to traffic in 2009 after the approaches are done.

(Owner of the Second Wujiang Bridge is the Embankment Construction and Management Company of Fulin; Engineer is T. Y. Lin International China; Contractor is Zhongtie Construction Group No. 8.)

5.3 Jiayue Bridge, Yuelai

The Jiayue Bridge (Fig. 10) crosses the Jialing River at the town of Yuelai in the northern district of metropolitan Chongqing. The bridge is about 70 m above the normal water level. It carries 6 lanes of highway traffic and two wide pedestrian/bicycle paths. The girder of the bridge is a single cell box with long cantilever slabs on both sides. The pedestrian/bicycle paths, each 5.5 m wide, are located underneath the roadway cantilever slabs, thus they are shielded from the hot summer sun and rain of the area. This also reduces the total width of the deck girder to about 27 meters.

The landscape of the Jialing valley in this area is very beautiful and delicate. The area is allocated for high end residential buildings. Aesthetics is therefore a very important consideration for the design of this structure. Arch, suspension and regular cable-stayed bridges are deemed too imposing for such a delicate landscape. Haunch box girder was considered but was found less attractive. Consequently an extradosed type bridge was selected for its low tower profile.

Fig. 10

The main span of 230 m was determined by the navigation requirement in the Jialing River.

The bridge girder was constructed by cantilever method with form travelers, which is a construction method with which the local contractors are very familiar. The pedestrian paths underneath the cantilever deck are erected after the single box girder has been completed. The cables are bundles of seven wire strands, either galvanized or epoxy filled for protection. They are anchored at the edges of the deck. At the tower end, the cables are anchored to a steel box encased in the concrete tower walls.

The towers are dual concrete box sections. The upper tower legs are inclining outwards to offer the passengers a more open view.

The bridge is scheduled to be open to traffic by the end of 2009.

(Owner of the Jiayue Bridge is Chongqing Land Properties Group; Engineer is T. Y. Lin International China, Contractor is Chongqing Bridge Construction Company)

5.4 The Twin River Bridges — Dongshuimen Bridge and Qianximen Bridge

The Dongshuimen Bridge over the Yangtze River and the Qianximen Bridge over the Jialing River are located at the tip of the Yuzhong Peninsula. Together, they are called the Twin River Bridges. Both are double deck structures carrying four lanes of traffic plus two pedestrian paths on their upper decks and two transit tracks on their lower decks. The girders are steel truss structure with orthotropic deck and the towers are made of concrete. Aesthetics were carefully considered for the design of these bridges because of their visibility in the city and their neighboring landmarks. A conventional cable-stayed bridge would have tall towers and many cables. This would hinder the view of the city. Therefore, a pair of partially cable-stayed girder bridges was selected (Fig. 11) for these two bridges.

Fig. 11 The Dongshuimen Bridge (left) and the Qianximen Bridge

The concept of a partially cable-stayed girder bridge[1] has been applied successfully to the design of several medium-span bridges in China, most notably the Sanhao Bridge in Shenyang[1]. While the spans of the Twin River Bridges are longer, the girder depths of these two bridges, at 13 m, are also much deeper. Thus, the span to girder depth ratio is comparable to that of the Sanhao Bridge.

The required minimum main span length of the Dongshuimen Bridge is 445 m. Thus, the span to girder depth ratio is $445/12 = 37$. The required minimum main span length of the Qianximen Bridge is 340 m. Its span to girder depth ratio is $340/12 = 28.3$. These ratios are wihtin the economic range of partially cable-stayed girder bridges.

The Dongshuimen Bridge will have two towers while the Qianximen Bridge will have one tower. The three towers are about 100 m high above the upper deck. Each tower will have the minimum number of cables as required by the structure. All cables will be located on a single plane on the center line of the bridge. The upper deck is an orthotropic steel deck with a minimum deck plate thickness of 16 mm.

It is the desire of the owner that these two bridges shall be signature structures of the City. With a single plane of cables in the middle of the box girder, the towers can either be a diamond shape or an inverted Y shape. However, those tower shapes would not have been sufficiently distinctive to satisfy the aesthetic requirement. After extensive studies, the very special tower shape as shown in Fig. 12 was adopted.

(Owner of the Twin River Bridges is Chongqing City Construction Investment Company; Engineer is a joint venture of Chongqing Communication Design & Research Institute and T. Y. Lin International China;

Fig. 12 Renderings of the Dongshuimen Bridge and the Qianximen Bridge

Contractor has not yet been selected.)

6 Bridge Capital of China

No matter in number, or in variety, or in the pioneering spirit, or in advancement of technology, the bridge collection in Chongqing is astonishing. It is well ahead of any other city in China. Even though there is no recognized definition of "bridge capital" in the dictionary, but with such a variety of spectacular bridge structures in the City, Chongqing deserves to be called the "Bridge Capital of China!"

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重庆桥梁建设的现状和需要研究的问题

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摘　要　介绍重庆桥梁的发展状况、特点,并针对重庆实际,指出了桥梁建设发展需要研究和解决的问题。

关键词　重庆桥梁　现状　特色　问题

The State-of-the-art of Bridges and Issues Need to be Researched in Chongqing

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Abstract: The paper introduced the development and characteristics of the bridges in Chongqing. Furthermore, based on the state-of-the-art bridges in Chongqing, the paper pointed out the problems of the development of bridge constructions needing to be studied and solved.

Key words: Bridges in Chongqing; State-of-the-art; Characteristics; Issues

1　重庆桥梁建设的飞速发展

重庆是一座典型的山水城市,山峦起伏、江河纵横、沟深谷宽。主城内有长江、嘉陵江环绕,两江在主城区朝天门汇合;涪陵、合川、奉节、巫山等中心城市也都江河交汇。重庆的发展离不开桥梁建设,而重庆社会和经济的快速发展又推动了重庆桥梁建设的飞速发展。

1980 年以前,在重庆境内 665 km 的长江上,没有一座公路桥梁,随着改革开放、重庆直辖和西部大开发的实施,重庆桥梁建设步伐逐步加快。据交通部 2007 年《交通年鉴》:到 2006 年,重庆市桥梁总数已达到 8 567 座,总长度 36.37 万米(363.7 km),2007 年底重庆桥梁数量又有突破,达到了 8 861 座,总长度达到 39.66 万米,以年 9% 的速度增长,其数量在中国 4 个直辖市中是最多的(见表 1)。

表 1　4 个直辖市桥梁数量比较表(2006 年底)

城市名称	桥梁座数/座	桥梁长度/m	桥梁座数比例	名次
北京	3 692	186 008	15.95	3
天津	2 404	221 892	10.39	4
上海	8 482	393 665	36.65	2
重庆	8 567	363 719	37.01	1
合计	23 145	967 214	100	

特别应指出,重庆近年正在施工的 1 200 多千米的高速公路上,桥隧比例很高(平均 50%),跨江

河的各类桥梁很多,可按里程的20%估计,预测到2010年,1 200 km高速路建成后桥梁总长度将达到60万米。

长江是横贯重庆东西的主干河流,在重庆境内总长665 km,它的支干流有嘉陵江、乌江、涪江、綦江、梅溪河、大宁河等百余条,丰富的主、支干流上密布着各类大跨径桥梁。据统计,目前重庆在长江上已建特大桥21座,在建的有7座,共28座,约占长江上桥梁总数的38%,重庆境内长江每隔24 km就有一座桥梁;在嘉陵江上已建特大桥17座,在建的有4座;在涪江、乌江上已建成特大桥9座。由此可见,重庆可以说是全国大江大河上桥梁最多的城市(如图1所示)。

图1 重庆市主城区两江环绕

重庆的桥梁除了数量多外,种类齐全、形态各异,包括了梁、拱、斜拉、悬索和组合体系等各类结构,称得上是一个桥梁博物馆。重庆的桥梁在造型上也新颖美观,一桥一景。

2 重庆桥梁的特色

重庆桥梁的建设规模比不上东部沿海地区,但很有特色。它总的特色体现在创新上,下面举几座有代表性的桥梁来说明。

(1)万县长江大桥——主跨420 m的钢筋混凝土拱桥

万县长江大桥(如图2所示)的主要特点是:在国内首先采用钢管混凝土劲性骨架成拱方法。先用斜拉扣挂法形成钢管混凝土劲性骨架,再在骨架上设模板,采用"先中箱、后边箱"、"先底板、后腹板再顶板、横向分块、纵向分段"、"六工作面"对称、同步浇筑C60混凝土,形成了高强混凝土与钢管混凝土劲性骨架组成的复合主拱结构,确保了世界最大跨拱桥的顺利建成,发展了大跨径混凝土拱桥建造技术。此项成果获2001年度国家科技进步一等奖。

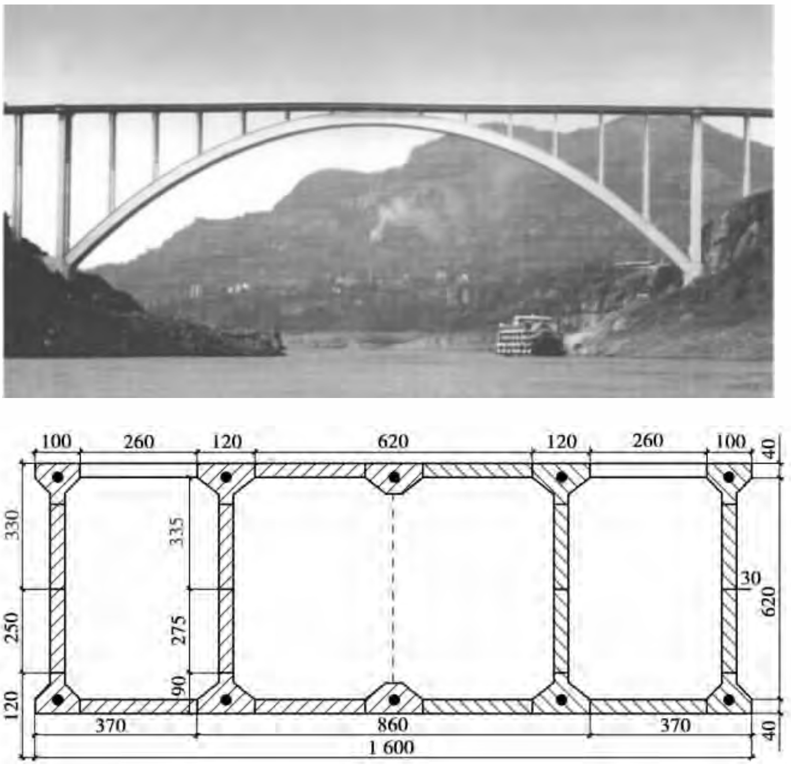

图 2　万县长江大桥

(2)巫山长江大桥——主孔跨径 460 m 的中承式钢管混凝土双肋拱桥

巫山长江大桥(如图 3 所示)的主要特点是:其跨径(主跨 492 m,净跨 460 m)、管径(1.22 m,壁厚 22 ~25 mm)和节段吊重(128 t,提升高度 280 m)居同类型桥梁之最。在设计理论方面,提出了钢管混凝土构件的收缩徐变计算理论和方法、钢管混凝土节点应力集中和疲劳寿命计算方法,以及考虑钢管初应力影响的钢管混凝土拱桥极值状态计算方法;在结构设计方面,按照全拱受力均衡,上下弦杆弯矩、轴力尽可能接近及主拱环形轮廓变化分明的原则,进行了结构体系优化,提出了内法兰拱肋接头和吊杆纵向限位装置等新技术;在施工方面,成功地采用了吊扣合一、复合式锚碇、自应力混凝土和分段连续灌注管内混凝土等新技术和新工艺。这些创新技术的应用,首先保证了结构的安全,特别是解决了管内混凝土脱空问题(经监测,管内混凝土浇筑密实,未发现脱空);其次是经济,全桥建安费只有 1.6 亿元,是所有长江大桥中造价最低的。巫山大桥一跨跨过巫峡,与高山、大江、深谷环境协调,雄伟壮丽,十分美观。

图 3　巫山长江大桥

(3)菜园坝长江大桥——连接市中区与南岸区公轨两用特大桥，是一座主跨 420 m 的拱式组合结构桥梁

菜园坝长江大桥(如图 4 所示)的主要特点是：刚构、桁梁、拱 3 种结构的组合，以及混凝土与钢 2 种材料的组合，达到了安全、经济、美观的统一。菜园坝大桥在结构上的主要创新点有两点：其一是将预应力混凝土 Y 形刚构、钢箱提篮拱和钢桁架 3 个相对分离的子结构，通过中跨系杆及边跨系杆连接成一整体，并首次采用独立的边跨系杆索配合竖向拉杆索，进行施工和大桥内力的主动控制；另外，由于下层轨道交通要有足够的净空和刚度，因此在设计上采用了强梁柔拱的结构，主拱设计为纤柔的等截面提篮式钢箱拱，简洁美观。

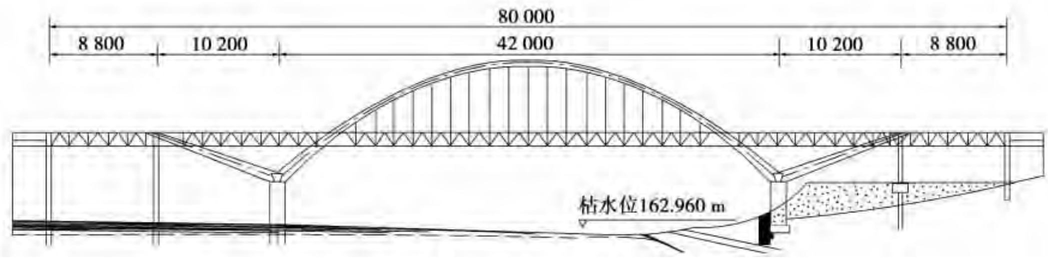

图 4　菜园坝长江大桥

(4)朝天门大桥——主跨 552 m 的中承式钢桁系杆拱桥

重庆朝天门长江大桥(如图 5 所示)主桥采用(190 + 552 + 190)m 的中承式钢桁架连续系杆拱桥，建成后将成为世界最大跨径拱桥，也是重庆市的标志性建筑。整体呈现三跨连续梁受力体系，其中，主跨 552 m 中 488 m 呈现系杆拱的受力特征。