Chapter 1

History of Sustainable Bridge Solutions

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Additional information is available at the end of the chapter

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Abstract

The chapter is a voice in the discussion concerning sustainable bridge development. Nowadays, the term has rather been abused, and therefore the presented approach refers to these elements of design, construction and maintenance of bridges—with regard to their role in transport and social life—which have been present in bridge construction for a long time and can be easily incorporated into the concept of sustainable bridge construction. Sustainable development, sustainable construction and so on are multidimensional. In the considered bridge construction area, looking at construction processes as interfering with the environment and which could and should be restricted is a new element. Nevertheless, other proven constructional solutions and technologies are characterised by their reliability. Assuming that the constructed bridges are to serve the next two or three generations of users, we can try to extrapolate current technical conditions on the next 30 or 60 years, i.e., up to three generations. We can do it if we know and are able to critically assess the history of bridge construction. Following this reasoning, the history in question is referred to in this paper, although rather subjectively and with the omission of numerous important personalities and technologies as well as instructive failures due to the publishing limitations.

Keywords: Bridges, History of Bridges, Aesthetics, Sustainability, Architecture

1. Introduction

Sustainable bridges is a term exemplifying the general idea of sustainable development. The concept is a result of the works of a UN commission—the World Commission on Environment and Development—conducted from December 1983 to December 1987 and concluded with the report *Our Common Future*. At present, several definitions of the basic concept and its specific component disciplines are in use. One of the general definitions emphasises preservation of natural environment by achieving the developmental objectives in a responsible way: *the present generations' responsibility to regenerate, maintain and improve planetary resources for use by future generations*. Nowadays, the idea has developed into specific disciplines, such as sustainable engineering, sustainable bridges [1] and sustainable design [2].

In the development of civilisation, an extensive and well-organised transportation system, i.e., roads, railway, bridges, air transport and maritime and inland navigation, safe both for people and environment, is of primary importance. The development and constant modernisation of road and rail infrastructure is connected with significant pollution emissions into the air, soil and water. Investments are accompanied by noise and traffic disruptions. These negative side effects have an equally strong impact both on people and environment. In general, they can result in a temporary or even permanent closing or changing of wildlife corridors, animal herd fragmentation, changing of nesting sites or habitats.

Roads and bridges, despite obvious differences, constitute a technically inseparable set. The name of the first and still functioning technical school, excellent *École nationale des ponts et chaussées* founded in 1747, is quite symptomatic here. Bridges as such belong to the elite area of civil engineering. This position stems from their civilisational, social, architectural as well as military role.

After the horrible experience of the first World War, the Briand-Kellogg treaty [3], renouncing war as an instrument of national policy, was concluded. History, including the most recent one, shows that military operations are still conducted on a different scale and so it happens that some are aimed at bridges. **Figure 1** shows the Hanoi bridge that was destroyed during the Vietnam War. Its crippled form is a dramatic monument to this war.

Figure 1. Hanoi Cầu Long Biên Bridge (1903) over the Red River—a war monument.

Sustainable bridge construction refers to the minimisation of harmful emissions during bridge construction. It is equally important, however, to design durable bridges, i.e., with minimum serviceability of 100 years as stipulated in the design standards [4]. The bridge longevity results from the structure maintenance therefore its design should take into consideration the ease of its future maintenance.

A design taking into account the future changes of traffic, both in terms of its volume and type, seems to be a great challenge. The existing methods of forecasting traffic changes cover periods from 5 to 10 years. Nobody can foresee what can happen in 50 years, [5]. Bridges have been built for thousands years and that is why it is easy to indicate the ones which have proved reliable according to various criteria. For this reason, they can be seen as sustainable bridges. The history of bridge construction referred to this paper is presented from such a perspective. In many cases, only the name of a bridge is mentioned, which results from its recognisability as well as an easy access to basic encyclopaedic information on the Internet.

2. Archaic period

The history of bridges can be told in many ways. It will always be a subjective representation, strongly affected by the author's attitude. This is also the case here.

The first large-scale bridge, recorded by Herodotus, was a structure for crossing the Dardanelles (Hellespont in the ancient times, the area of Çanakkale in Turkey at present), constructed by Greek constructor Mandrocles of Samos in 513 B.C. It was a ship pontoon bridge. Soon after, in 480 B.C., two other pontoon bridges were constructed by Xerxes' army, see *History of Herodotus* [6]. At the point of the bridge crossings, the Strait of the Dardanelles is 1.4 km wide. It should be noted that Herodotus' description of the bridges gives rise to doubts; therefore it can only be assessed in terms of likelihood.

In 55–53 B.C., during the wars with the Germanic peoples, Julius Caesar commissioned the construction of two wooden bridges over the river Rhine. At least two reconstructions of these bridges exist [7]. Another large-scale bridge was constructed during Emperor Trajan's war against Dacia in 105 A.D. by Greek architect Apollodorus of Damascus. Its remains, in the form of stone pillars, are to be found in a place with a poetic name: Turnu Severin. It was a wooden arch structure based on 20 massive supports where the Roman pozzolana cement was used. The bridge was immortalised in a relief on Trajan's column in the Foro di Traiano in Rome.

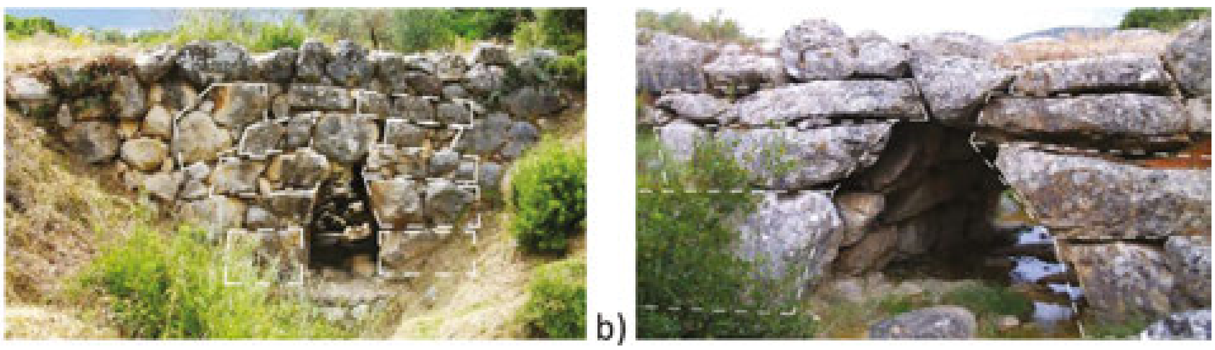
a) b)

Figure 2. Arch-corbel system of Mycenaean bridges: (a) Bridge A; (b) Bridge B.

All of the aforementioned bridges do not exist anymore, but in Peloponnesus there are still two stone bridges constructed with so-called *Cyclopean boulders* to be found, known as Mycenaean Bridges. The period of the Mycenaean culture falls in the mid-Bronze Era from approx. 3000 B.C. to 1000 B.C. Hence, it can be inferred that the bridges are at least 3000 years old and for that reason are considered the oldest existing bridges in the world. Given their age, they are in a superb technical condition. They are not large-scale objects—the width of the light of the flow opening is approx. 1.5 m, its height approx. 2 m, **Figure 2**.

It should be highlighted that Mycenaean bridges were elements of the road system, which today is known as *Mycenaean Highways* [8] —which may be a slightly exaggerated name. The term was first introduced by A. Jansen, the author of one of the chapters of this book.

Mycenaean bridges are very interesting from the point of view of structural mechanics and construction technology. At the first glance, they seem to be arch structures. But if so, one must admit that these arches are rather accidental. The arrangements of boulders of which the arches are made demonstrate the lack of knowledge with regard to the essence of the arch behaviour. As a matter of fact, they are corbel structures which—as a result of seismic earthquakes—have been degraded to the present shape. Hence, the currently observed cyclopean boulder arches are a result of the transformation of the corbel system into a possible mixed arch-corbel static system. The effort and stability of Mycenaean bridges were analysed in the paper [9]. Identification of the technology of Mycenaean bridges is a great challenge, **Figure 2**. The cantilever slab technology enables construction without scaffolding. If indeed it was so, Mycenaean bridges were a major constructional achievement. Despite the fact that Mycenaean bridges constitute a part of the heritage of mankind, they have not been sufficiently studied. Paradoxically, apart from taking external measures, their ultra-historical character makes it impossible to conduct standard research.

3. Times of the Roman Empire

The period of the Roman Empire saw an overwhelming abundance of stone, brick and stone-brick arch bridges—apart from military bridge structures, naturally. This period can also be equated with Roman roads. The system and quality of roads enabled movements of the Roman legions and also served civil purposes.

Before we start discussing Roman bridges, however, we need to look at a much older and historically very important road, namely, the Persian Royal Road [10]. It crossed the Persian Empire from Susa or from Persepolis to Smyrna (present-day Izmir). Depending on historical sources, the total length of the road amounted to 2600–3000 km. The road was built by the Persian king of kings, Darius I (c. 550–486 B.C.) and was used as a postal route. It took from 7 to 10 days for the system of courier stations and teams to cover the distance. The road was used by Alexander the Great, and then by the Romans. It was in service for more than 3000 years and coincided with the Silk Road to a considerable degree.

In the town of Diyarbakir (Kurdish: Amed) in south-eastern Anatolia, a bridge called Ten Eye Bridge has been in use till this day, **Figure 3**. It was constructed in the eleventh century, although its dating is connected with the conducted reconstruction. Some historical sources connect this place with the Royal Road and if this were to be the case, it would be one of the oldest bridge

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crossings in the world. Assuming that 1065 A.D. is a trustworthy date of the reconstruction, the bridge on the river Tiger (Dicle – tr.) comes from the Roman period.

Figure 3. The 10-Eye Bridge over the Dicle River in Diyarbakir.

Here, the dating of the Roman Empire should be highlighted. In most part of Europe, it covers the period until the fall of the Empire in 476 A.D. In the Mediterranean, it is seen as connected with the fall of Constantinople on 29 May 1453. There is a difference of almost one millennium. In these circumstances, Roman bridges in Turkey and Arab countries may be much younger than Roman bridges in Spain.

One of the first bridges on the river Tiber built in 62 B.C. is certainly Roman—according to the both modes of historical dating, **Figure 4**. There is a funny story connected with the bridge: when it was constructed, the payment for work was refused unless it was proved that the structure was durable. The photograph in **Figure 4** was taken in 2008. Nevertheless, the ordering party's anxiety is easier to understand if we take a look at other, even later, Roman bridges, as shown in **Figure 5**.

Figure 4. The Pons Fabricius built by Lucius Fabricius, 62 m long, 5.5 m wide.

The bridge is located on a Roman road bearing a Spanish name: *Via de La Plata*. It is over 700 m long. Its elements include processed granite arches. There are 60 arches based on massive pillars. They are heavy, reliable structures.

The Pons Fabricius marked the beginning of a new way of looking at bridges that, aesthetically, are relatively light and this trend has survived in Rome till this day. With the exception of the Ponte Pietro Nenni that carries an underground line, all the bridges in Rome have arches. Among them, one finds the first reinforced concrete bridge in the world, the Risorgimento of 100 m span, constructed in 1912 by F. Hennebique. Also, in 2011, a beautiful pedestrian steel footbridge with shallow arches was built—the Ponte dela Musica.

Figure 5. Puente Romano de Mérida, built in first century A.D., Guadiana River.

In the Roman period, bridges known as aqueducts were also built, slender and beautiful in their monumentality. The only load they carried was the dead load with an insignificant addition of flowing water, **Figure 6**.

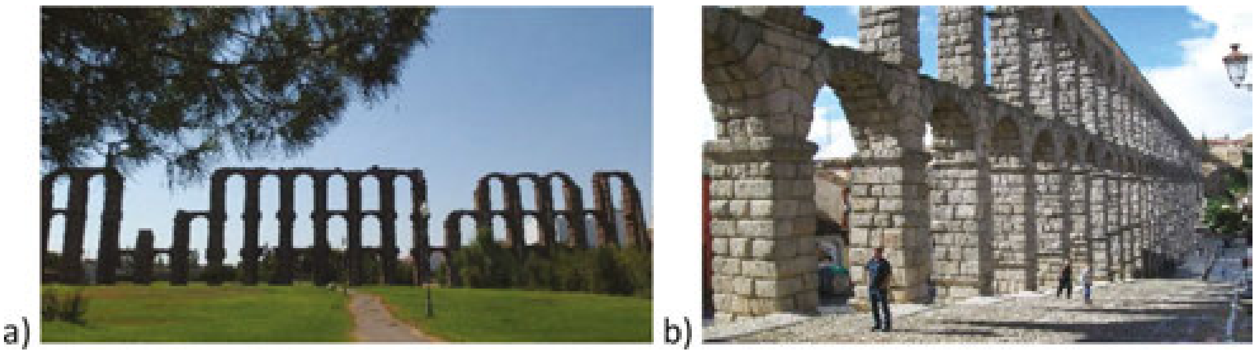

Figure 6. Roman aqueducts, first century A.D.: (a) Los Milagros (the miracles); (b) Segovia aqueduct.

It should be mentioned that during the Roman Empire, but 200 years later, tower aqueducts were constructed. Water flew in a leak-proof pipe located on relatively short arcades. The level differences were solved on the basis of the principle of communicating vessels according to, surprisingly, Pascal's theorem, see **Figure 7**.

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Figure 7. Views of the Aspendos aqueduct: (a) from the top; (b) from the ground level.

4. Bridges in the middle ages

During the European Middle Ages, stone arch bridges were continued to be built, although their variety was limited. Also, the road development slowed down. Bridges usually had a defensive character. **Figure 8** shows two bridges leading to the medieval capital of Spain, Toledo, which are a good example of the role and technique of the medieval bridge construction.

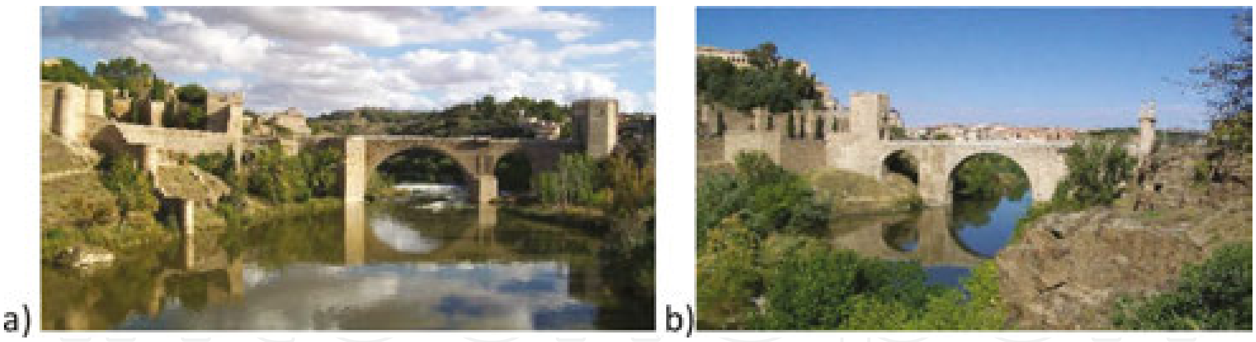

Figure 8. The Toledo bridges over the Tajo River: (a) St Martin's Bridge, fourteenth century; (b) Gothic Alcántara Bridge, thirteenth century.

The Toledo Alcántara Bridge should not be mistaken for another Roman bridge of the same name located in the vicinity of the town of Cáceres and constructed in 105 A.D.

In this period in Turkey, a bridge construction canon was developed. Nowadays, such structures are sometimes called Turkish. The bridges in question were still arch bridges, usually made of light colour stones. They have a main span and, possibly, additional spans that serve as flood relief channels in case of high water. It should be born in mind that in the case of the arch bridge, only the arch is the carrying element. The extended walls in arch bridges act only as a façade, very often hiding empty spaces. These spaces were frequently used as utility rooms by bridge guards and sometimes even as guest rooms for travellers. This was the case of the bridge on the river Batman in Turkey, twelfth century, **Figure 9**.

a) b)

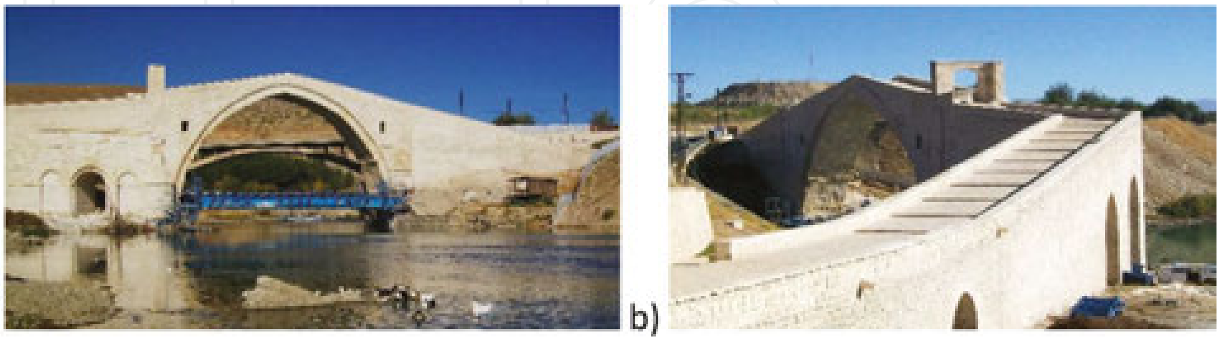

Figure 9. Malabadi Bridge near Sivan: (a) side view; (b) entrance to the bridge room.

A twin object, built by Mimar Hayruddin in sixteenth century, can be found in Mostara on the river Neretva. The stem of the name of the town, which is an adjective, comes from the word *most*, i.e., *bridge*.

a) b)

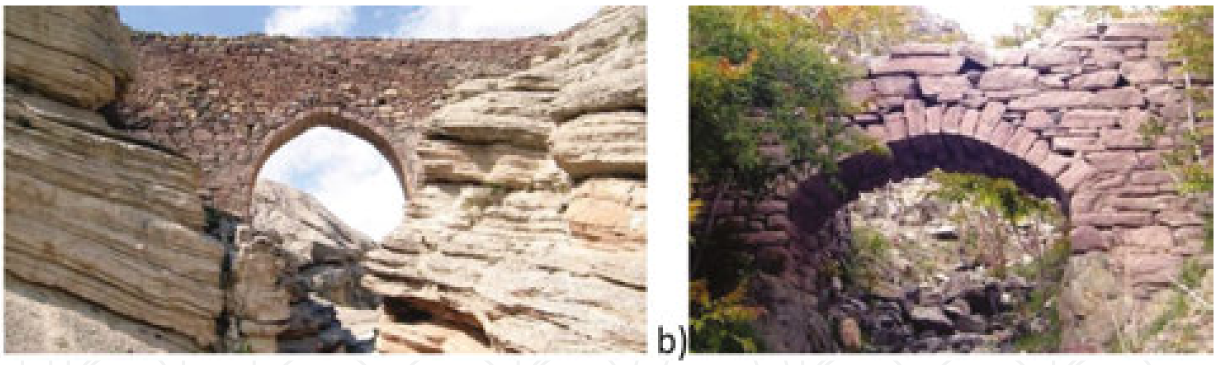

Figure 10. Stone arch bridges in the vicinity of Sille Village near Konya: (a) double parabolic arch structure; (b) parabolic arch with the deck partially ruined.

The popularity of arch bridges results from the arch mechanics. To offer an insight into the issue, we can refer to an exercise solved by students in the structural mechanics class. It is about a parabolic three-hinged arch, evenly loaded. Performing basic transform calculations we find that the bending moment at any point of the arch equals nought. It means that, in fact, the arch is not three-hinged but it is a sequence of hinges. Similarly, in the case of a shearing force we find that it equals naught at all the points. It is not a classical approach, but consequently reasoning we can conclude that the arch is a sequence of hinges functioning of which is based on a shear force. Another conclusion is that the only non-zero internal force in the arch is the force normal with regard to its cross-section, and, what is more, it is a compressive force. In practice, we can shape the sides of stone blocks in such a way that, geometrically, they form a parabolic arch. This arch is going to be a durable and efficient structure—on one condition. In arches, the outward-directed horizontal reaction, called *thrust*, is of primary importance. It has a significant impact and, more often than not, the lack of the proper ground resistance results in the destruction of the arch as a whole or its substantial weakening as a superstructure—at best. The discussed case of a parabolic arch equally loaded is a theoretical one, however, in the case of a real structure we can imagine a set of material points of the highest bearing capacity and that will be an illustration of such an arch. **Figure 10** shows two viaducts on a mountain path near Konya, made with processed stone blocks assembled without mortar.

The advantages of arches in bridge structures make this solution commonly used until this day. The photograph below shows an arch bridge destroyed to such a degree that the arch structure is plainly visible, **Figure 11**.

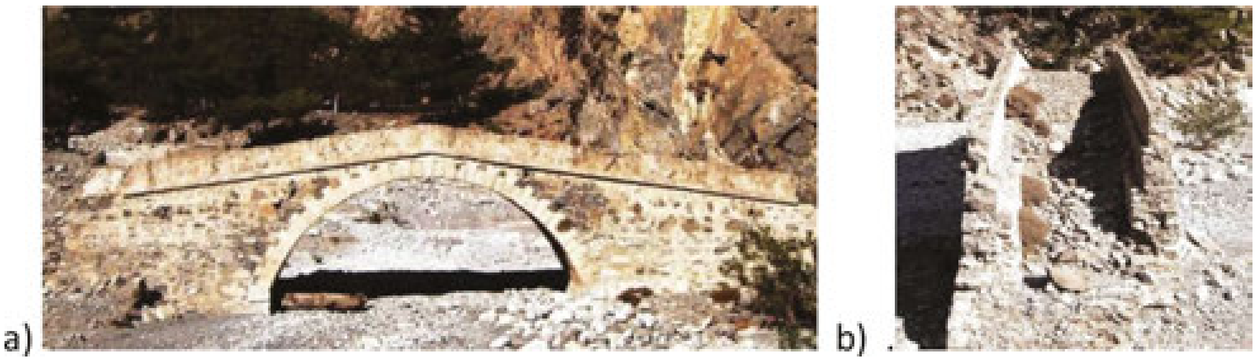

Figure 11. Structure of stone bridge, Samaria Gorge, Crete: (a) side view; (b) longitudinal view.

Numerous antique bridges were built without mortar. Among the objects shown here there are the Roman Bridge in Mérida and the aqueduct in Segovia. Nevertheless, the columns of the aqueduct of *Los Milagros* are composite, according to modern standards. The external cladding was used as permanent formwork, filled with pozzolana cement concrete.

5. Renaissance: Leonardo bridge over Golden Horn

Renaissance is strongly associated with an outstanding personality of this period, Leonardo Da Vinci. This genius had a brief albeit challenging bridge episode, **Figure 12**.

Through diplomatic channels he was asked to design a project of and construct a bridge over the Golden Horn (Haliç – tr.), an inlet of the Bosphorus in Istanbul. In 1502, an ambassador of Sultan Bayezid II came to Rome. It is probably then, from 1502 to 1503, that Leonardo made the sketch of the bridge that now can be found in the manuscript commonly known as *Paris Manuscript L* [11]. The manuscript pages are rather small, 7 × 10 cm, and the drawing itself is quite simple. Despite the fact that the drawing does not contain any dimensions, it is assumed that the bridge was supposed to be 240 m long and 23 m wide with the arch curvature of 40

m. The bridge was not built, however. In 2001 in Norway, creator Vebjorn Sand constructed a footbridge in the town of Ås [12], which was a reference to Leonardo da Vinci's concept. However—in the author's subjective view—it is only partially successful, both in the aesthetic sense and as an incorporation of the Renaissance genius' idea. Looking at the drawing in the manuscript, it is difficult to decide about the bridge structure. Sand's footbridge seems to be one of many possible interpretations.

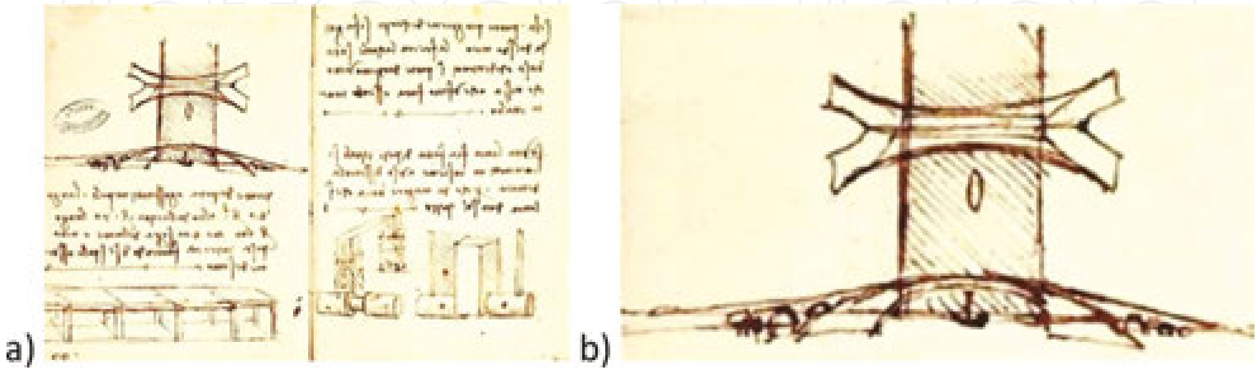

Figure 12. Golden Horn Bridge project, 1502. Paris Manuscript *L*: (a) 66th page of the manuscript; (b) bridge enlarged.

6. Wooden simple bridge

Wooden bridges have always been built. For this reason, a technology was developed which took into account the characteristics of wood as a material of relatively low strength, but at the same time commonly available and easy to handle. The strength of wooden bridges has always been low. It was good if the serviceability period amounted to 20 years. A wooden bridge is also the result of a skilful application of structural mechanics. For the above reasons, usually simple, mechanically pure solutions were chosen. Let us consider the most common wooden bridge, **Figure 13**. Abutments are meant to transfer two kinds of impacts. The first one refers to vertical reactions caused by loads on the carrying deck. For this reason, a row of poles was constructed under each girder. The other impact refers to active ground pressure behind an abutment. Here, the second row of poles was used—outer poles were put behind so-called planking. As a result, a retaining wall was obtained which was also additionally supported by its anchoring in the ground (deadman). The bridge wings were slanting, of variable heights.

An interesting solution is a saddle which enables reduction of support spans and the values of bending moments under the supports. In the case illustrated in **Figure 13**, the bridge beam is single but wooden bolster composite bridge beams were also used. The composition was not complete—from the modern perspective it should rather be called *partial integration*. The construction of wooden bridges was at least as complex as the modern bridge technology. The dimensions of a saddle are determined on the basis of a simple differential calculus assuming extreme curvatures of the beam and the saddle at the local point of contact. Paradoxically, the best work about wooden bridges is a book [13] written 100 years ago. The technology of wooden bridges is still in use in the case of temporary bridges. Additionally, there is a new option available which is connected with the ecofriendly recycled plastic technology, see [14]. Instead of natural or sawn wood, recycled plastic logs or panels are used which contributes to the minimisation of deforestation.

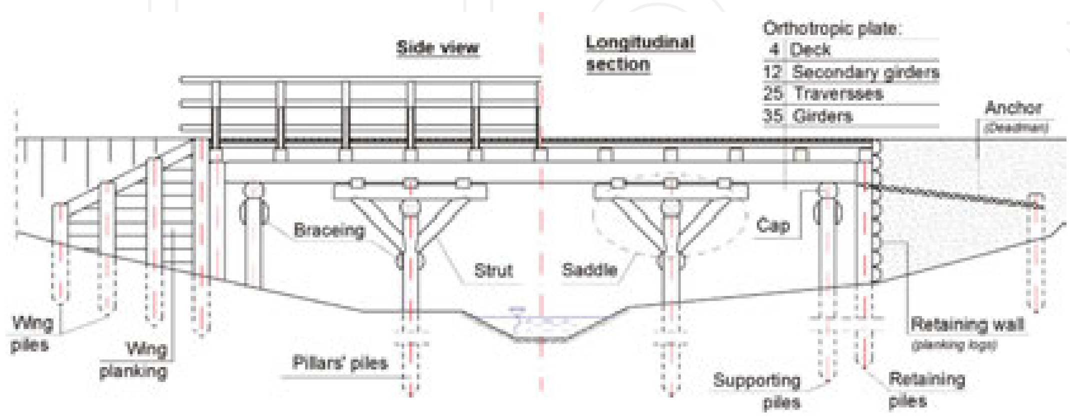

Figure 13. The scheme of a wooden bridge: carrying elements.

7. Iron bridges

The industrial revolution in England was a turning point in bridge construction. In 1779 an arch bridge, known as the Coalbrookdale Bridge or Iron Bridge [15], was constructed by Abraham Darby III with cast iron from his ironworks located in Shrewsbury, **Figure 14a**.

One hundred years later, bridges of spans reaching 160 m were built with wrought iron. **Figure 14b** shows a photograph of the bridge on the river Duro in Porto. It was constructed by T. Seyrig, Gustave Eiffel's associate. At present, the bridge has no utilitarian function, but it is one of the highlights of the city of Porto.

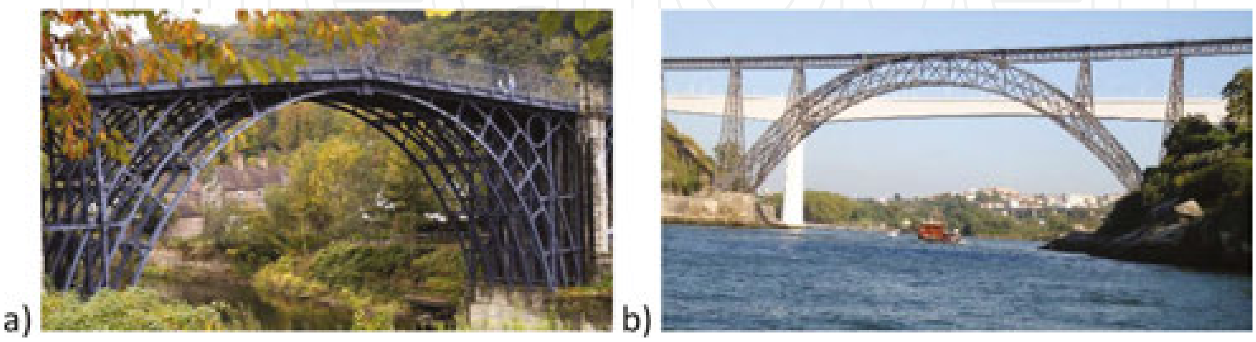

Figure 14. Cast iron bridges: (a) Iron Bridge, 1779 (*photo by Jason Smith* [16]); (b) Dona Maria-Pia Bridge, 1877 (*photo by Dr.Eng. W. Nurek*).

8. Reinforced concrete

Another turning point in bridge construction was the invention of Portland cement and, as a result, using concrete based on it as well as reinforced concrete. The first concrete bridge was a small park object in the botanic garden in Grenoble, **Figure 15**, constructed by Louis Vicat and his son. Vicat was also one on the inventors of cement.

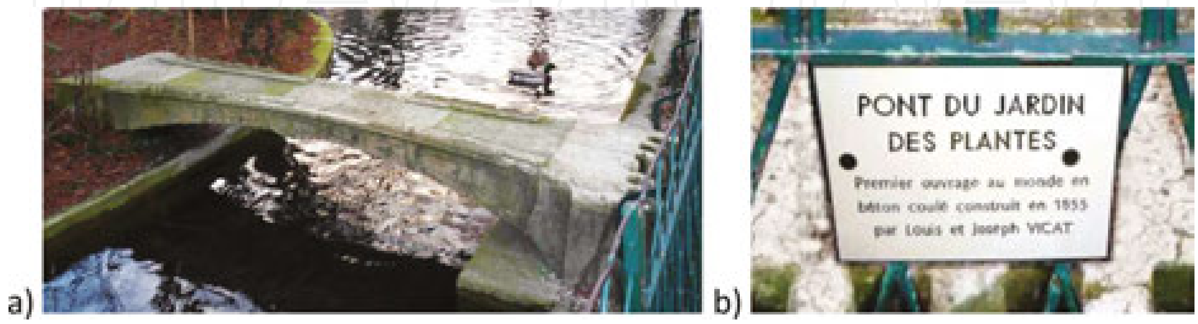

Figure 15. The first concrete bridge, Grenoble 1855: (a) view; (b) memory board (*photos by the courtesy of Prof. Françoise Videau*).

The undisputed *father* of reinforced concrete is Joseph Monier (1867), often mentioned simultaneously with Joseph Louis Lambot who constructed a reinforced concrete boat (1848). Monier gave its surname to the other name of reinforced concrete structures: people spoke of Monier arches or Monier ceilings. In Germany, the name *Monierbau* was initially used. Monier sold his patent to two great engineers, François Hennebique and Gustav Wayss. G. Wayss—the company Wayss u. Freytag—constructed majority of their bridges (about 350 structures) as Monier arches (arched shells) which from the structural point of view copied the stone and brick bridge technology with the only difference that a new material was used, namely, artificial stone: concrete reinforced with bars, originally used for the first time by Monier in the construction of the bridge in Chazelet (1875), see [16].

Figure 16. (a) François Hennebique (1842–1921); (b) global activity of *LBA Hennebique*, 1908; (c) the *LBA* issue of February–March, 1912, no. 165–166.

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Chronologically, between Vicat's bridge and Lambot's boat there is only an interval of 3 years, but the bridge in Chazelet was built 20 years later. It can be assumed then that the popularisation and implementation of the new technology lasted a similar amount of time.

Even a reinforced concrete bridge had to be invented by someone. Again, there are numerous candidates to the title of the inventor: T. Hyatt (1877), F. Coignet (1861), P. Christophe (1902). It seems, however, that François Hennebique can be indicated as one, **Figure 16a**. He was an author of several patents and, apart from conclusions from the author's bibliographic research, he is named as the reinforced concrete pioneer in various studies, e.g., [17].

Hennebique created a global company (**Figure 16b**) which employed the best engineers and architects building reinforced concrete structures including bridges, **Figure 16**. He offered ready-to-use projects, technology and very often materials as well. From the very beginning Hennebique developed a network of contractors. In practice, the company was known as *Le Système Hennebique* or *Béton Armé Hennebique*. The sale of structural and technological solutions was connected with intensive training and supervision provided by Hennebique.

An essential tool of Hennebique's success in building his company was the technical magazine *Le Béton Armé* [18], published from 1898 to 1939, **Figure 16c**. Apart from purely technical texts in the area of the theory of reinforced concrete as well as the practice, i.e., descriptions of the construction of reinforced concrete structures, one could find information about the network of the company's representatives and contractors. The magazine was richly illustrated with technical drawings, photographs of various construction stages and finished structures as well as advertisements of companies, products and technologies.

Thanks to a happy coincidence, in the city of Lublin in Poland there are two Hennebique beam bridges constructed by Polish engineer Marian Lutoslawski in 1908 and 1909, respectively. One of them has been renovated. After it was put into service, the city's cultural circles took it over and it has been called the *Bride of Culture* since, **Figure 17**.

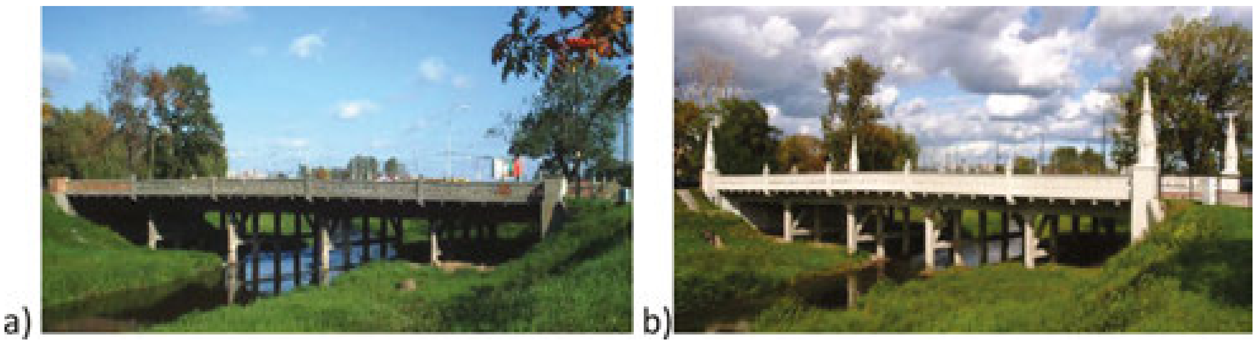

Figure 17. Bridge of Culture, Lublin: (a) before restoration, 2011; (b) after restoration, 2013.

The bridges in Lublin are examples of a successful transformation of the bridge technology using wood into the one of reinforced concrete, a new material at the beginning of the twentieth century, see [19].

9. Suspension bridges

The carrying elements of a suspension bridge is a set of pylons and a rope in its natural catenary shape. It is assumed that the origins of suspension bridges are hidden in remote history. The tradition of the construction of narrow footpaths in Asia, especially in Tibet, is widespread. The first modern chain suspension bridge was built over the Menai Strait in 1826, connecting the Welsh island of Anglesey to the mainland. Its maker was brilliant bridge constructor Thomas Telford (1757–1834), see [20].

A turning point in the suspension bridge construction took place at the turn of the nineteenth and twentieth centuries in New York. An engineer constructing suspension bridges in the United States was German immigrant John Augustus Roebling (1806–1869) who also produced wire ropes. Roebling started developing the production of a seven-strand wire rope on a ropewalk that he built on his farm in Saxonburg, Pennsylvania. Next, he built a large industrial complex for the production of wire suited to the needs of the bridges he constructed. His first and significant bridge—Roebling cooperated with two other engineers—was the rail Niagara Falls Bridge which remained in use from 1855 to 1897. The span was 251 m. In 1866, Roebling built a 322-m span bridge in Cincinnati, **Figure 18**.

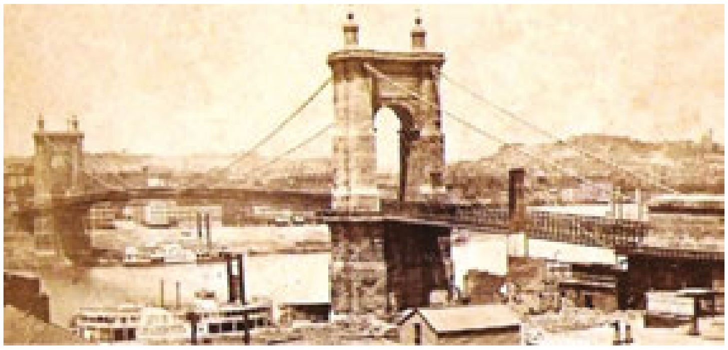

Figure 18. Roebling's suspension bridge in Cincinnati (1866) [21].

Figure 19. Suspension bridges in New York: left—Brooklin Bridge (1883), right—Williamsburg Bridge (1903) (*photo taken by Alicja Filipowska, 2015*).

Actually, it was a mixed system which nowadays is called the *hybrid suspension and cable stayed bridge*. In a manner of speaking Roebling *repeated* the above- mentioned bridge in New York in

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1883. The bridge is called the Brooklyn Bridge. In this case, however, the main span amounted to 486 m. New Yorker Henry Hornbostel (1867–1961) built the Williamsburg Bridge in 1903, see **Figure 19**. This is a road bridge of eight lanes. The longest middle span amounts to 490 m.

Contrary to Roebling, he used a steel frame to raise towers. In this case, the suspension ropes were vertical that became the classical solution for many years. In 1927, Swiss-American engineers Othmar Ammann (1879–1965) and Cass Gilbert (1859–1934) built the double-deck George Washington Bridge. Its middle span amounts to 1067 m. The Mid-Hudson Bridge was built in 1930. The chief engineer was Polish immigrant Ralph Modjeski (1861–1940). The longest span is 910 m, see [22].

The most famous American suspension bridge is naturally the Golden Gate Bridge, constructed in 1937. Its total length amounts to 2737 m, while the main span 1280 m, **Figure 20**.

Figure 20. Golden Gate Bridge, 1937: (a) side view; (b) road traffic (*photo by Alicja Filipowska, 2015*).

At present, the Akashi Kaikyō Bridge (Japan) has the longest central span of all suspension bridges—it is 1991 m long.

All the above-mentioned bridges have truss platforms. It is a proven and reliable solution. Simultaneously, suspension bridges with plate girder deck were constructed such as the Tacoma Narrows Bridge, for instance. The length of its main span amounts to 853 m. The bridge was opened for traffic on 1 July 1940. On 7 November 1940, the catastrophe stuck—and was filmed. The cause of it was the so-called aeroelastic flutter effect. For this reason, the bridge is unofficially known as *Galloping Gertie*. The studies and analyses conducted at that time showed that truss load-bearing structures should be used [23]. Nowadays, when the advanced finite element method (FEM) procedures are available, it is easy to demonstrate by means of numerical analyses that the causes of the catastrophe were correctly identified.

In 1966, the bridge over the Severn Bay near Beachley in Scotland was built. It is a low profile box carrying deck structure. The middle span is 988 m long. An unusual feature of the suspension cables carrying the deck is that they are not vertical, but arranged in a zigzag pattern. The diagonal arrangement of hangers—as compared to vertical ones—increase the dynamic stiffness that is additionally supported by tuned mass damper-harmonic absorbers.

The deck is an orthotropic steel box of the aerofoil shape. The bridge was tested and approved by the designers Freeman, Fox and Partners following wind tunnel tests.

The First Bosphorus Bridge constructed in Istanbul in 1973 is a replica of this bridge. The main span—the distance between the towers—is 1074 m, **Figure 21**. When opened, it was the second bridge crossing between Europe and Asia constructed since 480 B.C.

Figure 21. First Bosphorus Bridge: (a) side view; (b) tower and aerodynamic low profile deck.

Currently, the construction works of the third Bosphorus bridge—Yavuz Sultan Selim Köprüsü —are underway, according to the design by Michel Virlogeux and Jean-François Klein. The bridge has been designed as a hybrid structure.

10. Cable-stayed bridges

A cable-stayed bridge has one or more towers, from which straight cables carry the bridge deck as elastic supports. There is a clear analogy between the behaviour of backstays and cable-stayed bridges. The first known analysis of this problem comes from 1823 and was performed by C.L. Navier, see [24]. Diagonal rods in Bollman trusses also bring to one's mind cable-stayed

Figure 22. Cable stayed bridges: (a) Strömsund Bridge (1956) (*photo by Lars Falkdalen Lindahl* [25]); (b) the tower of the Bratislava SNU bridge, 1972.

bridges. In 1873 in London, the Albert Bridge, designed by Ordish and Bazalgette, was constructed. The first modern cable-stayed bridge is the Strömsund Bridge in Sweden, designed by Franz Dischinger (1956), **Figure 22a**.

Considering the development of the cable-stayed structure, one can specify the German period connected with German engineers F. Dischinger, U. Finsterwalder , F. Leonhardt, H. Homberg, H. Wittfoht, E. Jux and others. Naturally, cable-stayed bridges have been constructed everywhere. **Figure 22b** shows one on the most beautiful bridges of this kind, namely, the Bridge of the Slovak National Uprising in Bratislava, constructed in 1972. Another spectacular cable-stayed bridge is the bridge located at the outlet of Lake Maracaibo, designed by R. Morandi and built in 1962, see [26].

Figure 23. Stayed cable bridges: (a) segmental assembling of the Nissibi Euphrates Bridge, 2015; (b) Norman Foster's Millau Bridge (*photo by A. Leniak-Tomczyk, 2004*).

In the case of cable-stayed bridges at least two assembly technologies are available. The first one refers to a segmental bridge structure built in short sections. It is a very natural method of constructing such bridges. Successive segments are stabilised by attaching them to pylons by means of cables, **Figure 23a**. The other method consists in the incremental launching of a carrying-deck with the use of fixed and intermediate supports. After the launching, the bridge is rectified to its proper grade. An example here is the architecturally magnificent Millau Viaduct designed by M. Virlogeux and N. Foster (2004), **Figure 23b**.

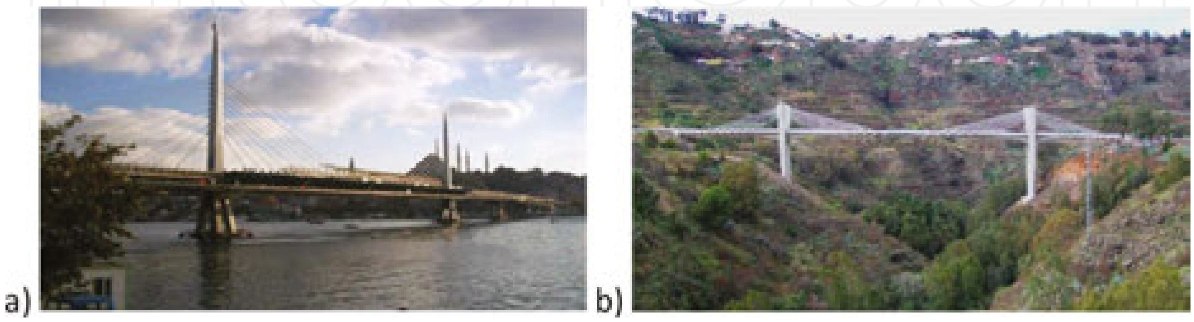


Figure 24. Visible cables: (a) the Golden Horn Metro Bridge, 2014; (b) extradosed Viaducto de Teror, Gran Canaria, 2010.

Cable-stayed bridges are aesthetically challenging. To highlight their attractiveness appropriate lighting is required, **Figure 24a**. **Figure 24b** shows a bridge in the mountainous part of Gran Canaria where an austere structure matches an equally austere mountainous landscape. The whiteness of the bridge contrasts with the surroundings. The backstays are clearly visible—paradoxically, thanks to cloudy weather. Very often backstays are not discernible at all and for this reason, at night special illumination is used.

In the family of cable-stayed bridges, a special group can be distinguished on constructional grounds, namely, *extradosed* bridges, **Figure 25b**. In this case, the inclination of cables measured from the deck level to the cables is significantly lower than Π/4. Projecting the normal force acting in the cable N onto horizontal and vertical directions we arrive at N_H, N_V components and, additionally, we obtain $N_H > N_V$. As a result there occurs a significant compression in the carrying-deck which in the extreme degree is manifested near the tower. The horizontal force can be used in the design as the force pre-stressing the deck longitudinally.

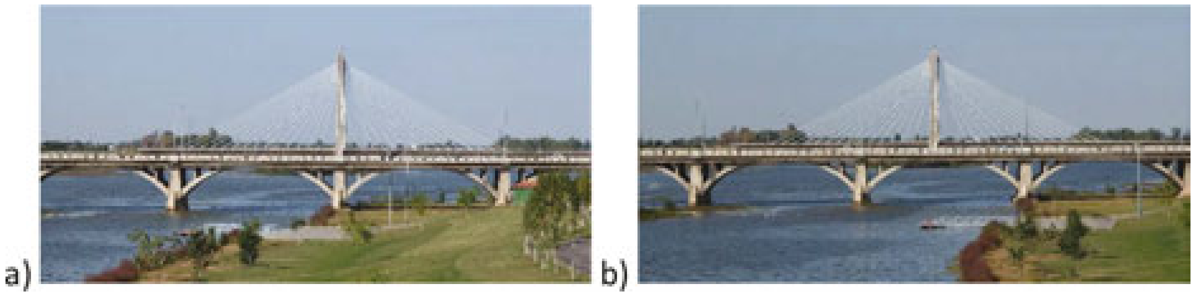


Figure 25. Badajoz, Spain: (a and b) views from the Roman Bridge.

During the design works and the construction of the Golden Horn Metro Bridge in Istanbul, there was an on-going global discussion about limiting the architectural dominance of a constructed bridge, see [27]. Despite the fact that the pylons demonstrated Ottoman features it was suggested that, with regard to the global cultural and architectural heritage of the area in the vicinity of Golden Horn, the bridge would constitute an extraneous dominant. The bridge was completed without any changes in 2015, see **Figure 24a**.

Short distances between bridges in cities contribute to amusing and sometimes even grotesque situations. Two gorgeous bridges in Sevilla can serve as an example. The Puente de la Barqueta is a tied-arch bridge designed by J. Arenas and J. Pantalerón. The other bridge is the cable-stayed Puente del Alamillo designed by S. Calatrava. The construction of the both bridges was completed in 1992. They are located on a straight strip of the oxbow lake of the river Guadalquivir, 1 km apart. Their views overlap, which can be rather irritating.

It is quite a common case in highly urbanised areas and, actually, it occurs in every city on a big river. **Figure 25** shows two frames of a movie that is, so to speak, created in the head of a passer-by walking on the Roman Bridge over the Guadiana River in Badajoz. Depending on the spectator's mood and perception it can appear as chaos or an interesting coincidence.

Cable-stayed bridges are efficient in terms of bridge structure mechanics when placed between cantilever and suspension bridges. On this position, they also prove to be economic solutions. It means that they can be used in the area of small architecture, even if beam or plate bridges are cheaper and better, in a sense. Above all, the pylon, as an interesting dominant, contributes significantly to the attractiveness of a local landscape, see **Figure 26**.

a) b)

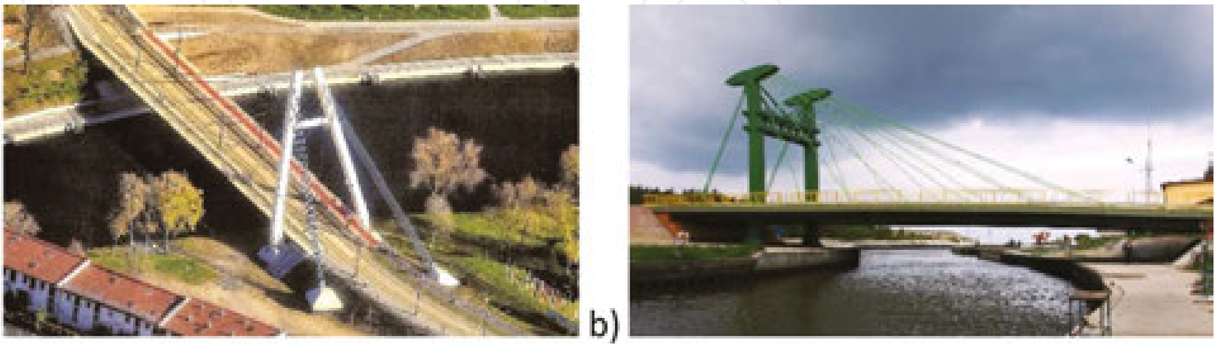


Figure 26. Architectural cable-stayed bridges: (a) the tram bridge in Bydgoszcz (*photo by courtesy of Gotowski Company*); (b) the bridge in Dźwirzyno over the Resko Channel (*photo by M. Delmaczyński*).

Figure 26a shows a tram bridge on the river Brda in Bydgoszcz, 75 m long. It was designed by K. Maciejewski and constructed in 2014. Among typical, ordinary urban buildings the short pylon is a moderate dominant contributing nevertheless to making the landscape more interesting when contrasted with the dynamics of the inclined pylon. Similar enhancement is visible in **Figure 26b**. The short pylon of a small, 51 m long bridge, located in the village of Dźwirzyno, is so different from the village buildings that it becomes a fascinating radical sculpture. It was designed by J. Siuda and M. Delmaczyński. After its construction in 2011, an increased demand for equally small but architecturally interesting bridges has been observed.

Figure 27. Arch bridge erection by cable-stayed supports at sunset, Estremadura, 2015.

The cable-stayed technology has been used as a temporary support for arch bridge scaffolding for many years. These are transitional arrangements and images but ones that are truly charming thanks to the additional spaciousness they create. Sometimes, as shown in **Figure 27**, an austere surrealist image is obtained. This short-lived aesthetic form refers directly to the art of performance as it disappears the moment the arch is built.

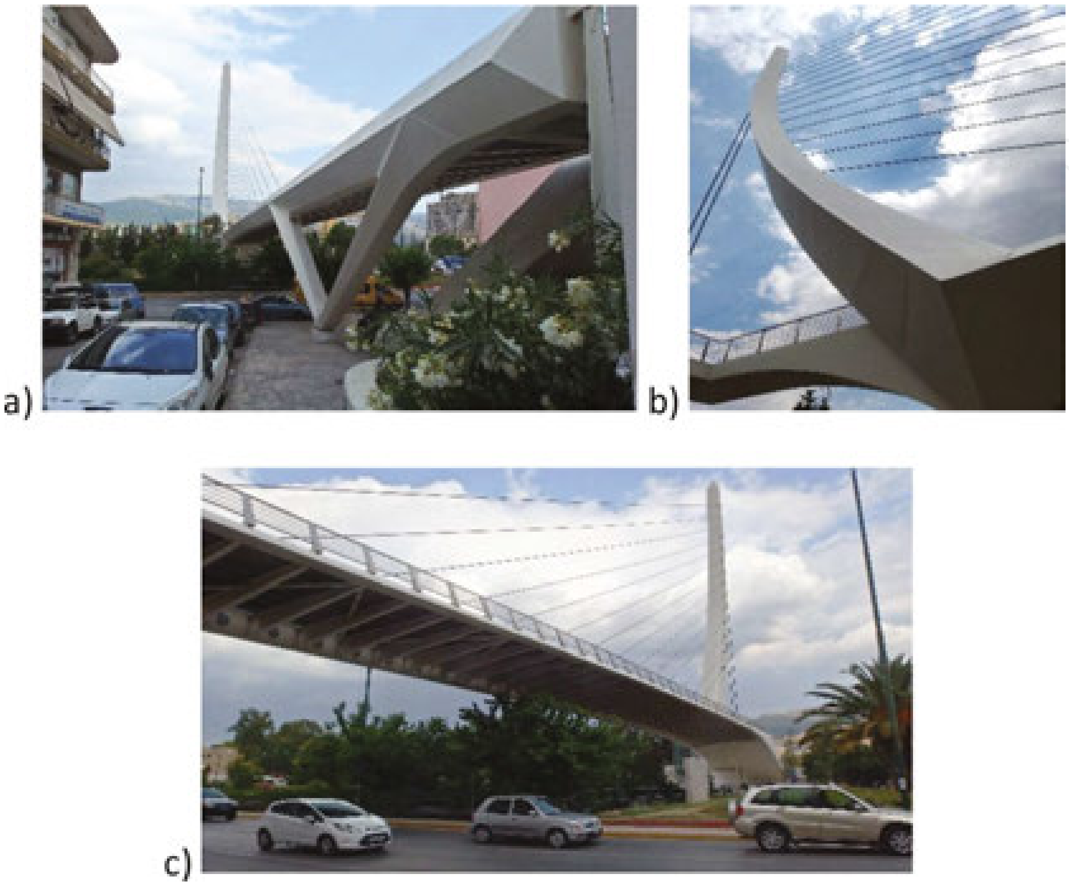


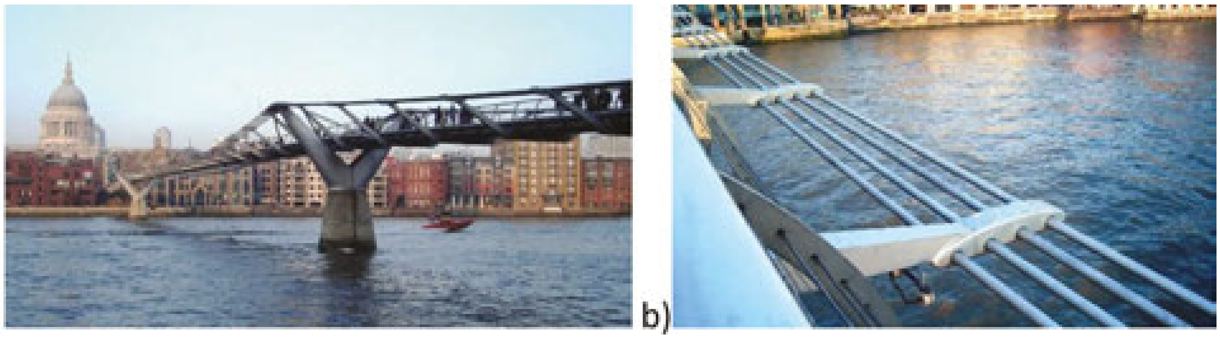
Figure 28. Katehaki footbridge, Athens, 2004: (a–c) different views of the bridge.

A separate place in architecture and structural engineering belongs to Santiago Calatrava, although in this paper he is mentioned only briefly. Calatrava, in the architectural millieu's opinion, is a creator of gigantic forms—spatial sculptures which enhance the landscapes of various cities around the world. As a bridge constructor, he broke a mental barrier existing in the area of bridge design where bridges were designed for bending as a dominant mechanical state. In the case of pedestrian footbridges he constructed bridges where carrying elements are screwed together. Due to this, the mental barrier has been broken.

Examples of gigantic sculptures in urban areas include the following bridges: the Puente del Alamillo in Sevilla, 1992, the Puente De La Mujer in Buenos Aires, 2001 and the Sundial near Redding, California, 2004. The Jerusalem Chords Bridge, however similar, is new concept. These bridges are purely white, the pylons are inclined by approx. 50° and they resemble each other, as images, to a high degree. However, the structural engineering of each of the bridges is different. The Alamino is a road bridge with a beam load-bearing structure identical to the one of the arch bridge Puente Lusitania in Mérida. The rest are pedestrian footbridges with screwed load-bearing structures. The Puente de la Mujer is a moveable bridge with a rotary movement about the vertical axis on the support with a pylon. The Sundial has a truss load-carrying structure. As demonstrated, each of these bridges is different and only for architects their images are identical.

In the author's opinion, the most interesting is the Katehaki Footbridge in Athens, 2004, **Figure 28**. The footbridge is never entirely visible and therefore mysterious—making one yearn for more. The pylon is slightly bent as a result of which it loses the original but at the same time primitive form of an opened set square and becomes similar to boats crossing the Mediterranean Sea. The footbridge is literally squeezed between uninteresting street buildings of Athens. A crossing passer-by who reaches one of its ends can look into the windows of the buildings located only 10 m away. The footbridge is in the middle of street traffic. The lack of space and the constant flow of passing vehicles contribute to the dynamics of the structure which, thanks to its white and slender elegance, floats above crowded streets of Athens.

The Millennium Bridge in London is a hybrid of two static schemes. There are deck segments supported by cables (*vide* the ribbon scheme) and at the same time the deck is suspended on the same cables as in the case of the suspension bridge. **Figure 29**.



a) b)

Figure 29. Millennium Bridge in London: (a) view of the bridge; (b) support detail.

The history of the bridge opening is a typical English story, i.e., starting from a total failure and ending in full glory, see, e.g., [28]. The bridge was conceived as an interesting design, quite innovative.

The opening day had been expected for a long time. Finally, on 10 June 2000, thousands (ca. 5000) of people were waiting to enter the bridge and walk to other side. At this moment, the new bridge entered into a state of unpleasant complex horizontal and vertical vibrations. It turned out that despite the use of advanced computational techniques and the designers' experience, the bridge demonstrated dynamical over-sensitiveness. The new bridge was closed on 12 June of the second millennium. Soon after, a diagnosing research was conducted which pinpointed the cause of the dynamic instability of the bridge. On its basis, it was decided to install a system of dampers which changed the dynamic response of the bridge. Two years later, the Millennium Footbridge was reopened and has been working properly ever since.

11. Instead of a summary

There are many bridges, constructors and technologies that should be and are described and discussed in various papers and monographs. From the wide range of existing bridge structures, one conclusion can certainly be drawn: every bridge is important.

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