AESTHETICS AND SUSTAINABILITY OF ARCH BRIDGES

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Abstract: *Main challenge during design of an attractive bridge is that its structure usually needs to appeal to three types of viewer – engineers, architects and the general public. Each of these groups has a different understanding of structures. However, there are numerous examples of fine bridge engineering at which all three groups can agree about functionality and beauty of structure and, many of them are arch bridges. According to the lists of the most popular bridges, created by general public; the historic bridges inscribed on the UNESCO World Heritage List and the structures admired by engineers, it can be concluded that arch bridges are considered as the most attractive bridge type from ancient aqueducts to the contemporary structures. Arch bridges in Croatia, shortly presented in the paper, are according to their structural, aesthetic or functional characteristics among the World top achievements of their time.*

1 INTRODUCTION

Bridges are significant structures. Comparing with buildings and other infrastructures, bridges are dominant in the environment not only by their dimensions, but also by their service life and the number of users during it. They serve to community and can be seen from different location (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). Consequently, it is not surprising that bridge engineering is often exposed to public judgment, more than other professions. Therefore, it is necessary to design not only reliable, durable and economical bridges, but also aesthetically pleasant structures.

Key factor at the beginning of bridge design process is understanding of natural, built and community context and identifying significant constraints. Context sensitive design has been applied for the first time during construction of first historical bridges, built by local labor and made of local material as a matter of natural choice. Great example of that sustainable method in more recent past is the reconstruction of the bridge across Krka River near Skradin (Fig. 1), led by the greatest Croatian bridge builder Kruno Tonković (1911-1989), professor at Faculty of Civil Engineering – University of Zagreb. The old bridge with steel arch trusses above the roadway was demolished in the II World war. All usable parts were incorporated into the new composite structure (the two steel arch tubes filled with high grade concrete). New bridge is much more economic than the old one, has a higher navigation clearance and wider roadway and is more logical and beautiful [1].

Design sensitive to context is valued by communities. Structures and landscapes that fit and enhance context are good for community pride and local identity, they are often more sustainable and self-reliant [2]. One type of structure may be acceptable or beautiful in one location while unacceptable or ugly in a different location.

Figure 1: Old bridge, destroyed during the WWII (left) and new bridge (right) across Krka River near Skradin

2 CULTURAL HERITAGE, ATTRACTIVENESS AND AESTHETICS OF ARCH BRIDGE

Arch bridges are considered as the most aesthetically pleasing bridge types. The arch is the most natural bridge type. Its shape clearly expresses its ability to carry loads across a river, canyon or sea channel. Arch bridges are an integral and important part of cultural heritage as powerful expression of a social community – its identity and values, but also of human advancements in technology. Among nine bridges specifically listed as UNESCO World

Heritage sites: (i) Old Bridge (Mostar) and (ii) Mehmed Paša Sokolović Bridge (Višegrad) in Bosnia and Herzegovina, (iii) Pont du Gard (Gard département) and (iv) Pont St-Bénézet (Avignon) in France, (v) Aqueduct of Segovia and (vi) Vizcaya Bridge (Portugalete) in Spain, (vii) Ironbridge Gorge (Coalbrookdale) and (viii) Pontcysyllte Aqueduct (Wales) in UK and Aqueduct of Vanvitelli (Campania) in Italy; eight of them are arch bridges: four aqueducts, two arches with one span and two multi-span arch bridges (Fig. 2). There are also many arch bridges within UNESCO protected historic city centers, e.g. Florence and Prague [3]. Despite small number of bridges inscribed on the UNESCO World Heritage List, many other historic arch bridges have been recognized as beautiful structures and become true symbols of the city and region and its people.

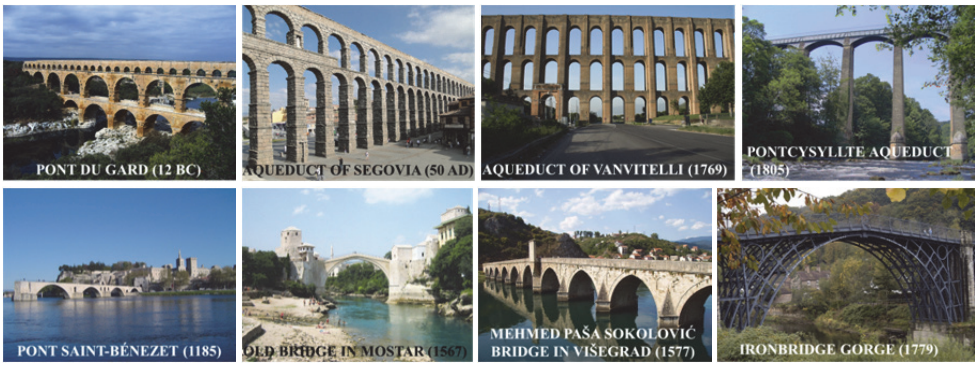


Figure 2: Arch bridges specifically listed as UNESCO World Heritage sites

Arch bridges are very popular structure and can be found very often on many unofficial lists of the most beautiful, unique and amazing bridges in the World [4-7]. It should be noted that those lists, created by general public, can vary significantly, since criteria for evaluation of structure and its aesthetics is not defined, therefore this lists can not be relevant for evaluation of aesthetics of arch bridges . However, according to the list [4-7], it can be concluded that arch bridges are considered as the most attractive bridge types from ancient aqueducts to the contemporary structures (Fig. 3). The attractiveness of one

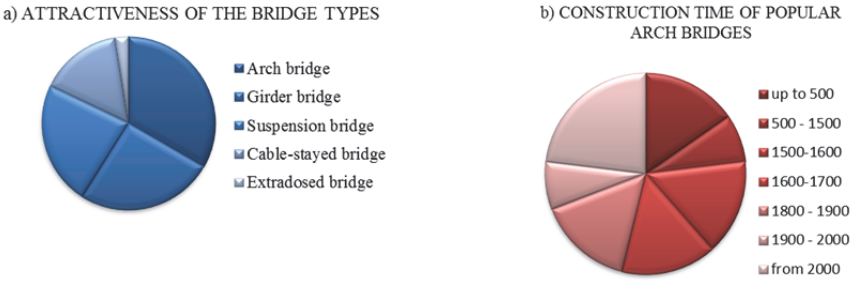


Figure 3: a) Attractiveness of the bridge types and b) construction time (year) of popular arch bridges according to [4-7]

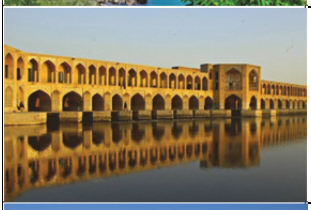
Bridge	Name	Location	Construction Time
	Ponte Vecchio	Florence, Italy	996 reconstructed in 1345
	Mostar Old Bridge	Mostar, Bosnia and Herzegovina	1566 reconstructed in 2004
	Khaju Bridge	Isfahan, Iran	1650
	Sydney Harbour Bridge	Sydney, Australia	1923-1932
	Gateshead Millennium Bridge	Gateshead, England	2000-2001

Table 1: Some of the most attractive arch bridges according to [4-7]

bridge depends on many factors, such as society, trends, culture, age and knowledge of evaluators. However, some bridges are almost on the all lists of most amazing or beautiful bridges (Table 1).

On the other hand, evaluation of bridge aesthetics performed by structural engineers includes certain criteria of excellence. To achieve recognition of experts in the field of structural engineering and be recognized as an icon bridge, the structure must have several or all following characteristics [8]:

- Innovation - icon bridges are generally ahead of their time. They provide unique and creative solutions to crossings. They are original, not merely a copy of another bridge. They may push or break the limits of engineering knowledge for the era in which they

were built. In addition, they are often constructed using advanced materials and techniques.

- Beauty - Whether through their form, their lines, their details or color, an icon bridge creates a lasting impression. Icon bridges are among the most photographed objects in the world and are often featured on postcards and calendars.
- Record - Icon bridges are often characterized by record size, stretching the limits of man's ingenuity and resources. Whether they possess longer spans, taller towers, or higher superstructures, icon bridges often exceed the scale of previous similar structures.
- Historical Significance - Icon bridges frequently hold historical significance. They are often the first of their kind, and they sometimes possess a unique historical or engineering significance.
- Durability - An icon bridge has stood the test of time and remains standing in all its glory, faithfully serving the people for whom it was built.
- Simplicity - Icon bridges generally are designed according to "form fallow function". They are natural; their behavior is obvious and makes sense. They are generally simple and understandable to the general public.
- Context sensitive design - Icon bridges are harmonious and complementary to their surroundings; they are ideally-suited for their location.

Bridge	Name	Location	Construction Time	Designer
	Camille de Hogues Bridge across Vienne River	Châtellerault, France	1899 - 1900	François Hennebique
	Salginatobel Bridge	Schiers, Switzerland,	1929 - 1930	Robert Maillart
	Plougastel Bridge	Plougastel-Daoulas, France	1926 - 1930	Eugène Freyssinet

Table 2: Concrete arch bridges designed by some of the world's most prominent engineers

- Landmark - Icon bridges become landmarks. They are easily recognized by the general public, and they take on a symbolism for the people or nation for whom they were built.

Most of those criteria had been fulfilled in concrete arch bridges designed by some of the world's most prominent engineers, brilliant inventors, passionate and creative builders: Hennebique, Maillart and Freyssineta (Table 2) [9, 10]. Camille de Hogues Bridge across Vienne River in France is a typical application of concepts developed by François Hennebique for a rational use of reinforced concrete. It is 144 m long, comprising 3 arches: the central span is 50 m long and the 2 side spans are 40 m long. Salginatobel Bridge is three-hinged arch bridge with span of 90 m. It won the competition not because of its aesthetic and elegant appearance or Maillart's revolutionary use of reinforced concrete, but because it was the cheapest project of the design ideas presented to the canton. Plougastel Bridge is one of the most famous bridges designed by Eugène Freyssinet, inventor of the prestressed concrete. It is a reinforced concrete, 888 m long, comprising three main spans, 188 m long each.

3 SUSTAINABILITY OF BRIDGES

Bridges have traditionally been designed by imminent individual and visionary engineers. The design procedure used to include three steps (Fig. 4a) [11]. The inputs are knowledge and experience; the constraints include client requirements, costs, time, codes and construction methods; and the results are two specific outputs: description and justification. Description is provided by drawings and specifications, while justification is accomplished by fulfilling codes requirements. The finest bridge design solution is achieved by integrating science, technology, and art (Fig. 4b) [12]. Each of these three abilities brings a separate and distinct quality to the design process. Science contributes analytical skills of math and geometry. Technology incorporates pragmatic knowledge of bridge design to the search for design excellence; e.g., construction practices, material uses, economics. Artistic judgment tempers science and technology to blend the design into an appealing work of beauty. These three abilities, applied in equal parts, produce a synergistic design effect - design excellence [12-13].

a) b)

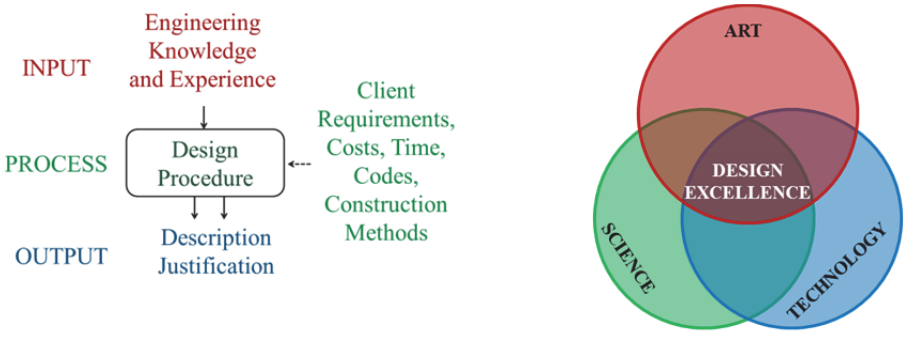


Figure 4: a) Model of structural design process,
b) Three components of design excellence

Planning, design and construction of bridges are more complex today than in the past, although the methods of structure analysis and check of various structural configurations as well as erection methods have improved significantly [14]. However, transport requirements as well as social and environmental constraints put on new bridges have become more complex. A simple model illustrates some of the many parameters to include in a bridge design process (Fig. 5). Therefore, holistic approach to bridge design is needed for the planning, design and construction of sustainable bridges.

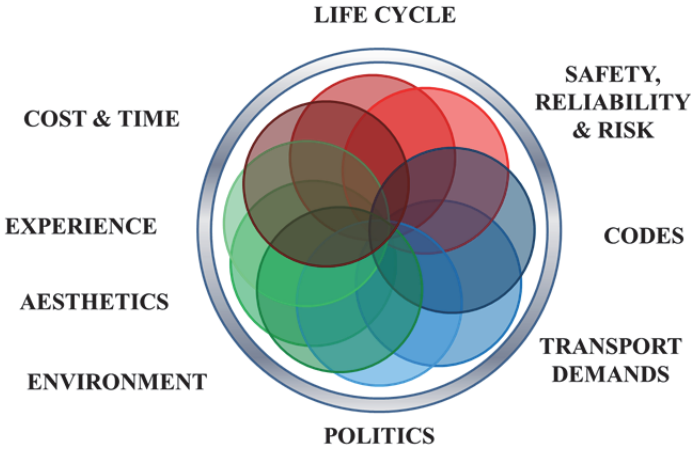


Figure 5: Holistic approach to bridge design

4 ARCH BRIDGES IN CROATIA

Regardless of the time of construction, well designed bridges provide a lasting legacy of excellence for future generations. Croatia is home to many striking examples of fine bridge engineering. Throughout the history the region was never falling far behind the state-of-the-art bridge engineering and technology [15]. Over the 1700 year long history of bridge building in the region many great bridge designs were conceived and realized, which are according to their structural, aesthetic or functional characteristics among the world top achievements of their time [15].

3.1 Masonry arch bridges

The oldest preserved bridges in the region date back to Roman times [15], most notably the aqueduct of the Roman Emperor Diocletian's Palace (today the very center of the city of Split) constructed during the years 284 to 305 to carry freshwater from the source of Jadro River over the distance of 9 km. The most impressive structure on this route is the Mostine Aqueduct (Fig. 6) with a total length of 234 m reaching to 19 m at the highest point. The two main spans of 8.9 m have a typical Roman pier-to-span ratio of 1:3. This aqueduct was one of the last large aqueducts built in the Roman Empire, as most triumphal examples of Roman arched architecture and engineering excellence.

Figure 6: Mostine Aqueduct in Split

Three interesting arch bridges: Pile Bridge, Revelin Bridge and Ploče Bridge (Fig. 7) were constructed to form the fortifications of the city of Dubrovnik, then centre of the Dubrovnik Republic [15]. These stone bridges were carefully designed according to classical architecture of mediaeval Dubrovnik, ruled by classical tradition and by harmonic proportions. The bridges approximately 500 years old still stand on the entrances into the Old Town of Dubrovnik. Their aesthetic values are timeless, as their strength.

Figure 7: Pile Bridge (left), Revelin Bridge (middle) and Ploče Bridge (right) in Dubrovnik

The Bridge across Tounjčica River in Tounj is probably one of the most interesting old stone bridges in Croatia due to its unconventional two-level arch structure. The lower level comprises three arch spans of 5.60 m and was erected in 1775. It was only 61 years later that an identical upper level was added in the course of overall road improvement and reconstruction project. This bridge was damaged in the WW2 and reconstructed in 1972, using the original stones of the old bridge [15]. The reconstruction design was developed by prof. Kruno Tonković. Although massive, the beauty of this bridge is achieved by applying the simplicity, order and symmetry of structure.

Two the most beautiful masonry arch bridges in Croatia were designed by bridge builder Milivoj Frković (1886-1946). His works are of exceptional aesthetic values, but at the same time provide for economical construction. The Bridge over Kupa River in Sisak (Fig. 9) was constructed from 1927 to 1934 and comprises four elegant arches across the river and three more over the riverbanks. It presents almost unattainable harmony achieved by a combination of brick and natural stone and a number of superiorly designed and constructed details. The bridge survived many wars, successfully resisted the ever increasing loading and is still today in everyday use as one of the most beautiful bridges of its style [15].

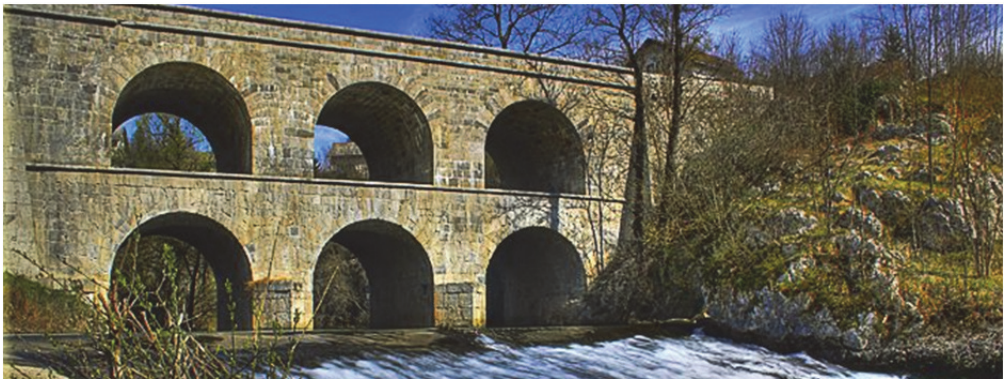


Figure 8: Two-level bridge acros Tounjčica River in Tounj

Another aesthetically pleasing structure, but built entirely in stone, was constructed to bridge the Lika River in Kosinj (Fig. 10). It consists of three well-proportioned arches of 18 m span with circular openings above the piers. Together with the stone edging and protrusions of distinctive bridge lines they fit superbly producing a unique image. Bridge was built in 1935. It was damaged during the WW2, but was rebuilt in its original form [15].

Figure 9: The Bridge across Kupa River in Sisak

Figure 10: The Bridge across Lika River in Kosinj

3.2 Steel arch bridges

The construction of railway lines started in the late 19th century. Generally, standardized steel truss bridges were used for this purpose. In the 1930, a railway bridge over the Sava River was planned in Zagreb. The city of Zagreb built the piers first, and afterwards announced the competition for the bridge design. A robust steel truss arch win the competition, but fortunately professor Erega designed an elegant tied arch bridge (Langer beam) as an alternative and it was finally chosen for the construction. The steel tied arch bridge comprises two arch ribs spaced at 9.6m, with the span of 134.5m (Fig.12). The rise of the arch is 16.93m, which gives rise to span ratio of f/L=16.93/134.5=1/7.94 [16].

Figure 11: The Railway Bridge in Zagreb

One of the most interesting steel arch bridge in Croatia is, already mentioned, the true two-hinged arch bridge over the Krka River in Skradin built in 1955 (Fig. 1, right). The bridge comprises two steel arch ribs with the span of 90m. The arches are of rectangular cross section and filled with concrete. Prof. Tonković also designed the central road bridge over the Sava River in Zagreb (Fig.12) , built in 1959 as a very shallow true two-hinged two rib steel arch of 100m span and 7.36m rise, with the rise to span ratio of 1:13.6 and composite superstructure. Prof. Tonković designed the Liberty Bridge with special care as a simple and beautiful structure, but took special care to design bridge equipment, e.g railings and lightening.

Figure 12: The Liberty Bridge in Zagreb

Two aesthetically very successful true two-hinged steel arch bridges have been constructed on the Adriatic National road. Maslenica Bridge (Fig. 13) built in 1961, was one of the most famous bridges in Croatia. The filigree steel arch bridge, harmoniously fitted into the steep, rocky coast of Novsko Ždrilo, became a veritable landmark and a significant part of cultural and structural heritage. The bridge was destroyed in a military operation during the Croatian Homeland War, but reconstructed in 2005 retaining the design characteristics of the original bridge. The two-hinged arch comprises two steel arch ribs (Fig.7), spaced at 8.0m (Fig.8). The arch span is 155.0m, and the rise is 41.45m, giving the rise-to-span ratio of f/L==1/3.74 [16].

Figure 13: Maslenica Bridge on the Adriatic Road

The true two-hinged arch bridge over Morine Bay near Šibenik was built in 1964. The bridge comprises two steel arch ribs (Fig. 13), spaced at 8.0m. The span of the arches is 134.0m, and the rise is 18.4m, which gives rise to span ratio of f/L=1/7.3.

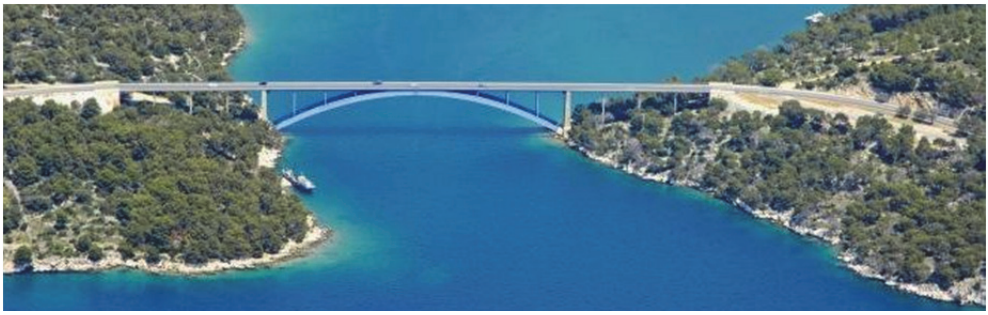


Figure 14: Morine Bridge

3.3 Reinforced concrete arch bridges

Among other structures, during more than 40 years of rich career, prof. Tonković designed three beautiful and structurally efficient concrete arch bridges, well harmonized with the environment.

The bridge over Korana River in Selište at the entrance of the Natinal Park Plitvice Lakes (Fig. 15) has an arch span of 60 m with a rise of 16.1 m. The arch consists of two vaults with a gradual increase of depth form the 90 cm at the crown to 147 cm at the abutments [17].

Figure 15: The bridge over Korana River in Selište

Harmony with an extremely demanding area has been achieved with an arch bridge over Slunjčica River in Slunj (Figure 12). The arch opening is 72.61 m with a rise to span ratio of 1:7.3. A light slab superstructure is set on two piers in transversal direction. Piers distance increases from 120 cm at the abutments to 180 cm at the crown, which is functional advantage due to loading transfer but also enlarges space impression of bridge. The arch consists of two vaults with a gradual increase of depth form the 85 cm at the crown to 120 cm at the abutments [17].

Figure 16: Bridge over Slunjcica River in Slunj

Bridge over Korana River in Karlovac (Fig. 13) was the last one constructed based upon Tonković design. Although the plane area with weak soil characteristics is not suitable for thrust arch systems, after detailed analyses Tonković choose main concrete arch bridge structure with a span of 56 m and rise to span ratio 1:9.7 together with beam approaches with spans of 12.5 m. For this bridge the main inspiration were the suggestions given by Freyssinet for his 1000 m span arch bridge. At this bridge professor Tonković analyzed on smaller scale his proposal for the 500 m span arch bridge for the Krk Island crossing which was later not accepted [17].

Figure 17: Bridge over Korana River in Karlovac

One of the most important accomplishments in Croatian bridge engineering are seven large reinforced concrete arch bridges, constructed over the past five decades with spans ranging from 140 m to almost 400 m (Table 2, Figure 18-20): Šibenik, Pag, Krk (two arches), Maslenica, Skradin and Cetina Bridges. The most famous among them is Krk Bridge (Figure 2), completed 33 years ago but still the largest spanning conventional reinforced concrete arch in the world. Adriatic Arch Bridges are world-renowned not only because of their large spans, but also due to introduction and subsequent improvements introduced in construction of reinforced concrete arches using the suspended cantilever technique [18]. In fact, the Šibenik Bridge is the first concrete arch in the world which was erected entirely by cantilever method.

Adriatic Arch Bridges	Construction Year	Span [m]	Rise [m]	Rise-to-span ratio
Šibenik Bridge	1964-1966	246	31	1/8
Pag Bridge	1967-1968	193	28	1/7
Krk Bridge (larger span)	1970-1980	390	60	1/6.5
Krk Bridge (smaller span)	1970-1980	244	47	1/5.2
Maslenica Bridge	1993-1997	200	65	1/3.1
Skradin Bridge	2003-2004	204	52	1/3.9
Cetina Bridge	2005-2007	140	21.5	1/6.5

Table 3 : Adriatic Arch Bridges

Figure 18: Krk Bridge

Figure 19: Šibenik Bridge (left) and Pag Bridge (right)

Figure 20: Maslenica Bridge (left), Skradin Bridge (middle) and Cetina Bridge (right)

The appropriate application of principles of aesthetics, e.g. order, simplicity and balance; with functional design of structures resulted in bridge forms integrated into maritime environment as they were forever present there. Adriatic arch bridges have improved life on islands and become landmarks.

8 CONCLUSION

Main challenge during design of an attractive bridge is that its structure usually needs to appeal to three types of viewer – engineers, architects and the general public. Each of these groups has a different understanding of structures. However, there are numerous examples where all three groups can agree about high level of functionality and extraordinary beauty of bridges, and many of them are arch structures. According to the list of most popular bridges, created by general public; historic bridges inscribed on the UNESCO World Heritage List and structures most admired by engineers it can be concluded that arch bridges are considered as the most attractive bridge type from ancient aqueducts to the contemporary structures.

Croatia is home to many striking examples of fine bridge engineering. Throughout the history the region was never falling far behind the state-of-the-art bridge engineering and technology. Over the 1700 year long history of bridge building in the region many great arch bridge designs were conceived and realized, which are according to their structural, aesthetic or functional characteristics among the World top achievements of their time.

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