CHAPTER

1

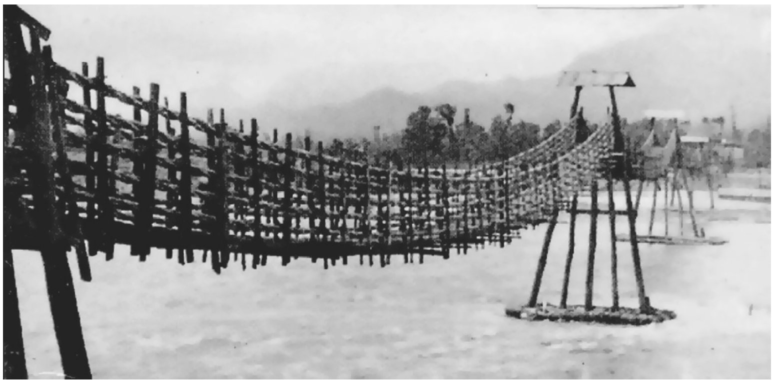
Introduction

1.1 HISTORICAL EVOLUTION OF BRIDGES

The glorious history of bridges is closely associated with the progress of human civilization spread over several centuries. The earliest bridge on record is that built on the river Nile by king Menes of Egypt as early as 2650 BC. Wooden bridges were built over the river Eupharetes during the reign of queen of Babylon in Iraq during 783 BC. Around 320 BC, Alexander 'the Great' built floating bridges for the passage of his army. Raina[1] cites examples of early timber beam and crude suspension bridges built over the Min river in China and the Himalayas as shown in Fig. 1.1. Etruscan and Romans, developed the art of building arched bridges using stones and bricks. The optimum profile of stone arch developed by early builders intuitively has seen very little changes over the years. The old stone arched bridge has been extensively used in almost all the countries for road as well as railway crossings. The series of stone masonry arched bridges across the river Seine in Paris shown in Fig. 1.2 are unique examples of human ingenuity. The proven durability of material and the long experience in intuitive proportioning made stone masonry arch bridges the most popular form of construction in the early days of railways until iron bridges made their way in the 17th century. Arched bridges continued to be the popular choice with materials like iron, steel and concrete mainly due to its superior aesthetical qualities besides structural efficiency of utilizing the entire cross-sectional area to resist the compressive forces.

In mid-19th century, demand for stronger and bigger bridges over larger rivers resulted in the use of cast iron and wrought iron replacing timber and stones for bridges. The first recorded use of iron in bridges was a chain bridge built in 1734 by the German army across the Oder river in Prussia. Cast iron being brittle was not found very suitable for building large bridges. An effective combination of cast iron for compression members and wrought iron for tension members was first used in trussed bridges around 1840 especially for railway bridges.

The development of steel by Bessemer in 1856 and the open hearth process by Sieman and Martin in 1861, paved the way for extensive use of steel and caught the imagination of bridge builders. Firth of Forth cantilever bridge of 520 m span and Roebling's suspension bridge of 490 m span were a few of the famous bridges of the 19th century and marked the beginning of modern era of bridge engineering.



(a) Fibre rope suspension form over the Min river in China (total length 552 m)

(b) Crude suspension form over the Himalayas

Fig. 1.1: Early timber suspension bridges over the Min river in China and over the Himalayas

By the turn of the century, widespread use and availability of structural steel sections and development of methods of analysis and design paved the way for large span, continuous, cantilever and arched bridges in steel exceeding spans of 500 m. Howrah bridge built in 1943 at Calcutta is a typical example of several outstanding bridges built using steel in the early 20th century.

Rapid advances in the development of theoretical analysis of the load response of the structural system of suspension bridges in the early part of 20th century resulted in the construction of many elegant bridges. The prominent among them are the Lindernathal's 450 m span Manhattan bridge built during 1909, the Steinman's Florianopolis bridge of span 340 m and the Delaware river bridge of 530 m span in 1926. The giant leap came with the construction of George Washington bridge with a span of 1060 m breaking the barrier of 1000 m. According to Stussi, Washington bridge is acclaimed as *the Great and most important step in the evolution of the art of bridge engineering.* The great architect, Le Corbusier, exclaimed that, "the Washington bridge is the most beautiful bridge in the world". This eight lane major roadway bridge without stiffening girders built by Amman, a Swiss engineer, is a significant breakthrough according to Navier and Roebling. Amman considered as the foremost bridge engineer in the world, during that period he also built Verrazano narrow bridge spanning 1300 m in New York which is considered as a

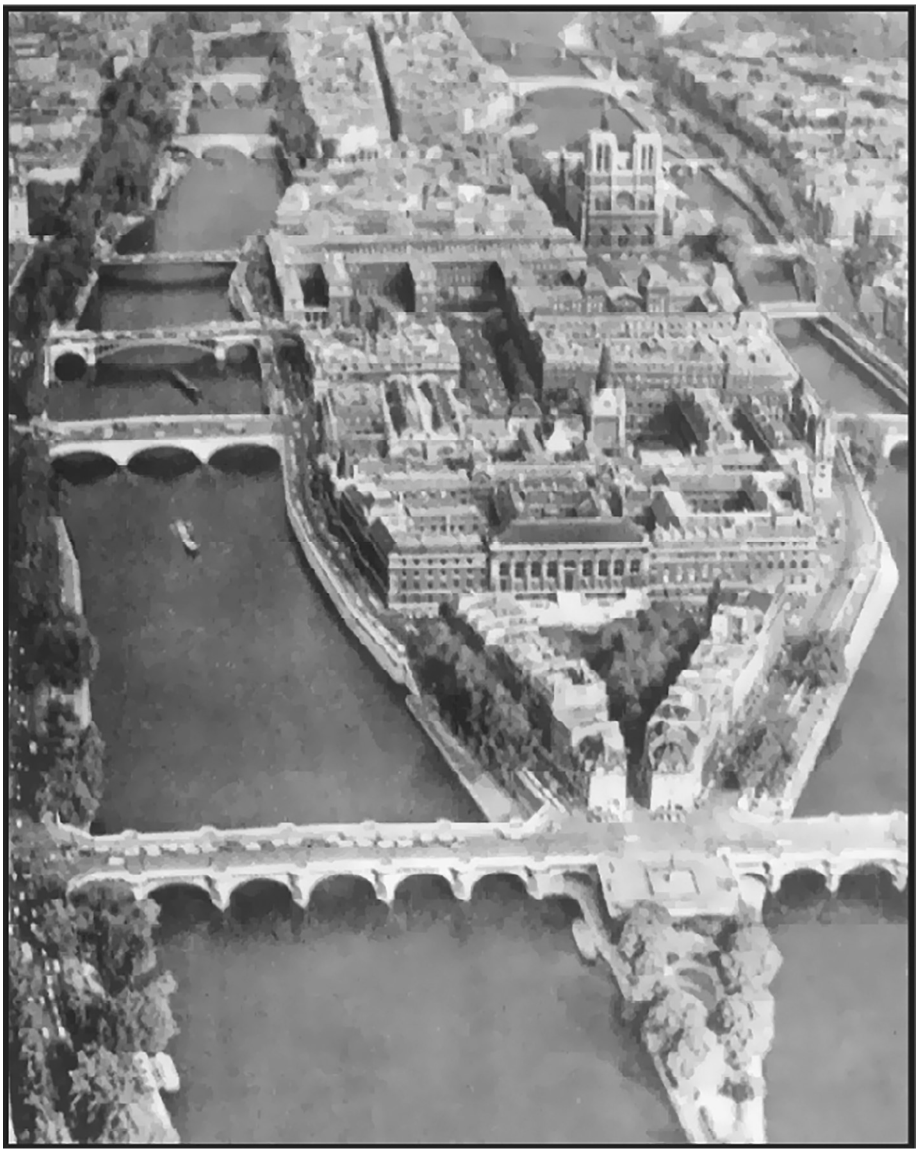


Fig. 1.2: Stone masonry arched bridges across the Siene river in Paris

masterpiece and opened for traffic in 1964 just a few months before he died. Figure 1.3 shows a typical steel trussed bridge of 360 m span at Baltimore, USA.

Postwar years saw the emergence of reinforced concrete as a suitable material for short and medium span bridges with the added advantage of durability against aggressive environmental conditions in comparison with steel. Tee beam and slab bridge decks (Fig. 1.4) were popular alongwith bow string (Fig. 1.5), balanced cantilever (Fig. 1.6), continuous girder (Fig. 1.7) and open spandrel arched bridge (Fig. 1.8) were also widely used throughout the world.

A revolutionary and path-breaking achievement in materials technology was witnessed in 1928 when Eugene Freyssinet,[2] a French engineer, introduced a new construction material designated as **'Prestressed Concrete'**. Freyssinet, who struggled for seven years

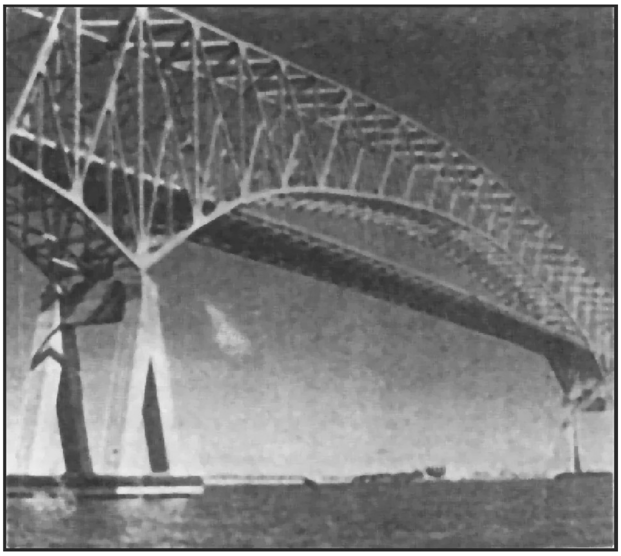
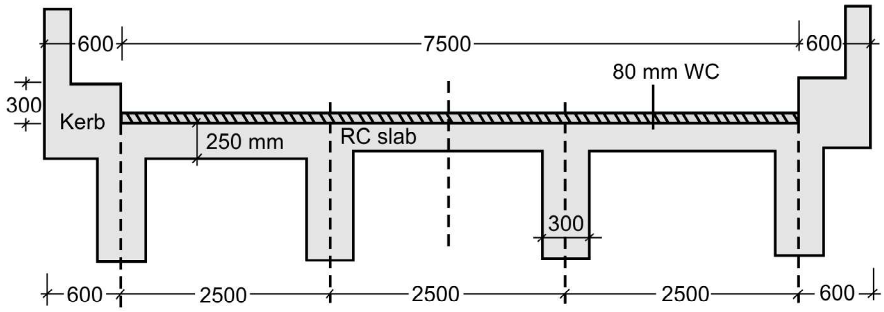
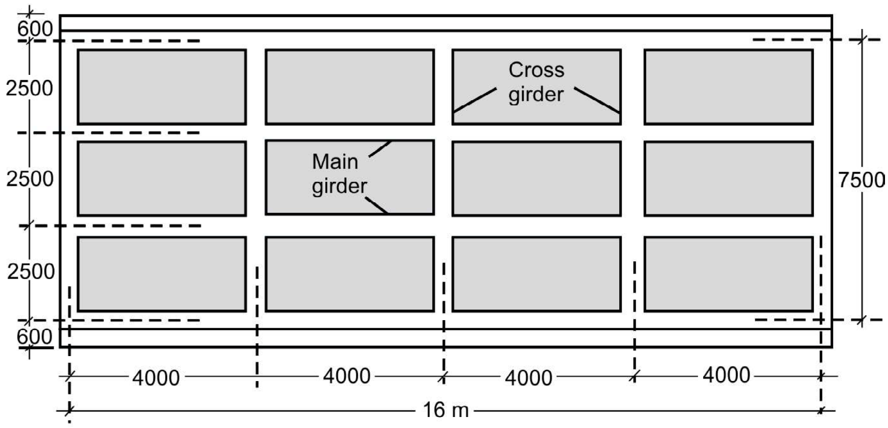


Fig. 1.3: Steel trussed bridge (360 m) at Baltimore, USA



(a) Cross-section of bridge deck



(b) Plan of bridge deck

Fig. 1.4: Tee beam and slab bridge decks

for the cause of prestressed concrete, found in the beginning that there were no buyers for his most exciting construction material. The big boom in prestressed concrete was

Fig. 1.5: Bow string girder bridge

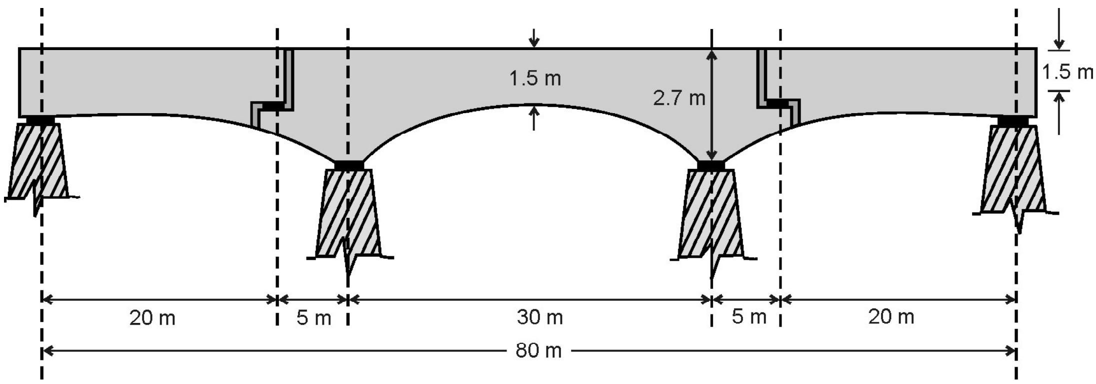


Fig. 1.6: Balanced cantilever bridge

witnessed after the World War II. In the beginning, prestressed concrete flourished in Europe and soon spread to all parts of the world.

The development of high strength concrete associated with significant improvements in the quality of cements and high strength steels of different forms, paved the way for its widespread application in bridge construction. In 1950s, prestressed concrete came to be used mostly for bridges of ever increasing spans coupled with rapidity and ease of

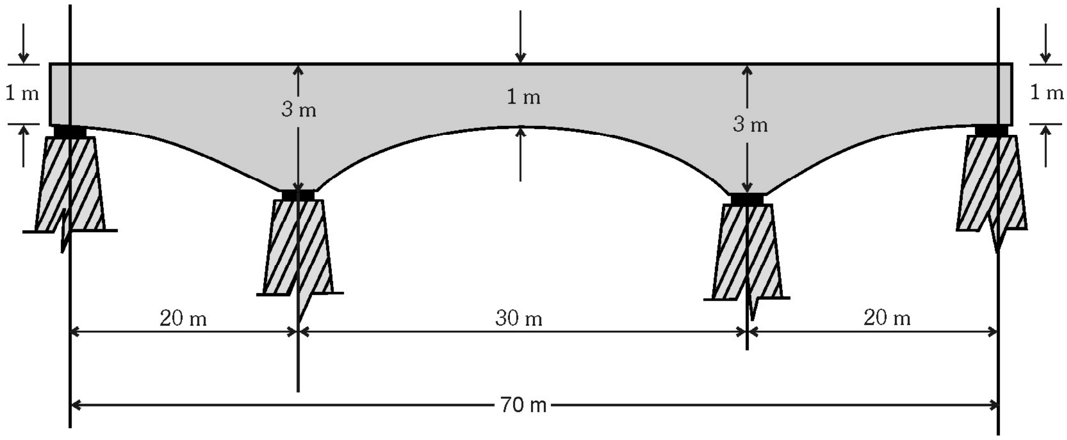


Fig. 1.7: Continuous girder bridge

Fig. 1.8: Open spandrel arched bridge

construction and competing in costs with other alternative types like steel and reinforced concrete.

Among the 500 bridges built in Germany during 1949–53, 70% of them used prestresed concrete. In 1949, prestressed concrete was introduced in USA in the construction of Magnel's walnut bridge and around the same time in India for the construction of Coleron bridge using Freyssinet system of anchorages. During the last 50 years, the achievements in building long span prestressed concrete bridges throughout the world are too numerous to document and the developments of new forms and construction techniques are growing at a dizzy pace. Ganga bridge at Patna, having 46 spans of 122 m each shown in Fig. 1.9 is a typical example of continuous prestressed concrete bridge ideally suited for long spans.

Another revolutionary approach in bridge construction first conceived by Dischinger, in 1938 and later put into practice in the construction of first modern cable stayed bridge is the Stromsund bridge in Sweden around 1953 by DEMAG. This paved the way for the construction of number of famous Rhine family cable stayed bridges with spans up to and exceeding 300 m.

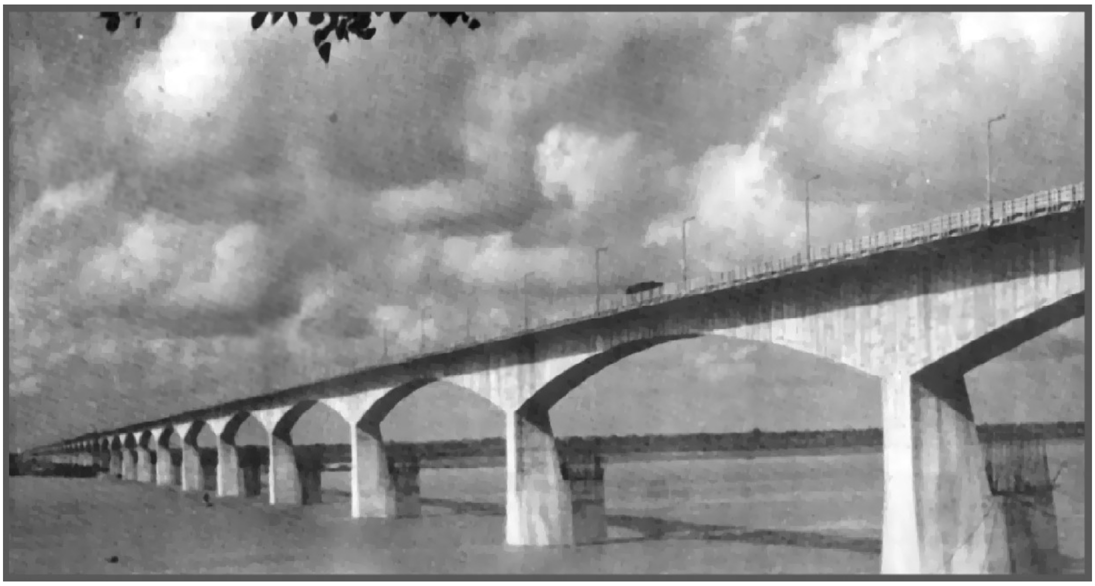


Fig. 1.9: The Ganga bridge at Patna

According to Leonhardt,[3] cable stayed system is technically, economically, aerodynamically and aesthetically superior to the classical suspension bridges for spans in the range of 750 to 1500 m. In the year 1960, beam bridges had reached spans up to 160 m and by 1970, the spans of beams had touched 230 m in Japan and for cable stayed bridges, designs were in progress for spans of 300 m. From 1970 onwards, the development of long span bridges in prestressed concrete with landmarks in span, form and construction technology is growing at an unprecedented pace. The panorama is so vast that it defies a simple survey.

The innovative cantilever construction method developed by Ulrich Finisterwalder[4] has stretched the span range of prestressed concrete bridges beyond 200 m. The Hamana bridge in Japan with a main span of 240 m is considered as a classic example of long span prestressed concrete bridges erected by cantilever construction method.

The combination of cable stays with box girder prestressed concrete decks have significantly extended the span range of highway bridges. Detailed studies by Fritz Leonhardt indicates that cable stayed bridges are structurally efficient and cost effective for low, medium and long span ranging from 40 to 1800 m. Pedestrian bridges spanning 40 m comprising a prestressed concrete deck with a depth of 250 to 300 mm supported by a few cable stays have been successfully built in Germany.

Vidyasagar Sethu (second Hooghly bridge) at Kolkata (Fig. 1.10) is an excellent example of a cable stayed three-lane highway bridge comprising a main span of 457 m and two side spans of 183 m. The composite deck is made up of a concrete slab 230 mm thick with two outer steel I-girders 28 m apart and a central girder.

The phenomenal development of prestressed concrete during the last five decades has expanded its scope of application and has led to increasingly imaginative forms of construction. Over the years, prestressed concrete has emerged as the choicest material for all kinds of structures. But the idea of prestressing arose out of bridges and naturally its most impressive and novel forms are found in long span prestressed concrete bridges.

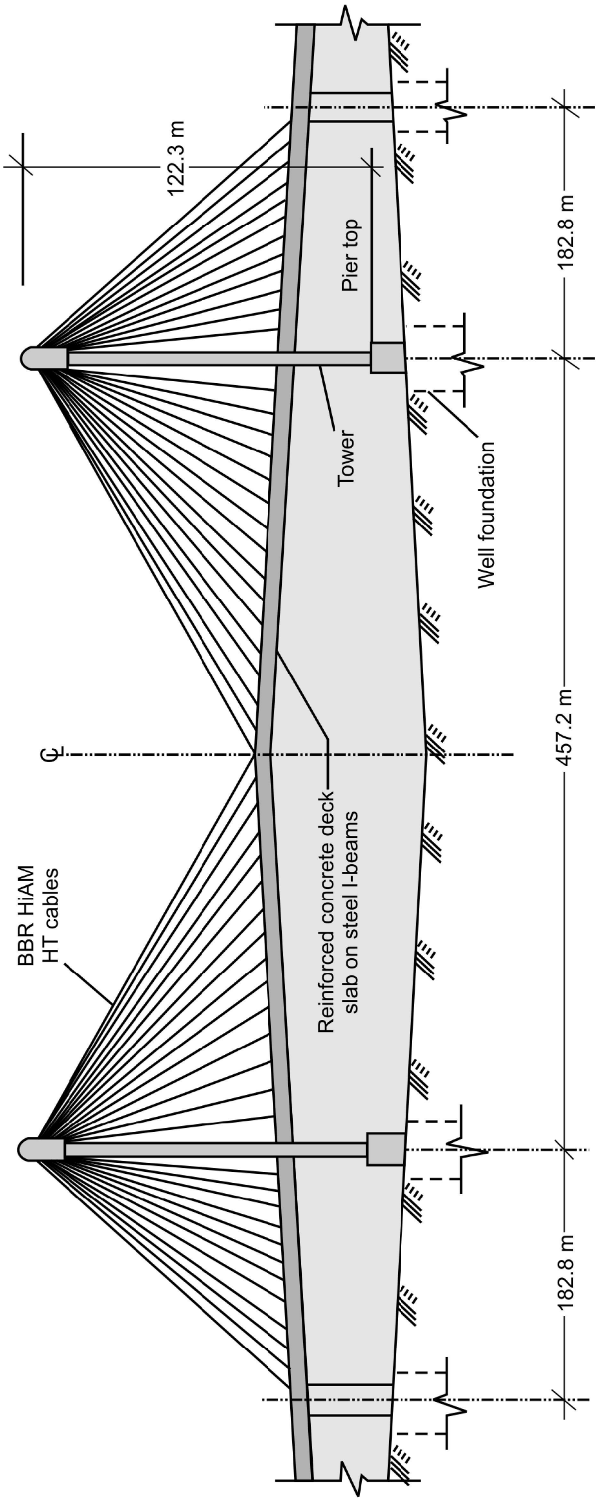


Fig. 1.10: Vidyasagar sethu cable stayed bridge

1.2 ADVANTAGES OF PRESTRESSED CONCRETE BRIDGES

Prestressed concrete comprising high strength concrete and high tensile steel is ideally suited for the construction of bridges due to its distinct advantages over other types of materials. Prestressed concrete offers immense technical advantages in comparison with other forms of construction such as steel and reinforced concrete. In fully prestressed members (type 1), the cross-section is efficiently utilized in resisting the stresses developed due to superimposed loads in comparison with a reinforced concrete section which is cracked under service loads. Within certain limits, a permanent dead load may be counteracted by increasing the eccentricity of the prestressing force in a prestressed concrete member, thus effecting savings in the quantity of material used in the structure.

In comparison with reinforced concrete members, prestressed members possess improved resistance to shear forces due to the effect of compressive prestress which reduces the principal tensile stress, thus eliminating the development of diagonal tension cracks. Curved cables generally used in long span members, reduce the shear forces developed at the support sections. The economy of prestressed concrete is well established for long span bridge structures.

According to Dean,[5] standardized precast bridge beams between 10 and 30 m long and precast prestressed piles have proved to be more economical than steel and reinforced concrete in the United States. According to Abeles,[6] precast prestressed concrete is economical for floors, roofs and bridges of spans up to 30 m and for cast *in situ* work up to 100 m. In the long span range, prestressed concrete is generally more economical than reinforced concrete and steel.

The deformation characteristics of prestressed concrete girders in bridges are superior to that of reinforced concrete since prestressed members have considerable resilience due to its capacity for completely recovering from substantial effects of overloading without undergoing any serious damage. Leonhardt[7] has reported that in prestressed girders of bridges, cracks which temporarily develop under occasional overloading close up completely on removal of the loads.

Bridge girders are normally subjected to repetitive loads leading to fatigue of members. Since the fatigue strength of prestressed concrete is comparatively better than that of other materials mainly due to the small stress variation in prestressing steel, it is preferred for dynamically loaded structures such as railway and roads bridges and machine foundations.

The experience accumulated in building prestressed concrete bridges over the last three decades in different countries has clearly indicated the superiority of prestressed concrete in terms of economy, slender form, aesthetics, performance in service and durability. The author in a separate monograph[8] has summarized the advantages of prestressed concrete bridges as follows:

1. The use of high strength concrete and high tensile steel results in slender sections which are aesthetically superior coupled with durability and overall economy.
2. Prestressed concrete bridges can be designed as class I type structures without any tensile stresses under service loads resulting in a crack free structure.
3. In comparison with steel bridges, prestressed concrete bridges require very little periodical maintenance.
4. Prestressed concrete is ideally suited for cantilever method of construction, both *in situ* and precast resulting in faster rate of construction of long span bridges.

5. Post-tensioned prestressed concrete finds extensive applications in long span continuous girder bridges of variable cross-section resulting in sleek structures with considerable savings in the overall cost of construction.
6. Prestressed concrete is ideally suited for composite bridge construction in which precast prestressed girders support the cast *in situ* concrete deck slab. This type of construction is very popular since it involves minimum disruption of traffic.
7. Combination of prestressed girders with cable stays are ideally suited for long span bridges with proven economy throughout the world.
8. In recent years, limited or partially prestressed concrete (type 3 structures) is preferred for bridge construction with significant savings in the quantity of costly high tensile steel used in bridge deck girders.

Twenty-first century will witness the application of prestressed concrete with cable stays for increasingly longer spans resulting in the reduction of piers and the associated foundation costs. The future bridges will be sleeker and aesthetically superior and blend with the local natural surroundings.

1.3 PRETENSIONED PRESTRESSED CONCRETE BRIDGE DECKS

The **long line system**[9] of pretensioning developed by Hoyer is ideally suited for casting pretensioned prestressed concrete bridge deck units of standard sizes and of various cross-sectional shapes such as single tee, double tee, hollow box, solid and voided slab, I- and Y-shaped girders. Pretensioned prestressed concrete bridge decks generally comprise precast pretensioned units used in conjunction with *cast-in situ* concrete topping slab resulting in composite bridge decks ideally suited for small and medium spans in the range of 10 to 30 m. In general, pretensioned beams are prestressed using straight tendons. The use of seven wire strands have been found to be advantageous in comparison with plain or indented high tensile wires. Deflected strands are employed in larger girders in USA.

In the United Kingdom, the precast prestressed I and inverted tee beam have been standardized by the Cement and Concrete Association, London for use in the construction of bridge decks of spans in the range of 7 to 36 m. Standard I section and tee section beams are widely employed in highway bridge decks in USA, Russia and European countries. Recently in UK, Y-beams have been developed to replace the M-beams introduced in 1960. The design and development of the Y-beams which are superior to M-beams are explicitly suited for medium spans in the range of 15 to 30 m. The salient features of widely used composite bridge decks with precast pretensioned standard beams are shown in Fig. 1.11.

Post-war construction in Japan has extensively used precast pretensioned girders for both railway and highway bridges. Pretensioned girders with I- and tee sections have been used on a large scale for the Tokyo–Nagoya and Osaka–Kobe expressways.[10]

1.4 POST-TENSIONED PRESTRESSED CONCRETE BRIDGE DECKS

Long span bridge decks are generally constructed using post-tensioned girders, since the self-weight of these girders being large, the cost of transportation and positioning of pretensioned girders is prohibitive. Post-tensioning is generally adopted for girder spans exceeding 20 m bridge decks with precast or *cast-in situ* post-tensioned girders of either tee or box type in conjunction with a *cast-in situ* slab is commonly adopted for spans

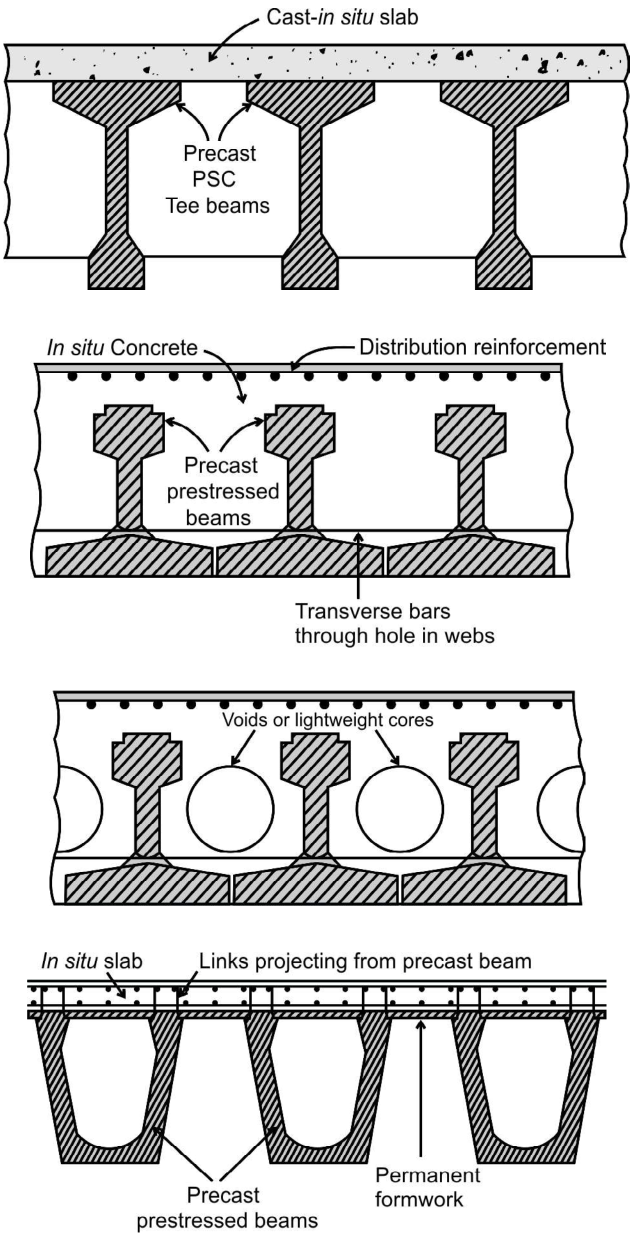


Fig. 1.11: Precast pretensioned bridge decks

exceeding 30 m. Another advantage of post-tensioned girders is the use of curved cables with varying eccentricity to suit the bending moments along the span in comparison with pretensioned girders in which the tendons are normally straight. The use of curved cables will enhance the shear resistance of post-tensioned girders in the vicinity of supports.

Post-tensioning is ideally suited for prestressing long span girders at the site of construction without the need for costly factory type installations like pretensioning beds. Modern long span bridges are constructed using segmental construction. In this method a number of segments of modular length can be combined by post-tensioning cables resulting in an integrated structure. In India a large number of long span bridges have been constructed using the cantilever method of construction. Some of the notable examples being the Barak bridge at Silchar, built in 1960 with a main span of 130 m and the Lubha bridge[10] in Assam with a span of 172 m between the bearings. Long span continuous prestressed concrete bridges are invariably built using modular multicelled box segments of variable depth using the post-tensioning system. Typical cross-sections of post-tensioned prestressed concrete bridge decks are shown in Fig. 1.12.

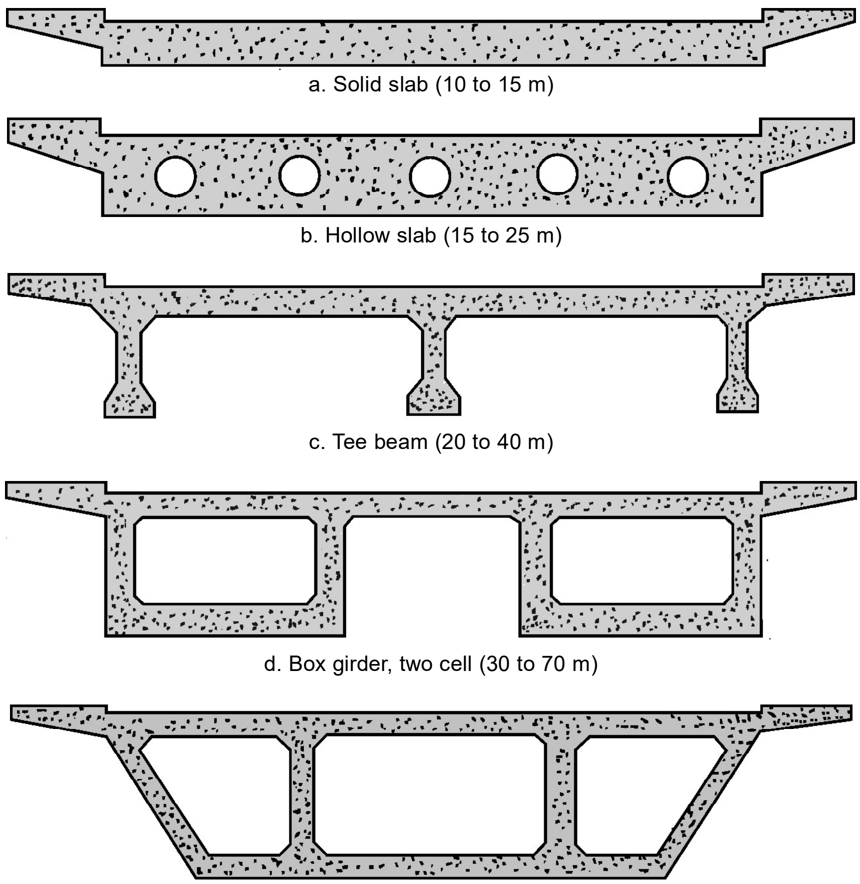


Fig. 1.12: Post-tensioned prestressed concrete bridge decks

Japan has been using post-tensioned prestressed concrete girders for the construction of railway and highway bridges on a large scale during the post-war period. Otogawa railway bridge with a span of 30 m was constructed on the Shigaragi line in 1954. The Harumi railway bridge with six spans and three of which being continuous spans of 21.3 m was constructed in 1957.[10]

1.5 MODERN TRENDS IN PRESTRESSED CONCRETE BRIDGES

Recent developments in the field of concrete technology indicates that it is possible to produce ultra high strength concrete[11] with a characteristic compressive strength exceeding 100 N/mm^2 and high tensile steel cable of superior quality and strength required for new types of prestressed concrete bridges. Innovations in construction techniques coupled with rapid advances in the design philosophy of complex bridge forms has paved the way for the development and widespread use of new types of prestressed concrete bridge decks for long spans.

The dawn of 21st century has seen the evolution of long span cable stayed bridges with hybrid decks using steel girders, concrete slabs and high tensile steel cable stays. The cantilever method of erection is the latest and the most economical and popular method for the construction of long span precast or cast *in situ* prestressed concrete segmental bridges. This method is also ideally suited for the construction of cable stayed bridge decks.

The newly planned second Vivekananda tollway bridge just north of Kolkata is an excellent example of an extradosed bridge, comprising a hybrid structure with elements of cable stayed post-tensioned prestressed concrete box girders. The nine span extradosed bridge stretching across India's Hooghly river is considered as Asia's first multi-span extradosed bridge and one of only three extradosed bridges in Asia outside Japan according to Egeman Ayna,[12] principal engineer of the International Bridge Technologies (IBT) who are the design consultants for the bridge project. The modern bridge having a total length of 880 m comprises seven spans of 110 m and two 55 m long spans.

The second Vivekananda bridge with a width of 28.6 m is an unusually wide extradosed structure catering to 8 lane traffic according to IRC standards.[13] The bridge deck (Fig. 1.13) comprising post-tensioned prestressed concrete box girders are supported by a single central suspension system instead of two planes of cable stays, eight cables comprising 63 to 73 strands each of 15 mm diameter extend from both sides of the 2 m wide pylons. The pylons of height 14 m are supported on Caisson foundations having a diameter of 11 m and sunk to a depth of 45 m below the river bed. The concrete wall thickness of the Caisson is 2 m.

According to Ayna, a typical box girder bridge would have had a depth of 6 m. However, the second Vivekananda bridge lowers that profile by approximately 2.5 m.

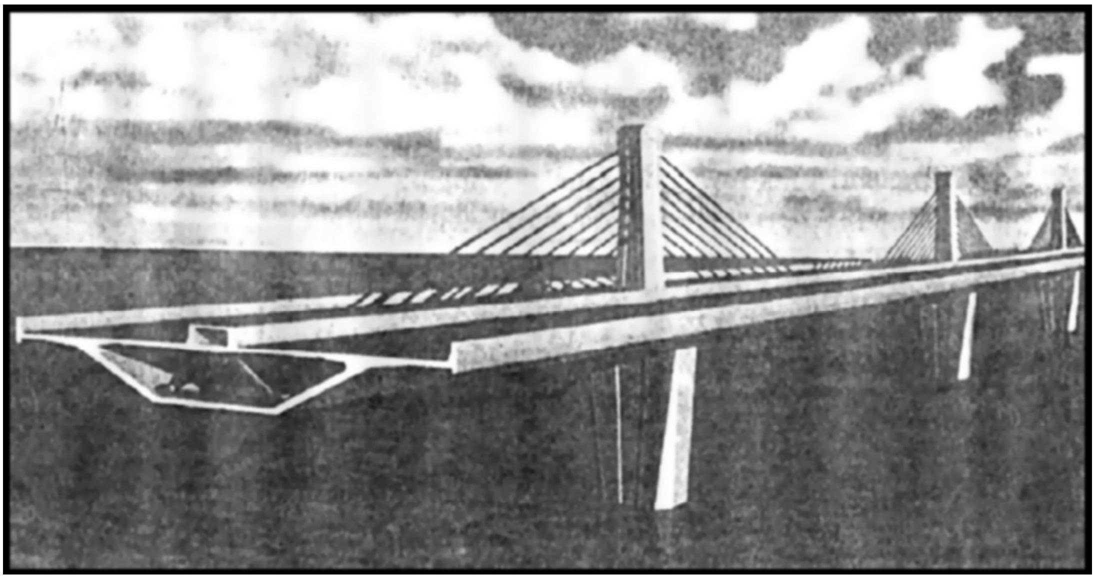


Fig. 1.13: Second Vivekananda extradosed PSC bridge across river Hooghly near Kolkata

Also the constant depth profile of bridges is a departure from the variable depth seen in other extradosed bridges. At present the bridge project is under execution by the well known construction firm M/s Larsen and Toubro Ltd. with its headquarters at Mumbai.

France being the homeland of the innovator of pretsressed concrete, Eugene Freyssinet, it is befitting that the tallest and longest cable stayed bridge recently opened for traffic in December 2004 is located outside the French town of Millau. The bridge extending over a length of 2.46 km is considered as an engineering feat since some of the bridge pillars rise gracefully to a height of more than 300 m. The bridge designed by the famous British architect Sir Norman Foster, is currently the world's tallest and longest cable stayed bridge shown in Fig. 1.14.

Fig. 1.14: World's tallest and longest cable stayed bridge in France (Courtesy: AFP)

A critical survey of long span bridges constructed in various countries during the last two decades indicates that the modern trend is to adopt cable stayed bridges with prestressed concrete decks as it is economical, structurally efficient and aesthetically superior in comparison with other types of bridges.

At present, China is leading the world in long span bridge construction using prestressed concrete. The Shibanpo bridge located at Chongquing in China is presently the longest span prestressed concrete bridge having a span of 330 m. During the period from 2000 to 2013 China has built the world's five longest span prestressed concrete bridges in the range of 265 to 330 m. During the same period, China is credited to have almost 50% of the longest span cable stayed bridges in the world covering the span of 800 to 1092 m.

The longest prestressed concrete beams ever manufactured have been successfully used in the main span of a new highway bridge in Zuidhorn, the Netherlands, according to a report by Sharon J Rehana.[14] The huge box beams spanning 68 m and weighing 218 metric tons are finding increased use in bridges and viaducts. Hans Beton Construction Company has produced these longest and heaviest prestressed concrete beams that the company has ever supplied.

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