Chapter 1

Introduction

1.1 Definition and Basic Forms

A bridge is a structure providing passage over an obstacle without closing the way beneath. The required passage may be for a road, a railway, pedestrians, a canal or a pipeline. The obstacle to be crossed may be a river, a road, railway or a valley.

There are six basic forms of bridge structures: beam bridges, truss bridges, arch bridges, cantilever bridges, suspension bridges and cable stayed bridges.

The beam bridge carries vertical loads by flexure. The truss bridge of simple span behaves like a beam because it carries vertical loads by bending. The top chords are in compression, and the bottom chords are in tension, while the vertical and diagonal members are either in tension or compression depending on their orientation. Loads are carried primarily in compression by the arch bridge, with the reactions at the supports (springing) being both vertical and horizontal forces. A cantilever bridge generally consists of three spans, of which the outer spans, known as anchor spans, are anchored down to the shore, and these cantilever over the channel. A suspended span is rested at the ends of the two cantilevers, and acts as a simply supported beam or truss. The cantilevers carry their loads by tension in the upper chords and compression in the lower chords. A suspension bridge carries vertical loads from the deck through curved cables in tension. These loads are transferred to the ground through towers and through anchorages. In a cable stayed bridge, the vertical loads on the deck are carried by the nearly straight inclined cables which are in tension. The towers transfer the cable forces to the foundation through vertical compression. The tensile forces in the stay cables induce horizontal compression in the deck. The above description presents the basic concepts of the different bridge forms in a simplified manner.

1.2 Components of a Bridge

The main parts of a bridge structure are:

(a) Decking, consisting of deck slab, girders, trusses, etc.;
(b) Bearings for the decking;
(c) Abutments and piers;
(d) Foundations for the abutments and the piers;
(e) River training works, like revetment for slopes for embankment at abutments, and aprons at river bed level;
(f) Approaches to the bridge to connect the bridge proper to the roads on either side; and
(g) Handrails, parapets and guard stones.

Some of the components of a typical bridge are shown in Fig. 1.1. The components

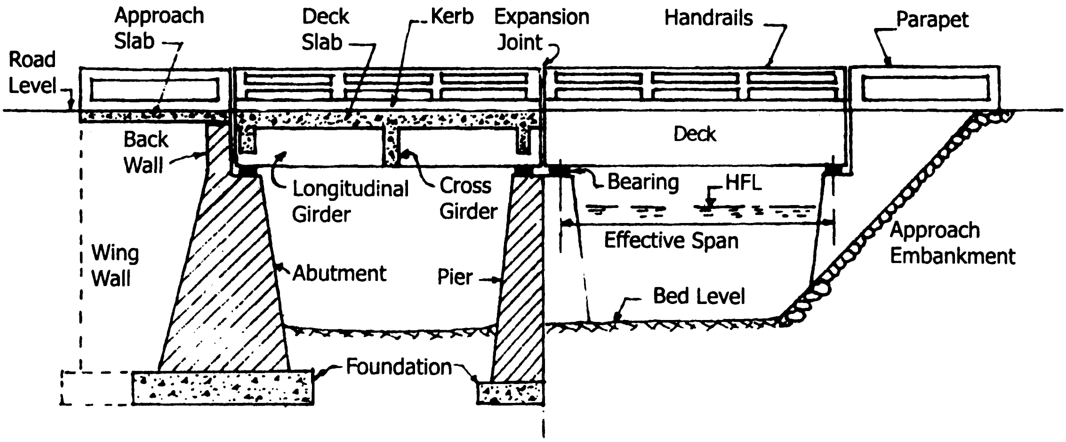

Figure 1.1 Components of a Typical Bridge.

above the level of bearings are grouped as superstructure, while the parts below the bearing level are classed as substructure. The portion below the bed level of a river bridge is called the foundation. The components below the bearing and above the foundation are often referred as substructure.

1.3 Classification

Bridges may be classified in many ways, as below:

(a) According to function as aqueduct (canal over a river), viaduct (road or railway over a valley), pedestrian, highway, railway, road-cum-rail or a pipeline bridge.

(b) According to the material of construction of superstructure as timber, masonry, iron, steel, reinforced concrete, prestressed concrete, composite or aluminium bridge.

(c) According to the form or type of superstructure as slab, beam, truss, arch, cable stayed or suspension bridge.

(d) According to the inter-span relations as simple, continuous or cantilever bridge.

(e) According to the position of the bridge floor relative to the superstructure as deck, through, half-through or suspended bridge.

(f) According to the method of connections of the different parts of the superstructure, particularly for steel construction, as pin-connected, riveted or welded bridge.

(g) According to the road level relative to the highest flood level of the river below, particularly for a highway bridge, as high-level or submersible bridge.

(h) According to the method of clearance for navigation as high-level, movable- bascule, movable-swing, movable-lift or transporter bridge.

(i) According to the length of bridge (total length between the inner faces of dirtwalls) as culvert (less than 6 m), minor bridge (6 to 60 m), major bridge (above 60 m) or a long span bridge when the main span of the major bridge is above 120 m.

(j) According to degree of redundancy as determinate or indeterminate bridge.

(k) According to the anticipated type of service and duration of use as permanent, temporary, military (pontoon, Bailey) bridge.

These classifications are not mutually exclusive. Any one type may overlap with others. For example, a multi-span highway bridge may consist of steel trusses of the through type and may be a high-level bridge over a river.

1.4 Importance of Bridges

Thomas B. Macaulay once said: "Of all inventions, the alphabet and the printing press alone excepted, those inventions which abridge distance have done the most for the civilization of our species". Since ancient times, bridges have been the most visible testimony to the contribution of engineers. Bridges have always figured prominently in human history. Cities have sprung up at a bridgehead or where at first a river could be forded at any time of the year; examples are London, Oxford, Cambridge, and Innsbruck. Some bridges embody the spirit and character of a people or a place, as the Brooklyn bridge for New York City, the Golden Gate Bridge for San Fransisco, the Tower bridge for London, the Harbour bridge for Sydney and the Howrah bridge for Kolkata. Bridges add beauty to cities, e.g., the bridges across the river Seine in Paris and the bridges across the river Thames in London. They enhance the vitality of the cities and aid the social, cultural and economic improvements of the areas around them.

Great battles have been fought for cities and their bridges. The mobility of an army at war is often affected by the availability or otherwise of bridges to cross rivers. That is why military training puts special emphasis on learning how to destroy bridges during combat and while retreating and how to build new ones quickly while advancing.

A bridge is an important element in a transportation system, as its capacity governs the capacity of the system, its failure or defective performance will result in serious disruption of traffic flow, and also the cost per km of bridge structure is many times that for the road or rail track on either side of the bridge. It is prudent, therefore, to devote special attention in design to ensure adequate strength and durability, consistent with safety and cost.

1.5 Historical Development

1.5.1 Early Bridges

The history of development of bridge construction is closely linked with the history of human civilization[1-4]. The efficiency and sophistication of design and the ingenious construction procedures kept pace with the advances in science, materials and technology. Fig. 1.2 outlines the development of the various forms. Nature fashioned the first bridges. The tree fallen accidentally across a stream was the earliest example of a beam type bridge. Similarly, the natural rock arch formed by erosion of the loose soil below and the creepers hanging from tree to tree allowing monkeys to cross from one bank to the other were the earliest forebears of the arch and the suspension bridges, respectively. The primitive man imitated nature and learned to build beam and suspension bridges. The ancient who felled a tree deliberately so that it fell across a stream and afforded him a crossing was the first bridge builder. Since the primitive man was a wanderer in search of food and shelter from the elements, the first structures he built were bridges.

Around 4000 BC, men were settling down to community life and were giving more thought for permanence of bridges. The lake dwellers in Switzerland pioneered the timber trestle construction which led later to timber bridges. At this time, the prototype of the

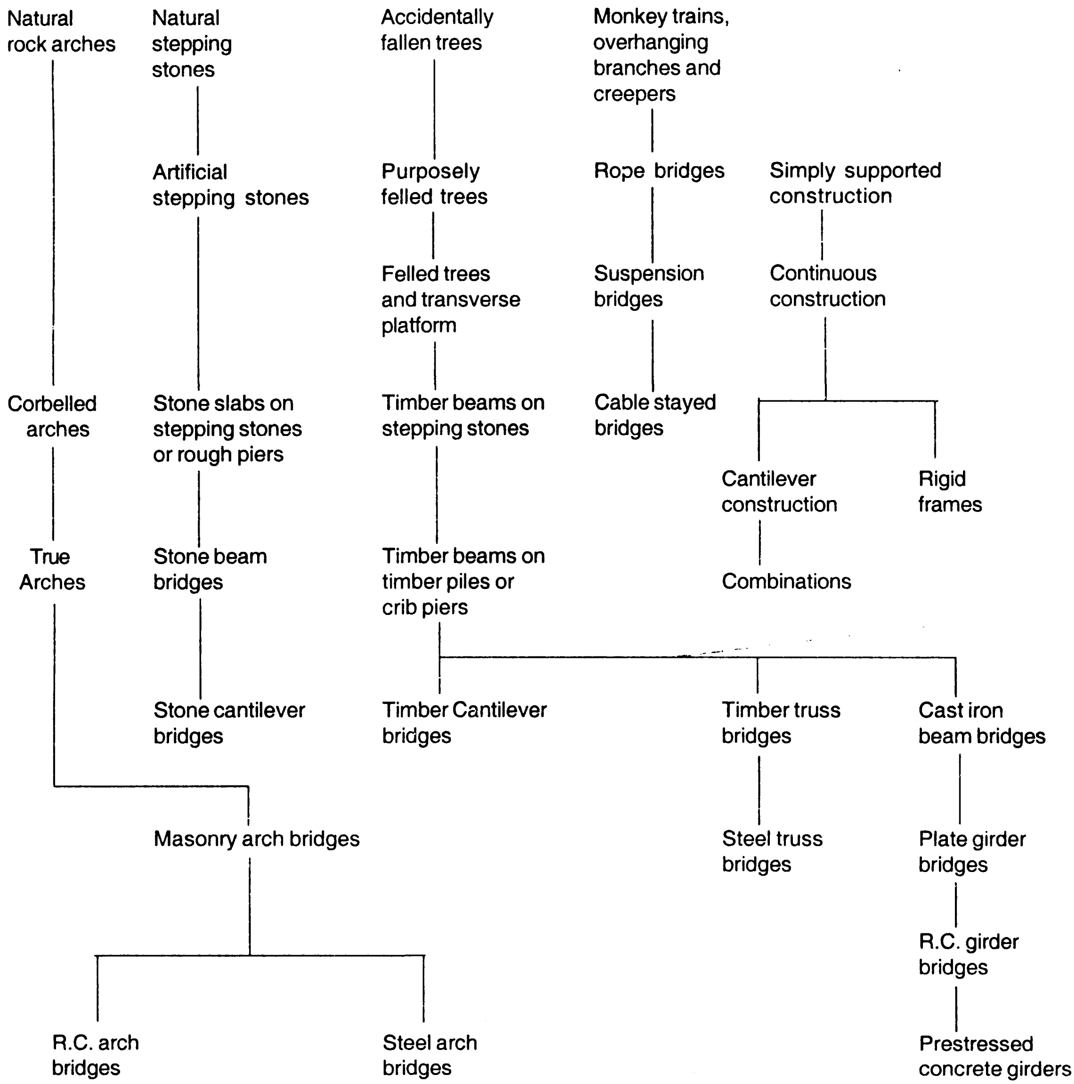

Figure 1.2 Development of Bridges.

modern suspension bridge was developed in India and China. Two parallel ropes were stretched between two banks and a level pedestrian platform was hung. India was also the birthplace of the cantilever bridge. Planks of wood, which were anchored at the two banks with heavy stones, were corbelled out progressively towards the midstream until the gap could be spanned by a single plank. During this time, the Mesopotamians developed the true arch bridge, the arch rib being made up of bricks or stones on end. The oldest bridge still standing is a pedestrian stone slab bridge across the Meles River in Smyrna, Turkey, which according to legend was used by the ancient Greek epic poet Homer and is at least 2800 years old.

1.5.2 Stone Masonry Bridges

The Romans were the pioneers in the art of bridge building. They introduced four significant developments: the discovery and use of natural cement; the development of the cofferdam; widespread use of semi-circular masonry arch; and the concept of public works. Between 200 BC and 260 AD, the Romans built many magnificent stone arch bridges. The arches were semi-circular using massive piers, so that, if one span got damaged in war, the others would remain standing. One famous bridge of this period is the Ponte Milvio across the Tiber river in Rome built in 109 BC and still in use[5]. Another magnificent example of Roman bridge building is the aqueduct, the Pont du Gard, built at Nimes, France, in 14 AD, consisting of three tiers of semi-circular arches composed of large rectangular stones assembled without mortar. The bridge expresses simplicity with repetition, symmetry and pleasant proportions. Yet another fine example of Roman bridge building is the Alcantara bridge at Toledo in Spain built by Caius Julius Lacer for Emperor Trajan in 98 AD. The arches have 29 m spans, with voussoirs accurately shaped without need for mortar for the joints. It is a plain, unadorned structure, but noble in its proportions and majestic in its simplicity. There is an inscription in Latin over the central tower: "I have left a bridge that shall remain for eternity". This epitomises the typical passionate desire of the Roman for eternal fame. Bridge construction was considered so important in ancient Rome that the Roman emperors adopted the title 'Pontifex Maximus', meaning 'Chief Bridge builder'.

The Chinese were building stone arch bridges since 250 B.C. The Zhaozhou Bridge (also known as the Anji bridge) built in 605 AD is a notable long-lived vehicular bridge today[6]. Situated about 350 km south-west of Beijing, it is a stone arch bridge of a single span of 37.6 m and rise of 7.2 m, with a roadway width of 9 m. The main arch ring is 1.03 m thick. Two small arches of 3.8 m and 2.85 m clear span penetrate each of the spandrels, and these serve to drain flood waters and also to reduce the bridge weight. The secret of its longevity was that the voussoirs were dressed exactly to match and there was no mortar joint. The form employed in this bridge was rarely seen in Europe prior to the late-16th century. In 1991, the Zhaozhou bridge was named among the world's cultural relics.

In the middle ages after the fall of Rome, the bridge building activity in Europe was mainly taken up by the religious orders. Medieval bridges adopted the pointed arch. With the pointed arch, the tendency to sag at the crown is less dangerous and the horizontal thrust at the springing is less. The Pont d'Avignon with 20 arch spans of about 34 m each built by St. Benezet over the Rhone river in 1188 and the Old London bridge across Thames river with 19 pointed arch spans of varied lengths built by Peter Colechurch in 1209 were examples of this period. Segmental curves were first used in Europe in the Ponte Vecchio Bridge, built at Florence, Italy in 1345. The medieval bridges were loaded with decorative and defensive towers, chapels, statues, shops and dwellings.

The dawn of Renaissance witnessed advances in theory, technical skill and mechanical appliances. In his treatise 'Four Books of Architecture' published in 1520, Palladio proposed the use of truss systems in bridge design. Galileo Galilei wrote the first book on the science of structural analysis in 1638 entitled Dialoghi delle Nouve Scienze (Dialogues on the New Science)[3]. Bridges were regarded as civic works of art and the bridge builder was recognised as a leader in progress and a creator of monuments. Stone masonry segmental arches were predominantly used in bridges. The Rialto Bridge in Venice, Italy, built in 1591 with a single segmental arch span of 27 m and a rise of 6 m, is typical of this period. Another magnificent example of this period is the Khaju bridge at Isfahan in Iran (1667) with eighteen pointed arches, carrying a 26 m wide roadway. The Bridge combined architecture and engineering in perfect harmony. It served also as a dam and included cool rooms for travelers.

The eighteenth century ushered in the age of reason. The first treatise on bridge engineering was published in 1716 by Henri Gautier, a French engineer. In 1716, the Corps des Ingenieurs de Ponts et Chaussees was founded for the scientific advancement of bridge construction; and in 1747, the Ecole de Ponts et Chaussees at Paris, the first bridge engineering school in the world, was founded, with Jean Perronet, 'Father of modern bridge building', as the first Director. Perronet perfected the masonry arch and introduced slender piers, his best work being the Pont de la Concorda at Paris built in 1791. John Rennie in England designed the New London bridge across Thames river using segmental masonry arches and the same was completed by his son in 1831. Another fine stone arch bridge is the Grosvenor bridge built by Harrison in 1832 with a span of 61 m. Many masonry arch bridges have been built in India adopting small spans, mainly for the railways, e.g. Thane railway bridge (1853).

1.5.3 Timber Bridges

Timber bridges served as an economic alternative during the years prior to the twentieth century, and were built adopting several structural types. The 400 m long timber trestle bridge across the Rhine built by Julius Caesar in 55 BC within a time span of ten days was a masterpiece of bold design and efficient site organization. The wooden arches of Japan (e.g. Kintaiko bridge, 1673) are examples of the primitive ingenuity and craft technology. Timber bridges have been used in Kashmir as cantilever bridges. Covered timber bridges, covered for protection of the timber from the weather, were popular during the late eighteenth century. Hans Grubenmann built a covered timber truss bridge with spans of 51 m and 58 m over the Rhine at Schaffhausen in 1755. Another notable timber bridge was the 'Colossus' bridge over the Schuylkill river at Fairmount, Pennsylvania, with an arch span of 104 m. This fine bridge, built in 1812 by Louis Wernwag, was destroyed by fire in 1838.

1.5.4 Iron Bridges

The Industrial Revolution ushered in the use of iron in bridges in place of stone and timber. The first iron bridge was built at Coalbrookdale in 1779 over the Severn in England by Abraham Darby and John Wilkinson. It consisted of five semicircular arch ribs in cast iron, joined together side by side to form a single arch span of 30 m. The construction details of the iron bridge followed the spirit of timber and masonry construction practice.

Wrought iron replaced cast iron in bridge construction during the period 1800-90. Wrought iron was ductile, malleable and strong in tension. In 1808, James Finley in Pennsylvania patented a design for a suspension bridge with wrought iron chain cables and level floor. Forty bridges of this design were built in USA within the next eight years. Wrought iron chains were used for a suspension bridge built by Thomas Telford across the Menai Straits in Wales in 1826 with a record-breaking span of 177 m. The Menai Straits bridge was the world's first iron suspension bridge for vehicles and also the world's first iron suspension bridge over sea water. Isambard Kingdom Brunel designed the Clifton suspension bridge in Bristol, UK in 1850 with a main span of 183 m using wrought iron chains, and the work was completed in 1864.

George Stephenson built the first iron railway bridge, the Gauntlet Viaduct, in 1823 on the Stockton-Darlington railway. The most famous of the early iron railway bridges is the

Britannia tubular bridge built by Robert Stephenson in 1850 across the Menai Strait. The bridge consisted of twin wrought iron tubes, continuous over four spans of 70, 140, 140 and 70 m. The design for this bridge was evolved using theory and model tests, and was the fore-runner for the present-day practice for the design of suspension bridges. The bridge continued in service till it was damaged by fire in 1970. Many truss bridges of the form Howe, Pratt, Whipple, Bolman, Fink, and Warren were built on the railways during this period. A notable example of the use of wrought iron is the Royal Albert bridge at Saltash, UK built in 1859 by Brunel.

A number of wrought iron railway bridges failed causing serious loss of lives. The most remembered failures are those of the Ashtabula, Ohio Howe truss bridge in 1876 killing 65 people and the Firth of Tay lattice girder bridge in Scotland in 1879 resulting in the death of 75 persons. The Ashtabula bridge collapsed due to derailment in a snow storm. The Tay bridge disaster was attributed to poor quality castings, unsuitable joints and inadequate wind resistance. These failures highlighted the inadequacy of wrought iron for bridges and led to a new era in bridge building, an era of specialization, research, careful detailing, thorough inspection and a more durable and stronger material - steel.

In 1884, Gustave Eiffel built the Garabit Viaduct (railway bridge) over the Truyere river near St. Flour, France. The 165 m main span of the bridge consisted of a crescent shaped two-hinged arch of wrought iron and represented the world's longest arch span when completed. The wide lateral spacing of the arch in plan towards the hinged supports increased the lateral stiffness of the structure, besides enhancing the visual impact of the crescent form. The arch gets narrower but deeper as it rises from the hinges. As mentioned by Billington[7], "the form is handsome in pure profile (its two-dimensional aspect) but in addition it provides visual surprise and delight from different perspectives (its three-dimensional aspect)".

1.5.5 Steel Arch and Truss Bridges

Though steel is said to have been known in China by 200 BC and in India by 500 BC, its widespread use materialized only in the latter half of nineteenth century after the discovery of the Bessemer process in 1856. Steel was first used extensively in the Eads Bridge at St. Louis, Missouri, built in 1874 as a steel arch bridge of three spans of 153, 158 and 153 m. The Eads Bridge, designed by James Buchanan Eads, was also the first bridge to use pneumatic caissons in USA, the first bridge to make extensive use of cantilever method of erection, and the first to specify and test for elastic limit and ultimate strength for steel. The first all-steel bridge was built at Glasgow, South Dakota in 1878. Steel was also used in the cables and spans of Brooklyn bridge during 1869-83. The Forth Railway bridge built by Baker and Fowler in 1889 featured steel plates of 51 MPa tensile strength. The bridge has two cantilevered spans of 513 m each. The Alexandre III bridge over Seine in Paris, France was built in 1900 with a main span of 107 m, adopting shallow arch ribs made up of moulded steel segments.

Inspired by the success of the Eads bridge, many fine steel arch bridges were built. Notable among these are the Hell Gate bridge at New York with a span of 297 m built in 1917, the Bayonne bridge (1931) with 504 m span and the Sydney Harbour bridge at Sydney, Australia, with a span of 503 m built in 1932. The deck type arch span is aesthetically the most pleasing. The Henry Hudson bridge built in 1936 with a span of 244 m and the Rainbow bridge at Niagara Falls built in 1941 with a span of 290 m are outstanding examples of beautiful steel arch bridges. The world's longest steel arch bridge has been the New River Gorge bridge in West Virginia built in 1977 using weathering steel with a span of 519 m. Currently, the Lupu bridge in Shanghai, built in 2004 with a span of 550 m, is the world's longest steel arch span bridge. Rising like a beautiful rainbow across the Huangpu river, the Lupu bridge adopted a combination of construction techniques of the arch bridge, the cable stayed bridge and the suspension bridge.

Consequent on the introduction of steel, the earlier truss forms yielded place to more efficient forms such as the Baltimore, Parker, Pennsylvania and K-truss types. In India, many major bridges were built with steel decks in the late nineteenth century and early twentieth century to carry the railway tracks across the major rivers. An example of such a bridge is the Upper Sone Railway bridge built in 1899 with an overall length of 3.1 km consisting of 93 spans of 30.5 m each. Truss bridges have been used economically in the span range of 100 to 200 m mainly for railway bridges. The world's longest simple steel truss bridge span is the suspended span of J.J. Barry bridge across Delaware river in USA built in 1973 with a span of 251 m.

1.5.6 Cantilever Bridges

The world's first modern cantilever bridge was built in 1867 by Heinrich Gerber across the river Main at Hassfurt, Germany, with a main span of 129 m. The world's most famous cantilever bridge is the Firth of Forth bridge in Scotland, built in 1889 with two main spans of 521 m. This bridge was designed by John Fowler and Benjamin Baker soon after the failure of the Tay bridge. So the design wind pressure was adopted conservatively as 2.68 kN/m^2, which was about 5.5 times the estimated wind pressure that toppled the Tay bridge. The bridge featured steel plates of specified minimum ultimate tensile strength of 463 MPa (30 $tons/in^2$). The designers had to devise innovative methods to present the concept of the cantilever bridge to the financiers. The maintenance of this bridge, particularly the needed routine painting to prevent rusting of the steel members, is a continuous and costly task.

The world's longest span cantilever bridge was built in 1917 at Quebec, over the St. Lawrence river, with a main span of 549 m. The first attempt to construct this bridge ended in failure due to miscalculation of the dead load and buckling of the web plates of the compression chord members near the south pier. The design was then revised and the structure was rebuilt. The Howrah bridge over the Hooghly river at Kolkata, built in 1943 with a main span of 457 m, has elegant aesthetics and possesses pleasing proportions among the suspended span, cantilever arms and the anchor spans. It was a notable achievement at the time of its construction. The Osaka Port bridge (also known as the Minato bridge), completed in 1974 with a main span of 510 m, applied advanced techniques of welding and was built with precision and without any accident. In view of the larger weight and labour involved compared with a cable stayed bridge of the same clear span, the cantilever bridge is not very popular at present.

1.5.7 Box Girder Bridges

Developments in welding technology and precision gas cutting techniques in the post second world war period facilitated the economical fabrication of monolithic structural steel box girders characterized by the use of thin stiffened plates and the closed form of cross section. The Cologne Deutz bridge built in 1952 was the world's first slender steel box girder bridge. Box girder bridges have exceptional torsional rigidity resulting in better transverse load distribution. Hence box girder steel bridges were constructed in many parts of the world. However, three major failures occurred under construction during 1970-71: at Milford Haven, UK and Melbourne, Australia in 1970 and at Koblenz, Germany in 1971. These collapses were attributable more to inefficient detailing of steelwork than to incorrect design of the effective section. After a number of studies, stringent requirements for design and workmanship have been prescribed. The Rio-Niteroi bridge in Brazil (1976) with 200-300-200 m spans is a record–span steel box girder bridge.

1.5.8 Reinforced Concrete Bridges

Concrete was used in 1840 for a 12 m span bridge across the Garoyne Canal at Grisoles in France. The first reinforced concrete bridge was built by Adair in 1871 as a 15 m span bridge across the Waveney at Homersfield, England. Soon after, a 6 m arch was built in 1889 at Golden Gate Park in San Francisco and a girder bridge was built in 1893 by Hennebique as an approach to a mill at Don, France. The adaptability of reinforced concrete to any architectural form and the increased efficiency in concrete construction resulted in its widespread use in bridge building. Robert Maillart in Switzerland produced fine arch bridges in reinforced concrete, utilizing the integrated structural action of thin arch slabs with monolithically cast stiffening beams, e.g. Salginatobel bridge and Schwandbach bridge (1930 and 1933, respectively). These bridges by Maillart are classical examples of structural art, exemplifying the design criteria: efficient use of materials, economy in cost and enhanced aesthetic expression. Another elegant arch bridge is the Bixby Creek bridge in California built in 1932 with a main span of 109.7 m and deck at 79.2 m above the stream bed. The longest span concrete arch bridge is the Wanxiang bridge in China built in 1996 with a span of 420 m and a rise-to-span ratio of 1:5.

The use of reinforced concrete for road bridges has become popular in India since the beginning of the twentieth century[8]. The bridge types adopted include: (a) simply supported slabs; (b) simply supported T-beam spans; (c) balanced cantilever with suspended spans; (d) arch and bow string girder; and (e) continuous or framed structure. Solid slab simply supported bridges were common in the 1920s. T-beam bridges have been used widely in the span range of 10 m to 25 m. Elegant arch bridges were built during 1920 to 1950. The Dum Dum bridge at Kolkata, built in 1926 with two arches of 24 m each, is the first major reinforced concrete arch bridge in India. The Coronation bridge (1941) across Teesta river in Bengal with a main arch span of 81.7 m and rise of 39.6 m is a particularly elegant structure, which has also proved to be durable. The Third Godavari Railway bridge built in 1996 with 28 spans of 97.5 m is a recent example of elegant concrete bowstring girder bridges.

1.5.9 Prestressed Concrete Bridges

The application of prestressing to concrete was pioneered by Eugene Freyssinet in France. He demonstrated the concept of artificial introduction of beneficial stresses in concrete members by the use of high strength steel tendons. His early works of Le Veurdre bridge (67.5-72-62.5 m spans) in 1911, Plougastel bridge (3 spans of 180 m) in 1930 and the Marne bridge at Esbly (74 m span) in 1939 represented path breaking efforts in concrete development. The first prestressed concrete (PSC) bridge in USA was the Walnut Lane bridge (22.6 + 48.8 + 22.6 m spans) in Philadelphia, PA built in 1949, while the first PSC bridge in Canada was the Mosquitto Creek bridge in Vancouver, BC, constructed in 1952. The Bendorf bridge over the Rhine in Germany with a main span of 208 m built in 1965 by Finsterwalder using free cantilever method with cast-in-situ concrete and short high tensile bar tendons marked a breakthrough in prestressed concrete bridge construction. Jean Muller designed the Choisy bridge in France in 1965 as the first PSC bridge using match cast precast segments and epoxy joints[9]. The Confederation bridge in Canada built in 1997 is a spectacular achievement in prestressed concrete. The bridge has a total length of 12.9 km. The main bridge has 44 spans of 250 m, involving extensive use of precast components, high-performance concrete and innovative construction techniques. The share of prestressed concrete bridges in the total of all new bridges has grown steadily since 1950 : e.g. the share in USA in 1994 is reported to be over 50% of all bridges built [10].

The construction in 1948 of three prestressed concrete railway bridges with spans ranging from 12.8 m to 19.2 m on the Assam Rail Link near Siliguri heralded the use of prestressing in bridge construction in India. The first prestressed concrete highway bridge built in India was the Palar bridge near Chingleput, built in 1954 with 23 spans of 27 m each. Since then, many prestressed concrete bridges have been successfully built in this country using innovative designs and construction techniques. The adoption of segmental cantilever construction facilitated the construction of girder bridges of longer spans and slender sections. Notable examples include the Barak bridge (1961) with a clear span of 122 m and the Ganga bridge at Patna (1982) with 45 spans of 121 m each and two end spans of 63.5 m. The incremental launching method has been used successfully in 1994 in the case of the Panvel Viaduct (spans 9 x 40 m + 2 x 30 m) on the Konkan railway and later for the Yamuna bridge on the Delhi Metro.

1.5.10 Cable Stayed Bridges

The cable stayed bridge is specially suited in the span range of 200 to 900 m and thus provides a transition between the continuous box girder bridge and the suspension bridge. It was developed in Germany during the post-World War II years in an effort to save steel which was then in short supply. The Stromsund bridge in Sweden, built in 1957 with a main span of 183 m, and the Dusseldorf North bridge built in 1958 with a span of 260 m are early examples. Since then many cable stayed bridges have been built all over the world, chiefly because they are economical and also because they are aesthetically attractive. Another well-known bridge in this category is the Maracaibo Lake bridge in Venezuela designed by Ricardo Morandi of Italy and built in 1963. The Sunshine Skyway bridge (1987) designed by Eugene Figg and Jean Muller over Tampa Bay in Florida, has a main span of 360 m with prestressed concrete deck and single-plane cables. The Dames Point bridge at Jacksonville, Florida, built in 1987 with a span of 390 m is the longest cable stayed bridge in USA. Designed by Howard Needles and Finsterwalder, the bridge features H-shaped R.C. towers and two-plane cables supporting R.C. deck girders. Currently, the Tatara bridge in Japan (1999) with a span of 890 m is the longest cable stayed bridge in the world. The Millau viaduct, completed in 2005, with six spans of 350 m and two spans of 240 m, supported on towers up to 235 m height is a unique cable stayed bridge.

India's first cable stayed vehicular bridge is the Akkar bridge in Sikkim completed in 1988 with two spans of 76.2 m each. The Second Hooghly bridge (Vidyasagar Setu), completed in 1992, with a central span of 457.2 m and two side spans of 182.9 m each, is a notable engineering achievement in India.

Table 1.1. The Progress in Bridge Building as Recorded in Successive Record Span Lengths.

Year	Bridge	Location	Type	Main Span Metres
B.C. 219	Martorell	Spain	Stone arch	37
A.D. 14	† Nera river	Lucca, Italy	Stone arch	43
104	† Trajan's	Danube river	Timber arch	52
1377	† Trezzo	Italy	Stone arch	77
1758	† Wettingen	Switzerland	Timber arch	119
1816	† Schuylkill falls	Philadelphia, Pa.	Suspension	124
1820	† Union (Tweed)	Berwick, England	Chain	137
1826	Menai strait	Wales	Chain	177
1834	† Fribourg	Switzerland	Suspension	265
1849	Wheeling	Ohio river	Suspension	308
1851	† Lewiston	Niagara river	Suspension	318
1867	Cincinnati	Ohio river	Suspension	322
1869	† Clifton	Niagara falls	Suspension	386
1883	Brooklyn	New York City	Suspension	486
1889	Forth	Scotland	Cantilever	521
1917	Quebec	Canada	Cantilever	549
1929	Ambassador	Detroit, Mich.	Suspension	564
1931	George Washington	New York City	Suspension	1067
1937	Golden Gate	San Francisco, Calif.	Suspension	1280
1964	Verrazano Narrows	New York City	Suspension	1298
1981	Humber	Humber, U.K.	Suspension	1410
1998	Akashi Kaikyo	Japan	Suspension	1991

† Not standing

1.5.11 Suspension Bridges

The concept of suspension bridges has originated from India and China. A few short bridges exist in the Himalayan region. However, the modern suspension bridges are mostly in USA, Europe, Japan and China. The suspension bridge has come to stay as the type best suited for very long spans. Thomas Telford built the Menai Straits eyebar suspension bridge with 177 m main span in 1826. The Wheeling bridge across the Ohio river in USA built by Charles Ellet in 1849 with a span of 308 m was the first long span wrought iron wire cable suspension bridge in the world. The Brooklyn bridge with a main span of 486 m , designed by John Roebling and completed in 1886 by Washington Roebling and Emily Warren-Roebling, was the first steel wire cable suspension bridge in the world. Other suspension bridges followed raising the record span. Othmar Amman designed the George Washington bridge in 1931. This was the first modern suspension bridge with a main span of 1067 m, nearly double the previous record. The Golden Gate bridge at San Francisco was completed in 1937 by Joseph Strauss with a record span of 1280 m. In 1940, the Tacoma Narrows bridge at Puget Sound, Washington, was opened to traffic as a beautiful bridge with a span of 853 m and stiffening plate girders only 2.4 m deep. The bridge collapsed the same year during a 68 km/h gale due to aerodynamic instability. This failure forcefully brought home the need for consideration of aerodynamic effects on suspension bridges and triggered many theoretical studies on the problem.

Table 1.2 The World's Longest Spans for Various Bridge Types.

Type	Bridge	Location	Date	Main Span Metres
Cable suspension	Akashi Kaikyo	Kobe-Naruto, Japan	1998	1991
Cable stayed - Steel	Tatara	Japan	1999	890
Cable stayed - Concrete Girder	Skarsund	Norway	1991	530
Cantilever	Quebec	Canada	1917	549
Steel arch	Lupu	Shanghai, China	2004	550
Concrete arch	Wanxiang	Yangzi river, China	1996	420
Continuous truss	Astoria	Oregon, USA	1966	376
Eyebar suspension	Florianopolis	Brazil	1926	340
Continuous steel girder	Niteroi	Brazil	1974	300
Simple truss	J.J. Barry	Delaware river, USA	1973	251
Prestressed concrete girder	Stolmasundet	Austevoll, Norway	1998	301
Concrete girder	Villeneure	France	1939	78
Tubular girder	Britannia	Menai strait	1850	140
Simple girder	Harlem river	New York city	1951	101
Masonry arch	Wuchao river	Hunan, China	1990	120
Vertical lift	Arthur Kill	Elizabeth, N.J.	1959	170
Wichert truss	Homestead	Pittsburg, Pa.	1937	163
Swing span	El- Ferdan	Suez, Egypt	2001	340
Bascule	Sault Ste. Marie	Michigan	1914	102
Single-leaf bascule	16th street	Chicago, Illinois	1919	79

The Severn bridge (1966) with a span of 988 m became a land mark in bridge construction. Its deck consisted of an all-welded steel stiffened box girder, streamlined and tapered at the edges. The shape was obtained after extensive wind-tunnel tests. This concept has since become the salient feature of European bridge design, and has been adopted for the Bosporus bridge (1973) at Istanbul and the Humber Estuary bridge at Humber, England (1981). The Humber bridge with a main span of 1410 m was the longest span bridge till 1998. Currently, the Akashi-Kaikyo bridge in Japan, completed in 1998, is the longest span bridge with a main span of 1991 m and side spans of 960 m. This great bridge is indicative of the irresistible urge of man to continually thrust forward. According to D.B. Steinman, bridge spans as large as 3000 m are practically feasible and will be built in the future.

1.5.12 Conclusion

The above discussion shows that the early bridges prior to the Industrial Revolution used designs in stone and timber. Better understanding of the properties of materials and advances in analysis led to applications first in cast iron, then in wrought iron and structural steel, and still later in reinforced concrete and prestressed concrete. Evolution of bridges also followed the industrial advancement. Thus innovations in bridge design were initiated mainly in UK in the early 19^{th} century, while advances were registered in USA and Switzerland from the late 19^{th} century to mid 20^{th} century. Significant strides were made in Germany and Japan in subsequent decades.

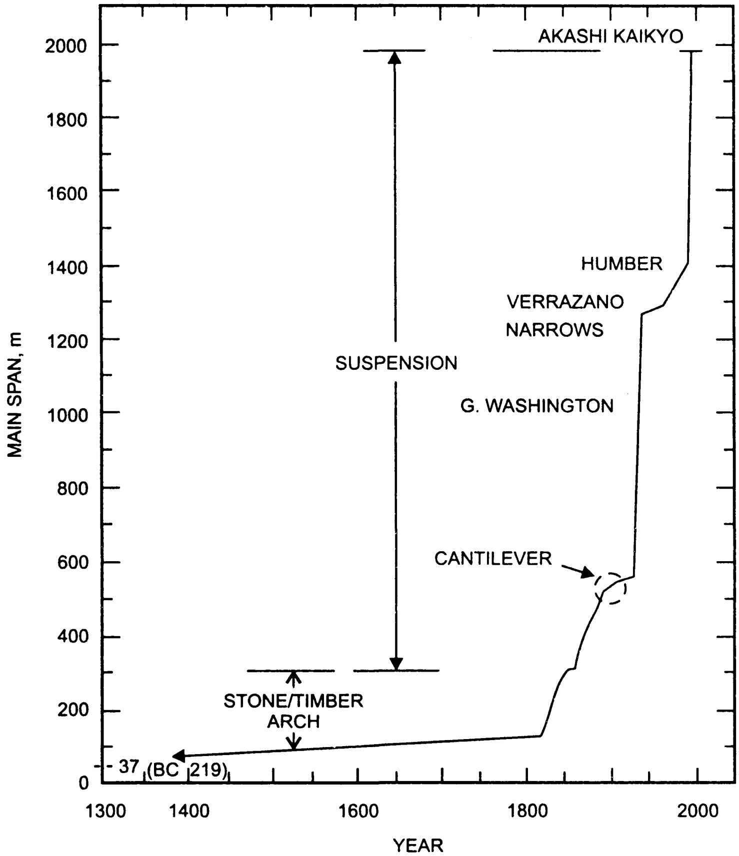

Figure 1.3 Growth in Bridge Spans.

The progress in bridge construction as recorded by successive record span lengths can be seen from Table 1.1 and Fig. 1.3. The world's longest spans for various bridge types are listed in Table 1.2. Data on the world's notable bridges of different categories are included in Tables C.1 to C.10 in Appendix C. In terms of total length, the longest bridge in the world is the Pontchartrain bridge, New Orleans, USA with a total length of 38.6 km built in 1956. A chronology of selected developments of bridges is listed in Appendix D to facilitate easy reference.

The design of long span bridges always poses a challenge to the ingenuity and to the perseverance of the designer. Every long span bridge brings in new problems in design concepts and new construction details. The designer chooses his solution with full freedom of decision, but with full responsibility for the success of the work. In fact, long span bridges are creative works, and serve as landmarks in the art of bridge building.

The above review serves to illustrate how bridge engineering has developed into a specialized subject drawing upon the advances in materials, theoretical analysis, construction techniques, computer applications and concepts in many branches of engineering. For example, the Bessemer method of steel production gave the impetus to steel bridges. The advances in welding techniques facilitated box sections for the deck of suspension bridges. The advent of computers aided the sophisticated analysis of cable stayed bridges and suspension bridges. The development of high strength steels and high strength concrete led to the widespread use of prestressed concrete bridges.

1.6 Conceptual Bridge Design

Prior to attempting the detailed design of a bridge, the designer must first visualize and form a mental image of the bridge at the proposed site with a detailed fitment of all the components. A possible configuration may appear as a flash of inspiration on rare occasions. But normally the configuration evolves slowly as the designer mentally examines the imagined structure with regard to the various requirements. Starting with a paper and a soft-leaded pencil, the designer should prepare sketches approximately to scale to put the mental images on paper. These sketches are continuously reviewed to check the function, applicability, economy, constructability and durability. They are then modified to improve on the likely performance. It should be ensured that the proposed structure conforms to the surrounding environment and the landscapes in the countryside or the cityscapes in urban centres as the case may be. The designer would do well to have his sketches reviewed by colleagues with a view to arrive at the best possible design. The decisions made at the conceptual design stage have a major influence on the performance quality and the life-cycle cost of the bridge. The preliminary design of the bridge is the outcome based on the designer's experience, capability and vision.

1.7 Case studies

Expertise in bridge design can best be gained through hands-on experience in design and construction of many bridge structures. Since this process may not be possible for all, the next best alternative is to learn from the experience of others, by studying in detail the evolution of bridge engineering through the available reports on the design provisions, construction features and performance data of different bridges, besides visiting sites of bridges under construction and in service. The aim of the case study is to examine the reasons for major decisions with regard to the selection of site, the choice of the structural form, the materials and construction techniques adopted, and the performance of the bridge. The engineer should try to get a thorough understanding of the design concepts of the structural system through a fundamental enquiry. Detailed studies of various examples of bridges with regard to their positive and negative aspects will help to create a data bank in the mind, which will lead to the ability to select and rate one's own design solutions. Rapid strides have been registered in the recent past in bridge design, detailing, construction technology and materials used for bridge construction. In order to facilitate identification of suitable case studies, the names of a number of important bridges with significant features as well as the names of a few famous bridge engineers have been mentioned at various points of discussion in the text along with references to the published literature. The author would urge the serious reader to develop a feel for the subject through a critical study of these references.

1.8 Standard Specifications

Bridge design is a complex problem, calling for creativity and practicability, while satisfying the basic requirements of safety and economy. Standard specifications and codes of practice have been evolved by the concerned government agencies and professional institutions, based on years of observation, research and development. The primary purpose of these codes is to ensure satisfactory design, detailing and construction of the structures, to achieve adequate safety, quality and durability. Conformance to the standards also affords reasonable protection against legal liability arising out of failures due to no fault of the designer. Since the public roads and railways in India are owned and controlled by government, the bridges built on them should follow specifications laid down by the respective authorities. All highway bridges in India have to be built in accordance with the Indian Roads Congress (IRC) Codes, besides Specifications prescribed by the Ministry of Road Transport & Highways, Government of India (MORTH). Similarly, the design of railway bridges should conform to Indian Railway Standard (IRS) Codes including the Bridge Rules and the Specifications laid down by the Research, Design & Standards Organisation (RDSO) of the Indian Railways. Wherever applicable, the specifications of the Bureau of Indian Standards should also be complied with. Some important specifications from these codes are indicated and discussed in this text. Unless mentioned otherwise, reference to 'the Code' in this text refers to the relevant provision in the IRC Bridge Code. The specifications in these codes undergo revision frequently. The bridge engineer is expected to be conversant with the different clauses in the latest revisions of the above codes.

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