The Architecture of Bridges

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Abstract: The paper looks at some bridge structures from ancient aqueducts to the most recent viaducts since people have always built structures that help them to cross terrain obstacles such as rivers, ravines and hills. Their primary goal has functionality and efficiency rather than aesthetic considerations and, yet from a time perspective, they still impress with their beauty and perfection. Gradually, architects began to take care of the form of bridges, as in the case of the Rialto Bridge in Venice. Nowadays, the most renowned architects, with Norman Foster in the lead, take up the design of bridge "architecture". Although technical solutions remain top priority, aesthetic qualities are widely recognized and appreciated.

Key words: Bridge, architecture, construction, innovativeness.

1. Introduction

The logic and simplicity of structures made engineering fashionable again among contemporary creators. This kind of aesthetics applied to other architectural objects raised admiration for pure structural and engineering form, and the structural engineer received the status of an artist just like the architect.

It is worth noting that bridges, viaducts and footbridges are very special engineering structures that have always been a feature of human civilization. They have been indispensable to man mainly because of their function but observers have never remained indifferent to their structure, form and aesthetics. Their construction mostly originated from an innovative idea of how to cover a distance while resulting from emanated novelty and marked technological progress. A review of the structure of bridges and river crossings gives a perfect picture of changes in bridge engineering that influence architectural form, also with reference to other objects. The style which was derived from the logic of engineering structures appeared in successive historical epochs and at various stages of architectural development.

Nowadays, we also see architects fascinated by the opportunity to create such objects. They are often remarkable feats of engineering like Santiago Calatrava’s structures. What attracts designers is the unique opportunity to create a large-scale form in open space. However, it seems indispensable nowadays to analyze each structure not only with respect to its aesthetic and architectural features but also its environmental impact. The problem of cultural and landscape context gains prominence because each technical structure, however beautiful, forms part of its surroundings and functions either as an element that improves them or degrades them. Unique bridge forms can add value to a cityscape, as in Rotterdam or Lisbon. An imposing symbol of the 21st century technology marks the open landscape in the vicinity of Millau, France, but it has not received an equally warm welcome as an epitome of beauty from all environment-oriented people.

2. Aqueducts

2.1 Europe

Ancient aqueducts that transported water and provided Romans with the luxury of having it in their private households and public spaces are still
impressive by their size, technological solutions and, first of all, their specific architecture. These underground pipelines or arcade-supported over-ground water conduits transported water from distant sources using the force of gravity. They were placed on constructions over rivers or uneven terrain and had characteristic tectonics. It was the technique of building arcades and the skill of mounting water conduits above ground that significantly shortened the distance the Roman aqueducts had to cover and contributed to their success. The gradient of the aqueducts was only several dozen centimeters per kilometer. They remain fascinating achievements that have charmed us with extraordinary engineering structure since antiquity.

Aqueducts had been known before, but it was the Romans who made them widespread. In the 2nd century AD, Rome was supplied with water by 11 aqueducts with a total length of 420 km of which only 47 km were carried above ground. The network supplied 1 million m$^3$ of spring water a day. Water was supplied to fountains, public baths, latrines and some private households.

The oldest aqueduct in Rome, the Aqua Appia, was built by Appius Claudius Caecus and Caius Plautius Venox in 312 BC mostly underground. It carried water from the Alban Hills which were over 16 km away. The second aqueduct was the Anio Vetus, constructed in 272 BC, which transported water from the source 63.5 km away. An over 300 m section of the aqueduct was supported by arches.

Roman aqueducts can be found not only in the Apennine peninsula but also all over the Roman Empire territories, e.g., the Diocletian Aqueduct in Split, Croatia, the Eifel Aqueduct supplying Cologne, Germany, which was used between 80-250 AD and, with auxiliary spurs, was 150 km long. One of the most impressive objects is Pont du Gard near Nimes, France. The Domitian Aqueduct in Segovia, Spain, was built in the 1st century AD and is the symbol of the city and still the most impressive structure due to its massive scale and state of preservation. The aqueduct in Segovia stretches from the northeastern end of the city across the city center and along the Plaza del Azoguejo, to the southwestern end of the old town.

These sophisticated and perfectly functional engineering structures reemerged many times later on in history. One of them is the Aguas Livres Aqueduct (Aqueduct of the Free Waters). It is a historic object that still supplies Lisbon with water and is one of the most remarkable examples of 18th century Portuguese engineering. The main course of the aqueduct covers 18 km, but the whole network of canals extends through nearly 58 km (Fig. 1). Lisbon had suffered from the lack of drinking water until King John V decided to have an aqueduct built to supply water from the sources in Caneças, in the municipality of Odivelas.

The construction started in 1731 under the guidance of Antonio Canevari, an Italian architect, who was replaced in 1732 by a group of Portuguese architects and engineers, including Manuel da Maia, Azevedo Fortes and Jose da Silva Pais. Between 1733 and 1736, the project was directed by Manuel da Maia. He in turn was replaced by Custódio Vieira, who headed the project until around 1747. The 941 m long centerpiece divided into 35 arches over the Alcantara valley was completed in 1744. The tallest arch is 65 m high. The arches are not spaced evenly. In 1748, the aqueduct started to supply Lisbon (the district of Amoreiras).

Fig. 1  The Aguas Livres Aqueduct Lisbon.
with water although the project was not completed at the time. The Mãe d’Agua Reservoir with a capacity of 5,500 m³ was built there to supply smaller underground reservoirs and fountains. Due to its engineering ingenuity and resilience, the aqueduct was one of the few objects in Lisbon that survived the massive earthquake of November 1, 1755.

2.2 Poland

Structures of this type, emulating models from the past, can be also found in Poland. One of them is the Fojutowo Aqueduct which was built in the years 1845-1849 to supply Łąki Czerskie near Czersk with water from the river Brda. The structure is 75 m long which makes it the longest object of this kind in Poland. The aqueduct was made from stone and yellow brick joined with lime while its bottom was sealed with glass wool and tar. At the moment, it is a unique monument of water engineering. The Mazurian Lake district in the northeastern part of Poland boasts Szlak Akweduktów (the Aqueduct Trail). Near the village of Stańczyki¹, there stand the huge viaducts of the defunct railway line Golap-Zytkiejmy. The bridges in Stańczyki are the tallest on this line and among the tallest in Poland with a length of 200 m and a height of 36 m. It is a five-span reinforced concrete structure with arches 15 m each. The structure has excellent proportions and the decorative elements of the piers resemble the Roman details of the Pont du Gard Aqueducts. That is why they were called Akwedukty Puszczy Romanickiej (the Romanicki Forest Aqueducts). The bridges in Stańczyki are the tallest on this line and among the tallest in Poland with a length of 200 m and a height of 36 m. It is a five-span reinforced concrete structure with arches 15 m each. The structure has excellent proportions and the decorative elements of the piers resemble the Roman details of the Pont du Gard Aqueducts. That is why they were called Akwedukty Puszczy Romanickiej (the Romanicki Forest Aqueducts). The first southern bridge began in Stańczyki in the years 1912-1914 and was completed in 1917 while the northern bridge was finished in 1918. Further works were stopped as World War I was drawing to a close. The cantilevered reinforced concrete structure with latticework railings still impresses the viewer. The twin five-span bridges run across the wide and deep valley of the river Błędzianka at a height of 36.5 m.

The oldest iron bridge in Poland [1] was built in Opatowek in 1824. It is situated in a park and crosses the artificial moat that surrounded the former palace on the southern side. It is a single-span arched structure with four main girders made of cast iron and comprising three segments joined with bolts.

The oldest wrought iron suspension bridge in Europe was built in Ozimek over the river Mała Panew in 1827 (length: 31.5 m; total width: 6.6 m; admissible vehicle weight: 3 t; number of spans: 1; built 1825-1827; refurbished 2009-2010). It is a chain suspension bridge made completely of wrought iron and as such should be considered the oldest structure of the type in the world. The Menai Iron Suspension Bridge which was built in England in 1826 and is thought to be the oldest suspended from stone pylons. The Ozimek Bridge was designed by Karl Schottelius, a royal steelworks inspector, and manufactured in the local Malapanew steelworks. It came into use in 1827. Nearly 57 t of iron castings and 14 t of steel were used for the construction. The Malapanew Steelworks chronicle gives an account of the weight test of the bridge: first, a herd of cattle were driven over the bridge; next, a loaded cart went quickly from one side to the other. The structural engineer calculated the bridge load capacity at 3 t but in fact it could bear a five times greater load. The bridge served the Ozimek-Zawadzkie route until 1938. Then it was used by pedestrians as an internal bridge of the Malapanew Steelworks until 2010.

In July 2009, an overhaul started. The bridge was disassembled, renovated and reassembled. The structure was strengthened with steel cables. In September 2010, the bridge was open to the public as a tourist attraction of the city.

3. Bridge of Leonardo da Vinci

An amazing story combines a visionary project of Leonardo da Vinci with modern times. In 1502, he made drawings of a single-span 240 m bridge. He designed the bridge for the Sultan Bayezid II as a

crossing over the Golden Horn in Constantinople where the river flows into the Bosphorus. The idea was to connect the river banks with a single-span structure that resembled a flattened bow. The author envisaged that the span could be narrowed in the middle and widened towards both ends anchored to the banks. The 300 year-old design concepts have been proven feasible.

The bridge was 24 m wide, 360 m long and 40 m tall at the highest point of the span.

In 1996, Sand Vebjørn [2], a Norwegian painter and artist, saw the drawing of the bridge at an exhibition of Leonardo da Vinci’s works. The drawing and the message behind the simple structure fascinated him so much that he spent the following 5 years looking for the original design, reinterpreting it and making a contemporary replica of the bridge. His project was supported by Norwegian Public Roads Administration and the architect Knut Selberg. On October 31, 2001, the footbridge was opened to the public and thus became the only engineering project of Leonardo to be implemented. The 108 m long footbridge in As, Norway, spans the E18 motorway that joins Oslo and Stockholm. Local granite was used for the construction. The Norwegian project became an implementation of Leonardo’s visionary design and went down in history as a unique cultural product combining the renaissance versatility and ingenuity with modern technology and, first of all, as an original and timeless idea to affirm the engineering genius of Leonardo da Vinci.

At this point, it might be worth reflecting on the value of drawing as a timeless means of communication among inventors, structural engineers and architects. Despite the fact that paper seems undurable, this way of recording ideas remains clear and understandable. It becomes a universal document whose concise graphics of hand-drawn lines are legible in any epoch. It is more valuable, the more widespread computer becomes, since digital record in binary code is deprived of individual features, unique tracing of lines or the mastery of Leonardo’s free hand rendering.

4. Bridges of New York

4.1 The Brooklyn Bridge

Big cities that are situated on water areas are famous for their bridges. To mention only the magnificent Ponte Vecchio in Florence or Rialto in Venice, shown as Fig. 2, they are original landmarks in urban space. New York bridges play a similar role although they are more recent structures. Looking at the bridges that join Manhattan with other boroughs, we can notice the technological progress that occurred within relatively short periods of time. Each new bridge was an example of new technological achievements and advances in engineering that added new value to the city’s architecture. The oldest of them all is the Brooklyn Bridge, a magnificent technological achievement of the turn of the century whose significance is unquestionable. It connects Manhattan and Brooklyn spanning the East River. The designer and builder of the bridge was John August Roebling assisted by Wilhelm Hildebrand. When he died as a result of an accident on the construction site, his son, Washington Roebling, took over. Its structure is a suspension/cable stayed hybrid. It has six lanes for motor vehicles, walkways and bicycle paths. It is built from steel, concrete and stone and has a total length of 1,825 m. The towers are 84 m high and the clearance...
at mid-span is 41 m. The construction of the bridge started in 1870 and was finished in 1883.

Its construction is part of the history of bridge building but the scale of the undertaking and its height are admired as part of the history of skyscrapers. It is the history of New York City, its engineering, architecture and culture.

The 19th century is also the time when beauty is beginning to be perceived in rational terms as admiration for innovative engineering achievements. In architecture, the old concept of proportion is replaced by the new concept of “form” which is based on experiencing emotions and which legitimizes breaking patterns and rules in search of beauty unrestrained by dictating and aiming at novelty and originality. Beauty seen in such terms turned to a new value which was expressive. Hence the expressive aesthetics of innovative engineering structures became a significant value that was recognized and admired.

4.2 The Bayonne Bridge

Another famous New York bridge is the 2,522 m long Bayonne Bridge. It was built by Cass Gilbert and Othmar Amman in 1931 and spans Kill van Kull to connect Bayonne, New Jersey with Staten Island, New York. It has four lanes for motor vehicle traffic and walkways for pedestrians. On its opening, it was awarded the prize for the most beautiful steel bridge by the American Institute for Steel Construction. It is still the fourth longest steel arch bridge in the world. Its concrete parts have recently been renovated by the company Modjeski & Masters. Here is an additional information that Rudolf Modrzejewski, co-founder of the firm, born in Bochnia, Poland in 1861, was the son of the Polish actress Helena Modrzejewska.

4.3 The Verrazano-Narrows Bridge

Yet, another significant bridge is the bridge built in the years 1964-1969. It is a double-deck suspension bridge which is the largest of its kind in the USA. It was the longest suspension bridge in the world until 1981. It has a total of 12 lanes. The longest span has 1,298 m. The pylons are 211.2 m high each. The clearance below is 69.5 m. It connects the boroughs of Staten Island and Brooklyn spanning the narrows. The bridge was named after Giovanni Verrazzano, an Italian explorer who was the first European to sail into the Hudson River estuary.

5. Bridges of Lisbon

5.1 The 25th of April Bridge

Similarly in Lisbon bridges mark technological progress since they shorten the distance between Europe and the city, it is because the mighty river Tagus encloses the city at the edge of the continent. In 1966, the first of the two bridges was built. At that time, it was one of the longest suspension bridges in the world and its length was 2,200 m. Until 1974, it was known as the Salazar Bridge but when Salazar was overthrown in 1974, the bridge was renamed the 25th of April Bridge (Ponte 25 de Abril). The 25th of April Bridge in Lisbon is often said to be a brother of the Golden Gate in San Francisco. In fact, it is very much like the San Francisco Oakland Bay Bridge since both were built by the same company (Fig. 3).

5.2 The Vasco da Gama Bridge

In March 1998, the Vasco da Gama Bridge was

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opened [3, 4]. It connects the capital of Portugal with Montijo. It has a total length of 17.2 km, including the length of the structure. There are three lanes for motor vehicles in each direction but the fourth one can be added if there is a need. In a record time of 44 months, they designed and built the longest bridge in southern Europe.

Some obstacles had to be overcome while making the design, such as protection of the salt marshes areas on the south of the river. The central bridge spans the sailing canal of Cala do Norte at the northern bank of the Tagus estuary (Fig. 4). There were also dangers resulting from the fact that Lisbon is situated in a seismic zone and a computer analysis of the structure was made to see how it would behave during an earthquake. Moreover, the bridge is situated at the mouth of the river Tagus where the environment is greatly affected by ocean water. Therefore, the underwater parts of the structure were safeguarded against the harmful effect of salt. Also, the parts of the structure affected by the ocean tides were protected.

6. Bridge of Robert Maillert

The way to revolutionary modernist reinforced concrete constructions was paved by the engineering achievements of Robert Maillert. The potential of reinforced concrete provided the designer with opportunities to create sophisticated architectural and engineering shapes with technical virtuosity. The technology and specific aesthetics he created are still irreplaceable.

The pioneering thought of Robert Maillart [5], a pupil of Hennebique, consisted in replacing the beam system with the concrete slab as a universal load bearing system used for ceilings, roofs, bridges and other engineering structures.

One of the best known objects is the Salginatobel three-hinged arch bridge which was built in the years 1929-1930. Its span is 92 m. The structure comprises a curved slab which is combined with the horizontal deck and vertical strengthening plates to make a complete whole. Elimination of superfluous details and bridge segments as well as focus on structure and engineering economy set new guidelines for architects and engineers. The arched planes suspended over a gorge added unprecedented dynamics to the structure as a whole.

The logic and simplicity of Maillart’s structures made engineering fashionable again among contemporary creators. This kind of aesthetics applied to other architectural objects raised admiration for pure structural and engineering form and the structural engineer received the status of an artist just like the architect.

7. Great Architects and Their Bridges

Contemporary bridge architecture is within the scope of interest of Santiago Calatrava³, Ben van Berkel [4], and Norman Foster.

7.1 The Erasmus Bridge

In the years 1990-1996, the Erasmus Bridge was built in Rotterdam, Holland⁴. It has a total length of 802 m and was designed by Ben van Berkel (Fig. 5). It is situated along the north-south axis of the city over the river Mass and links the city center with the postindustrial areas of the former harbor and warehouses. The postindustrial areas have been turned into residential districts and communication is vital to their further development. The bridge has become a

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The Erasmus Bridge, Rotterdam.

cityscape landmark due to its scale and original form. It has a prominent and slightly curved pylon which is 139 m. It is located near the northern bank since it serves the span with the bascule bridge. The aesthetics of the structure results from a perfect synthesis of sophisticated structural engineering and architectural quality. The bridge is an icon which refers not only to this particular place but also to its neighborhood. It seems to affirm technological development and the spirit of modern times (Fig. 5).

7.2 The Zubizuri Footbridge

The extraordinary quality of bridge architecture is clearly seen in the works of Santiago Calatrava. His expressive and unique creations perfectly reflect the rapid progress in structural engineering which affects architectural form and often predominates over it completely. The style derived from the logic of structural engineering becomes architecture which is deprived of any additions and is there to impress solely with its technological beauty. One of his first significant realizations was the Puente del Campo Volantin or Zubizuri Footbridge built in the years 1990-1997 in Bilbao, Spain. It is located in the vicinity of the Guggenheim Museum designed by Frank Ghery and perfectly fits the revitalized former port area of the city (Fig. 6). It crosses the river Ibaizabal at Arata Isozaki’s Atea towers erected in 2006. It was originally designed to link the left bank with the Uribitare railway station but the changes in the function of the space resulted in conflicts that ended in March 2009 with granting Calatrava damages for infringement of his copyright.

Puente de la Mujer in Buenos Aires, Argentina (1998-2001), is a rotating suspension footbridge and a landmark of the city. One part of the bridge swings to let sailing boats pass. It connects urban and port areas on opposite banks of the river and is a symbol of the new quality of the revitalized port town.

Another bridge of Calatrava’s placed in the cultural space of the city is the Samuel Beckett Bridge in Dublin, Ireland (1998-2009). The huge arch of the pylon with cable stays that support the road deck has a very specific shape. It was inspired by the sophisticated streamlined shape of the harpsichord which is a historic symbol of Ireland. In this way, a thoroughly modern form is a specific transformation of traditional symbols and a kind of tribute to Dublin and its inhabitants.

In 1992, a new bridge was built across the river Guadalquivir because of the expo. It is another
innovative and expressive structure with an inclined 142 m tall pylon as a kind of counterbalance to the 200 steel cables supporting the span.

7.3 The Millau Viaduct

Norman Foster, a well-known, much respected and very active architect, author of the faulty Millenium Bridge, London, took part in the Millau Viaduct project—the tallest cable-stayed road bridge in the world. It runs its 2.5 km course over the valley of the river Tarn in France [6]. It was in Norman Foster’s studio that the project was conceived with the support of the French structural engineer Michel Virlogeux. The result was a viaduct built on a curve whose spans were supported by an extraordinary technological structure. The magnificent structure has seven concrete piers ranging in height from 77.56 m to 244.96 m, when measured from the ground level to the deck. The support of Millau Viaduct on the tallest piers that have been built so far has secured the position of the tallest cable-stayed bridge in the world. Above the road-deck, 90 m tall masts were erected5.

This realization is admired for its minimum interference with the environment but also for the technology and engineering prowess. The beauty of modern technology is viewed as a new aesthetic value.

8. Conclusions

One may ask about the criteria for the selection of the bridges to be presented but the answer is difficult because bridges are innumerable and their aesthetic qualities are abundant [7-9]. Generally, the architect is just a viewer, a recipient who marvels at their appearance, their extraordinary structures which span great distances, the way they merge with the surroundings or are set within wide frames of the landscape. The architect hardly ever has a chance to participate in their design and has no say when it comes to making key structural decisions. This is the domain of bridge engineers with their vast knowledge resulting from years of studies, experience and talent. Thus, the range of information concerning the distinguishing among structural systems, the criteria for their selection as optimum solutions in the context of their location seem to be rather symbolic in the paper and such that would be available for wider public. Although the bridge structure and the material used are recognizable and are crucial for categorization, the architect still remains important. Therefore, he makes a subjective selection which results from the fascination with the beauty of the structures, the experienced feelings and, sometimes, under the influence of the magic of the engineers’ names or their major achievements.

The situation is similar as regards a deeper analysis of the history of the implementation of particular structures. Bridges and viaducts are always set in the times when they emerged. Nevertheless, this kind of information, however fascinating it may be, is not always crucial for the text which the author dedicates to the beauty of bridge structures.

It appears that the appeal of technical-style creations which focus on the functional simplicity of the structural form stripped of decorative details has been great over the last two millennia. And there is no need to prove that nearly every bridge or hangar, just like any other building—a church, a museum, an airport, which are structures created from the computations and imagination of a design engineer, can, at the same time, be brilliant architecture, the beauty of which lies in its asceticism.

It is worth bearing in mind that a bridge is not just an economical spatial form of structural engineering and architecture. It also involves a number of technical details such as color, the shape of abutments, piers, cornices, banisters, railings whose role in the overall impression are fully appreciated only by professionals such as designers who determine their shape. However, the color can sometimes go down in history as in the case of Golden Gate Bridge whose structural elements were painted international orange

for protection at the suggestion of Irving F. Morrow. The color was remembered as gold and gave the bridge its historical name.

References


