BER the international journal of bridge engineering management and research

History of Bridges: Materials and Structural Types of a Monument to Progress

Paolo Clemente*

Submitted: 03 August 2025 **Accepted:** 01 October 2025 **Publication date:** 10 October 2025

DOI: 10.70465/ber.v2i4.48

Abstract: The history of bridges is retraced as a witness to humanity's progress. The evolution of materials and structural typologies has enabled ever-longer spans to be achieved at sustainable costs. The availability of materials such as reinforced concrete and steel has offered new possibilities, unthinkable when using wood and masonry. Then girder bridges were built, followed later by cable-stayed and suspension bridges, as well as long-span arch bridges. The race for long spans continues. Bridges have always been, and always will be, monuments to progress.

Author keywords: History of Bridges; Materials; Structural typologies; Beam bridges; Arch bridges; Cable-stayed bridges; Suspension bridges

Introduction

The disasters that have affected bridges and viaducts all over the world in recent years have brought concerns about the safety of such structures not only to the attention of technicians and authorities but also among the general public. These events have sparked curiosity among them about how these structures work and how they evolved over time.[1] These disasters have led to a greater focus on the protection and maintenance of existing bridges. However, this is not possible without a deep understanding of their static and dynamic behavior and, therefore, a reliable knowledge of bridge design and construction.[2–4] Over time, various structural typologies have been developed and used, depending on the available materials and technologies, as well as on theoretical and practical knowledge derived from previous experiences.[5]

The evolution of bridges has followed the history of humanity, and the history of humanity itself could be studied and told through the evolution of bridges over time. Since the Neolithic age, the construction of a bridge has always been motivated by the need to overcome, with a vehicular or pedestrian path, an obstacle due to the geomorphology of the land, such as a river or a valley, to facilitate travel, contact, exchange, and trade with other peoples. The Romans, therefore, were great bridge builders, requiring fast and safe connections for the maintenance and control of their vast empire. With the fall of the Roman Empire and until the 9th century AD, interest in bridges decreased considerably because the political units extended over small territories and, consequently, could not afford the costs of construction and maintenance of these challenging structures.

Building a bridge has always been a challenge against the forces of nature, accompanied by the fear of failure: "Every span is something that can't be done until the men in steel helmets have driven in their last rivet," said Joseph Strauss, designer of the Golden Gate Bridge.[6] These difficulties have always fascinated people. The availability of new materials and the use of new technologies have revolutionized the way of building and conceiving bridges, but the admiration for ancient bridges that have survived to the present day is no less than that for modern long-span bridges.

In this paper, the materials and typologies used to overcome ever-longer spans at sustainable costs over time are reviewed. The availability of new materials, such as steel and reinforced concrete, has offered new possibilities in recent centuries, unthinkable with wood or masonry, such as the use of simple structural typologies like girder bridges, or those characterized by elements subject to traction, such as cable-stayed and suspension bridges.[7,8] The language and treatment are deliberately simple, to facilitate reading and understanding, with the goal of encouraging young researchers, as well as even non-bridge engineers, to deepen their knowledge of these magnificent civil engineering works.

Materials used for Bridges

Organic materials

Early bridges were made of natural fibers and were similar to the modern suspension bridges. The earliest evidence comes from a rope bridge on the Indus River near Swat, dating from 400 BC, although suspension bridges were probably

*Corresponding Author: Paolo Clemente.
Email: paolo.clemente59@gmail.com
Research Director, Formerly ENEA Casaccia Research Centre, 00123 Rome, Italy

Discussion period open till six months from the publication date. Please submit separate discussion for each individual paper. This paper is a part of the Vol. 2 of the International Journal of Bridge Engineering, Management and Research (BER), ISSN 3065-0569.

in use much earlier in Southeast Asia, South America, and Equatorial Africa. In India, one or two main bamboo cables were usually laid between trees used as pylons, from which a walkway of cross-reeds was suspended by means of handrail cables. Similar bridges, sometimes made of wicker ropes and twisted vines, still exist in the Himalayas and elsewhere in Southeast Asia. The Incas in South America built suspension bridges with aloe or woven wicker cables and natural rock pylons. Anchorages were made by attaching the cables to heavy, crossed wooden beams held in place by rocks. Maintenance was entrusted to nearby villages, which were responsible for repairing and replacing the cables every few years. In Equatorial Africa, various types of climbing plants were used to build bridges.

Later, wood was used. The primitive girder bridges were made of tree trunks placed between the two banks of a river. Wood was well suited to the construction of the girders, thanks to its ability to resist both tensile and compressive stresses in the direction parallel to the fibers. Its lightness made it particularly suitable for long spans. However, wood was very vulnerable to humidity and fire and had high deformability. Furthermore, constructing joints in wooden bridges was difficult. Because of these drawbacks, ancient wooden bridges have not withstood the passing of the centuries, and we only have indirect evidence of them.

The Pons Sublicius, the oldest bridge in Rome and famous after the legend of Horatius Cocles, was made of wood. Bridges built during a war were generally made of wood: in *De Bello Gallico* (Chapter 17, Book IV) there is a detailed description of the construction of a bridge over the Rhine River. A bas relief on Trajan's Column reproduces the famous bridge over the Danube River, built by Apollodorus in Romania in 103–105, at the time of the expedition of Emperor Trajan against the Dacians (Fig. 1). It was composed of 20 masonry piers, on which wooden arches with a span of 55 m rested. It was demolished after the death of Trajan, leaving only the piers as a testimony to human genius.

Figure 1. Bas relief on the Trajan's Column, which reproduces the famous Apollodorus' Bridge over the Danube

After a period in which bridges were mostly destroyed rather than built, following the fall of the Roman Empire, wood was rarely adopted for permanent bridges. Nevertheless, there were notable examples such as the bridge over the Grand Canal in Venice, where the Rialto Bridge now stands, and the bridge over the Brenta near Bassano, Italy, designed by Andrea Palladio in the 16th century. Palladio proposed several schemes for wooden bridges with longer spans, including an arch bridge with a span of 36 m. However, true masterpieces in the field of wooden bridges were built in Switzerland:[9]

- The Zurich Bridge, with a span of 40 m, and the Schaffhausen Bridge over the Rhine, with two spans of about 60 m, were both built by Johann Ulrich Grubenmann in 1770.
- The Wettingen Bridge, completed in 1788, has a span of 118 m.

Wood was used for bridges in America in the 19th and 20th centuries, while in Europe today wooden bridges are built mainly in the Nordic countries but also elsewhere, especially for walkways and in mountainous areas. An interesting example is the Traversina Footbridge, completed in 1996 in the Swiss Alps, with a span of 47 m, whose elements were transported to the site by helicopter. Particular care was taken in protecting the structural elements and in studying the oscillations induced by the wind.

The masonry arch

The arch is certainly the most notable invention of classical art in the field of tension and a notable development in bridge construction. The arch allowed the use of no-tension-resistant materials, such as masonry, for bridges. The masonry arch was the most widely used structural type in bridges until the mid-20th century.[10]

The arch was already known in the ancient civilizations of Egypt, Babylon, Persia, and Magna Graecia. The Romans created notable examples of bridges (Fig. 2) and aqueducts (Fig. 3) that have survived to this day, even outside Rome. They had great merit not only in having used the arch extensively but also in having used natural cement with pozzolana. The construction of bridges over the Tiber River (Fig. 4) was presided over by the *Collegium Pontificum*, headed by the Pontifex Maximus. The title of Pontifex, literally meaning "bridge builder," has been interpreted etymologically with reference to these great works of civil engineering. It later passed later to the Roman emperors and is still in use to designate the Pope.

It may seem strange, but the arch was used for many centuries without its static behavior being fully understood. Leonardo da Vinci proposed practical rules for the design of an arch, and some of his drawings demonstrate how he posed the problem of determining the thrust, that is, the horizontal action transmitted by the arch to the foundations at the springing. In the first treatise on bridges, written by Henri Gautier in 1714, relationships between the dimensions of the various parts were suggested, and attention was paid to the thrust, but no rules were given on how to evaluate it. Later, in 1730, Claude Antoine Couplet proposed the first theories on the determination of the pressure line and, therefore, of the thrust. Other eminent scholars, such as Charles Coulomb in 1773, Gabriel Lamé, and Émile Clapeyron in

Figure 2. The Roman Leproso Bridge, Benevento

Figure 3. The Pont du Gard, Nimes

Figure 4. The Pons Aelius, known as Ponte Sant'Angelo, Rome

1823, also studied the subject. Finally, the mystery of the thrust and how to proportion the abutments was discovered. Carlo Alberto Castigliano carried out detailed studies on the statics of arches in 1879. His analysis of the Ponte Mosca in Turin is notable.

The construction of an arch is done by laying voussoirs, either dry or with mortar, and requires a centering, that is, a temporary support, until the keystone is placed. This operation represents the closing of the arch, hence the name of the stone itself. The height of the keystone center relative to the springers divided by the span is the sag ratio of the arch. The secret of a masonry arch lies in its shape rather than in the quality of the materials.[11] The shape must guarantee that at least one possible thrust line of the acting loads can be found that lies within the arch profile, with a certain safety margin that depends on the material strength.[12,13]

Usually, Roman arches had a semicircular shape, not suitable for overcoming long spans. Lowered arches, that is, with a low sag ratio, appeared in Europe around the 14th century, after the journey of Marco Polo to China, where they had already been used. Notable examples of low sag ratio arches built in Europe are:

- The Ponte Vecchio in Florence, completed in 1325. It consists of three arches with a span of 28.7 m and a rise of 4.2 m. It is also one of the most famous inhabited bridges in the world (Fig. 5).
- The Rialto Bridge, which crosses the Grand Canal in Venice. It was opened in 1591 and has a span of 27 m.
- The Pont de la Concorde in Paris, completed in 1791 with spans of 31.2 m and a sag ratio of 1/8. It was designed by Jean-Rodolphe Perronet, founder of the École Royale des Ponts et Chaussées (Fig. 6).
- The Ponte Mosca (named after the architect who designed and built it), was the first stone bridge built in Turin over the Dora Riparia. It was completed in 1827, has a span of 55 m and a height of only 5.5 m with a width of 13.70 m.

A particularly remarkable bridge was the Stari Mostar on the Neretva River, designed by the Turkish architect Mimar Hajrudin on behalf of Sultan Suleiman the Magnificent and completed in 1566 (Fig. 7).[14] It looks like a part of the building on both banks and was probably the longest single-arch bridge at the time of its construction. The original bridge was destroyed on November 9, 1993, during the war in Bosnia and Herzegovina. At the end of hostilities, it was rebuilt as it was before the conflict, recovering original blocks from the waters of the river and shaping the new blocks from the same mine in the village of Ortijes, so that each faithfully reproduced the corresponding lost original one. The new bridge was completed on July 22, 2004.

Figure 5. The Ponte Vecchio, Florence

The masonry arch, now considered an obsolete structural type in most countries, is still used in some countries. In China, there are several stone arch bridges with spans exceeding 100 m that were built in the last century and

Figure 6. The Pont de la Concorde, Paris

Figure 7. The Stari Mostar

are characterized by a low sag-to-span ratio. Among these extraordinary realizations are:[15]

- The Changhung Bridge on the Nanpan River in Yunnan Province, with a span of 112.5 m and a clear width of 8.5 m, completed in 1961 (Fig. 8).
- The Chiuhsikou Bridge in Fengtu, Szechuan, with a span of 116 m, completed in 1972 (Fig. 9).
- The Dan River Bridge on the Xindan River along the Jin-Jiao highway, 10 km from Jicheng in Shanxi, completed in 2000. With its 146 m span and 82 m height, it is the longest masonry arch bridge in the world (Fig. 10).

In this regard, it should be remembered that Leonardo da Vinci proposed an arch bridge to cross the Golden Horn in Istanbul for Sultan Bayazid II, with a clear span of 240 m, a rise of 57 m, and a thickness varying from 42 m at the springing to 9 m at the crown. The bridge was not constructed due to the insurmountable difficulties in its execution, but its static efficiency has been demonstrated in recent times.

Rudimentary stone girder bridges were also built using large blocks. The oldest was a bridge over the Meles River at Smyrna, now Izmir, Turkey, probably built in 850 BC. Another example is over the East Dart River at Postbridge on Dartmoor in Devon, which is thought to date back to the 12th century and consists of huge granite slabs resting on granite piers. Finally, the Anping Bridge at Chuanchow, an important Chinese seaport during the Sung dynasty, is particularly impressive. It was completed in 1152 and consists

Figure 8. The Changhung Bridge on the Nanpan River, China

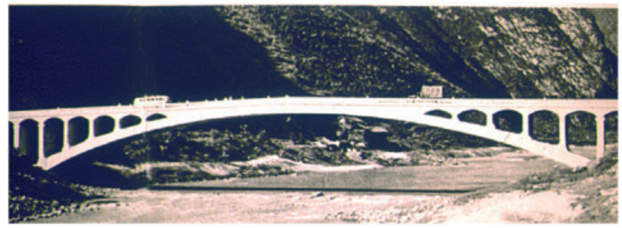

Figure 9. The Chiuhsikou Bridge in Fengtu, China

Figure 10. The Dan River Bridge on the Xindan River, China

of 331 stone piers, on which girders made of several stone blocks rest, for a total length of over 2000 m.

Metallic materials

In 1779, Abraham Darby III built the first cast iron bridge over the Severn River at Coalbrookdale, England (Fig. 11). In 1795, the bridge survived an overflow of the same river that destroyed many bridges. This occurrence demonstrated the better resistance of metal bridges, encouraging their use and development. The Iron Bridge is now considered a World Heritage Site by UNESCO.

However, cast iron was fragile and had poor tensile strength. Therefore, it was not used for a very long time and was soon replaced by steel. It should be noted that the construction technique was still strongly influenced by knowledge of wooden constructions in early metal bridges: dovetail joints and mortise and tenon joints were still used in internal joints.

With the use of steel, increasingly larger spans were realized, thanks also to the evolution of structural systems, from the simply supported beam to the continuous beam, from the solid wall beam to the truss, to the thrust systems with inclined or arched piers up to the suspension bridge. Among

Figure 11. The Iron Bridge over the Severn River at Coalbrookdale, England

Figure 12. The Garabit Viaduct on the Truyère River, France

the designers who have made the history of bridges, it must be remembered:

- Robert Stephenson designed the Britannia Bridge on the Menai Strait in North Wales in 1850. It is a continuous girder bridge with four spans: 72 m side spans and 142 m central spans. This bridge masterfully reflected the modern concept of steel girder bridges.
- Gustave Eiffel designed the Garabit Viaduct on the Truyère River in the Massif Central, France, in 1884. This bridge is approximately 560 m in total length, including an arch bridge with a span of 165 m and a height of 120 m with respect to the river (Fig. 12).

Other examples of bridges from the same period are:

- The Luiz I Bridge over the Douro River in Porto, with a span of 172.5 m, completed in 1885. The bridge had upper and lower lanes.
- The Paderno Bridge on the Adda River, with a parabolic arch with a span of 150 m. The bridge, completed in 1889, was surmounted by a double carriageway truss with a road on the upper deck and a railway on the lower deck.

The reinforced concrete

In 1867, the French gardener Joseph Monier obtained a patent for the construction of vases and containers in concrete with steel reinforcement. This was the beginning of reinforced concrete, which was then widely used in the 20th century. In this new material, there is a perfect collaboration between the concrete, which has a good compression strength and the task of giving rigidity to the structural elements, and steel, which has a good tensile strength. The reinforced concrete changed radically the world of construction, allowing any shape to be created and was also very competitive from an economic point of view.

In the construction of bridges, reinforced concrete was initially used with the previous shapes, typical of masonry, not fully exploiting its potential. Afterward, new shapes and anatomies of structures were used. Reinforced concrete does not have the potential of steel spanning long distances but has the advantages of having greater durability and being able to be shaped.

François Hennebique, the first great designer of reinforced concrete bridges, used this new material with great intuition. Referring to arch bridges, he proposed the technique of early removal of the centering to obtain partializations at the extrados of the springing with consequent lowering of the center of gravity of the resistant cross-sections. This led to an increase in the sag ratio with a reduction in thrust. The Risorgimento Bridge over the Tiber River in Rome was built with this technique in 1911. It has a span of 100 m and a height of only 10 m. It also represents a bold structure in terms of geometry and execution methods.

A new way of thinking about reinforced concrete architecture was introduced by Robert Maillart. He intuited the great potential of the new material and realized bridges of great elegance and dynamism, appropriately lightened compared to traditional masonry bridges. Among the bridges that have marked Maillart's work is the Tavanasa Bridge, built in 1905, on the Rhine River with a span of 51 m. In this bridge, the arch and the deck are connected in a central area and are separate at the springing. Another example is the Salgina Bridge (Fig. 13), built in 1930 in Schiers with a span of 90 m. In this bridge, arch and deck were connected by some vertical walls.

Figure 13. The Salgina Bridge, Schiers

The prestressed reinforced concrete

In arch bridges, jacks were used to space the various parts before the subsequent casting that joined them together. By artificially compressing the concrete in this way, Eugène Freyssinet intuited the possibility of introducing a state of coercion in a reinforced concrete beam to keep the material in compression everywhere when loads are applied. In reinforced concrete, in fact, the concrete is not used to its best advantage, since its poor tensile strength results, on the one hand, in the presence of material that does not collaborate statically and represents only dead weight, and on the other, in the formation of cracks with consequent exposure of the reinforcement and its oxidation.

The state of coercion is created by mutual contrast between steel cables stretched between the ends of the beam and the beam itself. The contrast can occur at the two ends of the beam, creating a prestressing with sliding cables, or by adhesion between steel and concrete, in which prestressing is given by means of adhering wires.

Due to the slow phenomena of concrete, known respectively as shrinkage (spontaneous reduction in volume) and viscosity (delayed deformation over time in the presence of a constant load), and the relaxation of steel (reduction in tension with constant deformation), the initially applied compression force tends to decrease over time. Therefore, the practical implementation of the prestressing technique was only possible when high-strength harmonic steels were produced, which allow for the application of significant initial prestressing forces. However, a high percentage of these (30–40%) is lost over a certain period of time.

Prestressing, therefore, has made it possible to create slender structures using reinforced concrete with longer spans. In the field of prestressed reinforced concrete bridges, Riccardo Morandi must be remembered. He was an experimental designer rather than a calculator, who operated by relying mainly on his brilliant intuition rather than on abstract theories. Seven patents on prestressing systems are due to his genius. Among the most interesting bridges, it is worth reminding the San Nicola Bridge in Benevento completed in 1955, the Bisantis Viaduct on the Fiumarella in Catanzaro completed in 1962 (Fig. 14), which includes an arch with a span of 235 m, and above all some cable-stayed bridges of great importance, which are described later in this paper.

Figure 14. The Bisantis Viaduct, Catanzaro

Mixed steel-concrete systems

Bridges made of steel beams and a reinforced concrete slab above them, in which the advantages of both materials have been exploited, have been widely used in recent decades. The steel beams are mainly entrusted with tensile stresses, while the concrete slab supports compressive stresses and has the task providing the sufficient rigidity and creating a surface suitable for supporting the road surface.

Steel-concrete was born in a rather casual way: it was noted that floors made of iron beams and a concrete slab, calculated considering only the iron beams as load structure and the slab as a dead load without any static contribution, behaved in reality better than expected. This was due to the contribution of the slab, because of composite action between steel and concrete. This adherence between beams and slab was favored by the presence, on the extrados of the beams, of the heads of the nails that opposed the sliding. Great advantages were obtained by improving this adherence.

In the current construction practice, metal beams are assembled by welding. Electro-welded pins are placed on the upper wings to counteract sliding between the upper wing and the concrete slab. Mixed structures made of prestressed reinforced concrete beams and a reinforced concrete slab are also very common. In these beams, prestressing is applied only to a limited part of the structure, particularly in the portion that would otherwise be subject to tension, with obvious advantages from an economic point of view.

Composite materials

The use of composite materials has been spreading for several decades. Among these, fiber-reinforced polymers (FRPs), already known in the aerospace, automotive, and naval industries, are mostly used. The first applications involved pedestrian walkways and cycle paths and, in some cases, also the decks of road bridges. Composite bridges have significant advantages.

The lightness leads to simplifications in transport operations and installation. Therefore, it is possible to prefabricate large structural elements to be assembled on site using cranes of non-excessive dimensions. The reduced loads require smaller foundations, with smaller excavations, and also determine lower seismic actions. Furthermore, the polymer matrix guarantees good durability. It requires little maintenance, primarily because of its high resistance to atmospheric agents, chemicals, fuels and deicing salts. It also offers greater sustainability due to the absence of harmful emissions during production and the lower energy required for production and transportation. Its mechanical strength is also greater than that of steel and concrete. Finally, it offers good resistance to fire, impact, and fatigue. The wide freedom in the choice of shapes should not be underestimated.

Up to now, their use has been limited by the lack of design standards and above all by the lack of experience using these materials by technicians, as well as by the poor knowledge and reliability of their mechanical properties.

Among the most interesting projects is the mobile bridge over the River Clwyd at Rhyl Harbour in Wales. It consists of two spans, each 30 m long, with a width varying from 3 to 4 m and weighing about 140 kN. The spans are hinged to a central box pier and can be lifted by means of cables pulled symmetrically from a central mast about 50 m high, to allow the passage of boats. The use of FRP has allowed the greatest possible weight savings and has reduced lifting times and energy consumption.

Structural Types

The availability of new materials also determined an evolution of the structural typologies, allowing the overcoming of ever-longer spans with sustainable costs. In beam bridges, which are mainly stressed by bending, the material is often poorly utilized. In a generic cross-section, the maximum compressive and traction tensions under the service loads occur only at the two ends, upper (extrados) and lower (intrados). This limitation is overcome by truss structures, in which the solid wall beam is replaced by a set of rods arranged according to the preferential directions of the main stresses and therefore subject to axial, tensile, or compressive stresses. In this way, the material use is optimized, minimizing its quantity and hence the structural weight, essential requirement when considering long spans. For bridges with longer spans, it is necessary to consider other static types, namely, the arch, the cable-stayed bridge, and the suspension bridge.

Beam bridges

The most common type currently used are beams supported by vertical piers. Generally, these are statically determinate structures, in which the beam of each span is simply supported on the piers and is independent of adjacent spans. Even for small spans, reinforced concrete is not advantageous from an economic point of view. Nowadays, in the field of girder bridges, the most commonly used materials are prestressed reinforced concrete and mixed steel-concrete systems, which offer significant advantages from a construction perspective. Prefabrication and subsequent assembly allow to build a bridge by launching the beams, without providing a centering. This procedure is particularly advantageous when the structure must cross a river or, in the case of overpasses, when it is not possible to interrupt traffic on the road or railway below. Launching can also be realized by longitudinal thrust, which allows the girder to be positioned even on very high piers and to span large distances in inaccessible areas.

The girder can have an open cross-section, composed of a set of parallel longitudinal beams, connected by transverse beams and a top slab that houses the roadway. Alternatively, the girder can have a box or multi-box cross-section, with a top slab, often protruding from the box, which houses the roadway (Fig. 15). The difference between the static behaviors of the two schemes consists essentially in the way of dealing with the torsional actions and, therefore, the rotation of the girder around its longitudinal axis. In an open cross-section, the effect of the torsional actions translates into an increase in bending in the beams (secondary torsion), especially the edge beams, while in the box cross-section it is faced by the primary torsional stiffness of the beam. The second solution allows for overcoming longer spans. In steel beams, the box can also be simulated by connecting the longitudinal beams at their lower flanges with braces in the horizontal plane.

In a simply supported beam, the most stressed section is at mid-span, where the maximum bending moment occurs. A continuous beam, that is, one resting on more than two supports, allows for the creation of spans longer than those of simply supported beams, as each span makes a counterweight action on the adjacent ones. Near the internal supports, the bending moment changes sign; the maximum absolute values of the bending moment occur at the internal supports and are lower (in the case of at least four supports) than the mid-span values of a simply supported beam of the same span. Often, for obvious economic reasons, beams with a variable height section are often used. The piers can have considerable heights, as in the following bridges:

- The Europa Bridge, a continuous six-span beam on the motorway between Brenner and Innsbruck, was the highest bridge in Europe at the time of its completion in 1963. It has a maximum span of 198 m, while the tallest pier is 146.5 m high (Fig. 16).
- The Italia Viaduct on the Lao River, completed in 1969 along the Salerno–Reggio Calabria highway, is a continuous beam with three spans: the central one of 175 m and the side spans of 125 m each. The tallest

(a) (b)

Figure 15. (a) Open cross-section and (b) prestressed reinforced multi-box cross-section

pier is 155 m high. It was the highest bridge in Europe until the completion of the Millau Viaduct in 2004.

Figure 16. The Europe Bridge

A continuous beam can be made statically determinate by adding hinges. If these are positioned in sections where the moment is almost zero for the main load condition, the advantages of the continuous beam in terms of stresses are retained, but also those of statically determinate beams with regards to distortions. The Gerber schemes are based on these considerations. The most common are those with three spans, with the central one longer than the lateral spans. In the Niagara scheme, the two hinges are placed along the central span, while in the Kentucky scheme there is one hinge for each of the lateral spans. The hinges are realized with the typical Gerber saddle, which leaves the total height of the section unchanged.

Arch bridges

Because of its shape, an arch supports external loads mainly through compressive stresses, with an almost uniform distribution in the generic cross-section and, therefore, allows an optimum use of the material. The theoretical limitation of the maximum span of an arch is related to instability problems, typical of structures subject to compression. The subject, approached as a pure scientific curiosity by Leonhard Euler towards the end of the 18th century, found enormous applications with the use of slender structures in the 20th century.

In the field of bridges, the arch always requires a girder, connected to it by vertical elements (columns or struts). The girder houses the road paving and contributes to the arch–beam structural system. Depending on the contribution of the girder, we move from a pure arch, in which the main structural element is the arch alone, while the beam only has the task of transferring the loads acting on it to the arch, to an arch with a stiffening girder, proposed and used by Robert Maillart. In this last latter scheme, a very precise separation of tasks occurs between the beam and the arch. The first, equipped with a high flexural stiffness, is entrusted with the bending moments; the second, instead, made of a very thin thickness, is stressed exclusively by simple compressive stresses. The columns or struts, which connect the beam and the vault, give the vault the stiffening necessary to avoid instability.

The main bridges realized with the Maillart's scheme have already been mentioned. Among the pure arches, we should mention the Sando Bridge in Stockholm, completed in 1943 with a span of 264 m and a rise of 45 m; the Sydney Bridge completed in 1964 with a span of 300 m; and the Wanxian Yangtze Bridge in China, completed in 1997, with a reinforced concrete arch having a span of 429 m and a rise of 85 m.

Steel arch bridges, built with a reticular structure, are also of considerable interest. In addition to the bridges already mentioned, it is worth recalling the following record-breaking bridges:

- The Sydney Harbour Bridge, completed in 1932, with a span of 503 m and a rise of 107 m. It carries four railway tracks and a roadway 17 m wide (Fig. 17).
- The New River Gorge Bridge in Fayetteville, West Virginia, completed in 1977, with a span of 518 m.
- The Lupu Bridge in Shanghai, completed in 2003, with a span of 550 m.
- The Chaotianmen Bridge in Chongqing, China, completed in 2009, with a span of 552 m.
- The Pingnan Third Bridge, on the Xun River near Pingnan, Guangxi, China, with a span of 575 m and a height of 140 m, opened to traffic on December 28, 2020.
- The Tian'e Longtan Bridge over the Hongshui River in the Guangxi Zhuang Autonomous Region, China, opened on February 1, 2024. With a span of 600 m, it is now the longest arch bridge in the world (Fig. 18).

Figure 17. The Sydney Harbour Bridge

When building an arch bridge, it is necessary to provide foundation structures that are capable of transmitting the thrust to the ground. If the foundation soil is not able to withstand such actions, a bowstring bridge can be considered, in which the horizontal force is absorbed by a chord, i.e., a tie rod that connects the arch ends. The chord may also act as a deck that houses the road paving and is suspended from the arch. In the Larsen scheme, the suspension elements are vertical; in the Nielsen scheme, the suspension elements are inclined.

Figure 18. The Tian'e Longtan Bridge, China

Recent constructions demonstrate a rediscovery of the arch for spanning medium to large distances, after limited use in the last decades of the 20th century. In medium spans, steel girder bridges or mixed system bridges are now very competitive, while the field of very large spans remains the domain of cable-stayed bridges and suspension bridges.

Cable-stayed bridges

In a cable-stayed bridge, the deck is supported by inclined cables, the stays, anchored at their other end to a pylon.[16–18] The idea of creating intermediate supports for the beam, by means of lower struts or upper tie rods, had already been known for some time and had been applied by Palladio. The first cable-stayed structures date back to the 17th century. Nevertheless, the cable-stayed bridge had a terrific development only in the last decades of the 20th century. The spans overcome so far are smaller than those of suspension bridges. The advantages of a cable-stayed bridge include greater savings in material, lower assembly cost, and, above all, lower deformability.[19]

As for arch bridges, also for cable-stayed bridges two limit schemes can be identified. The first is that of the bridge with a stiffening girder, which is characterized by a limited number of stays and a girder with a high bending stiffness. The second scheme is the reticular behavior scheme, in which the beam has only the task of transferring the load acting at each section to the two adjacent stays. A certain stiffness of the girder is, however, required to limit the local deformations due to the elongation of the stays.[20]

Riccardo Morandi was inspired by the first scheme when he designed the following prestigious bridges:

- The General Rafael Urdaneta Bridge on the Maracaibo Bay in Venezuela, inaugurated in 1962. The entire viaduct has a total length of about 8700 m and includes five main cable-stayed spans of 235 m each, supported by stays connected to the tops of six 92 m high towers. The deck is 46 m above the lake level. The bridge was initially designed with spans of 400 m, but these were reduced due to the exorbitant cost of the equipment needed for the construction.
- The Polcevera Viaduct in Genoa, built between 1963 and 1967, was part of the A10 motorway. It included two main cable-stayed spans of 210 m, with three towers of approximately 90 m in height. After the collapse of one of the three balanced cable-stayed systems (the first on the left in Fig. 19), which occurred on August 14, 2018, the viaduct was demolished on June 28, 2019. It has been replaced by a continuous beam with a total length of 1067 m and 19 spans, three of them of 100 m, while the others are 50 m, except for two of about 40 and 26 m, respectively. The new deck is composed of a steel box beam shaped like a ship's hull and a reinforced concrete slab. It is supported by elliptic reinforced concrete piers by means of curved surface sliders. The bridge is also equipped with an integrated monitoring system. The simple scheme allowed the construction to be completed in a very short time.[21]
- The Wadi al-Kuf Bridge on the Cyrenaican plateau in Libya, completed in 1971, features two pylons approximately 57 m high above road level and a central span of 282 m. It was the longest span bridge in Africa until 1984 (Fig. 20).
- The Pumarejo bridge (officially named after the president of Colombia, Laureano Gómez Castro, but better known throughout the country by the name of its client, the manager Alberto Pumarejo), was constructed between 1970 and 1974. It includes a main cable-stayed span of 140 m, which crosses the Magdalena River, 20 km from its mouth into the Caribbean Sea, near Barranquilla, Colombia.

Morandi's cable-stayed bridges are characterized by balanced systems with longitudinal A-shaped pylons. Two pairs of cables extend from the top of each pylon, respectively, upstream and downstream of it. The deck is cantilevered from a V-shaped trestle, which extends from the base of the pylon but is independent of it and is suspended from the stays at its ends. The deck's central section also rests on the top of the trestle, resulting in a continuous three-span beam. Buffer spans connect the described structures to each other and to the adjacent parts of the viaduct. During construction, the stays were made only of harmonic steel strands inserted into appropriate sheaths. Once the structure was completed and all permanent loads were applied, the strands were covered with a prestressed rectangular section concrete casting. Finally, the strands and the prestressed concrete were connected by injecting the sheaths. Therefore, the prestressed concrete part contributes only to the travelling loads.

The use of a high number of stays simplifies the construction details relating to the anchors of the girder, reduces assembly problems, and allows the construction of cable-stayed bridges with much longer spans.[22] In the 1970s, it was thought that the cable-stayed bridge would not be suitable for spans longer than 500 m, even though Fritz Leonhardt had proposed a cable-stayed bridge with a central span of 1300 m for the Strait of Messina.[23]

The presentation of the Normandie Bridge project at the Conference on Cable-Stayed Bridges in Bangkok in 1987 paved the way for the use of cable-stayed bridges to overcome very long spans.[24] The Japanese authorities decided

Figure 19. The Polcevera Viaduct, Genoa. The first balanced system on the left collapsed on August 14, 2018

Figure 20. The Wadi al-Kuf cable-stayed bridge, Libya

to change the design of the Tatara Bridge from a suspension bridge to a cable-stayed one. The Normandie Bridge (Fig. 21) was opened to traffic in January 1995. With its 856 m span, it set a new record for cable-stayed bridges, surpassing the Yang Pu Bridge in Shanghai, which had a span of 602 m. The project required detailed static and dynamic studies, which also included the aesthetic aspect, achieving a rare balance between engineering and architecture. The main features of the bridge are the aerodynamic shape of the deck, which reduces wind–induced actions and increases aerodynamic stability, and its high torsional stiffness. This stiffness is provided by the arrangement of the stays, anchored to the outside of the girder and converging at the center of the pylons. The pylons have an inverted Y shape, particularly suited to resist the horizontal actions of the wind. The beam is made of steel in the central part and of prestressed reinforced concrete in the parts near the pylons and in the lateral spans. It is rigidly constrained to the pylons and, in the side spans, is supported by several piers.

The Normandie Bridge lost its record as the longest cable-stayed bridge in the world (it still holds the record in Europe), but it was the first to enter the field of very long spans, which until then had been reserved for suspension bridges. In fact, in 1990 the Tatara Bridge in Japan was completed with a main span of 890 m. The record was subsequently broken by:

Figure 21. The Pont de Normandie, France

- The Sutong Yangtze River Bridge between Nantong and Changshu (a satellite city of Suzhou), completed in 2008, with a main span of 1088 m. The bridge was awarded the Outstanding Civil Engineering Achievement Award by the American Society of Civil Engineers in 2010.
- The Russky Bridge in Vladivostok (Fig. 22), completed in 2012, with a main span of 1104 m. It is currently the longest cable-stayed bridge in the world, with the longest stays (580 m) and pylons reaching 321 m. The design had to take into account the severe climatic conditions, with temperatures ranging from −31 to +37°C, ice formation of considerable thickness, wind speeds of up to 36 m/s and waves reaching 6 m. The deck is 29.5 m wide and accommodates two lanes in each direction.

It is also worth mentioning the Husutong Yangtze River Bridge, opened to traffic in 2020, which crosses the Yangtze River in Jiangsu, China. It is a combined rail and road bridge, with a main span of 1092 m.

Figure 22. The Russky Bridge, Vladivostok

The most recent cable-stayed bridges of greatest interest are in Asia, as well as the future record-breaking cable-stayed bridges. Among these is the Changtai Yangtze River Bridge, located between Changzhou and Taizhou in Jiangsu, China, with a main span of 1208 m. However, there are also interesting applications in Africa, such as:

- The Mubarak Peace Bridge, which crosses the Suez Canal at El-Qantara. The viaduct includes a main cable-stayed span of 400 m, providing a clearance of 70 m for navigation. The pylons, 154 m high, are shaped like Egyptian obelisks.
- The Mohammed VI Bridge (dedicated to the King of Morocco), on the Bou Regreg River near Rabat, Morocco, was inaugurated on July 7, 2016. It has a span of 376 m and two 200-m-high arched towers that symbolize the new gateways to the cities of Rabat and Salé.

Regarding the arrangement of the stays there are mainly two types. In a fan-shaped layout, the stays converge at the top of each pylon. The last outer stay (possibly composed of several cables), that is, the mooring stay, can be anchored either to the ground or to the girder. In the first case, the bridge has external anchors. In the second, the horizontal forces are closed within the structure, and the bridge is self-anchored. In this case, the last stay does not transmit any horizontal force to the ground, but strongly compresses the girder. The vertical force, however, must be resisted by an external support. The other type of stay arrangement is harp-shaped, with parallel stays all having the same inclination.

Among the other notable realizations, are:

- The Alamillo Bridge in Seville, a very striking and innovative structure completed in 1992. It consists of a real harp, with a 200 m span beam and a pylon inclined outward so as to use its own weight to balance the forces transmitted by the stays.
- The Millau Viaduct (Fig. 23), which crosses the Tarn Valley near Millau, France, opened to traffic in 2004. It was designed by Michel Virlogeux in collaboration with Foster and is one of the highest road bridges in the world, with the top of its pylon reaching 341 m. The girder was launched using the incremental longitudinal thrust technique.
- The Stonecutters Bridge in Hong Kong, completed in 2009. With its main span of 1018 m and pylons 298 m high, it was the second cable-stayed bridge in the world at the time of construction.
- The Yavuz Sultan Selim Bridge (Fig. 24), also known as the third bridge over the Bosphorus in Turkey, opened on August 26, 2016. This bridge presents a hybrid suspension–cable-stayed design, with a central span of 1408 m and a deck width of 58.4 m.
- The Hong Kong–Zhuhai–Macau Bridge, a series of bridges and tunnels designed and built to cross the Lingdingyang Canal and connect the cities of Hong Kong, Zhuhai, and Macau, the three major cities of the Pearl River Delta. The crossing, opened to traffic on October 23, 2018, has a total length of approximately 55 km, with a viaduct section of 29.6 km that includes three cable-stayed spans with a maximum span of 460 m.

Suspension bridges

The suspension bridge, which can be seen as an inverted arch, is the structural type that allows the longest spans. It generally has two parallel cables, from which the deck, which houses the road surface, is suspended by means of steel tie rods. The cables extend over three spans, the main span and two side spans. At the ends of the side spans, the cables can be anchored to the girder, which will be highly compressed, and the suspension bridge appears as an inverted thrust-eliminated arch. Alternatively, they can be anchored to the ground by means of foundation structures capable of transferring horizontal actions to the ground. In both cases, the anchors must transmit the vertical uplifting actions to the ground. The girder must support the loads locally, limiting deformations.[25] The importance of the bending stiffness of the girder compared to the extensional stiffness of the cables can be considerable for small and medium spans, but it decreases as the span increases and becomes insignificant in very long-span bridges.[26]

Figure 23. Two piers of the Millau Viaduct during construction

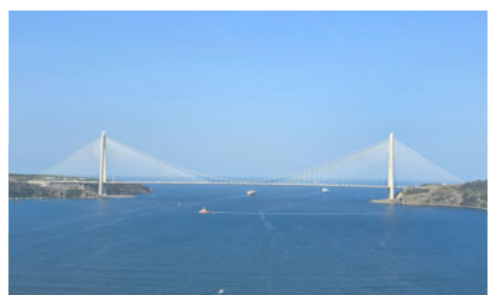

Figure 24. The Yavuz Sultan Selim Bridge, Bosphorus.

The considerable dimensions that are reached make suspension bridges extremely vulnerable to dynamic actions induced by the wind. The natural periods of vibration are very high, placing suspension bridges outside the range of seismic interest. Nevertheless, the evaluation of the effects of an earthquake is quite complex, since the pylons and anchors are very distant from each other and therefore subject to seismic actions of different intensity and characteristics.[27]

It has been said that the first suspension bridges had natural fiber cables. The first transformation occurred in

China, where the fiber cables were replaced by iron chains joined by bars of 1 inch diameter, and the pylons were often made of masonry. An elegant example of this type is a 60-m-long chain bridge over the Hwa Kiang River, built in 1632 and still standing. Many smaller chain bridges exist in northern China, and for safety reasons, the number of animals crossing the bridge at the same time is carefully limited.

The first suspension bridges of the modern era were built at the end of the 18th century in England and the United States. These too were chain bridges. At that time, the studies of Johann Bernoulli (1691) on the catenary and of Fuss (1794) on the parabolic cable were already known. The stability of the bridge was entrusted exclusively to the cables, while the beam had only the task of transferring the loads to the cables themselves.

There was great interest in suspension bridges also in France. Claude Navier visited England in 1821 with the aim of studying suspension bridges and, in 1823, he published his book *Mémoires sur les ponts suspendus*. In 1826, the 175 m Menai Straits Bridge was completed, which set an engineering standard for the future and set a world record for its length. The bridge, which impressed Navier and influenced most bridge engineers, was supported by chains with flat wrought iron links. Vertical and horizontal vibrations caused by the wind damaged it. The importance of the girder was then understood. This, with its bending stiffness, could reduce the high deformability of a suspension bridge under vertical loads.

Chain suspension bridges were also built in Italy. The Lima Bridge at Formali from 1840 still exists. The Real Ferdinando Bridge, near the mouth of the Garigliano River, has recently been restored, while only the four masonry pylons remain of the Calore Bridge near Benevento. These last two bridges were built by the Bourbons in 1830–1831, demonstrating their sensitivity to technological progress.

The technique improved rapidly, and in 1883 the Brooklyn Bridge in New York was completed. It has masonry pylons and a span of 486 m, that is, double the longest existing span. The development of the theory allowed the design of bridges with ever-greater spans.[28] There were some failures, such as the Tacoma Narrows Bridge in 1940, which had a span of 853 m and a girder only 2.44 m high. It collapsed under the action of the wind after days of agony, further highlighting the importance of the stiffness of the girder. The new bridge, built in 1950, has the same span but a 10-m-high girder. Today, the tendency is to create aerodynamically shaped girders, transparent to the wind, which cause the minimum possible disturbance to the natural flow of air. The behavior of the bridge is always studied with models in wind tunnels before construction.

After the Brooklyn Bridge, there was a gradual but remarkable increase in span:

- In 1932, the George Washington Bridge in New York was completed. It was the first bridge to exceed 1 km, with its main span of 1067 m.
- In 1937, it was the turn of the Golden Gate Bridge in San Francisco, an area very exposed to the currents and winds from the Pacific Ocean (Fig. 25). It has a span of 1280 m and is probably the most famous suspension bridge in the world.
- In 1964, the Verrazzano Bridge was opened to traffic. It connects Brooklyn to Staten Island in New York and is still the longest bridge in the United States, with its 1298 m span.
- In 1981, the record passed to the Humber Bridge between Barton-upon-Humber and Hessle in Humbershide, England, whose main span is 1410 m.
- In 1996, the Great Belt Link East Bridge in Denmark was completed, with a main suspended span of 1624 m. The deck has an aerodynamic cross-section offering little resistance to the wind.
- In 1998, the Akashi Kaikyo Bridge in Kobe, Japan (Fig. 26), was inaugurated. During construction, the bridge was subjected to the earthquake that destroyed Kobe on January 17, 1995. The event had a magnitude of 7.2 and an epicenter very close to the bridge. A relative displacement of about 1 m occurred between the pylons, and following this, the main span increased to 1991 m. The pylons and cables, already in place at the time of the earthquake, were not damaged. The design of the girder was revised to adapt it to the new length. The Akashi Kaikyo Bridge remained the longest bridge in the world for a long time.
- Finally, in March 2022, a year and a half ahead of schedule, the 1915 Çanakkale Bridge on the Dardanelles Strait in Turkey, between Asia and Europe, was inaugurated (Fig. 27). The suspended part has a total length of 3563 m, with a central span of 2023 m. The two pylons are submerged for 37 and 318 m above the water. The roadway, with three lanes in each direction, is 36 m wide and approximately 70 m above sea level. The deck is supported by multidirectional sliding spherical bearings at the abutments, while the transverse constraint is achieved by eight elastomeric bearings arranged vertically at the abutments and towers. The seismic protection system consists of eight special fluid-dynamic dissipators installed longitudinally between the suspended deck and the towers.

In addition to these, the following bridges deserve to be mentioned, although they did not set new records:

- The Firth Road Bridge in Edinburgh, completed in 1964. It was the first European bridge to exceed 1 km, having a span of 1006 m.
- The Bogazici Bridge, opened to traffic in 1973, with a span of 1074 m (Fig. 28), and the Fatih Sultan Mehmet Bridge, completed in 1987, with a span of 1090 m, both on the Bosphorus in Istanbul.
- The South Bisan in Japan, part of the Seto Ohashi Bridge, an engineering feat consisting of three suspension bridges, two cable-stayed bridges, one truss bridge and five viaducts, between the islands of Honshu and Shikoku. The bridge was completed in 1988 and has a main span of 1100 m.

- The Xihoumen Bridge in the Zhoushan Archipelago in China, completed in 2009, with a central span 1650 m long.

Figure 25. The Golden Gate Bridge, San Francisco

Figure 26. The Akashi Kaikyo Bridge, Kobe

Figure 27. The 1915 Çanakkale Bridge, Dardanelles Strait

Finally, the project to cross the Strait of Messina deserves special mention. In addition to the attractive proposals for an underground tunnel, rejected due to the considerable depth of the seabed, and the so-called Archimedes Bridge, an underwater tunnel anchored to the seabed, two main bridge options have been proposed: a cable-stayed bridge with pylons in the water and a suspension bridge with pylons on dry land. The latter was considered the viable solution. If built, the Messina Strait Bridge would have the longest span in the world, with 3300 m between the two pylons, far greater than the current maximum span. The deck, featuring an original aerodynamic shape and known as the Messina-type deck, is suspended by two pairs of cables.[29] The towers are 370 m high, and the foundations, both at the pylons and at the cable anchors to the ground, are very large. Special measures will be implemented at the towers and terminal structures to withstand horizontal forces and thermal effects.

Figure 28. The Bogazici Bridge, Istanbul

Conclusions

Bridge design requires expertise in road, hydraulic, geotechnical, structural, and environmental engineering. Project planning requires accurate and in-depth knowledge of the geomorphology of the area of interest. If the bridge spans a river, a thorough hydraulic study must be conducted, and the effects of the piers on water flow must be assessed. Once the bridge location, alignment, and geometric characteristics (namely, the span and transverse profile) are known, the connections with the road at the abutments must be defined. The results of the geotechnical investigations can also lead to a revision of the project, with modifications to the road layout. They are crucial in choosing the structural typology and foundation type.

The study of deformation and stress regimes is nowadays performed with the aid of sophisticated finite element calculation and analysis codes that allow for accurate modeling of all structural aspects. However, most existing structures were designed without such tools. The structure was reduced to a theoretical calculation model through a series of simplifications and hypotheses. When the definition of a suitable theoretical model was uncertain or the calculation models were unsatisfactory, an experimental model was realized and tested, especially in the case of large structures. Preliminary determination of the most severe load conditions among the infinite possibilities was essential, and this was accomplished by drawing influence lines. Particular attention was paid to studying the transverse position of the loads, for which various theories were developed that considered the non-negligible width of the beam itself.

Despite all these challenges, an old saying goes: "Give us the plans, and we will build a bridge to heaven or to hell."

The most daring challenge for the future is that of very long spans. The free space required for navigation, due to the increase in the size of boats and the volume of marine traffic, will determine the need to realize bridges with ever-longer spans. On the other hand, the lower cost of horizontal structures compared to that of deep foundations in water will favor the design of bridges with longer spans. This choice also reduces the risk of collision of boats against the piers. Therefore, the battle against the forces of nature continues and will require great technical knowledge, but also uncommon skills, intuition, and audacity.

As the span increases, the self-weight of a structure increases, and a high percentage of its load-bearing capacity is used to support itself. The limit span, that is, the span for which the bridge can support only its self-weight but no other loads, depends on the structural type, the resistance of the material used, and its weight per unit volume. For a cable of harmonic steel with a sag-to-span ratio equal to 0.1, the limit span is approximately 8000 m. Considering other permanent and travelling loads, it can be deduced that the limit span for a suspension bridge made of traditional materials is much lower. Therefore, the possibility of bridges with very long spans is related to the use of more resistant and lighter materials than the current ones.

Materials will continue to improve in the future, structural types will be optimized, and the construction of a bridge will always be something special: "When you build a bridge, you build something for all time," said Joseph Strauss.

References

[1] Clemente P. Monitoring and evaluation of bridges. Lessons from the Polcevera Viaduct collapse in Italy. *J Civil Struct Health Monit*. 2020;10(2):177–182. doi:10.1007/s13349-020-00384-6.

[2] Ormando C, Lucaferri V, Giocoli A, Clemente P, Buffarini G, Tofani A. Index of attention for a simplified condition assessment and classification of bridges. *Infrastructures*. 2024;9(8):125. doi:10.3390/infrastructures9080125.

[3] Buffarini G, Clemente P, Giovinazzi S, Ormando C, Pollino M, Rosato V. Preventing and managing risks induced by natural hazards to critical infrastructures. *Infrastructures*. 2022;7(6):76. doi:10.3390/infrastructures7060076.

[4] Buffarini G, Clemente P, Giovinazzi S, Ormando C, Scafati F. Structural assessment of the pedestrian bridge accessing Civita di Bagnoregio, Italy. *J Civil Struct Health Monitor*. 2023;13(8):1499–1516. doi:10.1007/s13349-022-00628-7.

[5] Kranakis E. *Constructing a Bridge*. Cambridge, Massachusetts: The MIT Press; 1997.

[6] Cassady S. *Spanning the Gate*. Santa Rosa, CA, USA: Square books; 1986.

[7] Raithel A. *Costruzioni di ponti*. Napoli: Liguori; 1962.

[8] Raithel A. *Ponti a travata*. Napoli: Liguori; 1970.

[9] Widmann R, Müller A. History and development stages in timber bridge construction in Switzerland. In: *Conference Proceedings 4th ICTB*. Biel/Bienne, Switzerland; 2022. doi:10.24451/779w-2t59.

[10] Clemente P, Ormando C. CM/SHM of historic masonry arch bridges. In: Karbhari VM, Ansari F, eds. *Condition Monitoring of Infrastructure Systems*. Sawton, Cambridge, UK: Woodhead Publishing Ltd; in press, Cap. 5. doi:10.1016/B978-0-443-38315-1.00027-1.

[11] Clemente P, Occhiuzzi A, Raithel A. Limit behavior of stone arch bridges. *J Struct Eng*. 1995;121(7):1045–1050. doi:10.1061/(ASCE)0773-9445(1995)121:7(1045).

[12] Clemente P, Saitta F. Analysis of no-tension material arch bridges with finite compression strength. *J Struct Eng*. 2017;143(1):04016145. doi:10.1061/(ASCE)ST.1943-541X.0001627.

[13] Clemente P, Saitta F, Ormando C, Buffarini G. Masonry arch bridges with finite compression strength subject to horizontal longitudinal seismic actions. *Appl Sci*. 2023;13(13):7509. doi:10.3390/app13137509.

[14] Dani F. *Il libro dei ponti*. Pomezia: SARIN; 1988.

[15] Mao YS. *Bridges in China: Old and New*. Peking: Forein Languages Press; 1978.

[16] Podolny W, Scalzi J. *Construction and Design of Cable-Stayed Bridges*. Hoboken, USA: John Wiley and Sons; 1976.

[17] Troitsky MS. *Cable-Stayed Bridges*. London: Crosby Loockwood Staples; 1977.

[18] Billington DP, Nazmy A. History and aesthetics of cable-stayed bridges. *J Struct Eng*. 1991;117(10):3103–3134. doi:10.1061/(ASCE)0733-9445(1991)117:10(3103).

[19] Clemente P, Marulo S, Lecce L, Bifulco A. Experimental modal analysis of the Garigliano cable-stayed bridge. *Soil Dyn Earthq Eng*. 1998;17(7–8):485–493. doi:10.1016/S0267-7261(98)00022-0.

[20] Clemente P, Bongiovanni G, Buffarini G, Saitta F. Structural health status assessment of a cable-stayed bridge by means of experimental vibration analysis. *J Civil Struct Health Monit*. 2019;9(5):655–669. doi:10.1007/s13349-019-00359-2.

[21] Clemente P, Ormando C. Monitoring system of the San Giorgio bridge at Genoa, Italy. *The Monitor*. Winter 2021. https://ishmii.org/the-monitor/.

[22] Podolny W. Future trends in cable-stayed bridges. *Proceedings of IASS Symposium Spatial Structures: Heritage, Present and Future (Milan, 1995)*. 1995;2:985–994; SGE Padova.

[23] Clemente P. On the limit span of cable-stayed structures. In: *IABSE Report Long-Span and High-Rise Structures*. Zurich: IABSE; 1998;79:287–292.

[24] Virlogeux M. The normandie bridge, France: a new record for cable-stayed bridges. *Struct Eng Int*. 1994;4(4):208–2013. doi:10.2749/101686694780601629.

[25] Pugsley A. *The Theory of Suspension Bridges*. 2nd ed. London: Arnold LTD; 1968.

[26] Clemente P, Nicolosi G, Raithel A. Preliminary design of very long-span suspension bridges. *Int J Eng Struct*. 2000;22(12):1699–1706. doi:10.1016/S0141-0296(99)00112-1.

[27] Clemente P. Effects of differential displacements between the ground anchors in suspension bridges. *Infrastructures*. 2024;9(11):211. doi:10.3390/infrastructures9110211.

[28] Buonopane SG, Billington DP. Theory and history of suspension bridge design from 1923 to 1940. *J Struct Eng*. 1993;119(3):954–977. doi:10.1061/(ASCE)0733-9445(1993)119.

[29] Brancaleoni F, Diana G. The aerodynamic design of the Messina Straits Bridge. *J Wind Eng Ind Aerodyn*. 1993;48(2–3):395–409. doi:10.1016/0167-6105(93)90148-H.