CHAPTER 2: LITERATURE REVIEW

The following chapter shall introduce the reader to past, present, and future in bridge engineering. The history of engineering is as old as mankind itself, and it is without doubt that technical progress and the rise of human society are deeply interwoven. Bridges have often played an essential role in technical advancement within Civil Engineering.

The development of important types of bridges and the changing use of materials and techniques of construction throughout history will be dealt with in the first part of this chapter. Notably, manifold legends and anecdotes are connected with the bridges of former eras. Studying the history of a bridge from its construction throughout its life will always also reveal a fascinating picture of the particular historical and cultural background.

The second part of this chapter introduces the main challenges that the current generation of bridge engineers and following generations will face. Three important areas of interest are identified. These are improvements in design, construction, maintenance, and rehabilitation of a bridge, application of high-performance materials, and creative structural concepts. As technology advances, many new ways of innovation thus open for the bridge engineer.

2.1   HISTORY OF BRIDGE CONSTRUCTION

The bridges described in the following sections are examples of their kind. A vast amount of literally thousands of bridges built requires choosing a few exemplary ones to show the main developments in bridge construction throughout the centuries. Any book examining bridges in a historical context will make its own choice, and studying these works can be of great value for understanding of the legacy of bridge engineering. The subdivision into certain periods in time shall provide a framework for the reader's orientation in the continuous process of history as it unfolds.

2.1.1 Ancient Structures

It will never be known who built the first actual bridge structure. Our knowledge of past days fades the further we look back into time. We can but assume that man, in his search for food and shelter from the elements and with his given curiosity, began exploring his natural environment. Crossing creeks and crevices with technical means thus was a matter of survival and progress, and bridges belong to the oldest structures ever built. The earliest bridges will have consisted of the natural materials available, namely wood and stone, and simple handmade ropes. In fact, there is only a handful of surviving structures that might even be considered prehistoric, e.g. the so-called Clapper bridges in the southern part of England, as Brown (1993) notes.

2.1.1.1 Ancient Structural Principles

The earliest cultures already used a variety of structural principles. The simplest form of a bridge, a beam supported at its two ends, may have been the predecessor of any other kind of bridges; perhaps turned into reality through use of a tree that was cut down or some flat stone plates used as lintels. Arches and cantilevers can be constructed of smaller pieces of material, held together by the compressive force of their own gravity or by ropes. These developments made larger spans possible as the superstructure would not have to be transported to the site in one complete piece anymore.

Probably the oldest stone arch bridge can be found crossing the River Meles with a single span at Smyrna in Turkey and dates back to the ninth century BC (Barker and Puckett 1997). Even suspension bridges are no new inventions of modern times but have already been in use for hundreds of years. Early examples are mentioned from many different places, such as India and the Himalaya, China, and from an expedition to Belgian Congo in the early years of this century (Brown 1993). Native tribes in Mexico, Peru, and other parts of South America, as Troitsky (1994) reports, also used them. He also mentions that cantilevering bridges were in use in China and also in ancient Greece as early as 1100 BC. Podolny and Muller (1982) give information on cantilevering bridges in Asia and mention that reports on wooden cantilevers from as early as the fourth century AD have survived.

2.1.1.2 Trial and Error

In some cases, authors of books or book chapters on the history of bridges use terms such as primitive, probably as opposed to the modern state-of-the-art engineering achievements. It is spoken of a lack of proper understanding, and of empirical methods. From today's point of view it is easy to come to such a judgement, but one should be careful not to diminish the outstanding achievements of the early builders. In our technical age with a well-developed infrastructure, computer communication, and heavy equipment readily available it is easy to forget about the real circumstances under which these structures were built. Since mathematics and the natural sciences had yet even begun being developed it is not astonishing that no engineering calculations and material testing as adhering to our modern understanding were performed. But a feeling for structures and materials was present in the minds of these ancient master builders. With this and much trial and error they built beautiful structures so solid and well engineered that many have survived the centuries until our days.

2.1.1.3 The Earliest Beginnings

Earliest cultures to use bridges according to our current knowledge were the Sumarians in Mesopotamia and the Egyptians, who used corbelled stone arches for the vaults of tombs (Brown 1993).

In the fifth century BC the Greek historian Herodotus, who lived from about 490 to 425 BC (Brown 1993), wrote the history of the ancient world. His report on the city of Babylon includes a description of the achievements of Queen Nitocris, who had embankments and a bridge with stone masonry piers and a timber deck built at the River Euphrates. This bridge is believed to have been built in about 780 BC (Troitsky 1994) and was built as described in the following (Greene 1987, p118).

> *"… and as near as possible to the middle of the city she built a bridge with the stones she had dug, binding the stones together with iron and lead. On this bridge she stretched, each morning, square hewn planks on which the people of Babylon*

> *could cross. By night the planks were withdrawn, so that the inhabitants might not keep crossing at night and steal from one another.”*

Herodotus' report does not tell about the construction of this bridge and leaves much room for imagination on how the bridge might actually have looked like. His second report on a bridge, however, gives a more detailed view. A floating pontoon bridge was used by Persian King Xerxes to cross the Hellespont with his large army in the year 480 BC (Brown 1993). Herodotus describes the bridge in detail (Greene 1987, pp482f):

> *“It is seven stades* (a stade was about 660 feet) *from Abydos to the land opposite. […] This is how they built the bridge: they set together both penteconters and triremes, three hundred and sixty to bear the bridge on the side nearest the Euxine and three hundred and fourteen for the other bridge, all at an oblique angle to the Pontus but parallel with the current of the Hellespont. This was done to lighten the strain on the cables. […] When the strait was bridged, they sawed logs of wood, making them equal to the width of the floating raft, and set these logs on the stretched cables, and then, having laid them together alongside, they fastened them together again at the top. Having done this, they strewed brushwood over it, and, having laid the brushwood in order, they carried earth on the top of that; they stamped down the earth and then put up a barrier on either side…”*

If one considers Herodotus' account to be accurate the bridge must have been a fairly impressive structure and without any equivalent at its time. Especially the description of how the pontoons were anchored indicates a well developed understanding of structural principles. Use of bridges for military needs was not uncommon in ancient times. Gaius Iulius Caesar (100 - 44 BC) is amongst the authors who left us very clear records of early bridges. In his *De Bello Gallico*, written in 51 or 50 BC, he mentions several bridges that he had his troops build during his conquest, e.g. across the Saône, and in the fourth book he describes the famous timber bridge built across the Rhine in 55 BC. This type of bridge was actually rebuilt a second time later during his conquest. His description of the structure is to such detail that several attempts were made to reconstruct it, and it shows the level of knowledge to which the engineering profession had grown by that time (Wiseman and Wiseman 1990, pp78-80):

> *“Two piles a foot and a half thick, slightly pointed at their lower ends and of lengths dictated by the varying depth of the river, were fastened together two feet apart. We used tackle to lower these into the river, where they were fixed in the bed and driven home by pile drivers, not vertically, as piles usually are, but obliquely, leaning in the direction on the current.*

Opposite these, 40 feet lower down the river, two more piles were fixed, joined together in the same way, though this time against the force of the current. These two pairs were then joined by a beam two feet wide, whose ends fitted exactly into the spaces between the two piles of each pair. The pairs were kept apart from each other by means of braces that secured each pile to the end of the beam. So the piles were kept apart, and held fast in the opposite direction, the structure being so strong and the laws of physics such that the greater the force of the current, the more tightly were the timbers held in place.

A series of these piles and beams was put in position and connected by lengths of timber set across them, with poles and bundles of sticks laid on top. The structure was strong, but additional piles were driven in obliquely on the downstream side of the bridge; these were joined with the main structure and acted as buttresses to take the force of the current. Other piles too were fixed a little way upstream from the bridge so that if the natives sent down tree trunks or boats to demolish it, these barriers would lessen their impact and prevent the bridge being damaged.

Ten days after the collection of the timber was begun, the work was completed and the army led across."

Troitsky (1994) reports on an even older Roman timber bridge, the Pons Sublicius. It is the oldest Roman bridge whose name is known, named after the Latin word for wooden piles. This bridge was built in about 620 BC by King Ancus Marcius and spanned the River Tiber (Adkins and Adkins 1994).

The brief record of timber bridges given in this section would not be complete without mentioning Appolodorus' bridge across the Danube. It was built in about 104 AD under Emperor Trajan (O'Connor 1993). Its magnitude – the length must have been more than a kilometer – and the unique structure of timber arches makes it special among the Roman bridges of which we have record.

2.1.1.4 Timber Bridges

Timber bridges and timber superstructures on stone piers will probably have been prevailing in many parts of the Roman Empire at that time. Wood was a cheap construction material and abundantly available on the European continent. Furthermore it can be readily cut to shape and transported with much less effort than stone. The Romans already knew nails as means of

connecting timber. Even the principle of wooden trusses was already known, as reliefs on both the Trajan's Column in Rome (AD 113) and the Column of Marcus Aurelius (AD 193) clearly show truss-type railings of military bridges (O'Connor 1993). However, there is no historic evidence that the Romans actually used the truss as a structural element in their bridges. Truss systems may have actually been used for the wooden falsework that was used for erection of stone masonry arches.

2.1.1.5 Stone Bridges

Apart from timber bridges, stone masonry arch structures are examples of the outstanding skills of the ancient Romans. The Roman stone arches where built on wooden falsework or centering which could be reused for the next arch once one had been completed. The semicircular spans rested on strong piers on foundations dug deeply into the riverbed. Brown (1993) points out that due to the width of these piers between the solid abutments the overall cross section of the river was reduced, thus increasing the speed of the current. To deal with this problem the Romans built pointed cutwaters at the piers. A very comprehensive study on Roman arches can be found in O'Connor (1993).

The arches used were voussoir arches, which are put together of tapered stones with a keystone that closes the arch. Compressive forces from the dead load and the weight of traffic on the bridge hold the stones together even without use of any mortar. Corbelled arches, on the other hand, consist of stones put on top of each other in a cantilevering manner until they two halves finally meet in the middle. This principle was already known prior to Roman times and was used in vaulted tombs throughout the Old World. Both different arch types are shown in Figure 2-1.
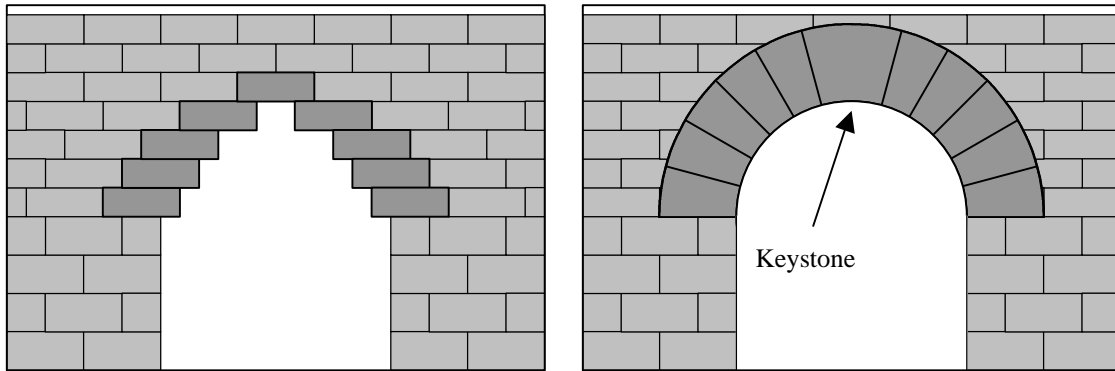
Figure 2-1: Corbelled Arch and Voussoir Arch

2.1.1.6 Aqueducts and Viaducts

The Roman infrastructure system was very well developed. It served both military and civil uses by providing an extensive network of roads. Aqueducts and viaducts of the Roman era can still be found scattered over the former Roman Empire, primarily in Italy, France, and Spain. Some Roman bridges or their remainders are also located in England, Africa and Asia Minor (O'Connor 1993).

Probably the best-known Roman aqueduct is the Pont du Gard near Nîmes in Southern France, which is shown in Figure 2-2. Built by Marcus Vipsanius Agrippa (64 - 12 BC) in about 19 BC, this structure was part of an aqueduct carrying water over more than 40 km (Liebenberg 1992). The crossing of the River Gard has an impressive height of 47.4 m above the river, consisting of three levels of semicircular arches that support the covered channel on top. The spans of the two lower levels are up to 22.4 m wide. All of its stone masonry was built without use of mortar except for the topmost level. A more recent addition to the Pont du Gard built in 1747 provides a walkway next to the bottom arch level that is an exact copy of the Roman architecture (Leonhardt 1982). Another well-known aqueduct can be found at Segovia in Spain.

Figure 2-2: The Pont du Gard, Nîmes, France (taken from Brown 1993, p18)

Sextus Iulius Frontius (c. 35 - 104 AD) wrote *De Aquis Urbis Romae* on the history and technology of the Roman aqueducts (O'Connor 1993). Aqueducts were used to provide thermae, baths, and public fountains with water; few residential buildings had an own connection. However though, the amount of water available for every citizen is estimated to have equaled or even exceeded today's standards for water supply systems. Adkins and Adkins (1994) speak of half a million to a million cubic meters of water that were provided through Rome's aqueducts per day.

Located in Spain is a bridge that attracts interest because of its scale and the magnificent setting. The Puente de Alcántara crosses the River Tagus at Caceres close to the border to Portugal with six elegant masonry arches as shown in Figure 2-3. Again, these arches were built without the use of mortar. The name of the bridge contains some redundancy, since it is derived from an old Arabic term for 'bridge'. The two main arches with a gate on the roadway are higher than the Pont du Gard and remain the longest Roman arches, both spanning 30 m (Brown 1993). The name of the Roman engineer who built this masterpiece in 98 AD under Emperor Trajan is known. Caius Iulius Lacer's tomb is found nearby, and the gate with the famous inscription *Pontem perpetui mansuram in saecula mundi* (I leave a bridge forever in the centuries of the world) has survived the centuries (Gies 1963, p16).

Figure 2-3: The Puente de Alcántara, Caceres, Spain (taken from Brown 1993, p25)

Even earlier dates the Pons Augustus or Ponte d'Augusto in Rimini, Italy. It was begun under Emperor Augustus and finished in 20 AD under Emperor Tiberius (O'Connor 1993) and is considered one of the most beautiful Roman bridges known. Five solid spans of only medium lengths between 8 and 10.6 m are decorated in an extraordinary way, with niches framed by pilasters over each pier (Steinman and Watson 1941). Andrea Palladio, architect of the Renaissance, used this bridge to develop his own bridges, and thus spread the fame of this bridge across Europe, as Gies (1963) writes.

Rome itself still houses ancient bridges built during the Roman era. Brown (1993) gives information that eight major masonry bridges are known of in Rome, of which six still exist at the River Tiber. They are the Ponte Rotto or Pons Aemilius, of which only a single span remains, initially built in the second century BC, the Ponte Mollo (or Milvio) or Pons Mulvius, built 110 BC; and the Ponte dei Quattro Capi or Pons Fabricius, built 62 BC. The Ponte Cestius was built 43 BC and altered under subsequent emperors. Considered to be the most beautiful of Rome's bridges is the Pons Aelius (now known as Ponte Sant'Angelo), built AD 134 under Emperor Hadrian. Giovanni Lorenzo Bernini (1598 - 1680) modified it in 1668 by adding statues of angels and a cast iron railing. The Ponte Sant'Angelo is shown in Figure 2-4. The Ponte Sisto, the youngest bridge of this ensemble, was built in AD 370.

Figure 2-4: The Ponte Sant'Angelo, Rome, Italy (taken from Leonhardt 1984, p69)

2.1.1.7 Religious Symbolism

An interesting fact in the context of early bridge building is religious symbolism. Higher positions in Roman hierarchy often involved both spiritual and practical tasks, such as control of the markets and storage facilities, or the building activities. O'Connor (1993, p2) tells that bridge building supervision "was placed in the care of the high priest, who received the title *pontifex*, commonly translated as 'bridge builder', from the Latin *pons* (bridge) and *facere* (to make or build)." This title, *pontifex maximus*, was passed on to later Roman emperors and through early Christian bishops even to the present Pope. In this context O'Connor (1993, p3) offers the explanation that this important title symbolized the "bridge from God to man…"

2.1.1.8 Vitruvius' De Architectura

The famous Roman architect and engineer Marcus Vitruvius Pollio (Morgan 1960) does not specifically mention bridges in his work *De Architectura* (The Ten Books on Architecture), which was written in the first century BC. However, aqueducts are the topic of a whole chapter in Book Eight, and cofferdams, important for erecting bridge piers in riverbeds, are described in detail in a section on harbors, breakwaters, and shipyards. According to him, a double enclosing was constructed of wooden stakes with ties between them, into which clays was placed and compacted. Afterwards, the water within the cofferdam was removed (several different engines to pump water, such as water wheels and mills, and the water screw are described by him), and work on the pier foundations could begin. In case the soil was to soft Vitruvius advised to stake the soil with piles.

Another fact of particular interest for today's engineers is the description of concrete that Vitruvius gives. In a comprehensive list of construction materials the origin and use of *pozzolana* is described, a volcanic material that performs a cementitious reaction if mixed as a powder with lime, rubble, and water. This reaction is hydraulic; i.e. the concrete obtained, called *opus caementitium*, can harden even under water. Together with use of brick masonry and natural stone, as well as with timber and sand, the Romans had an enormous range of flexibility in constructing their buildings and structures. A truly unique example of their skills is the Pantheon

in Rome, built under Emperor Hadrian around the year AD 125. It is topped with a majestic 43.2-m wide dome made of ring layers of concrete (Harries 1995). Use of lighter aggregates towards the top, stress-relieving masonry rings, regular voids on the inside and tapering of the dome to reduce its weight provide the structural stability that has made the Pantheon withstand all influences until the present day.

2.1.1.9 Contributions of Ancient Bridge Building

In conclusion, the main bridge construction principles were already known and used to some extent in ancient times. Due to lack of surviving timber structures one can only rely on historical reports and depictions of these. Prevailing structures in ancient times were the semicircular stone arch bridges, many of which have survived until the present day. Roman builders left a legacy of impressive structures in all parts of former Roman Empire. Arch structures were intelligently used both for heavy traffic and elaborate water supply systems; temporary timber structures also served military purposes. These systems were developed to the full extent that was technically possible and were not to be surpassed in mastery until many centuries later.

Engineering knowledge was already documented systematically by authors such as Vitruvius, whose work influenced the builders of later centuries considerably. Great builders and artists, such as Bramante, Michelangelo, and Palladio were careful students of his works.

2.1.2   The Middle Ages

For the historical overview given in this study, the term Middle Ages refers to the period of time between the fifth and the late fifteenth century; other authors may set somewhat different limits, e.g. the eleventh to the sixteenth century (Troitsky 1994). Thus, spanning a time of about a thousand years in one section of this study can necessarily not cover all bridges built, but give a representative selection of the achievements that were made. Their significance and history will be discussed further in this section.

2.1.2.1 Preservation of Roman Knowledge

After more than 1,200 years of existence, the once mighty Roman Empire finally fell apart around the fifth century AD (Adkins and Adkins 1994), and a period of anarchy and chaos began. Invasions of the Eternal City destroyed much of the former grandeur. The major achievements of the Roman civilization began to be forgotten, and their cities were deserted. Bridges as large and solid as the Roman bridges were to be built again only centuries later. Gies (1963) reports that the predominant community structures in Europe of the eighth and ninth century were small feudal agricultural states. The knowledge of Roman culture was kept in monasteries scattered across the old continent. Ancient authors, such as Vitruvius, were copied by hand many times by the monks who thus preserved these treasures for future generations.

2.1.2.2 Bridges in the Middle East and Asia

At about the same time another rise of bridge building began. Had the Romans themselves vanished in Europe, their influence on the Middle East and even Asia began to prosper. Persian rulers built pointed brick arches, and the coming blossom of bridge building reached as far as China, as Gies (1963) reports. The Chinese skillfully built elegant segmental stone arches with roadways that followed the swinging shape of the arch, and they also built cantilevers of timber on stone piers. According to Gies (1963) examples were reported by the thirteenth century Venetian explorer Marco Polo (c. 1254 - 1324), who traveled Asia for several decades and contributed much to the European view of the world. Indian cultures undertook own bridge building under this influence and further developed the suspension bridges.

2.1.2.3 Revival of European Bridge Building

Finally, the art of bridge building also began to blossom in Europe again. Most authors particularly mention the importance of the church in the Middle Ages that contributed to this

development. Contacts with the Middle East were made during the crusades, when the pilgrims and knights saw evidence of the skills of Arabian cultures.

Importance of the church in these times cannot be exaggerated, since in many cases the order that in society existed was enforced primarily by clergymen who held court, regulated merchants' fairs, and kept the monasteries as centers of knowledge and spiritual experience. It has already been mentioned in Section 2.1.1.7 how the ancient title *pontifex maximus* of the Roman high priest became to be used by the Popes.

The church had considerable influence on all major medieval building undertakings. The biggest of these structures, the awe-inspiring cathedrals and large stone bridges, would not have been built otherwise. Working on them was considered to be pious work (Gies 1963) and was thus a very honorable task to be performed. Some religious orders formed to bring progress to hospices and to build bridges for the travelers' sake (Steinman and Watson 1941). Spreading from Italy, where the *Fratres Pontifices* originated from, similar brotherhoods also formed in other countries, e.g. France (*Frères Pontiffes*) and England (*Brothers of the Bridge*).
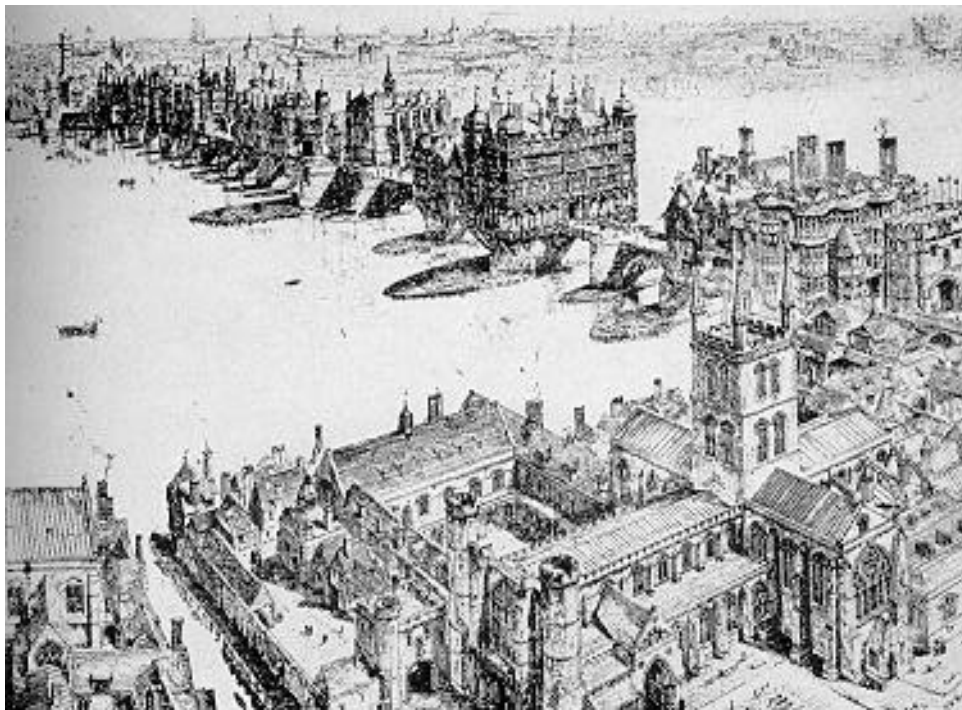
2.1.2.4 Construction and History of Old London Bridge

Probably the most colorful and vivid history, unsurpassed by any other, is related to a bridge located in a city that gained an enormous growth in the medieval times (Gies 1963, p47). London had been founded by the Romans, who called it Londinium. Little is known about the centuries after the Romans had left and about former bridges in London, although there is arguments for an early timber structure that crossed the Thames in AD 993 (Gies 1963).

Peter of Colechurch, a monk from a nearby district of the city, was the builder of Old London Bridge, which was built between 1176 and 1209. He was never to see his bridge finished, since he died in 1205 and was buried in the chapel that he had built on the bridge. As can be seen in Figure 2-5, Old London Bridge altogether consisted of nineteen pointed masonry arches on crude piers with large cutwaters, none of them equal in shape. A drawbridge was also included in the structure. Piles were rammed into the soft bed of the river on which the piers rested. The bridge

must have seemed very massive and inelegant to an observer, and its appearance would change even further with later centuries. Fortifications on the bridge, namely the two towering gates were added. It became customs to display the heads of executed prisoners on top of this gate, and after building a new tower for a decayed one, it was thereafter called Traitor's Gate (Gies 1963).

As the length of Old London Bridge was only about 300 m the massive piers of Old London Bridge took away more than half of the width of the river so that the speed of the current increased tremendously. Boats with passengers were said to be "shooting the bridge" when they passed under it, and records of numerous accidents have been reported (Gies 1963, p40).

Figure 2-5: Old London Bridge, London, Great Britain

(taken from Steinman and Watson 1941, p69)

Located in the heart of London, Old London Bridge served the city for more than six hundred years, and for most of this time, about five and a half centuries, it remained the only solid passing

of the Thames. In 1740 finally, Westminster Bridge was built, and in 1831 building a new bridge at the old location was begun.

Over all this long time Old London Bridge continuously changed its appearance. Apart from the chapel already mentioned, more buildings were added on top of the superstructure. Except for a few openings where the river could actually be seen from the roadway, the bridge in its later days carried literally dozens of houses. These were crammed at both sides of the roadway, leaving only relatively little space in the middle. Wooden frames held the houses together over the roadway, and some reportedly even had basements under the arch spans, leaving even less room for boats to pass. Even wheels were erected under several spans to power watermills. Merchandising flourished on the bridge and tolls were collected for passing it. The ease of water supply and wastewater removal at the bridge made it a favorite place for the trades of the Londoners, Gies (1963) lines out.

Many anecdotes and legends are attached to Old London Bridge. It even once happened that a complete house fell off the bridge into the Thames. As Steinman and Watson (1941, p64) put it, the "life story of this six-hundred-year-old bridge would fill many a good-sized volume and would include exciting accounts of fire, tournaments, battles, fairs, royal processions, dramas, songs, and dances." A highly readable description of these centuries full of history is given in a chapter by Gies (1963).

2.1.2.5 The Pont d'Avignon

As with Old London Bridge the bridge over the Rhône at Avignon has a legendary history. It is not exactly known who the builder was; some sources mention the name of Brother Bénoît as the builder, who began work on the bridge in 1178. The legend, however, is related to the vision of a local shepherd named Bénèzet, after which the Bishop of Avignon had the bridge built. In comparison with Old London Bridge, though built almost at the same time, the Pont d'Avignon was much more elegant. It bridged the 900-m long distance with twenty or twenty-one elliptical arches of which only four remain with spans up to 35 m, longer than any Roman arches. All other

spans were destroyed in wars and through ice on the river. The Pont d'Avignon was built in merely ten years (Brown 1993). A new arch shape, the so-called three-centered arch was used for the spans, which composed of two segments of a circle that are connected with a smaller curved segment at their top.

In accuracy of the stone masonry and with its majestic elegance the Pont d'Avignon was the first bridge in Europe that could achieve and surpass the Roman level of engineering. The remaining arches carry a small chapel at which the roadway of the bridge narrows down to only 2 m for defense purposes. Bénèzet died prior to completion in 1184 and was buried in the chapel.

2.1.2.6 Further Notable Medieval Bridges

Several other medieval bridges are worth being mentioned in this overview of medieval bridge building. The Pont Valentré at Cahors in France, shown in Figure 2-6, is about 150 years younger than the Pont d'Avignon. It resembles its older brother with its pointed slender arches and the triangular cutwaters, but has been preserved completely. Six regular arches of 16.5 m span length and three watchtowers at its ends and in its middle (Brown 1993) give the bridge over the Lot a graceful appearance.

Figure 2-6: The Pont Valentré, Cahors, France (taken from Brown 1993, p29)

A multiuse bridge from 1345 that was built by Taddeo Gaddi (c. 1300 - 1366) can be found in the old merchants' city of Florence in Italy. Although it then had a relatively small in population from today's point of view, Florence was an important center for trades of all kinds. It also was home to the famous Medici, a family clan that had gained enormous wealth and influence through banking and commerce since the thirteenth century. Later, they also supported the fine arts and thus contributed to Florence becoming a major cultural center of Europe of the Renaissance. Today, unlike any other city, Florence houses buildings from the Renaissance times. The Ponte Vecchio crosses the River Arno with three shallow arch spans, of which the

middle span reaches 30 m length. Figure 2-7 shows this truly unique bridge. In this bridge for the first time segmental arches were used. The segmental arch consists of an arch with less than a semicircular curvature, thus having a much smaller rise. Later the bridge was extended and turned into a covered bridge by building shops at both sides of the roadway and a gallery above these that connects the Uffizi and Pitti Palaces (Brown 1993). The shops are still in use by goldsmiths today.

Figure 2-7: The Ponte Vecchio, Florence, Italy (taken from Leonhardt 1984, p75)

Steinman and Watson (1941) report of covered medieval timber bridges that have been preserved until today, especially a pair of bridges in Lucerne, Switzerland. Both bridges, the Kapellbrücke and the Spreuerbrücke, are crossing the River Reuss and were part of the medieval city's

fortifications. The Kapellbrücke with the so-called Wasserturm (watertower) is said to date from 1333 (Steinman and Watson 1941) and has its name from a nearby chapel of St. Peter. It is shown in Figure 2-8. Paintings under the roof show scenes from the local history. Similar in shape, the Spreuerbrücke was completed in 1408. It features a large amount of pictures under its wooden roof that depict a Dance of Death, painted in the seventeenth century, as Gies (1963) reports.

Figure 2-8: The Kapellbrücke, Lucerne, Switzerland (taken from Brown 1993, p76)

The last bridge to be mentioned in this account is in itself a link between different historical eras. The Charles Bridge (Karluv Most) in Prague in the Czech Republic was built after a flood in 1342 had destroyed a previous structure across the River Vltava. Emperor Charles IV had the new bridge begun in 1357 under the leadership of Peter Parlér. Its total length of almost 520 m was achieved by building sixteen arches with a maximum span of 23.4 m. The bridge is not

exactly straight, but has two slight curves in its longitudinal axis, probably because the builder thus utilized more favorable ground conditions for the pier foundations. A mixture of styles can be found in the bridge; the arches are still Roman in their almost semicircular shape, whereas the solid triangular cutwaters are clearly medieval (Brown 1983). Two decorated towers are found at the bridge with one of them dating back to the twelfth century, being renovated in 1590 in the Renaissance style. Especially the thirty Baroque statues of Saints on the parapets, mostly of stone, have made the bridge famous. Construction was mainly finished by the end of the fourteenth century, although some reports point out a period of one and a half centuries (Brown 1993). However, the many changes and additions of later times contributed to the unique appearance of the bridge, which is a symbol of the city of Prague itself.

Figure 2-9: The Charles Bridge, Prague, Czech Republic (taken from Brown 1993, p32)

2.1.2.7 Purpose of Medieval Bridges

A very important characterization of medieval bridge building and their decorations is given by Steinman and Watson (1941), who lay out that medieval bridges served the following purposes:

They served military, spiritual, and even commercial and residential functions. Thus, medieval bridges were the first example of real multipurpose bridges and were indeed closely linked with the lives of their contemporaries. This multi-purpose concept later reappears in the twentieth century as an expectation for the future of bridge utilization and is discussed in Section 2.2.3.3.4.

2.1.2.8 Contributions of Medieval Bridge Building

During medieval times bridge construction was revived in the Old World with considerable influence of the church. Construction was based on empirical knowledge of materials and structural behavior. The level of mastery and accuracy that the Roman engineers had set in their stone masonry was hardly reached again until the coming era that had just began to dawn. Sometimes the bridges were even built with rubble and a brick veneer, as Steinman and Watson (1941) point out. They also note that building solid foundations for the massive piers was a problem, as especially the mortar employed was not made of the durable hydraulic cement that the Romans had used, but normal lime mortar. Span lengths rarely surpassed Roman achievements.

Development was made, however, in the shape of arches. Formerly only semicircular arches with a height of half their diameter had been used in Europe. Now pointed and even flat segmental arches offered much flexibility for span-to-rise ratios. An advantage of pointed arches was that they put less load on the falsework, which makes their construction easier (Troitsky 1994). Even some multi-centered elliptical arches were constructed, as e.g. in the Pont d'Avignon.

In conclusion it can be stated that although the bridges of the Middle Ages are impressive in their history, few real engineering developments were made in the art of bridge construction, except for more varied shapes of the arches, especially in longer multi-span river crossings.

2.1.3   The Renaissance

Had the church and its focus on the spiritual world strongly influenced people of the medieval times, the Renaissance brought along a change in thinking. Renaissance literally translated means rebirth, in a classical sense. The Renaissance times put "emphasis on this life, not on that of the hereafter" (Steinman and Watson 1941, p71). The importance of learning and the accumulation of knowledge grew again after the first European universities had been formed as early as the thirteenth century. Along with this new mentality went commercial growth, more traffic, and naturally also the need for more and better roads and bridges. Arts explored new areas and the natural sciences were prospering in their development. Multi-talented personalities performed their work during those times. Steinman and Watson (1941) specifically name Leonardo da Vinci, Filippo Brunelleschi, Michelangelo Buonarroti, Georgius Agricola, Nicholas Copernicus, Galileo Galilei, and Francis Bacon, not to forget William Shakespeare, Johannes Kepler, Tycho Brahe, Blaise Pascal, Christiaan Huygens, Isaac Newton, Robert Hooke, and others. It is this colorful and creative mixture that makes the Renaissance a very interesting era in the development of humanity.

2.1.3.1 Renaissance Trusses

During the Renaissance, the truss system was developed further for use in bridge construction. Known since Roman times, the truss now was finally seen as a means of superstructure in itself. Every truss relies on the geometrical principle that the very shape of a triangle cannot be changed without disrupting the length of any of its sides. Gies (1963, p100) puts this in a clear sentence, "a triangle cannot be distorted." Structures constructed of triangles – or, in modern times, of their spatial equivalent, the tetrahedron – thus are very strong. Regardless of the stiffness of its hinges the truss is resistant to forces imposed. Many special truss configurations developed later in building covered bridges in America (see Section 2.1.4.6), carrying the names of their developers, and there is virtually no limit to the possibilities of the truss principle.

2.1.3.2 Palladio's I Quattro Libri dell'Architettura

Andrea Palladio (1508 - 1580), born in Padua as Andrea di Pietro dalla Gondola, described several different trusses in his *I Quattro Libri dell'Architettura* (The Four Books of Architecture) (Palladio 1570), also mentioning an arched truss. An example of his designs is shown in Figure 2-10.
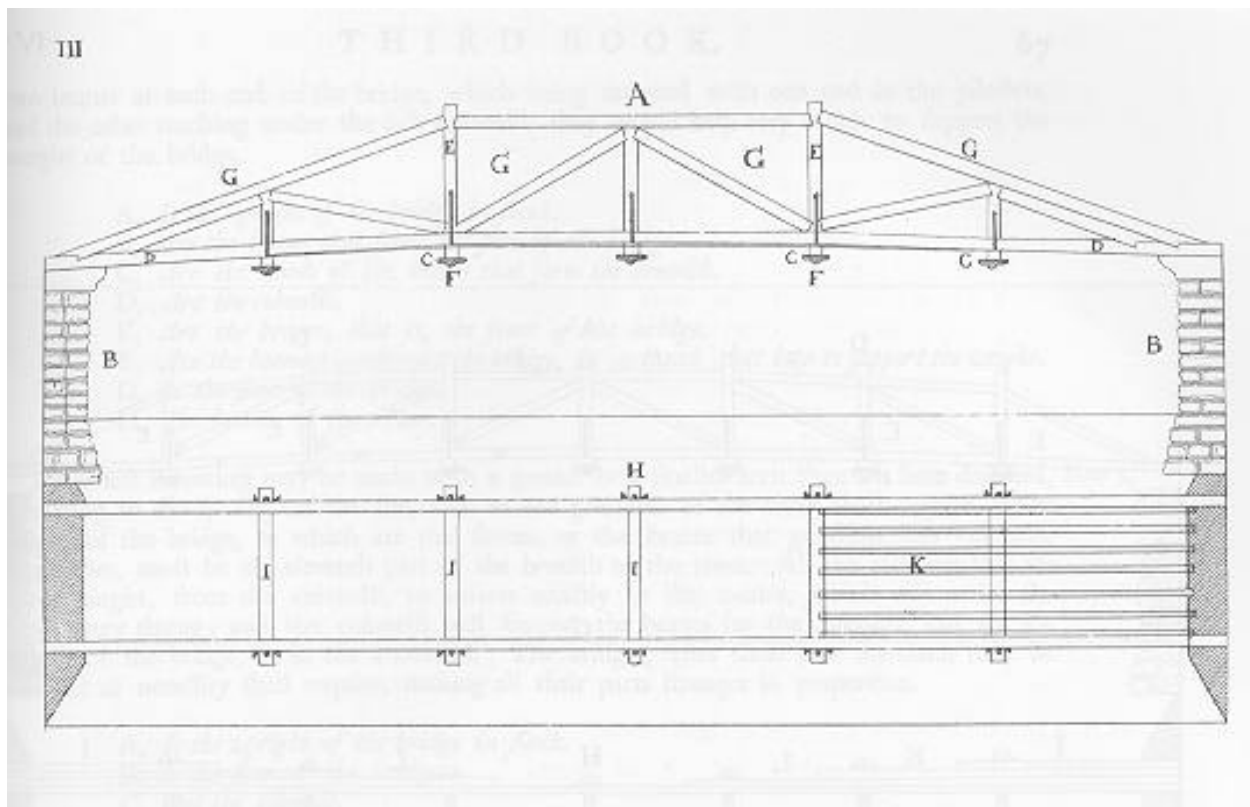

Figure 2-10: Palladian Truss (taken from Palladio 1570, p66)

He made use of the so-called king post truss, which consisted of a triangle that had a vertical member resting on the lower chord, the king post (Gies 1963). These designs for the most part were not used in practice until much later, as his ideas still were very advanced for his times. Palladio, according to Steinman and Watson (1941) was strongly influenced by Vitruvius, whose *De Architectura* he translated. Palladio revived the classical architectural orders that Vitruvius

had described and wrote extensively about materials and geometrical proportioning, private and public buildings, and about roads and ancient and modern bridges. Truss structures had already been used extensively in building construction, specifically for roof trusses, and it is astonishing that no major bridges of the truss system where built earlier.

2.1.3.3 Veranzio's Machinae Novae

Brown (1993) mentions the ideas of another outstanding architect and engineer, Fausto Veranzio (or Faustus Verantius, 1551 - 1617), who published his *Machinae Novae* (Veranzio 1615) in about 1615. Interesting about this work is both the technical contents, and the way of publication. Veranzio compiled a comprehensive volume of existing and theoretical mechanical engines, mostly watermills, windmills, clocks, a parachute – similar to da Vinci's (1452 - 1519) design – and some agricultural tools. Most important, however, are the depictions and descriptions of bridges that appeared. A very simple truss, wooden arch bridges, and even a masonry arch with prestressing rods are included. Modern looking suspension bridges made of ropes or iron eyebars are further presented in considerable detail.

Two editions of *Machinae Novae* are known, one of which contains the copperplate engravings and the text in Latin and Italian, another edition additionally contains the text in old-fashioned Spanish, French and German. Several other books of mechanical engines were published in about this time. The afterword of Veranzio's facsimile edition mentions a number of other authors.

2.1.3.4 The Rialto Bridge

Similar in concept to the Ponte Vecchio, but completely different in its appearance is the Rialto Bridge in Venice, Italy, over the Canale Grande, built 1587 - 1591 when a previous bridge over the Grand Canal was to be replaced because of obsolescence. Venice by this time was a flourishing merchants' and seafarers' city. Over several decades a variety of proposals were submitted to the Venetian Senate, including a design by Palladio until the final design by

Antonio da Ponte (1512 - 1597) was chosen. A single 27-m long segmental arch spans the waters with a 6.4 m rise and the considerable width of 22.9 m (Brown 1993). The Rialto Bridge is shown in Figure 2-11.

Figure 2-11: The Rialto Bridge, Venice, Italy (taken from Leonhardt 1984, p96)

Most difficult to construct were the foundations, which required stepped groups of piles to be rammed into the soft ground close to existing buildings, onto which masonry layers were placed. A mechanical pile hammer was used (Steinman and Watson 1941) to drive the piles to refusal. Doubts as to the stability of the foundations arose in public and interrupted the construction process. Finally construction was resumed after an investigation by the Venetian Senate decided in favor of da Ponte and his work. Major falsework was erected to build the single span. The

courses of stones in most of the superstructure were laid in voussoir-like fashion radial to the centerpoint of the arch, giving the arch an enormous stability. Shortly after completion the bridge really proved to be stable when it withstood an earthquake without any damages. Two rows of small shops at both sides of the bridge with a center roof above give the bridge its typical unique appearance (Brown 1993, pp36f).

2.1.3.5 French Renaissance Bridge Building

France became an important location in bridge building in the Renaissance. King Louis XIV had the so-called *Corps des Ponts and Chaussées* established in 1716 in order to promote the building and maintenance of the national road system. Derived from the success of this group the *École des Ponts et Chaussées* was founded and became the first real engineering school worldwide. An experienced engineer, Jean-Rodolphe Perronet (1708 - 1794) took the lead of this institution. Brown (1993) also provides background information on Perronet's most important discovery. When noticing that an arch of a bridge under construction was leaning to the still-to-be-built span Perronet realized that the arches mutually exerted horizontal thrust. This principle he used for the Pont de Neuilly, built 1771 to 1772 across the Seine north of Paris with five elliptical 36.6-m spans. The arches he constructed were extraordinarily shallow and rested on very slender piers of only 4 m width, with strong abutments resisting the thrust from the arches. Perronet also experimented with horse-driven piles (Gies 1963). Furthermore, the Pont de Neuilly incorporated a relatively new shape of the arches themselves – a tapered edge of the arches called *corne de vache* created a shadow that underlined the arches and made their front view appear even shallower, as can be see in Figure 2-12. This *corne de vache*, or splayed arch (Steinman and Watson 1941), had been used for the first time in another stone arch erected in Paris, the Pont Notre Dame, built by the priest Fra Giovanni Giocondo between 1500 and 1507 (Gies 1963). This special design, according to Gies (1963) also facilitates a broader deck and funnels the passage of floodwaters through the arch.
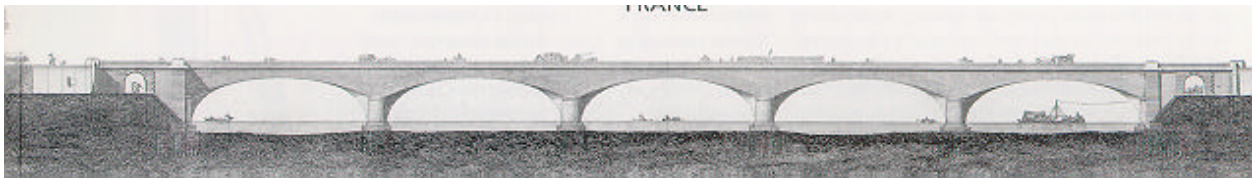
Figure 2-12: The Pont de Neuilly, Paris, France (taken from Brown 1993, p42)

However, the new construction scheme of shallow segmental arches required that the arches were erected on falsework simultaneously. Previous constructions had mostly utilized very solid piers that carried an arch even when its neighbors had not been completed yet. In this case, construction of the superstructure was done during one year only, which employed a large work crew. Perronet used sophisticated means to construct the foundations. The bucket wheels to dewater the cofferdams were powered by the current of the river itself (Brown 1993). Despite the elaborate manner of construction and the reduced weight of the long-spanning bridge, there were still some settlements of the piers. The Pont de Neuilly remained in service until 1956, when it was removed.

Perronet built several other bridges. His final works, the Pont de la Concorde in Paris, built 1787 to 1791, remains an example of extraordinary engineering achievement. Its five arches with slightly increasing span lengths towards the middle arch bridge the Seine are shown in Figure 2-13. The parapet of this bridge is not massive, as usually built until then, but an open balustrade that gives the bridge further lightness (Leonhardt 1984).

Figure 2-13: The Pont de la Concorde, Paris, France (taken from Leonhardt 1984, p83)

Another well-known bridge of the same era shall not remain unmentioned at this point, as it is a very beautiful structure of harmonic proportions, shown in Figure 2-14. The Pont Neuf, which literally means "New Bridge", is located at one end of the Seine Island and was built between 1578 and 1607. Leonhardt (1984) notes the unusual width of 20.8 m, which also incorporated the *corne de vache* principle. The Seine Island divides the bridge into two parts, a longer northern half with seven arches, and a southern half with five skewed arches. The pier width is only 4.5 m. Cofferdams were employed, but regarding the foundations Steinman and Watson (1941) report that initially no pile foundation was built to withstand the scour of the river current, making repair work necessary.

Figure 2-14: The Pont Neuf, Paris, France (taken from Leonhardt 1984, p92)

2.1.3.6 English Renaissance Bridge Building

After Old London Bridge had served the British capital for about 550 years, finally plans for a new bridge were made. Westminster Bridge was built between 1740 and 1747, carrying out a thirteen-span version with semicircular arches and pronounced piers. As the foundations were the most difficult part of the works, the Westminster Bridge Commission asked the builder, Charles Labelye, to first only build the foundations until further notice (Brown 1993). Labelye was a graduate of the *École des Ponts et Chaussées* that was mentioned in Section 2.1.3.5 (Gies 1963). Brown further reports that Labelye efficiently used a timber caisson, whose base remained under layers of masonry whereas the sides could be detached and reused. Père Romain, who was consulted by the designer Jules-Hardouin Mansart in building the Pont Royal in Paris, had first

used the caisson technique in 1685 (Gies 1963). Labelye furthermore employed horse-driven piledriving machines that were far more effective than manually driven machines. But even with these sophisticated techniques foundation of bridges remained difficult, for some considerable settlement in one of the piers of Westminster Bridge required extensive repair work around the pier.

2.1.3.7 Contributions of Renaissance Bridge Building

The Renaissance times brought more daring bridge structures with them. The piers of the bridges became more slender as the span-to-rise ratios of the bridges became larger. Had the ratio formerly mostly been very small, the Renaissance bridges brought along a considerable increase in span-to-rise ratios. Most importantly, the bridge builders used elliptical arches, as the three-centered arch, and very shallow segmental arches to their full extent.

Although there were still some problems with foundations of the piers, a variety of methods, e.g. using piledriving machines and cofferdams as well as the first caissons had been used in practice and builders were confident in these methods. The need to follow suitable ground conditions in the riverbed diminished, so that more flexibility in location of bridges and their piers grew.

The bridges naturally had to withstand the same environmental influences, but they were mastered in different ways now. Longer slender spans with fewer piers diminished the problem of scour at the foundations considerably, and the builders also experimented with cutwater shapes different from the triangular medieval type, i.e. more rounded forms as for the Pont de la Concorde. Tapered edges, called *corne de vache*, could better lead the waters through the bridge in case of floods. Piers were not built extremely solid anymore to withstand the construction loads from an unfinished arch and to withstand the pressures exerted by floodwaters and ice on the river. Segmental arches were shallower than semicircular arches. However though, their abutments needed to be strong to withstand the horizontal forces that arose from these arches. It has already been mentioned that segmental arches required considerable work efforts to erect all spans at the same time.

Summarizing, the Renaissance did not only change the appearance of bridges, but also successfully experimented with new principles in bridge construction, thus giving later builders a bigger variety of choice how to build their bridges at hand. A new revolution was still to come that did not arise from varying stone arches anymore, but that opened new horizons through introduction of a new material into bridge construction – iron.

2.1.4 The Industrial Revolution

The country in which the Industrial Revolution took its beginning was England. The development of spinning and weaving machines and the development of the steam engine and later of the steam locomotive all fall into this time. England had rich resources in coal and iron ore that supported the progress of industrialization. With growing industrial production, railway tracks were spreading across the country and required building many new bridges to cross natural obstacles.

2.1.4.1 The Ironbridge

Brown (1993) reports of the Englishman Robert Mylne (1734 - 1811), who made an important contribution to modern bridge building; he sketched the design of a small bridge with iron arches. The bridge that he had depicted was never built, but the first step had been done. After other engineers had produced similar designs for small iron arches, finally a bridge was built in 1777 to 1779 that opened the way to a new chapter in the history of bridge building. The first bridge built completely of iron is now a cherished British monument.

The Coalbrookdale region at the River Severn can be considered one of the centers from which the Industrial Revolution spread. The location of this developing mining area with furnaces to melt iron made it ideal to built the first bridge of cast iron. Cast iron is strong in both tension and compression, making very slender members possible. The Ironbridge near Coalbrookdale is shown in Figure 2-15. It has a single span of 30.5 m that rests between two masonry abutments.

Five semicircular ribs that were cast in two halves formed the arch. Its erection over a deep valley took only three months. In its design the Ironbridge relied on masonry and timber structures, which was specifically apparent in the dovetail joints and wedges utilized (Brown 1993). Appreciation of the new possibilities that lay in the material iron had just begun. Bridge projects that fully utilized the advantages of iron were realized in the next decades to come.

Figure 2-15: The Ironbridge, Coalbrookdale, Great Britain (taken from Brown 1993, p44)

2.1.4.2 Early Iron Structures

Some names are closely linked to the further development of iron bridges. Thomas Telford (1757 - 1834) is considered one of the greatest British engineers. He was born in Scotland, worked in the area of the Ironbridge, and he started building bridges a few years after the Ironbridge itself had been built. Telford pioneered the art of building bridges of iron in the following years.

A truly beautiful bridge that was built in 1815 after his design is the Craigellachie Bridge over the River Spey in Scotland, which is shown in Figure 2-16. It consists of a slender trussed arch with a gently curved roadway supported on a framework of diagonals. The bridge rests on inclined masonry abutments, each decorated with two circular towers in medieval style.

Figure 2-16: The Craigellachie Bridge, Great Britain (taken from Leonhardt 1984, p222)

In 1805 Telford built a major iron-trough aqueduct at Pontcysyllte in Scotland to drag boats across. It carries a canal at a maximum of 38.7 m over ground across the River Dee on a length of 307 m. Its nineteen arches have a span of 13.7 m and consist of cast iron members (Brown 1993).

The thin-walled waterway rests on the arches that are separated by masonry diaphragms on top of the stone masonry piers, and it is strengthened by stiffening ribs at its outside that give the large structure a regular pattern.

The great number of different structures that were built under Telford's supervision is a good example of the broad scope of projects that a civil engineer of the nineteenth century could participate in. Telford became the first president of the Institution of Civil Engineers, as Gies (1963) reports. His greatest achievement, the Menai Strait Bridge, will be presented in the following Section 2.1.4.4.

John Rennie (1761 - 1821), also of Scottish roots, developed designs for iron arches similar to the one at Coalbrookdale, but was mainly involved in masonry bridges and gathered considerable experience and reputation with these. His work gave London the Waterloo Bridge. It was built between 1810 and 1817 and consisted of nine plain elliptical granite arches of 36.6 m span with 6.1-m thick piers, which were decorated with two Doric columns on each side. Rennie decided upon use of cofferdams for all piers. Steam engines provided the power for pumps to dewater the cofferdams. Afterwards, prefabricated falsework was delivered by barges, setting it into place for the next arch once the previous one had been completed (Brown 1993). In 1930 the bridge was demolished because of unstable foundations and later replaced with a new bridge.

John Rennie built many masonry aqueducts in the growing canal system, of which the Lune Aqueduct, built in 1798 with strong semicircular arches, remains the largest in Great Britain (Brown 1993). He built the impressive Southwark Bridge across the Thames, a massive cast iron structure with three spans. The heavy center span had a length of 73.2 m and a rise of 7.3 m. Again, cofferdams were used to found the piers properly. Rennie also designed the replacement for Old London Bridge, whose story has been told briefly in Section 2.1.2.4. In 1746 a commission under Charles Labelye surveyed the bridge and later commissions made proposals to remove the buildings from its superstructure, perform some widening, and to replace two middle arches with a longer span. One proposal for the replacement that was never built came from Thomas Telford, who designed a 183-m cast iron arch. Rennie's son finally built New London Bridge with five elliptical spans between 39.6 and 43.6 m long. John Rennie died before the work had been begun. The bridge was opened in 1831 and survived until 1971 when the

remainders were transported to Lake Havasu City in Arizona to be re-erected there (Brown 1993). Figure 2-17 shows New London Bridge in its original state.

Figure 2-17: New London Bridge, London, Great Britain
(taken from Steinman and Watson 1941, p108)

2.1.4.3 Early Suspension Bridges

The modern suspension bridges particularly rely on the work of James Finley, who was a judge and justice of the peace in Pennsylvania and died in 1828 (Steinman and Watson 1941). He received several patents on chain suspension bridges. Although some of the bridges he built later collapsed, their construction was an important milestone in the development of modern

suspension bridges. All the important features of suspension bridges were incorporated in his designs: Towers holding the main chain cables, with hangers supporting the deck, which sometimes was stiffened with a truss. In 1809 a bridge near Philadelphia even incorporated a multi-span system. Shortly thereafter, the first temporary bridges with wire cables made of wrought iron appeared, and the eyebar chain cables were developed further. Tests were performed to gather data on the tensile strength.

In 1834, the Grand Pont Suspendu was completed in Fribourg, Switzerland to carry the traffic between Bern and Lausanne with a single span of 273 m length. Wire strands were grouped together to form the long and heavy main cables. However, the bridge construction was still conservative in the way the cables were constructed, as Brown (1993) points out. Severe corrosion problems required repair of the cable anchorages, the Grand Pont Suspendu was finally replaced by another structure. French engineer Henri Vicat invented the air-spun cables thereafter, which are used in all major suspension bridges today.

2.1.4.4 The Menai Strait Bridge

When working on road surveying, Telford proposed a three-span iron arch bridge (Gies 1963) to cross the Menai Strait in Wales with a roadway. His revised design of 1818 for a suspension bridge was chosen for construction. Classical semicircular masonry arches lead to the main suspended span of 176 m length that is shown in Figure 2-18. The massive masonry towers were erected between 1820 and the beginning of 1825. Altogether, sixteen chain cables needed to be hoisted from barges to the towers to support the roadway via hangers.

An intensive testing program of the iron bars of which the chains consisted had been performed, and Gies (1963) reports that the chains were designed in such a way that single elements could be replaced independently. In the years following the completion problems with wind undulations occurred. Several repairs and retrofitting became necessary, including bracing between the chains and a trussed railing, until the iron chains were finally replaced with steel (Brown 1993).

Figure 2-18: The Menai Strait Bridge, Great Britain (taken from Brown 1993, p58)
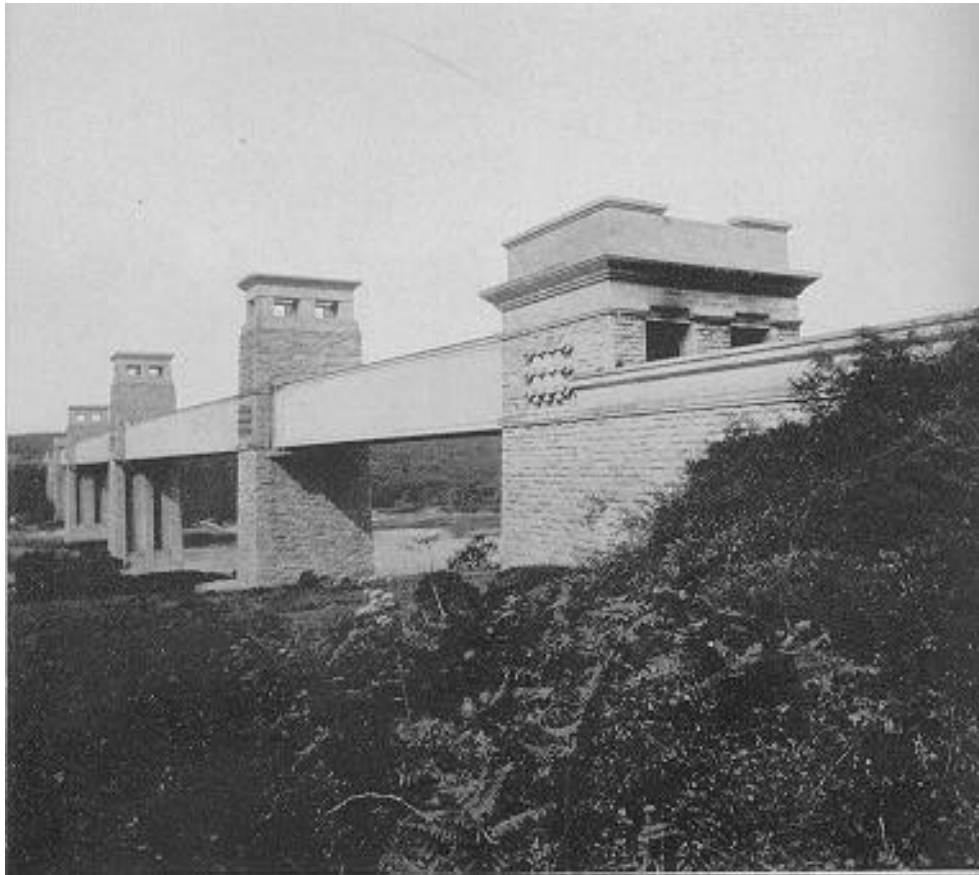
2.1.4.5 The Britannia Bridge

George Stephenson (1781 - 1848) is often referred to as the "Father of the Railways", because of his further development of the recently invented steam-driven locomotives. James Watt had come up with a steam engine in the early 1780s, and by the beginning of the nineteenth century, the first attempts of steam locomotives appeared.

Stephenson grew up near Newcastle in a coal-mining district surrounded by engines in workshops that inspired his talent and in 1814 built one of the early locomotives. Further improvements were made to his locomotives, until in 1825 he opened the Stockton and Darlington Railway, the world's first public railways. Thus he considerably influenced the then growing "Railway Mania", which according to Brown (1993, p62) around the mid-nineteenth century literally doubled the number of bridges in Great Britain.

Stephenson's son, Robert Stephenson (1803 - 1859) was an assistant in his father's company and contributed to his father's most famous work, the "Rocket", which in 1829 achieved a record

speed of about 57.9 km/h (36 mph). He also became an outstanding bridge engineer, who built a number of railway bridges. Most famous of these is the Britannia Bridge that also crossed the Menai Strait, close to Telford's daring structure. The Britannia Bridge is shown in its original state in Figure 2-19. It was built from 1846 to 1850 and consisted of four pairs of wrought-iron tubes that were chosen because of rigidity and requirements for free traffic flow under the bridge. First, the abutments and three massive towers were erected, with the highest tower in the middle being founded on a small island in the stream. The towers were high enough to permit additional chain stays to support the tubes, but as Gies (1963) writes, a testing program proved that the box cross sections would be able to support themselves under all expected traffic loads.

Figure 2-19: The Britannia Bridge, Great Britain
(taken from Steinman and Watson 1941, p109)

Brown (1993) gives a detailed account of the further history of the bridge. Erection of the two side spans was done on timber falsework, with the tubes being riveted together from plates and angles on site. Each tube measured 4.47 m in width and 9.1 m in height, leaving enough space for railway trains to pass through. The two center spans of more than 140 m in length were hoisted up from barges and while performing this, timber was being placed under them to hold them in place. Stephenson opened the bridge himself and put the last rivet into the bridge. In 1970 a fire damaged the bridge so badly the most of its unique superstructure had to be removed and be replaced with a new structure.

2.1.4.6 Covered Bridges

A type of bridges specifically used in the United States was the covered bridge. By the beginning of the nineteenth century, after the War of Independence, the former colonies were working on building better road connections to promote trade (Brown 1993). Timber was a very cheap material to build with and existed plenty. The bridges built at that time were enclosed with a triangular roof to protect the timber structure against decaying. This principle was not new; it had previously been used in bridges such as the Kapellbrücke and the Spreuerbrücke of Switzerland that have been introduced in Section 2.1.2.6. Furthermore, even the sides of the bridge could be enclosed with wall panels, giving the American covered bridges their typical appearance. Several authors have given detailed accounts of covered bridges in the United States and their story. The surviving bridges are now precious remainders of past times.

The structural system of these timber bridges consisted of trusses, sometimes in combination with arches. Lattice trusses with grids of diagonals were also used, thus putting together the load-carrying system of many small members. Invented by Ithiel Town of Connecticut in 1820, the Town lattice truss became a great success.

Two other truss types need not be forgotten at this point. The Burr arch truss, developed by Theodore Burr in 1815 (Brown 1993) that combined a multiple king post truss with a single wooden arch. The Long truss, utilized by Colonel Stephen H. Long of 1830 (Gies 1963) and

anticipated by Palladio may have been developed from combination of upright and inverted king post trusses, creating the typical crossed diagonals bracing the frame. Several different types of trusses are shown in Figure 2-20. Thus Palladian principles were rediscovered and put to full use in the U.S. Reports are given on a very remarkable structure that was built in 1811 and was destroyed by fire in 1838. The "Colossus" Bridge had a single 103.6-m long span over the Schuylkill River in Pennsylvania (Gies 1963, p107). It consisted of two trussed arches with iron diagonals that carried a gently curved roadway over the stream.
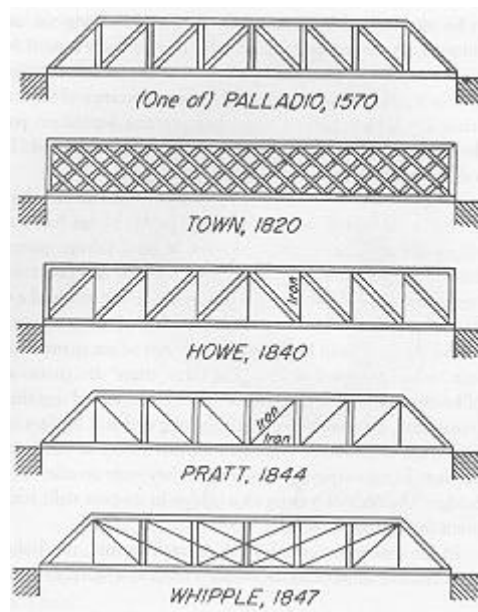

Figure 2-20: Different Truss Types (taken from Petroski 1995, p36)

2.1.4.7 Railway Bridges

A revival of timber structures also took place in Great Britain. The famous British engineer Isambard Kingdom Brunel (1806 - 1859) built them. Much less known than other of his accomplishments, e.g. the steam ship "Great Eastern", completed in 1858, the timber viaducts dominated the era around the middle of the nineteenth century. Brown (1993) specifically notes that Brunel put emphasis on economy and availability of materials for his structures, and timber

was chosen for a great number of viaducts. The shapes of these viaducts were of great variety, including beams, trusses, and a bowstring arch of 35 m span (Brown 1993). A bowstring arch consists of the load-carrying arch that spans the obstacle, with its ends connected by tension members that can sometimes also serve as deck for the bridge, which withstand the horizontal forces. The piers of the timber viaducts also showed creativity. They employed many different forms of timber trusses and masonry, some of them tapering vertically. Figure 2-21 shows an example of such a timber railway viaduct.

Figure 2-21: Timber Railway Viaduct (taken from Brown 1993, p66)

Around the middle of the nineteenth century the growing American railway systems required more and more bridges to cross the natural obstacles. Trusses in manifold configurations were employed and improved through use of cast iron tension members in the trusses, e.g. the diagonals. Later, wrought iron was used more and more to carry the increasing live loads.

Throughout this "learning period", as Brown (1993, p78) calls it, failures of trusses occurred, as better understanding of the truss system statics and the materials employed still was emerging.

Particularly high dynamic live loads need to be dealt with in railway bridge structures. The ever-changing stresses imposed by trains passing generate fatigue of the materials and especially the joints between structural members require careful planning and execution. At the same time, the railway tracks only allow a minimum of horizontal sag for reasons of driving comfort and safety. Thus, the stiffness of the whole structural systems is extremely important for railway bridges.

2.1.4.8 Failure of the Tay Bridge

One of the most prominent bridge failures occurred in 1879 in Great Britain. Providing a link in the railway route from England to Scotland, the shallow Firth of Tay was bridged by Sir Thomas Bouch with 85 spans of altogether 3,246 m. Construction was carried out between 1871 to 1877. Bouch had designed trusses that rested on masonry piers, which were founded with cast-iron piles and caissons. To provide navigation spans for ship traffic thirteen riveted lattice trusses, so-called "High Girders" through which the trains passed were implemented (Gies 1963, pp135f). An overall view of the bridge is given in Figure 2-22. On the whole, no particularly innovative features were implemented in this structure; the only remarkable fact about it was its length. Brown (1993) mentions that much difficulty occurred in constructing the pier foundations and in lifting the trusses on top of the piers, including accidents with some fatalities. As it later turned out, some of the members consisted of low-quality material and workmanship and maintenance of the bridge could be considered poor (Gies 1963). The bridge had not been designed strong enough to be safe in all cases; especially the girders lacked sufficient bracing. When a mail train crossed the bridge in December of 1879, a heavy storm blew down the main girders, causing all 75 persons aboard to die.

Figure 2-22: The Tay Bridge, Great Britain (taken from Brown 1993, p70)

After this disaster had happened, Brown (1993) writes, design of bridges against dynamic wind pressures was improved considerably. The Tay disaster had not been the only bridge failure, as more trusses failed and caused some railway accidents, one of the worst ones occurring in Winter of 1876 when an iron Howe truss over Ashtabula Creek in Ohio collapsed under a train during a storm. Trusses of wood or iron in the Eastern United States were apt to failure. Especially joints between members and the materials themselves were weak spots of the bridges. Founded as early as 1852, the American Society of Civil Engineers then initiated regular bridge inspections, as Gies (1963) reports. The Tay Bridge was finally completed with a modified and strengthened design several years later.

2.1.4.9 Contributions of Bridge Building during the Industrial Revolution

One of the most important features of the Industrial Revolution was the extensive development and enormously growing use of a new source of power – the steam engine. Shifting away from manual labor towards machines, e.g. for piledriving and making use of steam-driven locomotives instead of the traditional horse-drawn vehicles brought a massive change in bridge construction. The bridges had to serve the new function of carrying heavy dynamic loads from the trains passing over them.

Furthermore, as outlined above, the new construction material iron brought much innovation into the shapes and structural systems of bridges. Use of iron – first as cast and later as wrought iron – and understanding its characteristics and capabilities as a construction material (high tensile and compressive strength) opened new paths for bridge designers. It became possible to have considerably light members that were strong enough to carry the increasing live loads of steam locomotives, and they could be prefabricated, to speed up construction. The common I-beam shape appeared for structural members, though riveted together from plates and angles, since welding not been invented yet.

Building bridges for the growing railway systems brought an enormous growth both in number and variety of bridges. The characteristics of railway traffic – heavy, dynamic live loads – also required the engineers to deal with these new stresses. New shapes were emerging slowly and many of the bridges built in this time still show the strong influence of the classical concepts. As Brown (1993) notes, many railway bridges in the very beginning therefore were conservative masonry arches. Classical forms such as the arch were complemented with new shapes, e.g. trusses and suspension systems or even replaced by them. A large number of different shapes of bridges began appearing during the Industrial Revolution. Iron arches and trusses surpassed simple precast iron beams in span length and the early suspension bridges took the spans even further. Trusses were not only used as stiffening elements but as load-carrying structures in themselves.

The early suspension bridges, first with chain cables and soon after with wire cables, allowed spans that had never been achieved before. Methods to construct the main cables of suspension bridges on site with special spinning machines were invented and opened the door to suspension bridges with yet longer and longer spans to be built after the middle of the nineteenth century.

Equipped with new materials and methods the bridge engineers of the Industrial Revolution initiated a boom in bridge building that brought great advancement.

2.1.5   The Great Bridges

Of the many bridges of different structural types and sizes, a few shall be presented the following paragraphs to give an impression of the enormous growth that bridge building has seen since the days of the Industrial Revolution. It shall be clearly stated that any of these bridges has a long and very interesting history from the initial concept to its construction and beyond, and some authors have attempted to explore these. Especially suspension bridges continuously impressed with longer and longer spans, and until today this development that begun in the U.S. in the later nineteenth century has come to no end.

2.1.5.1 The St. Louis Bridge

Captain James B. Eads (1820 - 1887) was raised at the banks of the banks of the mighty Mississippi, where he started doing business in recovering wrecks from the riverbed (Gies 1963). Later he turned on to successfully building military vessels during the Civil War. Bridging the Mississippi had been thought of earlier, but the site imposed some severe difficulties, namely the soft soil and the strong current of the wide river that would have caused scour to bridge foundations. According to Gies (1963), John A. Roebling was one of the men that submitted proposals. Finally, Eads produced a design for a bridge with three tubular steel arches on stone piers. Sir Henry Bessemer (1813 - 1859) had developed the process of producing steel from crude metal in industrial amounts in 1856. After being molten in blast furnaces the metal was treated in the converter with stream of air, burning some of the carbon content. Steel was still an extremely expensive material and was new to use in construction.

Founding the piers and the abutment of the St. Louis Bridge on the deep, sloping bedrock on one of the shores required use of pneumatic caissons as had been previously used in France, as Gies (1963) writes. Work on the foundations began in 1867. The caissons, large hollow boxes of iron plates, each with a pressurized working chamber under the pier that could be reached through airlocks, were floated into place. While workers removed the soft soil with a new sand-pumping device other workers stacked masonry on top of the chamber, pressing the caisson further down. Many workers in the caisson suffered from the caisson disease, called "the bends" (Brown 1993,

p83) and a considerable number died until slow decompression and improved working conditions relieved the situation.
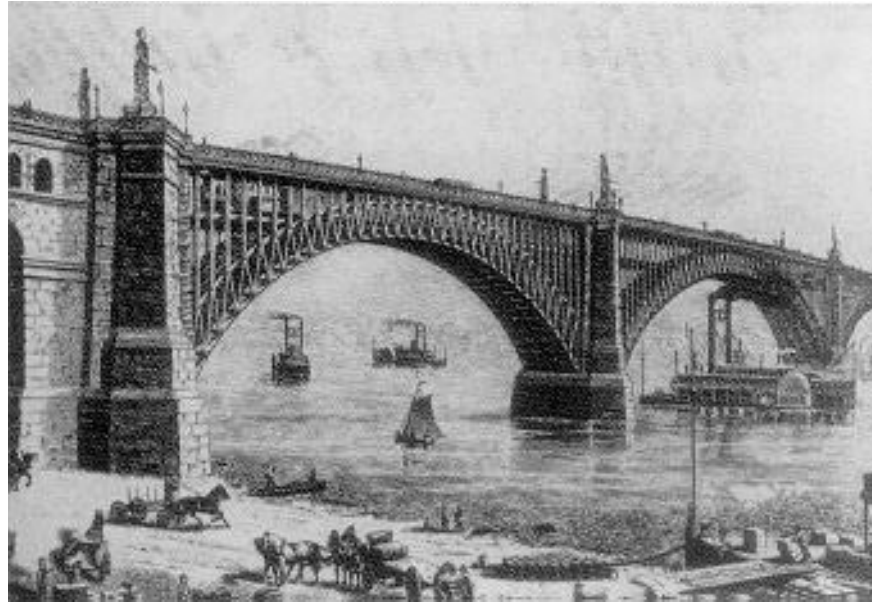

Figure 2-23: The St. Louis Bridge, St. Louis, U.S. (taken from Troitsky 1994, p19)

Much clearance was needed for the bridge, which had arch spans of 153, 158.5, and 153 m, carrying a double deck for both vehicles and railroad. Reportedly, Eads presented the contracting steel suppliers with tough specifications that ensured the superior quality of the material. When the arch halves had been installed through cantilevering from scaffolding on top of the piers, they were closed and the supporting cables were removed (Gies 1963). In 1874, the bridge was finally finished. A contemporary view of the finished bridge is shown in Figure 2-23.

2.1.5.2 The Brooklyn Bridge

John A. Roebling (1806 - 1869) was an immigrant from Germany who collected experience with suspension bridges on the 250-m span over Niagara Gorge that was built from 1851 to 1855.

Roebling had an own plant for wire cables that were used for suspension bridges (Brown 1993). The Niagara Railroad Suspension Bridge had a double deck for both road traffic and railway traffic with a deep truss superstructure. The four main cables all were air-spun and additionally enclosed in wire for protection. When in 1854 the longer Wheeling Suspension Bridge over Ohio River collapsed in strong winds Roebling added cables below the bridge to stabilize it against wind-induced movements.

In New York City plans were made to cross the East River with a major suspension bridge. Roebling's design for the Brooklyn Bridge comprised a bridge with a daring span length, 486 m, which is more than 1,500 feet. Unfortunately, Roebling was killed in an accident when surveying the bridge site before construction had even begun (Brown 1993). It was his son, Col. Washington A. Roebling (1837 - 1926), who had worked on other bridge projects and who supervised construction of his father's masterpiece when it began in 1869. Large caissons were employed for construction of the foundations. The soil to be cut through was less deep than for the St. Louis Bridge, but it was harder and construction showed only slow progress, so that finally even blasting had to be used under the caisson (Brown 1993). Workers suffered from several accidents that happened during work in the caissons and from the caisson sickness. On the New York side of the East River the pier had to be founded deeper, and in 1872 Roebling himself became paralyzed from the caisson sickness. Construction proceeded successfully with his wife, Emily W. Roebling, carrying instructions to the site personnel. The architecturally shaped towers with their gothic openings grew until the main cables were installed from which vertical hangers were suspended. Additional radiating stays and a trussed deck provided the necessary stiffness of the superstructure (Brown 1993). Brooklyn Bridge was completed in 1883 and since then has been one of New York City's landmarks.

2.1.5.3 The Forth Rail Bridge

In comparison with the shallow Firth of Tay the second major railway crossing for routes heading north in Great Britain at the Firth of Forth created more difficulties because of the greater depth. After the catastrophic failure of the Tay Bridge the initial design by Sir Thomas Bouch was

quickly abandoned. Sir John Fowler and Sir Benjamin Baker came up with an innovative design to build "not only the largest but also the strongest, stiffest, and hence the safest, bridge in the world" (Brown 1993, p72). They designed a solid bridge with three towers of tubular steel framework resting on circular caissons, making use of a small island in the middle of the stream. These towers of 100.6 m height extend over the waters with cantilever arms that were built parallel to both sides for stability during construction. The cantilevers are supported from above by strong struts attached to the top of the pylons, from below by struts curving upward, with major bracing made of diagonal trusswork. Between the cantilevers, two suspended girder spans of 107 m length that were also built cantilevering are carried, giving the main spans an overall length of 521 m. Gies (1963) points out that this statically determinate systems simplified calculation considerably, as opposed to e.g. a continuous truss. The huge main spans and approaches of the Forth Rail Bridge are shown in Figure 2-24.

Figure 2-24: The Forth Rail Bridge, Great Britain (taken from Brown 1993, p72)

The approaches to this impressive bridge consist of some masonry arches on shore and further towards the main spans, of trusses on masonry piers. The mighty bridge with its typical reddish brown color was built between 1882 and 1889. Although of magnificent scale and uniquely strong but simple shape, the Forth Rail Bridge remained very conservative in its construction principles, all of which had been utilized in earlier projects and in its material utilization.

2.1.5.4 The George Washington Bridge

Othmar H. Ammann (1879 - 1965) grew up and was educated in Switzerland before he came to the U.S. (Petroski 1995). By that time the enormous growth of suspension bridge spans had begun. Ammann first worked under Gustav Lindenthal (1850 - 1935), who oversaw construction of the Hell Gate Bridge, a major steel arch erected with cantilevering from 1912 to 1916 in New York. The George Washington Bridge across the Hudson River was built from 1927 to 1931. Its dimensions are most impressive, the suspended span being twice that of the Brooklyn Bridge, 1,067 m long between steel towers that are 183 m high. Construction of the foundations provided fewer difficulties, cofferdams were needed only for one of the tower foundations. Two pairs of suspension cables and groups of vertical hangers carry the trussed deck. Originally it had been intended to enclose the riveted framework of the steel towers with a decorative stone cladding. Later this idea was abandoned, probably also due to cost reasons by the end of the 1920s, revealing the lightness and aesthetics of a steel substructure and superstructure. In 1962 a second roadway was added below the original deck to increase the capacity of the bridge and Ammann was made "guest of honor at the second inauguration" of his bridge (Brown 1993, p102).

2.1.5.5 Failure of the Quebec Bridge

The designer of the Quebec Bridge, Theodore Cooper (1839 - 1919) had worked with James B. Eads in St. Louis before he started a career of his own in New York (Petroski 1995). His ill-fated greatest work was the Quebec Bridge over the St. Lawrence River in Canada. Similar in appearance to the Forth Rail Bridge, the Quebec Bridge would only have only one span and

straight cantilever struts. Compared with the Forth Rail Bridge authors generally agree that the Quebec Bridge was less well shaped. Cooper modified the original design of a 488-m long span (1,600 foot) to a longer main span of 549 m (1,800 foot) in order to avoid deep tower foundations (p102). The official investigation revealed, Petroski (1995) writes, that during design the total weight of the bridge had been determined by a rough estimate that was not properly adjusted to later design changes. Construction began in 1904 and had progressed to cantilevering more than 230 m in August of 1907 (Brown 1993). At that time buckling occurred in the riveted rectangular base struts. Cooper himself was not present on site himself; in fact he had almost completely been in New York during construction. Several days after the first problems had been noticed southern cantilever collapsed and fell, causing 85 workers to die. Another tragedy was about to happen years later when the 195-m long suspended middle span was hoisted into place in 1916. The steel structure fell and caused more fatalities. Finally, the bridge was completed as shown in Figure 2-25.
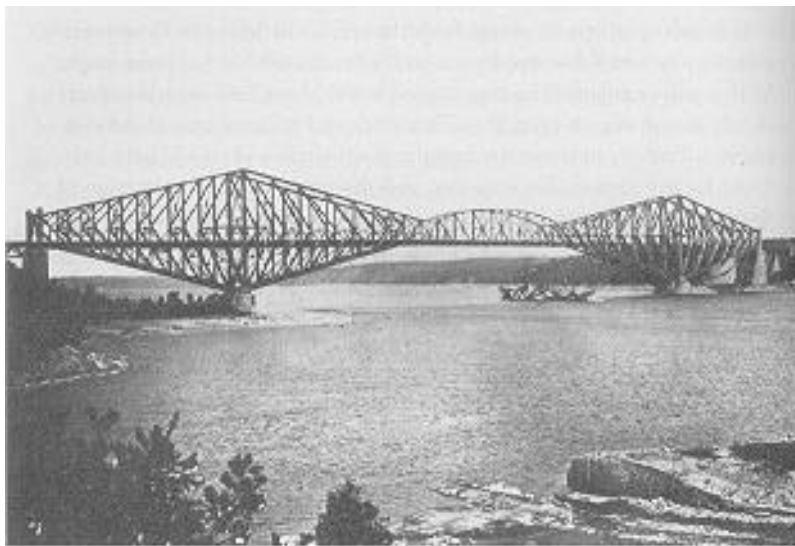

Figure 2-25: The Quebec Bridge, Canada (taken from Petroski 1995, p118)

2.1.5.6 Failure of the Tacoma Narrows Bridge

Another prominent bridge failure occurred in 1940. The Tacoma Narrows Bridge was built in Washington State over the Puget Sound. Leon S. Moisseiff (1872 - 1943), who had participated in building the George Washington Bridge and several other major projects (Petroski 1995), designed a suspension bridge with a 853-m long main span. The plate girder deck was planned to be only 2.4 m deep and 11.9 m wide for two lanes of traffic, making it an extremely slender and light superstructure for reasons of economy. After its opening in 1940 it was realized that the new bridge was susceptible to motion under even "quite light winds, which not only caused it to sway from side to side but also sent rippling waves along the deck" (Brown 1993, pp106f). Soon the bridge received the nickname "Galloping Gertie" for this behavior. Additional stay cables were installed but did not have the intended effect.
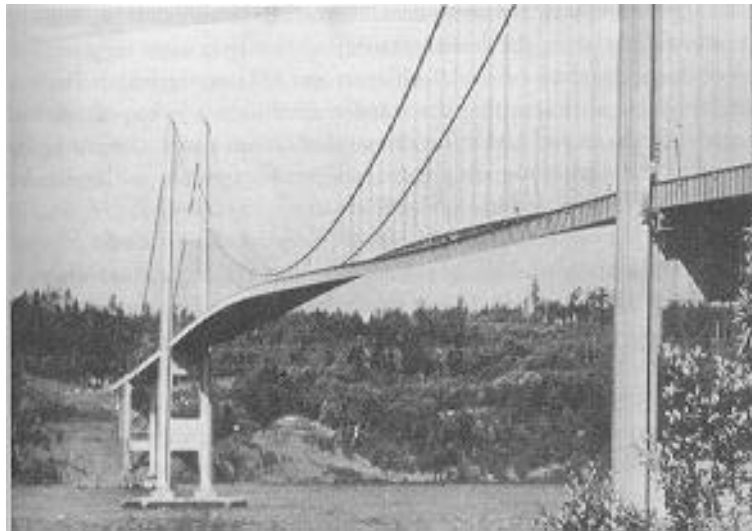

Figure 2-26: The Tacoma Narrows Bridge Prior to Failure
(taken from Petroski 1995, p101)

Oscillations of the flexible suspension bridges under wind influence were not completely unknown to the engineering profession, though. Other suspension bridges had exhibited similar behavior, e.g. the Bronx-Whitestone Bridge in New York City and the Deer Island Bridge in

Maine that were both completed in 1939. Even the Golden Gate Bridge, completed two years earlier by Joseph B. Strauss (1870 - 1938) with Charles A. Ellis (1876 - 1949), moved because of winds (Petroski 1995). It rather seems that these motions were not percepted as being potentially hazardous to bridge structures.

Brown (1993, pp106f) reports that under a modest wind of 68 km/h (42 mph) the Tacoma Narrows Bridge began to undergo "severe lateral twisting of the deck as well as longitudinal rippling." By this time the bridge was closed for through traffic and the following sequence of events was filmed. The oscillations increased in amplitude until the steel superstructure ruptured from the suspended hangers and fell into the sound.

After this failure the focus of attention was finally put on the aerodynamic behavior of suspension bridges. Analysis of the aerodynamic behavior was performed with scaled models in wind tunnels Subsequent bridges were built under the impression of the failure of the Tacoma Narrows Bridge with strong trusses stiffening the deck. They included e.g. the replacement for the fallen structure, the 1,158-m long Mackinac Strait Bridge in Michigan, built 1954 to 1957 by David B. Steinman (1886 - 1960), and the breathtaking 1,298-m long Verrazano Narrows Bridge in New York, which was built from 1959 to 1964 by Amman (Brown 1993).

Other engineers, especially Fritz Leonhardt drew different conclusions from the failure of the Tacoma Narrows Bridge, as will be described in Section 2.2.3.1.

2.1.5.7 The Severn Bridge

Between 1961 and 1966 the Severn Bridge, shown in Figure 2-27, was built in Great Britain. The bridge is interesting for several reasons. It is a 987.5-m long suspension bridge that took a radical change from the common American way of design, as Leonhardt (1984) points out. Instead of incorporating a major stiffening truss to provide rigidity against wind-induced oscillations the bridge superstructure consists of a 3-m deep steel box girder with pointed edges. Wind tunnel tests were performed to examine the aerodynamic behavior of this cross-section. This *aerofoil deck* is based on an idea by German engineer Fritz Leonhardt and will be explained in Section

2.2.3.1. Large prefabricated segments were lifted into place from barges on the river below after the light bolted steel towers and the main cables had been erected. Further notable are the suspended hangers that carry the deck because they are inclined in the longitudinal direction, thus giving a zigzag composition that is "intended to improve structural damping" (Brown 1993, p116). Brown (1993) gives further information that due to increased traffic the bridge was strengthened and upgraded two decades after its completion.

Figure 2-27: The Severn Bridge, Great Britain (taken from Leonhardt 1984, p293)

2.1.5.8 Contributions of Bridge Building between Nineteenth and Twentieth Century

From the second half of the nineteenth century until the middle of the twentieth century a considerable number of major bridge projects was realized, particularly in the U.S. Use of steel instead of cast or wrought iron became common and was developed to longer and longer spans. Long-span steel bridges were built as large arches, cantilever bridges, and impressive suspension bridges. After major failures the problem of wind stability of suspension bridges had finally been recognized and attempts to relieve it were developed, mostly trussed decks and bracing with stay cables. Around the second half of the twentieth century two types of suspension bridges existed, incorporating the classic truss-type deck and, newly developing, with aerodynamically shaped steel box girder superstructures.

During the Industrial Revolution a vast number of railway routes had been built and the bridges of those times had been adapted to these traffic loads. After the turn of the century the growing automobile traffic changed design requirements for new bridges.

Innovations did not only occur in the structures themselves but also in ways of constructing them. James B. Eads and other builders made use of very large iron caissons that were pressurized to construct the foundations of bridge piers. These large cylindrical devices were brought into place and sunk down into the riverbed. Workers then excavated the soft soil until they reached bedrock that was stable enough. The working conditions in pressurized chambers under the stone piers that were piled up were quite hard and many of the workers got ill or even died until it became known that slow depressurization was necessary.

2.1.6 The Era of Concrete Bridges and Beyond

The following sections will introduce the wide range of modern bridge structures and their development. The main focus is placed on concrete structures. Historic developments and characteristics of certain types of concrete bridges will be presented. Certain specialties in bridges will not be discussed, e.g. moving bridges of all kinds (i.e. bascule bridges, lift and swing

bridges), and highway bridges, many of which are made of prefabricated concrete beams. The specific problems of skewed and curved bridges are also excluded from this section.

2.1.6.1 Concrete Characteristics

Concrete had already been commonly in use in Roman times, as described in Section 2.1.1.8. Simple mortars had already been used much earlier. Strong and waterproof mortars as the Romans had used, however, were only rediscovered around the late eighteenth century, as Brown (1993) notes.

Concrete is an artificial stone-like inhomogeneous material that is produced by mixing specified amounts of cement, water, and aggregates. The first two ingredients react chemically to a hard matrix, which acts as a binder. Most of the volume of the concrete is taken by aggregates, which is the fill material. In modern concrete design mixtures special mineral additives or chemical admixtures are added to influence certain properties of the concrete. Strength can be increased through use of special types of cement and a low water-cement ratio; workability can be improved with retarders and superplasticizers; and durability depends on the volume of air enclosed within the concrete. Proportions and chemistry of the ingredients as well as the manner of placement and curing determine the final concrete properties.

Concrete is the universal construction material of modern times due to several advantages. It is formable into virtually any shape with formwork, its ingredients are relatively cheap and can be found ubiquitously, it has a high compressive strength and, provided good quality of workmanship, is very durable at little maintenance cost.

Reinforced concrete is a composite material that is composed of concrete and steel members that are embedded and bonded to it. These steel bars or mats fulfill the purpose of enhancing the resistance of a reinforced concrete member to tensile stresses, as concrete alone is strong in compression but has less resistance to tension that is applied. The amount and location of the reinforcement needed for a certain structure is determined during its design. In sound concrete

the steel reinforcement is protected by the natural alkalinity of the concrete that creates a passifying layer on the steel surface.

2.1.6.2 Early Concrete Structures

Several names are linked with the beginnings of reinforced concrete. A comprehensive historical review of the developments that led to application of reinforced concrete in the construction industry is given by Menn (1990). In 1756 John Smeaton came up with a way of cement production and in 1824 the mason Joseph Aspdin invented Portland cement in England. Thaddeus Hyatt (1816 - 1901) examined behavior of concrete beams as early as 1850 in the U.S. Some years later, in 1867, French engineer Joseph Monier received a patent on flowerpots whose concrete was reinforced with a steel mesh. Monier also became first in building a bridge of reinforced concrete in 1875 (Menn 1990). In the years to come, the first scientific approaches to the behavior and analysis of reinforced concrete were taken and opened the way to more and more advanced structures. French engineer François Hennebique (1842 - 1931) researched T-shaped beams and received patents on these around 1892, after which a larger number of bridges was built in European countries in the following years. While construction of reinforced concrete bridges spread across Europe, the first national codes for reinforced concrete appeared. According to Menn (1990), prior to the 1930s steel bridges still dominated the U.S. landscape since they were cheaper and allowed rapid erection. In later years reinforced concrete bridges became more common in the New World.

2.1.6.3 Concrete Arch Bridges

Robert Maillart (1872 - 1940) was exploring the structural possibilities of the new construction material in an impressive diversity of arch bridges in Switzerland. Located predominantly in mountainous terrain the more than 40 bridges he designed were ingenious in their slenderness, variability of shapes and beauty. It can be said that in his structures all possibilities of concrete, including superior compressive strength and formability were used to their full extent. One of his

more known structures is the daring shallow arch of the Salginatobel Bridge that spans 90 m. In this bridge the superstructure was dissolved to a slender arch that carried the deck with transverse wall panels. Melaragno (1998, p19) in this context uses the term "structural art" to capture the spirit of this unique family of concrete structures.

2.1.6.4 Prestressed Concrete Bridges

As early as 1888 a German engineer had examined prestressed concrete members (Menn 1990). Yet it was Eugène Freyssinet (1879 - 1962), a graduate of the *École des Ponts et Chaussées*, who is considered the father of prestressed concrete bridges. His most known bridge is the Plougastel Bridge that was built between 1925 and 1930 in France. A construction stage of this bridge is shown in Figure 2-28.
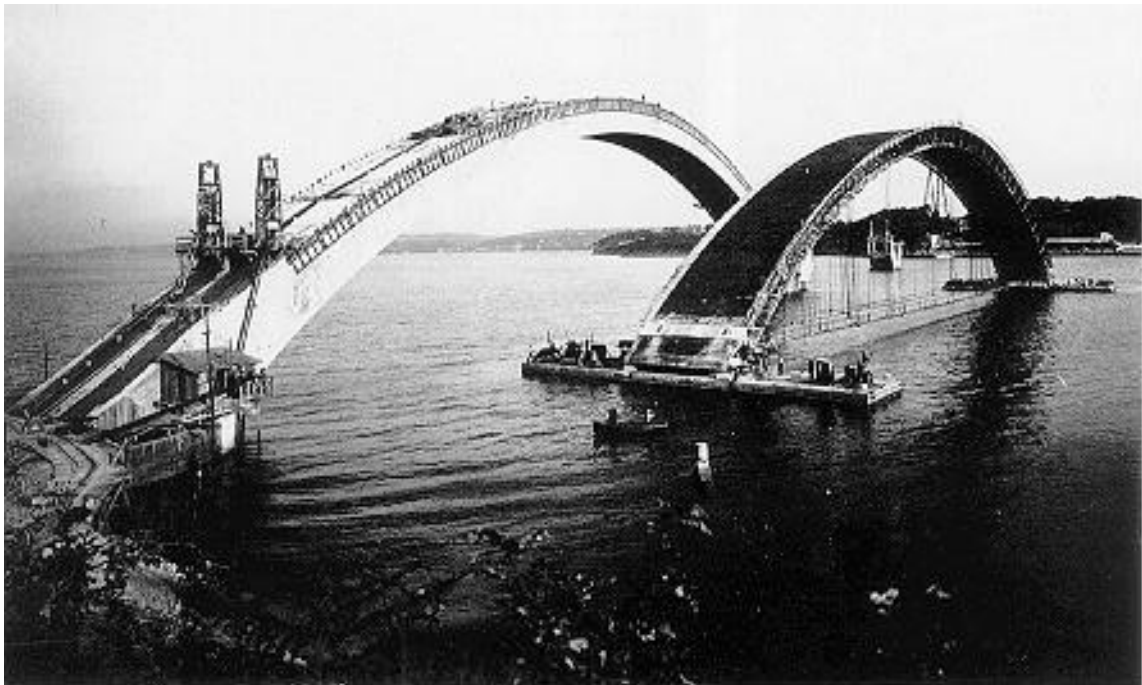

Figure 2-28: The Plougastel Bridge under Construction (taken from Brown 1993, p122)

Three 186-m long arches of still normal reinforced concrete with a box girder cross-section support a two level truss deck for road traffic and railway. For this bridge Freyssinet employed large timber falsework that was brought into place by pontoons and reused for all three arch spans. Brown (1993) stresses the importance of this bridge with respect to prestressing, since it was the Plougastel Bridge where Freyssinet became aware of the phenomenon of concrete creep, which needs to be considered in prestressed construction. Freyssinet implemented jacking the concrete bridge spans apart prior to closure of the midspan gap to account for creep. Principles of prestressing are presented in Section 4.1.

Between 1941 and 1949 a famous family of six prestressed concrete bridges were built after Freyssinet's design at the River Marne in France, five of them with similar spans of 74 m (Menn 1990). These bridges were shallow frames with vertically prestressed thin girder webs (Brown 1993). Segments for these bridges were delivered by barges and lifted into place in larger sets. Freyssinet came up with concepts for "both pre-tensioned and post-tensioned concrete" (Menn 1990, p30) and thus initiated the rapid development of prestressed concrete bridges.

2.1.6.5 Concrete Bridges after the Second World War

After the Second World War the European transportation infrastructure needed to be rebuilt and extended. Steel box girders could now be put together by welding instead of riveting. Some of the first of these bridges were built at the Rhine by German engineer Fritz Leonhardt (born 1909), who also designed a large number of concrete structures. Box girders, which had been used for the arches of the Plougastel Bridge, were more and more introduced in steel and concrete bridge construction as better understanding of the properties and the inherent advantages of closed hollow cross-sections grew. These features of box girders will be discussed in more detail in Section 3.7. Prestressed concrete bridges were built in large numbers. In Germany, Franz Dischinger (1887 - 1953) built prestressed concrete bridges with a system different from Freyssinet's; he used unbonded tendons that did not reach widespread application until much later due to problems with loss of prestressing force (Menn 1990). Subsequent development of different prestressing systems was therefore based on the original Freyssinet system. Cast-in-

place cantilever bridges have been built for almost half a century. Ulrich Finsterwalder, student of Dischinger, took the first step in erection with the balanced cantilevering method when he built the 62-m long span of the Lahn Bridge at Balduinstein in Germany between 1950 and 1951 (Fletcher 1984).

Prestressing of concrete bridges reduced deflections, prevented cracking, and allowed higher loads to be carried by the bridges (Menn 1990). Freyssinet's system of implementing full prestressing was not very economical, though. Therefore, partial prestressing became prevalent as it was introduced into the design codes. Partial prestressing permitted limited tensile stresses in concrete and made use of mild reinforcement to alleviate the cracking of the concrete because of these stresses.

Precast segmental construction emerged in the early 1960s, as Menn (1990) also reports. In the following decades, solutions for the problem of segments joints were developed, including match-casting of the segments at the precasting yard, implementation of shear keys, and use of epoxy agents that sealed and glued the joint faces together. More on precast segmental construction can be found in Section 4.2.1.1.
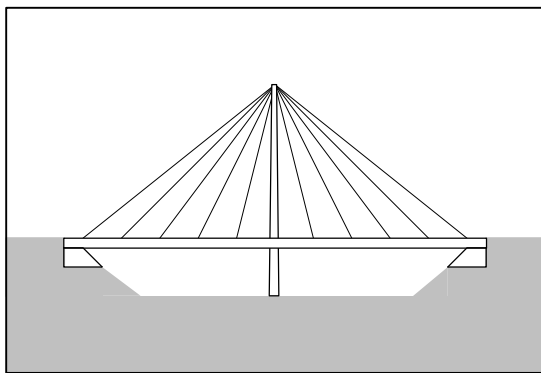
In the decades since the first prestressed concrete bridges were built many technological achievements have been made. Research allowed better understanding of the internal flow of forces in concrete and in the embedded steel and helped improving material properties of these construction materials.
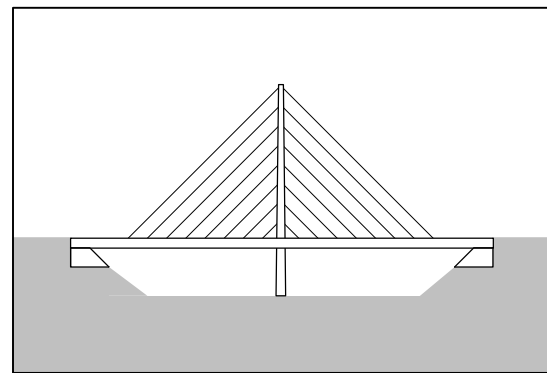
2.1.6.6 Cable-Stayed Bridges

Cable-stayed bridges can appear in many different ways. The bridge pylons and the bridge superstructure can be made either of concrete or steel, or be a composite of concrete and steel members. Pylons can be shaped in a great number of ways, including A, H, X, and inverted V and Y-shapes, or combinations and variations of these.

In a cable-stayed bridge inclined straight stay cables that are attached to pylons above the deck carry the bridge deck. A multitude of arrangements for pylons and cable layout exists.
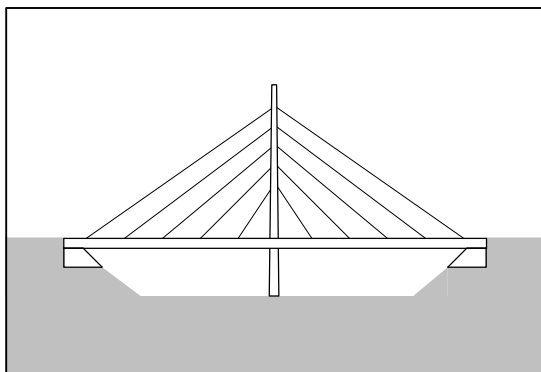
Furthermore, the bridge can be designed with one central or two lateral planes of stay cables that can even be inclined toward each other. Cable-stayed bridges can have several different arrangements for the stay cables, as explained in Table 2-1. The respective arrangements are shown in Figure 2-29. Cable arrangements do not necessarily have to be exactly symmetric about the tower. Variations and combinations between these types are possible. Cables can be anchored both on the deck and at the pylon or can run continuously over a saddle at the top of the pylon. The anchorages for the stay cables are critical structural details that have to be resistant to corrosion and fatigue.
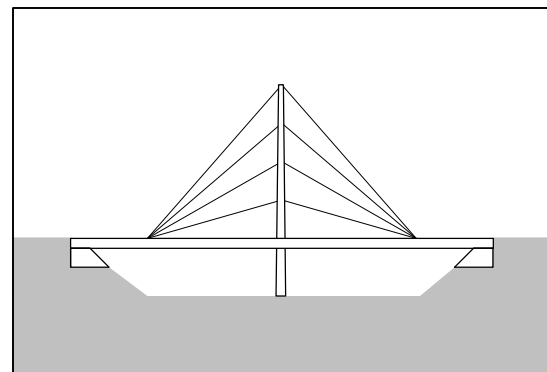
Fan Arrangement

Harp Arrangement

Half-Fan Arrangement

Star Arrangement

Figure 2-29: Stay Cable Arrangements

Table 2-1: Stay Cable Arrangements

Cable Arrangement	Description
Fan (often called radiating)	Cables run radiating from one point at pylon
Harp	Cables run parallel from equal spacing at pylon
Half-fan (often called fan)	Combination of fan and harp arrangement
Star	Cables run from several points at pylon to one location at deck

Cable-stayed bridges are not an invention of the twentieth century. Some attempts to built bridges supported by stay cables were already made in previous centuries, but did not prove successful, as means of calculation for the statically highly indeterminate system and adequate materials for the cables were lacking (Brown 1993). Cable stays were applied in the superstructure of the Brooklyn Bridge, as mentioned in Section 2.1.5.2 to add stiffening to the suspension system.

Cable-stayed bridges were revived after the Second World War when economical rebuilding of the transportation infrastructure in Europe became a prime issue. Franz Dischinger had already implemented stay cables to support the deck of a suspended railway bridge (Brown 1993). Amongst the first modern cable-stayed bridges was a family of three cable-stayed bridges over the Rhine at Düsseldorf with steel superstructures that were built by German engineer Leonhardt (1984) around 1952. One of them, the Oberkassel Rhine Bridge, is shown in Figure 2-30. These slender bridges, of remarkable clearness and simplicity in their appearance all have a harp-type cable arrangement. Since then, a great number of cable-stayed bridges have been built all over the world, of which just very few shall be mentioned in this overview.

**Figure 2-30: The Oberkassel Rhine Bridge, Düsseldorf, Germany
(taken from Leonhardt 1984, p260)**

The first concrete cable-stayed bridge was the Lake Maracaibo Bridge in Venezuela, which was built between 1958 and 1962. The designer Riccardo Morandi came up with a major concrete structure with five main spans of 235 m length (Brown 1993). He designed uniquely shaped pier tables that had a massive complex X-shaped substructure, which carried A-shaped towers above the deck level. The central concrete spans were comparatively massive to achieve stiffness and were suspended with one group of stay cables on each side of the towers. A view of the structure with its characteristic approaches is shown in Figure 2-31.

Figure 2-31: The Lake Maracaibo Bridge, Venezuela (taken from Leonhardt 1984, p271)

Later bridges incorporated a greater number of regularly spaced cables that provided almost continuous support for the bridge deck. Menn (1990) calls this type of multi-cable bridges the second generation of cable-stayed bridges. He mentions the Pont de Brotonne in France, completed in 1976, as the first example of a bridge of the second generation. The Pont de Brotonne is shown in Figure 2-32. Its main span of 320 m length is supported by a single central plane of fanning stay cables. Leonhardt (1984) specifically points at the stiffness that can be achieved with such a structural system despite the slender deck girder, making the bridge suitable even for railroads. With the larger dead load of concrete bridges better damping of vibrations is achieved as Podolny (1981) writes. Concrete is also suitable for the bridge deck because it can withstand the longitudinal horizontal stresses that the inclined stays induce in the bridge superstructure. Podolny (1981) further mentions that concrete cable-stayed bridges incur only small deflections from live load, as the ratio of live load to dead load is relatively small.

Figure 2-32: The Pont de Brotonne, France (taken from Leonhardt 1984, p270)

Several advantages make cable-stayed bridges very economical structures. Due to the almost continuous elastic support of the deck (Podolny 1981) of multi-cable arrangements sufficient overall stiffness can be achieved even with slender superstructure girders. Multi-cable systems are aesthetically advantageous because of their apparent lightness. They have a high degree of structural redundancy and even allow repair or replacement of single stays with relative ease. It is possible to optimize the stay cable prestressing sequence towards a more equal stress state in the structural system. The overall structural system allows quick construction in comparison with e.g. suspension bridges, especially by use of precast elements. Another major advantage is that cable-stayed bridges do not require large anchorages at the abutments as necessary to hold the main cables in suspension bridges. Cable-stayed bridges are economical especially for span ranges between about 250 and 300 m, as Swiggum et al. cite (1994). Even much longer spans have been built up to date.

With improved analytical capabilities due to modern computer software the statically highly indeterminate system of cable-stayed bridges can be analyzed very accurately. Better analysis

techniques for aerodynamic and seismic behavior with scaled models in wind canals and computer simulation of the structure allowed optimizing bridge cross-sections. The scaling process requires special consideration because all properties of a bridge have to be scaled for examination in a wind tunnel. A model test e.g. included "scaled stiffness, mass, inertia, geometry and, "we hope," scaled damping, the most difficult aspect" (Fairweather 1987, p. 62). The trend, according to Fairweather (1987) in this area is to incorporate aerodynamic testing not only for verification of an existing design, but to also use it directly during the initial design. With aerodynamic testing it is also possible to evaluate the effects of innovative details for both aerodynamic and seismic resistance. These details can be mass dampers or tuned damping systems at bearings, joints, and cable anchorages, installation of interconnecting ties between the stay cables, and special shaping and texturing of the cables sheathing to prevent vibrations from wind and rain.

Cable-stayed bridges are ideally erected with the cantilevering method. The stay cables hence serve to support growing cantilever arms from above and will also be the permanent supporting system for the bridge superstructure. Goñi (1995) gives a profound example of a major cable-stayed bridge, the Chesapeake and Delaware Canal Bridge. It was erected using progressive placement and was completed in 1995. According to him, the 229-m long main span consists of two parallel box girders that are interconnected by so-called delta frames and supported by a single plane of stays in harp-type arrangement. It was put together from precast segments that were placed by a crane at the tip of each cantilever. After placement of the segments new stay cables were installed and initially prestressed. Construction loads resulted especially from the cranes on the cantilevers and the placement of precast segments. A detailed computer analysis of the erection procedure that included several hundred construction steps (e.g. segment placement, tendon installation, and changes in prestressing forces or loads) was performed. With respect to the motions of the uncompleted cantilever due to winds, Normile (1994) points at the need to provide sufficient stiffness in the bridge superstructure for construction.

2.1.6.7 Recent Bridge Projects

Several impressive large-span bridges have been completed in recent years. The three most important examples to be mentioned are the Pont de Normandie in France, the Akashi Kaikyo Bridge in Japan, and the East Bridge of the Great Belt Link in Denmark. A brief comparison of these three breathtaking projects will be given in Table 2-2, based on information from Brown (1993), Robison (1993), Normile (1994) and the Honshu-Shikoku Bridge Authority (1998). The currently longest bridge in the world, the Akashi Kaiyo Bridge is shown in Figure 2-33.

Table 2-2: Recent Major Bridge Projects

Name	Pont de Normandie	Akashi Kaikyo Bridge	Great Belt East Bridge
Location	France / Brittany	Japan / Akashi Strait	Denmark / Great Belt
Type	Cable-stayed (two-plane half-fan)	Suspension	Suspension
Main span	856 m	1,991 m	1,624 m
Total length of main bridge	2,141 m	3,911 m	2,694 m
Maximum clearance	59 m	65 m	65 m
Towers (above sea level)	214 m, concrete, inverted Y	297 m, steel, X-bracing	254 m, concrete, cross-beam
Deck	Aerofoil	Truss	Aerofoil
Remarks	Main span partly in balanced cantilever construction, central part made of steel	Towers withstood Kobe Earthquake in 1995, towers were displaced by 1 m	Main span segments erected suspended from midspan inwards
Construction	1988 – 1995	1988 - 1998	1991 - 1998

Figure 2-33: The Akashi Kaikyo Bridge, Japan

(taken from Honshu-Shikoku Bridge Authority 1998, p1)

2.1.6.8 Contributions of Modern Concrete Bridge Construction

The introduction of concrete into bridge construction opened almost unlimited new possibilities for the profession. The several advantages of concrete, such as free formability, strength, and durability came to full use in bridge construction and contributed much to successful use of concrete in other branches. Through use of steel reinforcement to bear the tensile stresses in the members a composite material was created that combined positive characteristics of both concrete and steel and could be strengthened exactly as needed for a certain structure. Prestressing concrete by means of tendons that are installed in the bridge superstructure made extremely long, yet economical spans possible. European engineers, such as Freyssinet carried the prestressing concepts further. Other engineers, e.g. Maillart explored structural possibilities along with artful shaping of concrete bridges.

Along with growing understanding of the properties of the new material went the development of a variety of construction methods that will be presented in Section 4.2. Choice of either cast-in-

place construction, precast construction, or a combination of both methods made it possible to adapt construction procedures exactly to the requirements of the specific site and the project conditions.

The concept of box girder superstructures had already been used in bridges as e.g. the Britannia Bridge. Since the end of the Second World War the versatile box girders have become a widely used type of superstructure cross-section.

With cable-stayed bridges a relatively new type of bridge rapidly developed in the second half of the twentieth century. Economical and elegant long-span cable-stayed bridges were subsequently built that were only surpassed in length by a handful of the longest of all bridges, which are suspension bridges.

2.2   FUTURE CHALLENGES IN BRIDGE ENGINEERING

Having given an overview of more than two millennia in bridge building with some discussion of the impact of developments on later bridge engineering, the following paragraphs shall look ahead. The second half of this chapter will give an overview of the wide spectrum of future challenges. As opposed to the history of bridges, for which an abundance of literature can be found in any library, books or articles on the future of bridge construction are more rare.

How can predictions be made at all? The basic approach is to identify current problem areas and trends in research interests. With some imagination, it is then possible to derive ideas of where bridge engineering may be heading. These predictions will certainly not be exact, but they give an impression of future challenges. New concepts are emerging, yet there is still very little experience with the practical application of these. It will take creativity and sometimes also courage to face them.

The following sections will outline these areas of challenge for coming generations of bridge engineers. Three main areas are identified: Dealing with the engineering approach towards the

complete project life-cycle, including design, construction, maintenance, and rehabilitation; secondly new or improved materials; and finally new types of structures are discussed.

2.2.1   Improvements in Design, Construction, Maintenance, and Rehabilitation

The construction industry is unique in the way that most of its structures are one-of-a-kind products. As opposed to industrial manufacturing, the construction industry in most cases produces structures that are adapted to the owner's specific wishes and to constraints imposed by site conditions and technical possibilities. The processes that lead to the complete structure are discussed in much more detail in Chapter 3. Here, some areas of possible improvements shall be pointed out.

2.2.1.1 Improvements in Design

Since the construction of a real structure is the ultimate goal of all design, the design process inevitably needs to consider the requirements and limitations of construction methods. Current issues in improving design for construction focus on better designs through an increased team effort of all parties involved. Construction engineering concepts, such as Design-Build Construction and Partnering all deal with trying to foster close cooperation and improve communication to achieve better overall project performance.

Apart from managerial improvements, especially the development of prestressed concrete segmental bridges has given designers a wide range of possibilities at hand. In addition to the possibilities inherent to this kind of concrete, designers are able to choose from improved or newly developed materials. More information on high-performance materials is given in Section 2.2.2. Use of advanced materials of higher strength, less weight, and improved durability will allow smaller structural members for substructures and superstructures and less dead load of the structures that they form. Up to a certain point these improvements remain well within the classic design methodology, but as Podolny (1998, p26) writes, with enhanced materials and new

structural concepts necessity can arise "to deal with new limit states, such as user sensitivity to vibration or claustrophobic reaction to long tubular structures or tunnels." With these advanced materials in innovative structures, the center of attention may shift even more to the serviceability of the structures. Podolny and Muller (1982) state that at some time a situation is reached where stress criteria are not determining anymore, but are overruled by limitations to deformations. They also point at the increased necessity to examine special failure modes of slender, yet strong structural members, such as buckling. Fabrication tolerances would have to be included in these considerations.

In the past two decades, the enormous development of computer capabilities has certainly provided engineers with much better tools for performing a vast amount of analytical calculations in very short time. Still, it has to be cautioned about too much relying on computer results and the models on which they are based. Issues of modeling structures for analytical purposes will be discussed in Section 3.5.1.

2.2.1.2 Improvements in Construction

The core issues governing the actual construction process are safety and economy, with the latter one referring especially to a smooth construction process on budget and within time scheduled. Quality control is necessary to ensure that the structure and its parts are built according to the specifications. Control of all these goals is the main task of construction management.

Depending on the actual construction method employed to the specific project, various ways of simplifying and speeding up construction works for economy exist. Examples provided in technical literature are e.g. increased use of precast elements to speed up construction on site, such as prefabricating webs for cast-in-place box girders (Mathivat 1983). Podolny and Muller (1982) give an example of a modified method of incremental launching, where the concrete deck for a steel superstructure is cast and launched forward stepwise, thus reducing the need for formwork considerably. More methods of combining different erection methods and implementing both precast and cast-in-place segments where advantageous are conceivable.

In future, introduction of more automated equipment on site can help accomplish certain repetitive tasks. The uniqueness and complex conditions of every site, as well as the multitude of tasks to be performed during construction yet still make such automation very difficult. Use of improved equipment, e.g. modular formwork and shoring systems, are but small steps towards the goals outlined above.

2.2.1.3 Improvements in Maintenance and Rehabilitation

Bridges have to withstand a large variety of environmental influences during their service life. The natural environment induces stresses in the structure e.g. through temperature gradients. Strong winds, flood events and seismic events put the structural stability and integrity to a test. Corrosive chemicals in water and air, as well as present through deicing agents for roadways affect the soundness of the materials. Dynamic loads from traffic and winds generate fatigue. Construction details, as e.g. joints, bearings, and anchorages suffer from wear and tear. Apart from these influences various forms of impact, e.g. from passing vehicles or ship traffic need to be anticipates in design of the structure.

Maintenance of bridges comprises regular inspections, renewal of e.g. protective exterior coatings, replacement of parts as e.g. worn out bridge bearings, and other minor repairs. A certain percentage of total construction cost is commonly budgeted for annual maintenance of bridges under service. Inspections are required in order to keep informed on the current state of the bridge. Future development of technical systems could support or even replace these inspections. Sensors built into the structure could then be used to measure the current state of deterioration, e.g. in the bridge deck and to detect weaknesses. Links with computer databases and software for so-called bridge management systems could then help interpreting the data collected. Accessing these data will allow for decisions as to the measures required to keep the structure at a serviceable condition.

Measures that simplify construction work can also make repair and rehabilitation work easier. Modularization of structural members and good accessibility of the whole assembly will

contribute to performing repair and rehabilitation work with greater ease. Structural details affected by wear and tear and thus most susceptible to corrosion are traditionally bearings and joints. Reducing the number of complicated details and focussing efforts on good detailing of these will contribute to a longer service life of the whole structure. Good design will also anticipate easy replacement of these parts.

Another most important factor for the length of bridge service life is materials. As will be described in Section 2.2.2, high-performance materials can have improved durability to environmental conditions. Less weight of structural members due to stronger materials will simplify handling these members. Workability is another factor that can determine the high performance of a material. In the area of materials for repair and rehabilitation development of coatings, epoxy grouts, fiber reinforcement, and other materials enables the repairs to be very specific adapting to the problem.

2.2.1.4 Smart Bridges

Smart bridges are bridges that incorporate control systems to measure environmental conditions with sensors and process this information to generate a response. These systems can have different ways of functioning. According to Zuk (1993, pp3-8), so-called *level I systems* produce "some kind of alert or warning" and comprise "sensors, data processors, communications systems, and signaling devices." Zuk gives a comprehensive list of different sensors and explains the following possibilities for practical use of level I systems. They can alert to impacts, overloading, flood events, wind, scour, ice on bridge decks, seismicity, cracking, fatigue, deck delamination, and corrosion.

As opposed to the aforementioned level I systems, Zuk understands *level II systems* as systems where dynamical measurement of data is performed and an active response mechanism in the bridges to counteract any detrimental influence is controlled. He mentions Cathodic Protection of metals, e.g. reinforcement against corrosion as an example of a promising technology, as well as deicing systems for bridge decks. Smart materials with custom-made properties for any spatial

direction, and even with reactive capabilities "when sensing a change in pressure, temperature, or electrical current" (Zuk 1993, p9) can be implemented in reactive systems. Another application of smart systems mentioned by Zuk (1993, p11) is "Intelligent Vehicle Highway Systems", that guide vehicles on their journey and help preventing accidents, e.g. collisions with bridge piers.

Various applications of smart systems are directly dealing with the structural safety of the bridge. These are e.g. self-adjusting hydraulic bearings, tuned mass dampers, and "aerodynamic appendages" (Zuk 1993, p11), e.g. as "wing flaps from aircraft technology, a controllable airfoil deck" (Podolny 1998, p26). All these structural mechanisms are supposed to help maintaining stability of the bridge under dynamic loads.

Making structures as e.g. bridges 'smart' is currently being researched in multiple areas of engineering, including materials science and electronics. Common application of systems as the outlined ones, however, will still take time. Not only technical functionality, but also economic feasibility first has to be proven in field studies.

2.2.2   High-Performance Materials

The term high-performance refers to an outstanding performance of a material in one or several of its properties as compared with common use of this material. Although this generic definition may sound theoretical it has a very practical background.

When speaking of high-performance materials in construction the first notion is often the strength of materials, e.g. use of high-strength concrete in high-rise buildings. However, obviously high-performance materials need not only be of high strength. High-performance of materials refers to a wide range of properties. Key issues equally important for the overall performance of materials are workability for construction and durability during their service life. A good designer will carefully specify values for material properties. Generally any material can show outstanding performance in some of its properties. Podolny (1998) discusses properties of high-performance concrete (HPC), high-performance steel (HPS), high-performance aluminum alloys, and fiber reinforced polymer composites (FRP) in bridge construction.

2.2.2.1 Strength and Other Mechanical Properties

Under the three headings strength and material properties, workability, and durability the features that indicate high-performance will be described in the following paragraphs. Basic mechanical properties of a material are strength, toughness, and ductility. With respect to high-strength materials, Podolny and Muller (1982) write that by the early 1980s application of high-strength concrete in highway bridges were still in its very beginnings. Materials can be isotropic, meaning that properties are the same in all three-dimensional directions. Certain materials, however, are anisotropic and have properties that depend on direction of the material with respect to stresses. Wood is an example for an anisotropic material. Composites can be anisotropic and can have custom-designed properties in different spatial directions.

2.2.2.2 Workability

Regarding workability a multitude of physical and chemical material properties needs to be looked at to determine the performance. Specific weight of the material is very important to determine the size of modules that might be prefabricated, transported, and put into place. Lightweight materials with sufficiently high strength facilitate prefabrication and allow quick and easy erection. With respect to metal alloys, Podolny (1998) mentions criteria such as formability and weldability. For concrete structures, workability is the ease of placement of fresh concrete. Suitability for transportation and placement, e.g. pumpability, duration of setting, and consolidation of the concrete are the main issues in workability. To achieve high durability of the concrete structure, proper curing and finishing are important. Especially permeability of the concrete determines its resistance to corrosion from intruding moisture and chemicals that affect the steel reinforcement within. A certain amount of air volume in the concrete will serve to protect it against freeze-thaw action.

2.2.2.3 Durability

Durability of the material means that a material has very slow deterioration under service conditions. For concrete the design mixture and the aforementioned careful placement and curing are critical for the final product to have resistance to the chemical environment, e.g. deicing detergents and physical wear and tear, e.g. abrasion. Epoxy-coated reinforcement bars, fiber-reinforced polymer modified concrete mixtures, and polymer coatings for concrete surfaces are examples for measures to achieve high durability. Fire resistance and resistance to fatigue under dynamic loading also needs to be considered. Finally, choice of materials can be influenced by the ease of repair works. High durability will result in reduced maintenance cost.

2.2.2.4 Composites

Composites can be used in two variants in the Construction Industry. Structural members of the bridge superstructure can consist of different materials, e.g. in a composite bridge with a concrete deck cast onto steel trusswork. Especially the connection between these members, e.g. with shear studs, requires special attention. On the other hand, the material of a member itself can be a composite made of several ingredients. Reinforced concrete is a simple example for a composite material; it can also be combined with fiber material and polymers to create composites. These sophisticated composite materials today still have a high price in comparison with classic construction materials, such as concrete and steel.

In any case, for both structural and material composites, compatibility of materials is the main issue of design. Similar to requirements for compatibility between repair materials and the original substance, chemical and mechanical properties of the ingredients of composites need to be matched.

2.2.3   Innovative Structural Concepts

Literature on the history of bridges in some cases contains a brief description of bridge projects that are planned for the near future and discusses their technical data. Most of these have a considerable scale due to the nature of their proposed setting. These plans include e.g. bridging the Strait of Messina; other proposals have even been developed for the Strait of Gibraltar and a connection at the Bering Strait between the Northern American Continent and Russia. Plans for bridging major straits separating countries or even continents with unique bridges whose dimensions are measured in kilometers rather than in meters could give the wrong impression that bridge engineering generally is only heading towards larger and larger spans. Future bridge building will not only consist of a few super-span bridges; these are but a part of future developments. Quite the largest amount of bridges has always been of a small to medium scale, and future developments are not expected to change this situation. Melaragno (1998, p237) fittingly calls these bridges the "silent majority". An uncounted number of simple highway overpasses, small pedestrian bridges, and the like serve their purpose "without the glamour associated with the major bridges around the world" (Melaragno 1998, p248). Quality of design and construction for these bridges is at least as important as for major projects, as they are ubiquitous in our built environment.

The bridges of today's infrastructure system will still serve for more years or decades. They have to be inspected regularly, and maintenance work and minor repairs will be one. Finally, it will not be economic anymore to slow down the deterioration process with intensive repair work, and the bridges will by and by have to be replaced in coming decades. Other reasons why new bridges will be needed are mentioned in Zuk (1988b), such as population expansion, demographic shifts, economic pressures, and general obsolescence.

The present means of bridging obstacles will be developed further in the future. As new materials and composites of existing materials are being developed, the structures will inevitably change their shape and utilize the possibilities that these materials offer to an increased extent. Dealing with possibilities in structural design, three ways exist to come up with new concepts:

- Enhancement of existing types of structures through improvements in some of their features;

- Combination of existing concepts to come up with a new solution;

- Development of completely new concepts, probably the most difficult and exciting of all three ways.

2.2.3.1 Enhancing Existing Structural Concepts

Enhancing existing types of structures can be done in various ways. Material properties of high-performance materials have already been discussed in Section 2.2.2. But improving the properties of a material and thus optimizing its utilization need not be the only way of enhancement. Other examples are:

- Use of improved details, e.g. bearings, expansion joints, anchorages, and dampers;

- Use of continuous superstructures with less joint details for better durability;

- Use of tendons with textured surfaces or interconnected stays that are less susceptible to fluttering and vibration;

- Use of prefabricated elements to simplify and speed up construction;

- Stronger implementation of architectural concepts in the design and awareness of principles of aesthetics.

Enhancing the design of substructure and superstructure can have both structural and aesthetic advantages. Leonhardt (1984) e.g. reports on the Lake Maracaibo Bridge in Venezuela, which was designed by Riccardo Morandi. Approaches to this bridge have rising V-shaped pier tables with slender columns. The main bridge itself with six A-shaped towers over heavy pier tables

with crossed legs and may not attract undisputed approval. Especially use of more slender and lighter pier tables and a multi-cable arrangement is proposed by Leonhardt (1984). Multi-cable arrangements in this case allow a more even distribution of the superstructure weight and make the whole bridge look lighter. More information on cables-stayed bridges is given in Section 2.1.6.6. A large variety of pier shapes have been used in practice, some of these with A, H, X, or inverted V or Y-shapes. Apart from the clear expression of the structural system, they can also improve the appearance of the structure through their simple, yet interesting shaping.

An example of enhancing a whole family of structures that is worth being mentioned is the *monocable suspension bridge*, shown in Figure 2-34. The initial idea for the monocable suspension bridge was put forward by the German engineer Fritz Leonhardt in 1953 (Leonhardt 1984) under the impression of the failure of the Tacoma Narrows Bridge in 1940. Section 2.1.5.6 gives more information on this event. Where many American engineers reacted to this failure by building sturdy trusses into further suspension bridges to provide rigidity to wind forces, Leonhardt proposed to build a suspension bridge with one main cable only. Inclined hangers attached to this cable would support the deck. As he further reports, tests with scaled models showed the stability of this type of structures, due to the inclined planes of hangers and their zigzag arrangement.

In conjunction with these developments, Leonhardt also developed the so-called *aerofoil deck*. This deck does not consist of a truss system anymore, but is rather a flat, aerodynamic box girder with long pointed flanges. The tests showed that the steel box girder need not be closed over its circumference, the braced bottom part can be left open.

A major monocable suspension bridge has not been built so far, although at least two very appealing proposals had been submitted, 1960 for the Tagus Bridge in Portugal and 1961 for a bridge across the Rhine in Germany (Leonhardt 1984). Both bridges were finally realized in the traditional form of suspension bridges with trussed decks – Leonhardt's idea was presumably too innovative for its time.

Figure 2-34: Monocable Suspension Bridge (taken from Leonhardt 1984, p292)

Brown (1993) gives an impression of the theoretical limits for span lengths for today's high-strength steel bridge types. Being able to support at least their own weight, according to these calculations, trusses could reach 500 m, arches 1,500 m, cable-stayed bridges 2,500 m, and suspension bridges about 5,000 m in length.

2.2.3.2 Combination of Existing Structural Concepts

Combining existing concepts may be useful in coming up with unusual structural solutions. However, there are arguments that speak against this way of improvement. The construction process may become more complicated and thus more expensive. Aesthetics are of prime importance in bridge design, as discussed in Section 3.3, and a mixture of structural elements will not necessarily satisfy the observer, since structural simplicity and pleasing appearance of the bridge may be disturbed. Examples for combinations of structural concepts are:

- Use of trussed superstructures in suspension or cable-stayed bridges;

- Use of stay cables and trusswork to support, brace, and stiffen structures;

- Use of e.g. arch superstructures that carry the deck below with suspension cables or above with columns.

An example of a combination of structural concepts from a conceptual study to cross the Strait of Messina is shown in Figure 2-35.

Figure 2-35: Combination of Structural Concepts (taken from Petroski 1995, p367)

A prominent example of a hybrid between suspension bridge and major cantilever spans is the proposal by T. Y. Lin for a permanent crossing of the Strait of Gibraltar, connecting Europe and Africa (Melaragno 1998).

2.2.3.3 Development of New Structural Concepts

Developing a completely new concept is the most difficult, but also the most challenging and rewarding of the methods pointed out. In his report on futuristic bridges Zuk (1988b) distinguishes between minor, major, and radical changes in future bridge construction. It is these radical changes that relate to the completely new concepts discussed here. The following sections give summaries of notions developed in Zuk's report and other concepts.

2.2.3.3.1   Kinetic Structures

Different types of movable structures or structures with movable elements exist, such as lifting bridges, swing bridges and bascule bridges that move parts of their superstructure to open for ship traffic to pass.

The military has long used movable bridges and pontoon bridges that can be transported and put together with armored equipment. Zuk (1988b, p7) appropriately describes that those "structures will look more like large machines than traditional bridges in that they will employ motors, rotating members, telescoping arms, and the like." While he anticipates them to be mostly a temporary replacement of old bridges under repair it is also possible that kinetic bridges will be used as permanent structures in smaller applications. The serviceability limits of deflection and vibration as well as robustness of the moving mechanisms and susceptibility to creep would have to be examined carefully for kinetic bridges.

2.2.3.3.2   Underwater Bridges

These structures that resemble floating tunnels anchored to the seabed would have the advantage that ship traffic would remain undisturbed. Stabilization of underwater bridges with corrosion-resistant cables is essential for structural integrity and would have to be a research issue. Apart from that it would have to be examined how fatigue due to movements of the water body around the structures influences the structural materials. To resist the deep currents, Zuk (1988b) stresses that they would need a streamlined shape. Means of construction would resemble building tunnels and also maintenance and repair concepts would be derived from tunnel construction. Although underwater bridges would provide means to cross waters, they should be better defined as submerged floating tunnels, since the very definition of bridges includes crossing over an obstacle.

2.2.3.3.3   Stress Ribbon Bridges

Stress ribbon bridges have already been used for smaller pedestrian bridges (Zuk 1988a). In this type of bridge very slender prestressed concrete ribbons are hung between the piers. German engineer Ulrich Finsterwalder developed this type of bridges for a proposal to cross the Bosporus in Turkey in 1958 (Podolny and Muller 1982). His design is shown in Figure 2-36. A major disadvantage of stress ribbon bridges is the deflection and probable vibrations of the deck, which make them less suitable for vehicle traffic. However, aerodynamic analysis has "indicated that a stress ribbon bridge is safe against torsional oscillation", Podolny and Muller (1982, p546) report. They also point at the heavy abutments necessary to withstand the tension that the ribbon induces. The unusual sagging shape of the ribbon in connection with the common perception of concrete as a rigid material might complicate public acceptance of this bridge type. Further development is necessary to make stress ribbon bridges become a feasible way of building bridges.
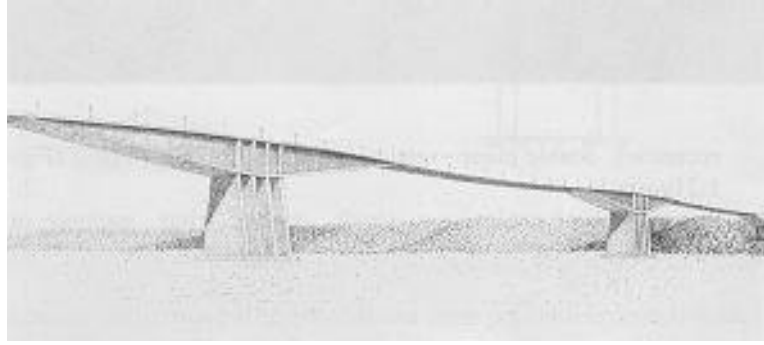
Figure 2-36: Stress Ribbon Bridge (taken from Liebenberg 1992, p38)

2.2.3.3.4   Multiuse Bridges

The most famous of all multiuse bridges, the Old London Bridge has already been introduced in Section 2.1.2.4. This type, also mentioned by Zuk (1988b), does not really introduce a new structural system, but rather comes along with a multifunctional use. Thus, a multiuse bridge would not only carry traffic routes, such as roads and railway tracks, but would also have residential and commercial functions with e.g. parking facilities in the lower parts of the bridge (Zuk 1988a). Building this type of bridge would become a very community-oriented task to provide a sound bridge structure with acceptable public and private facilities at the same time.

2.2.3.3.5   High-Art Bridges

Since many bridges built in the last years have been quite strict and simple in their appearance, especially concerning their plain concrete surfaces, a trend may develop to give bridges a more artful appearance. Use of colors, textured and structured surfaces and covers, and an aesthetically pleasing shaping might be put more focus on, making bridges more sculptures than simply objects of technology. Implementation examples could be representational structures for international exhibitions and technology parks. Zuk (1988b) already provides the limiting factor for this development, which is the cost of such decorative measures. Therefore he expects that

the number of high-art bridges will remain small. Yet on the whole a more conscious design with respect to aesthetics may be anticipated in bridge engineering.

2.2.3.3.6   Spatial Structures

So far, most bridges showed a very clear structural system with identifiable main members. Often smaller bridges are even statically determinate. In trusses, in suspension bridges, and in cable-stayed bridges this situation changes towards a statically highly indeterminate superstructure system with many smaller members that carry the deck. Structural indetermination introduces redundancy and increases structural safety. It can also allow replacement of single members while maintaining structural integrity. Podolny and Muller (1982, p548) explain this structural redundancy with the ability for loads to "redistribute by seeking an alternate load path." Complex analytical calculations of the structural behavior under different load cases are necessary to examine statically indeterminate systems for possible modes of failure.

Carrying this idea further, spatial network structures can be developed. These would consist of many smaller elements, such as trusswork and cables, which would make very large, yet light structures possible. Elements of these structures would predominantly carry axial forces. Special node connections between elements would have to be developed to allow for easy construction and to have flexibility for removal of single elements if required. Zuk (1988a, pp7-10) provides an example for such a combination of truss elements and cables: The so-called "Skyrail" system would consist of longitudinal cables wound around stiffening diaphragms. A system particular for mega-span bridges is outlined by Gibson (1998, p29), who reports of ideas for a so-called "Space Web". Advantages of this system, in which "a chain of three-dimensional arches made from cabling, which creates a horizontal suspension mechanism resistant to wind and earthquake forces", are mentioned. These advantages are anticipated to be less cost than suspension bridges, possibility to bridge extremely large obstacles with spans of about 3.2 km or more, and advantages in the erection sequence (Gibson 1998, p29).

Elements for spatial structures can be pre-assembled in sets that are transported to the site and are installed. Steel, lightweight metal alloys, or advanced plastics could be used as structural materials. However, special attention needs to be paid to the degree of complexity both for construction process and for later maintenance, and for an aesthetically pleasing appearance. Certainly, spatial bridge structures would have to fulfill all common requirements of structural safety and serviceability to become competitive solutions in bridge engineering.

Application of the outlined principle is not new in the construction industry. As mentioned above, bridge types such as trusses, suspension, and cable-stayed bridges already implemented trusswork and cables in manifold variants. Metal trusswork is often used for wide-spanning roofs, such as "roof structures for large, column-free sport facilities, auditoriums, civic centers, and the like" (Podolny and Muller 1982, p548). Further development of trussed structure is, however, still possible.

2.2.3.3.7   Concrete Trusswork

Examples for truss application even in concrete bridges can be found in the technical literature. Podolny and Muller (1982, p547) report of a bridge proposal that had prestressed concrete trusses instead of the usual inclined solid box girder webs, thus forming a system of "multitriangular-cell concrete box girder" elements. They give several examples of prestressed concrete truss bridges, including the trussed box superstructure of the Mangfall Bridge in Austria, built in 1959, a proposal for a precast truss by Freyssinet (pp392-394), and the arch-shaped trussed Rip Bridge in Australia (Wheen 1979a, 1979b). The Mangfall Bridge is shown in Figure 2-37. Another idea by Freyssinet was longitudinal confinement of prestressed concrete members in a jacket creating "permanently biaxial transverse compressive stress", which proved very high load-carrying capacity in tests (Podolny and Muller 1982, p399). Menn (1990) mentions the Rue Lafayette Bridge, which was finished in 1928 in Paris and consisted of two spans with parallel reinforced concrete trusses without prestressing.

Figure 2-37: Concrete Trusswork in Mangfall Bridge, Austria

(taken from Leonhardt 1984, p203)

Other futuristic ideas for bridge structures are presented by Podolny (1998), who reports on aerodynamically shaped tubular superstructures with traffic enclosed within and on three-dimensional tubular space frames, which, in conjunction with advanced materials, would provide both light and stiff structural solutions.

2.2.3.3.8   Bioengineering

An interesting and promising approach that has only been little been developed is the use of bioengineering in construction. The main point of this approach is the examination of principles in natural structures, especially in the living environment. Applications of bioengineering knowledge are found in the aerospace industry, which has implemented e.g. specially textured foils on the surface of airplanes to decrease air resistance. A similar approach is possible for construction engineering. The variety of natural structures is worth being examined further under

an engineering point of view. Research need not be limited to bridge construction, other areas will also be influenced, e.g. building technology may explore new means of heating and insulation, the construction materials industry may find new means in utilization of biologically produced or modified polymers, and the like. The following examples shall merely give an impression of structures and concepts that nature has developed:

- Cobwebs, which form strong but extremely light networks;

- Grass and corn, which incorporate both strength and flexibility;

- Tress and shrubs, composed of strong wood fibers tower their environment;

- Crystals, which have an enormous strength through their regular inner composition and also show interesting electrochemical effects;

- Bee honeycombs, whose regular geometrical structure makes them stiff and light;

- Bones, which have an interior matrix network adapted to the flow of forces;

- Thermal insulation, which allows animals to inhabit roughest climates.

2.2.4 Conclusion

With the prospects and possibilities presented above one can say that the future of bridges has just begun. The three main areas of future development that were pointed out in the previous sections show that the range of ideas to be explored is very wide. Some of these ideas may prove impractical within the technical environment, while others will become feasible once the existing technologies have been developed further. The approaches mentioned will contribute to the development of amazing new structures. Only the fascination that is characteristic for bridge engineering field will remain the same that it has always been, during the many centuries that have passed since the first bridges were erected.