AESTHETICS OF CONTEMPORARY ARCH BRIDGES

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SUMMARY

The arch is a quintessential bridge form, and although definitions of beauty change with time the arch is generally considered the most pleasing of bridge forms. A review of the evolution of aesthetical considerations in design of arch bridges is attempted in the paper. The guidelines on bridge aesthetics are evaluated. The potential role of architects is discussed. Immense aesthetical potential of arch bridges is elaborated upon with special emphasis on contemporary structures.

Keywords: *Aesthetics, structural art, engineer, architect, arch, spatial bridge, iconic bridge.*

1. INTRODUCTION

Bridge engineering is exposed to public judgment and assessment, often more than other professions [1]. Due to their size and prominence, bridges are often the most visible and striking components of the built environment. They have an overwhelming impact on the surrounding environment, which can enhance the surrounding landscape or be ruinous. They can be seen from different locations (on/under the bridge, from close up, faraway, from other roads) and in different conditions (standing, moving: at varying speed and in a variety of vehicles), and they invariably leave a strong impression on people.

One of the most beautiful impressions of the bridges was written by Croatian Nobel Prize winner, Ivo Andrić, in short story titled Bridges [2]: "*Of all the things created and built by humankind as a part of life's effort, nothing in my mind is better or worthier than bridges. They are more important than houses, more sacred, and more universal than temples. They belong to all and treat all alike; they are useful, always built for a purpose, at a spot where most human needs entwine; they are more durable than other buildings and serve no secret or evil purpose.*"

This strong impression on bridges should inspire engineers to learn the secrets of load-bearing structures, to take advantage of available building materials and to achieve functional, economical, but also aesthetically pleasing bridges in creative enthusiasm of structural art.

Bridges are generally looked upon purely as manifestations of technical achievement rather than architecture.

The mission of a bridge is nothing more than the continuation of a path, road or railway across a physical obstacle, such as a gorge, a river, a valley or another road or railway.

The means to accomplish this mission is simply the structure. Hence, the art of bridge building primarily lies in the recognition and abstract interpretation of forces in the structure and secondly in the development of appropriate structural forms that use the strength and other special properties of the materials in a most efficient way. But, the technical perfection of the means to attain the mission alone is not enough. The shapes and proportions of each bridge component should be chosen in such a way that the bridge appears as a single object, rather than an assemblage of separate parts and only then also the aesthetic perfection can be achieved.

Throughout the history of bridge building structure and aesthetic expression were inextricably bound together. The most famous engineers of our past have made aesthetics an explicit element in their work.

Nowadays aesthetic considerations of form remain of superior importance to bridges, which is not a case with buildings, where the structure has become hidden by outer fabric, claddings, suspended ceilings and curtain walling.

The arch is a quintessential bridge form, and although definitions of beauty change with time the arch is generally considered the most pleasing of bridge forms. Even those untrained in engineering seem to intuitively appreciate that form of a true arch bridge expresses fully its load-carrying ability.

A review of the evolution of aesthetical considerations in design of arch bridges is attempted in the paper. The guidelines on bridge aesthetics are evaluated. The potential role of architects is discussed. Immense aesthetical potential of arch bridges is elaborated upon with special emphasis on contemporary structures. The thoughts expressed in the paper are our own and hence necessarily subjective.

2. AESTHETICS OF ARCH BRIDGES IN HISTORY

The famous Vitruvian triad from 1st century B.C., function, structure and beauty ("firmitas, utilitas, venustas" in Latin original), rephrased by Enzo Siviero [3] for the architecture of bridges as the "three rule": structure, form and spirit, is still valid today.

It embodies the prerequisites of satisfying safety and functional requirements, but includes also the other lasting quality of elegance or beauty.

The understanding of "utilitas" and "firmitas" is easy, since it is tied to the present state of knowledge and everyday practice, while "venustas" is more elusive. Beauty is a quality of things themselves, which cannot be rationally quantified, and hence the judgment differs from person to person, depending on cultural background, education, personal feelings and sensitiveness. But beautiful is "what is generally and necessarily felt to be beautiful" (Immanuel Kant) and hence if majority of people agree that something is beautiful it is.

Vitruvius conspicuously does not mention economy, which is very important in modern assessments. He either assumes that economy is implicitly included, or as in his time free slave labour was available it was not an issue.

Everybody agrees on the classical beauty of Roman arch bridges and aqueducts (Fig. 1a-c), such as Alcantara Bridge, Ponte Sant'Angelo in Rome and Pont du Gard Aqueduct. The iconic bridges of the Middle Ages (Fig. 1d-e), such as the Ponte Vecchio in Florence and the Charles Bridge in Prague are admired by millions of visitors each year. Nobody questions inherent beauty of the landmark Rennaissance bridges (Fig. 1f-h), the

Rialto in Venice, the Santa Trinita in Florence and the Pont Neuf in Paris or the Ottoman Old Bridge in Mostar (Fig. 1i). The stone arch bridges reached its climax with Jean Rodolphe Perronet in the 18th century, who amongst other bridges built the famous la Concorde Bridge in Paris (Fig. 1j) with very slender piers and light and elegant arches in perfect harmony with the Place de la Concorde in front of it.

All these stone arch bridges are some of the most acclaimed human built structures expressing the construction state of the art of their time and clearly displaying the creativity of their builders, in full accordance with the Vitruvian axioms. The arrangement and construction of these bridges followed certain strictness and order in the embellishment of design, partly based on tradition and partly on social culture. These bridges are admired not only for their artistry and impressive form, but also for the extraordinary effort to build them with so limited technology of their time.

Fig. 1. *Stone arch bridges: a) Alcantara Bridge, b) Ponte Sant'Angelo, c) Pont du Gard, d) Ponte Vecchio, e) Charles Bridge, f) Rialto Bridge, g) Santa Trinita Bridge, h) Pont Neuf, i) Ottoman Old Bridge and j) la Concorde Bridge.*

The 19th century was a time of new material – of iron and steel. The Craigellachie Bridge (Fig. 2a) is considered as the first modern metal arch – not built up of voussoirs in imitation of the masonry arch, but constructed of trussed arch and spandrel. Arch historians compared its appearance to "spider web". His designer Thomas Telford is credited with defining structural art as the personal expression of structure within the constraints of efficiency and economy already in 1812. The development of various arch bridge types was facilitated through improvements of material and by the advancement of science of bridge engineering. It should be noted that their rise-to-span ratios were smaller (down to f/L = 1/17.1), than used nowadays. All arch types were known and constructed. Firstly, only deck arch bridges were built, and through arch bridges were introduced only later, with only very few half through arch bridges ever constructed. Great attention was placed on their appearance and the deck arch was considered as the most naturally pleasing type because of its functional clarity, as it „satisfies the aesthetic requirement of keeping the roadway line dominant, clear and uninterrupted" [4]. The longer span arch bridges were exclusively of trussed type. The most striking trussed deck steel arch bridge of the 19th century is the Eads Bridge across the Mississippi River in St. Louis USA (Fig. 2b). The chief bridge engineer Captain James Eads introduced remarkable innovations to bridge building, the free cantilever method for the arch construction and the foundations on deep caissons, both remarkable achievements at that time. Gustave Eiffel designed the famous Maria Pia Bridge in Porto (Fig. 2c) as a two-hinged crescent arch used to carry the railway across the River Douro at a height of 60m above the river. In the Garabit Viaduct (Fig. 2d), one of the most spectacular bridges

ever built, Eiffel greatly improved upon his Maria Pia Bridge design, adopting the same two-hinged crescent arch form but employing an arch visually separated from the thin horizontal girder. The famous Alexandre III Bridge (Fig. 2e) spanning the Seine River in Paris is notably one of the most beautiful bridges ever built, because it is in perfect agreement with urbanism and architecture of its surroundings. The Mirabeau Bridge (Fig. 2f) is modest but perfect, a peaceful structure fully befitting the modern buildings on the left bank. The Bonn-Beul Bridge, with all details thought through in accordance with aesthetics of that time, was one of the most beautiful bridges in Germany (Fig. 2g). Another aesthetically pleasing railway bridge was spanning the Rhine River at Engers (Fig. 2h). The main span was bridged by iron trussed tied through arch of 188m span. Its form has been repeated in many modern steel tied through arch bridges. The half-through truss arch railway bridge across the Hell Gate in New York (Fig. 2i), designed by Gustav Lindenthal, is an engineering masterpiece. The bottom arch truss chord is of parabolic shape and carries almost the whole dead load, as the bridge was constructed as three-hinged with a hinge in the bottom chord at the crown. The famous Swiss born engineer Othmar H. Ammann designed the graceful half-through trussed arch Bayonne Bridge (Fig. 2j) in New York, with no monumental masonry abutments, and with both chords of the arch continuing down below the deck. The iconic Sydney Harbour Bridge with its monumental towers at the arch springings (Fig. 2k), resembles the Hell Gate Bridge. However, the upper chord of the Sydney arch terminates before the towers, thus accentuating the path in which the loads are carried from the arch into the abutments, while the structural role of individual components at the Hell Gate Bridge is somewhat obscured though by the connection of the arch to the towers, designed to further emphasize the overall massiveness of the structure. A variation of through tied arch bridge which looks similar but actually behaves differently is the Langer beam, a through tied arch bridge with rigid deck and light arch. An example is the Green Bridge in Zagreb, Croatia (Fig. 2l) [4]. Its aesthetical appeal is rather questionable, particularly because the depth of the deck is larger on the approach spans than under the arch itself.

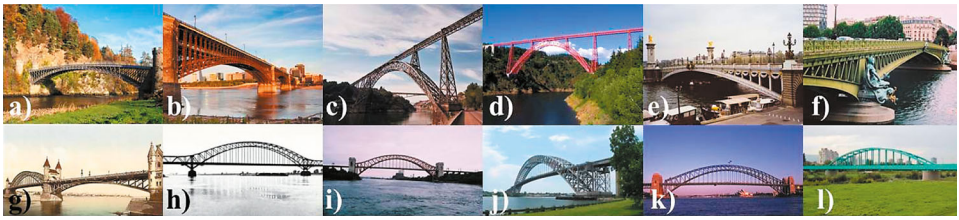

Fig. 2. *Metal arch bridges: a) Craigellachie Bridge, b) Eads Bridge, c) Maria Pia Bridge, d) Garabit Viaduct, e) Alexandre III Bridge, f) Mirabeau Bridge, g) Bonn-Beul Bridge, h) Railway Bridge Engers, i) Hell Gate Bridge, j) Bayonne Bridge, k) Sydney Harbour Bridge and l) Green Bridge.*

Concrete as a new material came at the beginning of the 20th century. Numerous concrete true arch bridges were built, in the beginning mostly based on forms of the previous masonry bridges. But the achievements of three engineers, François Hennebique, Robert Maillart and Eugène Freyssinet, stood out [5]. Francois Hennebique invented and patented his reinforced concrete construction system and bridges based on his patent were built throughout the world. His Camille de Houges Arch Bridge (Fig. 3a) has a rise to span ratio of 1/10.4. Eugène Freyssinet was one of the world's most prominent engineers, a brilliant inventor, passionate and creative builder. He endeavoured to raise

the limits of the use of concrete by building large bridges and various other structures and is credited as the inventor of prestressed concrete. His most famous arch bridges are the Villeneuve-sur-Lot Bridge (Fig. 3b), the Saint-Pierre-du-Vauvray Bridge over Seine (Fig. 3c), and the Albert Louppe Bridge at Plougastel on the Elorn (Fig. 3d). According to David Billington [6] "it was the elegance of his construction procedures both visually and in concept (that) made Freyssinet world-famous both to engineers and architects." Robert Maillart was the major structural artist of the early 20th century. He invented a new form for three-hinged arches that included his own invention of the hollow box in reinforced concrete. His famous Salginatobel Bridge (Fig. 3e) was declared the thirteenth International Historic Civil Engineering Landmark in 1991 and was the first concrete bridge to be named so, and is considered as masterpiece by both engineers and architects. The Salginatobel Bridge arch is thinnest at the crown and at the springings, thickening in between to reflect the shape of the bending moment diagram of a three-hinged structure. Among long span concrete arch bridges of that time one of the boldest and most striking is the Sandö Bridge across Ångerman River in northern Sweden (Fig. 3.f). The circular spandrel columns are extremely slender supporting the deck without head beams.

Fig. 3. *Concrete arch bridges: a) Camille de Houges Arch Bridge, b) Villeneuve-sur-Lot Bridge, c) Saint-Pierre-du-Vauvray Bridge, d) Albert Louppe Bridge, e) Salginatobel Bridge and f) Sandö Bridge.*

3. EVOLUTION OF MODERN BRIDGE AESTHETICS

One of the first thorough treatises on the aesthetics of bridges was published by R. Baumeister in the book *Brückenbau* by Landsberg already in 1904 [7]. The chapter on *Art forms of bridge building* contains aesthetical relations in general, and also recommendations for design of different bridge types, their superstructures, piers abutments and even railings, analysed on the examples of many existing bridges. While this treatise of course reflects the view on aesthetics of its time, it clearly states that bridges should be treated not only as science but also as art. The freedom in choosing an appropriate bridge form, devoid of any embellishments, is exemplified and it is claimed that for such a beauty the taste costs nothing. The bridge should be treated as the whole. If needed the architect should help with details or the engineer and the architect should work together from the beginning, where the latter validates aesthetical considerations already at the conceptual stage, but with full appreciation for the technical and economic thoughts of the engineer. Symmetry evokes the impression of grandeur and clarity. Most of these deliberations are still valid and represent important issues in the aesthetics of bridge design today.

A substantial discussion of bridge aesthetics both in Europe and in the U.S. came about in the thirties of the last century. Famous American engineer C.S. Whitney observed in 1929: *„A weak bridge is admittedly more dangerous than an ugly one, but to seek strength at the lowest cost with no regard for appearance is only one degree worse than it would be to attempt a beautiful design without thought of stability."* At that time many authors and most designers believed in some sort of collaboration in bridge design

between the engineer and the architect, but some like Friedrich Hartmann emphasized that modern design required a break with established rules and that proper design required a new theoretical knowledge that was foreign to architects [8]. His book [9] is still interesting today because of its many illustrations and his critical comments on them. He clearly preferred steel bridges to concrete ones, mainly because of their lighter appearance, and tended to avoid general arguments based on rules. But his most important contribution was his assertion that engineers should employ shapes immanent to the contemporary materials and free themselves from the prescriptions of the past, so often based on the ideas of architects, who in the course of their education only heard about structural forms of previous times. Eberhard in his contribution on aesthetics of steel bridges [10] wrote that the fundamental principle of all architecture is to reveal closely the purpose of the structure, and that engineer should accomplish clarity and truth in expression, choosing forms and materials that most naturally fulfil their purpose. „A bridge becomes a work of art, when as a whole and in all its members it clearly expresses the purpose of carrying and guiding traffic".

The beauty or ugliness of a bridge depends on how it is perceived by people. Here the Gestalt („unified whole") theory of psychology may help. This theory explains how people perceive things and following Gestalt principles can make designs more coherent, connected or unified. The key idea is that we see the whole as more than the sum of its parts. The fundamental principle of Gestalt is the law of Prägnanz (good figure, law of simplicity), which says that we that we prefer things that are simple, clear and ordered, and hence instinctively safer. The other important principle deal with Symmetry which gives us a feeling of solidity and Order, which we tend to seek and that it is in our nature to impose order on chaos. Other principles state that objects are perceived as more related, if they are visually connected (Uniform Connectedness), if they are arranged on a line or curve implying that we shall continue our perception of shapes beyond their ending points (Continuation), if they are parallel to each other (Parallelism), if they are closer together (Proximity), or of they share similar characteristics (Similarity). The Past Experience principle is difficult to generalize, because it is unique to the individual and may depend on the cultural background. Gestalt principles make designs more coherent, connected or unified and most of them are embedded in the contemporary writings on bridge aesthetics.

The famous Sullivan proposition „Form follows function" in the context of bridge design has become the motto of most texts on bridge aesthetics, generally with the connotation that efficient structural behaviour and low construction cost are sufficient conditions for visual elegance. This is the view held by most American writers on aesthetics of bridges [11]. David Billington re-invented the term „structural art" and defined the greatest works of structural art and design to be those that integrate three tenets: economy, efficiency, and elegance [6]. Efficiency concerns using the minimum amount of material consistent with adequate performance and safety; economy refers to achieving a competitive construction cost consistent with minimal maintenance requirements; and elegance is defined as emphasizing aesthetics to the greatest degree consistent with efficiency and economy. Consequently, structural art is quite distinct from the visual maxims of architecture because structural artists seek elegance without compromising safety, serviceability, and economy. The foremost European bridge designers, such as the late Fritz Leonhardt, Christian Menn and Michel Virlogeux amongst others, also share the modernist faith that bridges should be economic, efficient, and elegant, but believe that structural efficiency and cost are necessary but not sufficient conditions to conceive a beautiful bridge. In his paper [12] Fritz Leonhardt elaborated upon basics of aesthetics and announced guide-lines for aesthetic design, which appeared in his book on bridge aesthetics [13], which although written many years ago still remains the bible for bridge

designers. His criteria that an aesthetically pleasant bridge should satisfy: (1) Fulfilment of purpose/function, (2) Proportion, (3) Order, (4) Refinement of form, (5) Integration into the environment, (6) Surface texture, (7) Colour, (8) Character, (9) Complexity and (10) Incorporating nature, should be considered not as rules but as guidelines. It should be mentioned that they were actually conceived in the thirties of the last century within a group of engineers and architects who were assigned to improve the aesthetics of design for new Autobahn bridges to be built at that time [14]. A short version of his recommendations for aesthetics of structures is given in [15]. Leonhardt emphasized that the simple application of these rules will not in itself lead to beautiful bridges. The designer must still possess imagination, intuition and a sense for form and beauty, „a certain gift" as he put it. However, he noted that the design process is restricted by functional requirements, limits of the site and strict building regulations. He linked his vision of aesthetics to ethics; designers have to have moral responsibility to mankind and nature. "*Ethics implies humility and modesty, virtues that we find lacking in many designers of the last few decades; they have been replaced by a tendency toward the spectacular, the sensational and the gigantic. Because of exaggerated ambition and vanity, and spurred by the desire to impress, these designers created unnecessary fashions, lacking true qualities of beauty*". But the greatest quality of this book is that Fritz Leonhardt included data on an immense number of bridges and he did not refrain from explicitly criticizing them in regard to their visual appeal. His deliberations were echoed by Christian Menn [16, 17], who stressed the importance of compatibility of bridges with their environment, and their own visual appearance. The compatibility with environment entails both (i) the spatial component, regarding scale and character of the landscape and topography as well as of the man-made environment and (ii) the temporal component, which considers history and tradition of local bridge construction, state of technology and culture. The bridge itself should exhibits technical efficiency, order and unity of the whole structure, and artistic shaping, whereby only artistic refinements need not be considered already at the conceptual stage. Michel Virlogeux reiterated similar views [18, 19], emphasizing that „*elegance and beauty of a bridge come from its structural efficiency expressed in shapes that are in agreement with its particular site and emphatically not from fantasy*". He called for pure design respecting the direct flow of forces, elegant proportions and structurally logical shapes.

These engineers and others also agree on the role of architects in the design of bridges. Fritz Leonhardt writes that the engineer designs bridges and architect advices to improve their visual appearance [15], Rene Walther thinks that the statical concept should be made by the engineer and the architect should concentrate on the perfection of structural detailing [20], and Christian Menn states that architects, who usually have limited structural knowledge and hardly ever consider structural requirements or construction economics, create bridges of false grandeur, trying to make them „dramatic" or „important" [21]. Michel Virlogeux is more straightforward, writing that architects are designing some major bridges only for fantasy and provocation, bridges that are structural nonsense and whose high cost is unacceptable in societies with wide-spread unemployment and other social miseries [19]. Armando Rito believes that the engineer should himself be responsible for the aesthetics of his structures and that no adviser can rescue the visual appearance of a poorly designed structure or conceal its inadequacy [22].

It may be concluded that since the beginning of the 20th century the engineers unanimously believe that only a sound structural design, taking into account all the requirements of context and place, which only engineers can accomplish, can provide a good foundation for an aesthetically pleasing bridge.

4. CONTEMPORARY AESTHETICS OF ARCH BRIDGES

4.1. Introduction

People think of the bridge as primarily and really merely a bridge; after that, and occasionally, it might possibly express much else besides; and as such an expression it would then become a symbol. But the bridge, if it is a true bridge, is never first of all a mere bridge and then afterward a symbol. And just as little is the bridge in the first place exclusively a symbol, in the sense that it expresses something that strictly speaking does not belong to it. If we take the bridge strictly as such, it never appears as an expression [23]. In our opinion these words of Martin Heidegger apply foremost to arch bridges.

With examples that follow we attempt to demonstrate the aesthetical merits of arch bridges. The choice of presented bridges has necessarily been subjective; many beautiful bridges have been left out.

The beauty of arch bridges primarily depends on their statical and structural logic, as their main load-carrying system dominates their appearance that even the general public can easily understand and appreciate. Considering proportions this implies that the arch depth should be clearly larger than that of spandrel columns and the deck in true arch bridges or just the deck in through and half through arch bridges. This does not necessarily mean that all deck stiffened arches of Maillart type or Langer beams are visually inferior, but in general we do believe so.

4.2. True arches

„*The arch is the strongest embodiment of a bridge, its shape expresses obviously its ability to carry loads across a river, valley or gorge. Therefore, arch bridges are considered beautiful by their evidently suitable shape. This is valid for small and large arch bridges alike*“[13].

The Arrabida Bridge designed by Edgar Cardoso (Fig. 4a), was bold for the construction at its time, is functional, simple and beautiful, and it became the landmark and the pride of Porto [24]. The arch depth is reduced from 4.5m at the springings to 3.0m at the crown. The visual impact from underneath is emphasized by the two arch ribs interconnected by an elegant diamond shaped bracing system (Fig. 4b).

The Morbihan Bridge (Fig. 4c) at La Roche Bernard was designed by Michel Virlogeux and the architect Charles Lavigne refined the arch shape at connections to its abutments, so that the flow of forces from the concrete arch to the foundations is fully revealed to the viewer (Fig. 4d). Another innovation was placing a pedestrian walkway on the arch.

The famous Krk Bridges in Croatia exhibit all the features of perfect design (Fig. 5a).

Fig. 4. *a), b) Arrábida Bridge and c), d) Morbihan Bridge.*

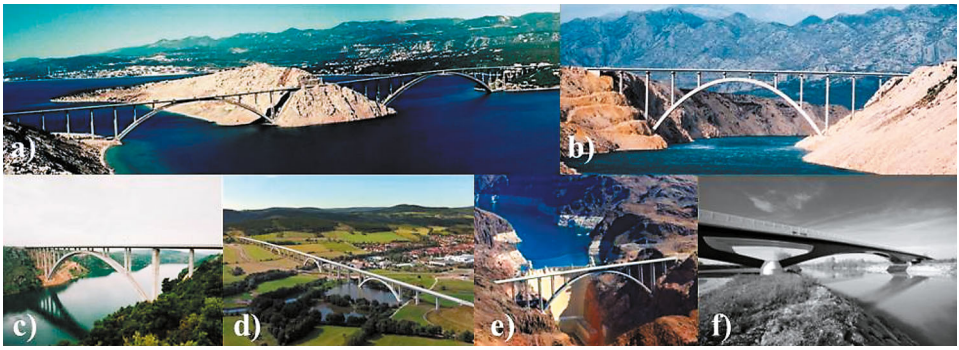

Fig. 5. *a) Krk Bridge, b) Maslenica Bridge, c) Krka bridge, d) Ilmtal-Bridge, e) Mike O'Callaghan Pat Tillman Memorial Bridge and f) Viaduct in San Donà di Piave.*

The shape of the Maslenica Strait in Croatia practically imposes the arch structure as a natural bridge solution to span the canyon (Fig. 5b) [25]. This arch bridge the first major structure built on the new Adriatic Motorway, its construction commencing during the Homeland War. The bridge thus became a landmark and a symbol of victory and independence for the people of Croatia. All structural elements are made of concrete and although quite sturdy they blend quite well into the rugged rock-type mountainous environment. In general this bridge is considered quite an engineering feat, especially considering the time and the context, when it was built. The elegance of the Krka River Bridge has been enhanced by choosing of a slender composite superstructure, visually detached from its supports and almost looking as if it were hovering in space (Fig. 5c), and by avoiding the head-beams on tops of the spandrel columns.

Ten arch bridges with arch spans from 90 m to 270 m are recently built on high speed railway route VDE 8.1 Erfurt-Nuremberg across the Thuringian Forest in Germany (Fig. 5d) [26]. Mike O'Callaghan Pat Tillman Memorial Bridge at Hoover Dam (Fig. 5e) is designed as elegant concrete arch bridge with span of 323 m to complement and not compete with one of the most famous engineering landmarks in the U.S. [27]. A series of true arches can be aesthetically pleasant in contrast to through arches. Viaduct in San Donà di Piave in north Italy (Fig. 5f), designed by Enzo Siviero, comprises five shallow arches, with spans from 90 to 100 meters, excellently incorporated in the flat environment [28].

4.3. Through and fly bird arches

There is much more room for creativity and originality of expression in the design of through and half-through arch bridges, than of true arch bridges.

Arches of almost all through and half-through bridges are made of steel. We are currently witnesses of revival of such bridges, most prominently in China with the completion of the Chaotianmen Yangtze River Bridge of 552 m span (Fig. 6a) and the Lu Pu Bridge of 550 m span (Fig. 6b), setting new world records [29]. In Europe they appear in a wide variety of architectural forms and structural solutions. They have become very popular and have been built on railway lines because of their inherent stiffness much larger than that of cable-stayed bridges, on roads and highways, and as

footbridges, where advantages of steel as structural material may be effectively applied to design unique and aesthetically most pleasing structures.

In aesthetical considerations the Fehmarnsund Bridge (Fig. 6c), built almost fifty years ago, cannot be left out. This steel through tied network arch with inclined hangers for combined road and railway traffic, designed in collaboration with the architect Gerd Lohmer is “a classic among the bridges” [30].

Some more recent examples of steel basket handle shaped through tied arch bridges for road traffic are the Dunaújváros Danube Bridge in Hungary (Fig. 6d) [31], the Apollo Bridge in Bratislava in Slovakia (Fig. 6e) [32], and the Tangermünde Bridge in Germany (Fig. 6f), which was selected over beam and cable-stayed alternatives after an evaluation considering criteria of construction costs, fitting in the landscape, environment protection, aesthetics, serviceability and maintenance.

Our competition entry for a new road bridge across the Sava River in Zagreb was a steel arch (Fig. 7) [33]. The structure was chosen by the engineer and the architect refined the shapes. The diamond-shaped forms of arches and pier bents are unique and the superstructure is slender and functional. Two main columns are of such a form that they visually represent the continuation of main span arches to the foundations. The whole design task was approached integrally, so that the resulting bridge structure looks as a whole, which by combining technological advancement and poetry accentuates the sense of identity and cultural significance of its site. The winning design was unfortunately for us a cable-stayed bridge.

Fig. 6. *a) Chaotianmen Yangtze River Bridge, b) Lu Pu Bridge, c) Fehmarnsund Bridge, d) Dunaújváros Bridge, e) Apollo Bridge and f) Tangermünde Bridge.*

Fig. 7. *Jarun Bridge: a) location and b) night view.*

Fig. 8. *a) Barqueta Bridge and b) Third Millennium Bridge.*

The original arch form with a centrally placed single arch rib splitting into two inclined struts on both ends clearly showing the flow of forces, and expressing grandeur and elegance was invented by the engineer Juan José Arenas and the architect Marcos Panteleón for the Barqueta Bridge in Sevilla (Fig. 8a) [34]. This split arch form was repeated in concrete for the Third Millennium Bridge in Zaragoza of 216.0 m span (Fig. 8b) also designed by Juan José Arenas. Thanks to its urban function and location in the city and the quality of its aesthetic and structural design, it has become an icon of the city and a worldwide engineering feat. High strength, self-compacting white concrete was used in almost the entire bridge (C60/75 in the deck and C75/90 in the arch) to take slenderness to the limit [35].

The two among the first bridges designed by Santiago Calatrava, road bridges Bach de Roda Bridge in Barcelona of small span (Fig. 9a) and a long-span Lusitania Bridge at Merida (Fig. 9b) are both based on a structural idea; they are visually simple and readable in spite of their technical complexity, they combine concrete and steel material in a unique way, the composition of their structures produces rather unusual structural expression, the crossing is integrated into the environment which is totally transformed in the immediate vicinity, and they are detailed and artificially illuminated so that their structural dynamic is emphasized to convey a particular sense of arrested movement. The third road bridge designed by Santiago Calatrava, the Pont de l'Europe Bridge in Orléans (Fig. 9c), is a through steel arch located at the downstream side of the bridge in an inclined plane of 22° to the vertical [36]. This bridge may be bold and extravagant, but it cannot be asserted that this bridge fulfils the recommended design principles because, due to the location of the arch and highly asymmetrical form of the cross sections, the global stability of the bridge relies primarily on torsion. The arch inclination also creates bending in a horizontal plane and all the resulting deformations had to be accounted for by appropriate pre-camber.

The half-through single concrete arch of the Svinesund Bridge (Fig. 9d) between Norway and Sweden emphasizes the equality between two neighbouring countries [37]. The extremely slender continuous arch runs between twin separated steel decks conveying the impression of a simple structure with clearly defined lines seen from all viewpoints. The elegance of the arch was made possible by fixing it to the deck, which supports it laterally. This bridge quickly became a landmark and a symbol of the Art of Engineering, demonstrating that even for major bridges limits can still be moved further, if there is a mutual respect between architects and engineers working together.

Recently, a substantial number of steel through arch railway bridges on low terrain crossing some of the major European rivers have been constructed around Europe during the past decades. Their main advantage in comparison with solid beam or truss bridges was their appearance and in comparison with cable stayed bridges their much higher

Fig. 9. *a) Bach de Roda Bridge, b) Lusitania Bridge, c) Pont de l'Europe Bridge, d) Svinesund Bridge, e) Donzère Bridge and f) Mornas Bridge.*

inherent stiffness, a condition especially important for high speed rails. While most of them are of classical form usually with two inwardly inclined arch ribs, bowstring bridges on the Mediterranean TGV line, the Donzère Bridge (Fig. 9e) and the twin bridges of Mornas (Fig. 9f) and Mondragon, designed by famous architects, have rather unusual innovative forms [38].

4.4. Footbridges

Nowhere is the search for new and dramatic shapes more pronounced than in footbridges located in the modern urban landscape. For arch bridges it meant the arrival of a new form called spatial arch bridge at the end of the last millennium, designed mostly by architects in an attempt to provide symbols of originality, innovation and progress. Most of these bridges are inclined steel arches placed eccentrically only on one side with either curved or straight hanging deck below. Their forms do not exhibit simplicity and clear flow of forces; torsion is not avoided but exclusively relied upon to carry loads, and even the vertical forces, due to their geometrical and structural configurations, induce bending and shear not contained in the arch plane. The advancement of this arch bridge type was only made possible by current technological development, with faster computers enabling highly complicated structural analysis and close-to-reality simulations and with new computer-aided manufacture technologies creating buildable shapes that would otherwise be impossible to produce [39]. Santiago Calatrava was probably the first to design spatial arch footbridges, such as La Devesa in Ripoll (Fig. 10a) and Campo Volantin in Bilbao (Fig. 10b). But, probably the most striking is the Gateshead Millenium Bridge (Fig. 10c). This tilting bridge, composed of a pair of steel arches spanning 100 m, rotates 40 degrees to allow the passage of vessels underneath.

Fig. 10. *a) La Devesa Bridge, b) Campo Volantin Bridge and c) Gateshead Millenium Bridge.*

Fig. 11. *a) Three Countries Bridge, b) Brno Bridge and c) Brno-Komarov Bridge.*

The competition-winning concept design was developed in collaboration of engineers Gilford Graham & Partners and Wilkinson Eyre Architects. Utilizing its inventive pivoted solution, the bridge overcame site constraints with its geometric simplicity and triggered the regeneration of the surrounding area. But its broad social and aesthetic impact came at very high cost [40].

The winning design for the Three Countries Footbridge between Germany and France, came from collaboration of LAP engineers and Feichtinger Architectes (Fig. 11a). The basic conceptual idea of spanning the Rhine River with an extremely slim asymmetric arch structure symbolizes the strong connection between these two countries [41]. The arch is unique in its design, as the northern arch stands vertical and the southern arch leans against it with an inclination of 18°. The arch rise to span ratio is only f/L=1/13. The arch cross sections are very different, chosen so that the asymmetry is also mirrored in them. Instead of the standard bridge piers, which would obstruct the view, additional structures are utilized as natural continuations of the arch.

That elegant and beautiful bridges but also economic bridges can be designed without the assistance of architects has been proven by Jiri Strasky. Among many bridges that he has designed, two footbridges are highlighted, the bridge across the Svratka River in Brno (Fig. 11b) composed of his trademark a stress ribbon deck, which is supported by a flat arch and the bridge across the Svratka River in Brno-Komarov (Fig. 11c), with a pre-stressed concrete deck formed by a spine girder, suspended on a central CFST arch of 58.5 m span [42].

5. CONCLUSION

The famous Vitruvian principles are still universally accepted today, but their interpretation might vary. The arch is a classic bridge form, and although definitions of beauty change with time, the arch is generally considered the most pleasing of all bridge forms.

The portrayed stone bridges of the distant past, metal bridges of the 19th and the 20th century and the concrete bridges of the early 20th century, they all reflect forms and materials of their times, they all have become essential visual components in their physical and cultural context, and they all demonstrate the mastery of their builders. It is commonly believed that aesthetics costs money, but some of the greatest historic metal arch bridges designed by Gustave Eiffel and concrete bridges designed by Robert Maillart were built only because they were the most cost effective, which forced these designers to create new forms and fully exploit their talent.

The foundations of the contemporary bridge aesthetics were laid at the beginning of the 20th century. The foremost contemporary European and American engineers, although their philosophies may subtly differ, all share the modernist dogma that bridges should

be economic, efficient, and elegant. All of them believe that bridge design should remain in the realm of engineers, and that the collaboration with architects is welcome only if it is based on mutual respect and likely restricted to the refinement of shapes, chosen by engineers. Qualities such as extravagance, whimsicality, and massiveness are not really appreciated.

Almost all of the portrayed contemporary arch bridges to demonstrate their aesthetical merits do fulfil the three tenets of structural art. Their beauty primarily depends on their statical and structural logic, arising from their principal duty to be an efficient structure. The arch as their main load-carrying system dominates their appearance, clearly showing the flow of forces. They are harmonious and contextually sensitive, fitting well into their surroundings. We deliberately selected to present also a few arch bridges, which were intentionally designed just to be different, with forms not exhibiting simplicity and clear flow of forces. It remains to be seen whether they will endure the test of time, but maybe there is room even for such structure-as-sculpture arch bridges in our world, if their costs are not prohibitively high.

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