HISTORY AND CLASSIFICATION OF THREE-HINGED ARCH BRIDGES

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SUMMARY

Two classifications of three-hinged arch bridges, one according to the main material of the bridge structure and the other according to the bridge type, are presented. A strong correlation between building material, i.e., metal, concrete and timber, and construction time is demonstrated. The correlation between the bridge type, i.e., deck arch, half-through and through, and either building material, constriction time or span is weaker. Nevertheless, the open spandrel deck arch bridge is the dominant type in all periods regardless of the building material and span. Both classifications are based on the extensive historical overview including 70 of the most representative three-hinged arch bridges.

Keywords: *Three-hinged arch bridge, history, classification, building material, types of arch, deck arch bridge, half-through arch bridge, through arch bridge.*

1. INTRODUCTION

The three-hinged arch bridge was one of the first bridge types that structural calculations were devised for. Nevertheless, no comprehensive historical overview and classification of these bridges has ever been compiled. This paper aims at providing the first step towards these two issues.

The three-hinged arch is one of the simplest structural systems: it consists of two supporting components connected by hinges (pin-joints). Two hinges are near the abutments, each at either end of a structure, and the third hinge is fitted at the crown of the arch. The third hinge makes the structure a bit more expensive and difficult to construct. However, the three-hinged arch is "frequently built because it has the advantage of being isostatic" [1]. The three-hinged arch has been used in many bridges because "the bending forces in the arch are not affected by support deformation nor phenomena of creep, shrinkage or temperature. They will only be affected if deformations are large and the arch loses shape, which would lead us to a non-linear problem in the structure" [1]. Although the three-hinged arch was first used for bridges, it was later used for roofs of wide span buildings as well.

Ever since the three-hinged arch was first described in 1861 by Claus Köpke [2], the development of three-hinged arch bridges coincided strongly (though some exceptions exist) with the development of various materials these bridges were made of. Therefore, the classification of these bridges based on the building material is presented in Section 2 together with the historical overview. However, the bridge type, i.e., the position of a deck relative to the arch, is far less correlated with the construction time. Hence, the classification of these bridges in regard to the bridge type is described separately in Section 3.

Both classifications are based on the list including the most representative three-hinged arch bridges. In total, 70 bridges are considered. Most of them (56) can be found on Structurae web page [3]. In many cases the detailed specifications had to be found elsewhere while 17 bridges listed on Structurae had to be omitted due to insufficient data. Furthermore, 14 important bridges not found on Structurae (marked with * in Tables 1, 2 and 3) were included to make this research as comprehensive as possible.

2. HISTORY OF THREE-HINGED ARCH BRIDGES

An overview of the three-hinged arch bridges from the beginnings to the present day indicates the three periods in regard to the material these bridges were made of: metal, concrete and timber [4]. The first period encompasses the second half of the 19th century when metal, i.e., cast-iron, wrought-iron and steel, become major material for innovations in structures. The second period starts at the beginning of the 20th century when the bridge engineers and designers turned to the newly developed reinforced concrete and its forerunners (tamped concrete and stone), and finished with the prestressed concrete in 1960's. The third period comes at the last quarter of the 20th century when the glued laminated timber (glulam) was improved enough to sustain the impacts of the exterior environment and could thus be used for making bridges.

The most representative three-hinged arch bridges made in metal, concrete and timber are listed in Tables 1, 2 and 3, respectively. The rightmost column in Tables 1, 2 and 3 contains the bridge subtype classified regarding to the bridge type as explained in Section 3.

2.1. Metal three-hinged arch bridges

Four years after the first three-hinged structure was described theoretically, the Unterspree Bridge (Unterspree Brücke) (1865) in Berlin, Germany, was constructed. It was designed by civil engineer Johann Wilhelm Schwedler [5]. This road and railway bridge was made of wrought-iron three-hinged arches with a span of 17 m. The three-hinged arch structure consisted of two base hinges which were just near the springings and the third hinge was at the crown of the arch. They demolished the bridge in 1887 and replace it with a stone one.

The oldest three-hinged bridge still in use is the Hradecky Bridge (Hradeckega most) (1867) over the River Ljubljanica in Ljubljana, Slovenia [6]. It was designed and built in 1867 by Johann Hermann. The structure is made of prefabricated cast-iron trusses, its arch has the span of 30.35 m. In 1930 the road bridge was dismantled and a year later it was reinstalled at the new location. In 2010 the bridge had been dismantled for the second time and following a complete renovation, it has been reinstalled in 2011 at the third location in Ljubljana [7].

By the end of 19th century steel replaced iron for bridge construction and thus the spans could become much longer. Instead of a three-hinged truss arch the diagonal trusses were eliminated so that the main part of the structure becomes an arch with the spandrel columns. The first example of such type of a structure is the famous Alexandre III

Bridge (Pont Alexandre-III) (1900) in Paris, France, with a span of 107 m and an extraordinary low rise to span ratio of 1/17. The Fragnée Bridge (Pont de Fragnée) (1904) in Liege, Belgium has the same structure. It consists of three spans where the middle span is longer, i.e, 53.7 m, 57.7 m and 53.7 m.

At the same year the new structural type of a three-hinge arch bridge, i.e., the half-through deck bridge, was introduced in Paris, France. The Austerlitz Viaduct (Viaduc d'Austerlitz) (1904) with a span of 140 m over the River Seine is a three-hinge arch steel bridge. Two base hinges (one at each side of the structure) are just above the deck of the bridge, not near the abutments, and the third hinge is at the crown of the arch. The deck of the Austerlitz Viaduct is only 11 m above water. The railway bridge near La Roche-Bernard (Pont de La Roche-Bernard) (1911), France, was of the same type. A span between the abutments was 198.27 m while the span between the hinges in half-through arch was 112 m. This steel bridge was destroyed in August 1944.

One of the latest steel three-hinged arch bridges was built in Spišské Podhradie D1 Motorway (Estakáda Spišské Podhradie na diaľnici D1), Slovakia, and opened in 2012. This multiple arch bridge consists of seven spans each 60 m long. Four spandrel columns on each side of the crown hinge support the road deck.

Table 1. *List of metal three-hinged arch bridges.*

Name in original language	Year of completion	Material	Span [m]	Subtype
Unterspree-Brücke (D)*	1865-1887	wrought iron	5 × 17	trussed deck
Hradeckega most (SLO)	1867;1932;2011	cast iron	30.40	trussed deck
Steigerbrücke (A)*	1869-1898	iron	?	trussed deck
Kleine Ungarbrücke (A)*	1872; 1898	iron	34.50	trussed deck
Panther Hollow Bridge (USA)	1896	steel	109.8	trussed deck
Franzensbrücke (A)	1899-1945	steel	53	trussed deck
Pont Alexandre-III (F)	1900	steel	107.50	open+vert.c.
Confederate Avenue Bridge (USA)	1903-1997	steel	82.35	trussed deck
Pont de Fragnée (B)	1904	steel	53+57+53	open+vert.c.
Viaduc d'Austerlitz (F)*	1904	steel	140	half-through
Pont de la Roche-Bernard (F)	1911-1944	steel	112	half-through
Pont de Monéteau (F)	1913	steel	75	half-through
Fairfax Bridge (USA)	1921	steel	73.2	open+vert.c.
40th Street Bridge, Pittsburgh (USA)	1924	steel	3 × 109.7	open+vault
Wearmouth Bridge (UK)	1929	steel	?	half-through
Modrow Road Bridge (USA)	1958	steel	61	open+vert.c.
Ponte Salsipuedes (Ecuador)	1960	steel	186	open+vert.c.
Estakáda Spišské Podhradie D1(SLK)	2012	steel	7 × ca 60	open+vert.c.

2.2. Concrete three-hinged arch bridges

At the end of the 19th century the engineers tried to design and build three-hinged arch bridges using different kind of concretes. First they used tamped concrete, a kind of a non-reinforced concrete. The first three-hinged bridge ever made in tamped concrete is the Danube Bridge (Donaubrücke) in Munderkingen, Germany. It was constructed in 1893 by Karl von Leibbrand and had a span of 50 m. This road bridge was made as a three-hinged arch in a new form: the spandrel space between the arch and the deck above was filled with the material. The bridge was destroyed by German troops in April 1945.

The first three-hinged bridge in reinforced concrete was made using the Melan System. The basic idea of this system, invented by an Austrian/Czech civil engineer Josef Melan, is to construct a light steel truss arch between abutments and to embed it in the concrete. The first three-hinged arch bridge using this system was the bridge with a span of 42.2 m over the River Steyr (Schwimmschulbrücke) (1898) in Steyr, Austria, but it was demolished in 1959. The spandrels of this road bridge were filled with the material. The second three-hinged bridge ever made using the Melan System of reinforced concrete is the Dragon Bridge (Zmajski most) (1901) in Ljubljana, Slovenia. It is 15 m wide and its arch spans 33.34 m across the River Ljubljanica [6]. It is important that the spandrel is not fully filled with the material so the bridge is lighter. Today the Dragon Bridge is the oldest three-hinged bridge made in reinforced concrete using the Melan System in the world.

At approximately the same time as Melan, a French engineer and self-educated builder François Hennebique designed Camille de Hogues Bridge (Pont Camille-de-Hogues) (1900) in Châtellerault, France, this time in reinforced concrete as we know it today. The structure is a multiple three-hinged arch bridge: the main span is 50 m long and the two side spans are 40 m long. The bridge deck is separated from the arch and connected to the arch only by vertical columns. At the time of its construction, this bridge was the longest of all reinforced concrete bridges.

The third man who designed three-hinged bridges using the reinforced concrete was Swiss engineer Robert Maillart. In 1899 he designed his first three-hinged arch bridge, the Stauffacher Bridge (Stauffacherbrücke) in Zürich, Switzerland, made of unreinforced concrete and a span of 39.6 m. Maillart was not satisfied with the material because the bridge looked like an old stone bridge where the spandrel space was filled with the material. His first three-hinged bridge in reinforced concrete is the Zuoz Bridge (Innbrücke) (1901) over the River Inn in Zuoz, Switzerland. The three-hinged arch was designed as a curved arch where the deck is connected by longitudinal walls that turn the complete structure into a hollow-box girder with a span of 37.5 metres [8].

The popularity of stone bridges based on the three-hinged design never matched their reinforced concrete counterparts. The oldest two existing examples of stone three-hinged bridges are the Luitpold Bridge (Luitpoldbrücke) (1901) and the Max Joseph Bridge (Max-Joseph-Brücke) (1903), both constructed in Munich, Germany, and designed by an architect Theodor Fischer. They have the same spans of 63 m and the spandrel space is filled with the material. Both road bridges are still in use.

The three-hinged arch bridges were not always constructed without problems. For instance, in 1911 French engineer Eugene Freysinnet decided to fix all three crown hinges of his Le Veurdre Bridge (Pont du Veurdre) in Le Veurdre, France. This multiple arch bridge was opened in 1910 and had spans of 64 m, 72 m and 64 m. It was made in reinforced concrete as an open spandrel arch bridge with diagonals. One year after its construction a deformation of 13 cm was noticed at the middle hinge of each arch.

Table 2. *List of concrete three-hinged arch bridges.*

Original name	Year	Material	Span [m]	Subtype
Donaubrücke Munderkingen (D)	1893-1945	tamped conc.	50	closed spand.
Schwimmschulbrücke (A)*	1898-1959	Melan conc.	42.20	closed spand.
Stauffacherbrücke (CH)*	1899	tamped conc.	39.60	closed spand.
Pont Camille-de-Hogues (F)*	1900	reinforced c.	40+50+40	open+vert.c.
Zmajski most (SLO)	1901	Melan conc.	33.34	open+vault
Zuoz Brücke (CH)	1901	reinforced c.	38	closed+h.box
Luitpoldbrücke (D)	1901	stone	63	closed spand.
Max-Joseph-Brücke (D)	1902	stone	63	closed spand.
Isarbrücke Grünwald (D)	1904	reinforced c.	2 × 70	open+vert.c.
Neckarbrücke (D)	1905-1945	reinforced c.	5 × 40	open+vault
Wallstrassenbrücke (D)	1905-1945	tamped conc.	57	open+vert.c.
Rheinbrücke, Tavanasa (CH)	1906-1927	reinforced c.	51	closed+h.box
Illerbrücken Kempten (D) (3 bridges)	1906	tamped conc.	64.5	closed spand.
Pont d'Amélie-les-Bains (F)	1909	reinforced c.	46	open+vert.c.
Neckareisenbahnbrücke,Tübingen(D)	1910	reinforced c.	104	closed spand.
Sitterviadukt (CH)	1910	stone	25	closed spand.
Pont du Veurdre (F)	1910-1944	reinforced c.	64+72+64	open+diag.c.
Malmskillnadsbron (S)	1911	reinforced c.	24	closed spand.
Pont Neuf de Montauban (F)	1912	reinforced c.	53+56	open+vert.c
Kanalbrücke, Minden (D)	1914	reinforced c.	6×36.50	closed spand.
Horotiu Bridge (NZ)	1921	reinforced c.	38.4	half-through
Pont de Kerlosquer (F)	1924	reinforced c.	26	open+vert.c.
Pont de Persan-Beaumont (F)	1924-1940	reinforced c.	50	through
Pont de la D50 sur l'Artuby (F)	1927	reinforced c.	107	open+vert.c.
Petritorbrücke (D)	1929-2003	reinforced c.	29	closed spand.
Salginatobelbrücke (CH)	1930	reinforced c.	90	open+vert.c.
Pont de Renory (B)*	1930	reinforced c.	?	open+vault
Rossgrabenbrücke (CH)	1932	reinforced c.	82	open+vert.c.
Felseggbrücke (CH)	1932	reinforced c.	72	open+vert.c.
Adolf-Hitler-Brücke (D)	1934-1944	reinforced c.	107	closed spand.
Pont de Vessy (CH)	1937	reinforced c.	56	open+X wall
Simmebrücke Garstatt (CH)	1939	reinforced c.	32	open+wall
Brücke im Zuge, Churerstrasse (CH)	1940	reinforced c.	?	open
Ponte Lussia, Vagli (I)	1953	reinforced c.	70	open+vert.c
Averserrheinbrücke Letziwald (CH)	1959	reinforced c.	66.5	open+vert.c
Pont de la Grande Côte (F)	1960	prestressed c.	101	closed spand.
Pennine Way Footbridge (GB)	1965	prestressed c.	67.1	open
Rizhsky Rail Bridge (Russia)	?	reinforced c.	120	open

Freyssinet decided to jack up the bridge back to its original position and fixed the top hinges by filling it with concrete. So fixed, the bridge was well used for another 33 years before it was dynamited in September 1944.

Robert Maillart become by far the most important engineer that designed three-hinged bridges. He upgraded his construction designs with architectural improvements [8]. His most known achievement is the Salginatobel Bridge (Salginatobelbrücke) (1930) with the imposing span of 90 m while the total length is 133 m. Its main element is a hollow concrete box girder over the central part of the arch. The road deck is supported by reinforced concrete columns above the arch.

Two years later Maillart designed the Rossgraben Bridge (Rossgrabenbrücke) (1932) in Canton of Berne, Switzerland, with a span of 82 m. The Felsegg Bridge (Felseggbrücke) (1932) in Canton of Saint Gallen, Switzerland, with a span of 72 m is the first bridge with two parallel three-hinged arches made in reinforced concrete, and the deck is supported by reinforced concrete walls. He also designed another important three-hinged arch bridge, the Vessy Bridge (Pont de Vessy) (1937) near Geneva, Switzerland, with a span of 56 m between the base hinges. The arch is constructed in three parallel sections and the vertical supports are connecting the road deck and the three-hinged arch with the X shaped walls. But with the Garstatt Bridge (Simmebrücke) (1939) in Canton of Berne, where the span is 32 m, Maillart went even further and pushed a concept of a three-hinged arch to its limits: the underside of each half-span rises in a straight line from the base hinge to the top hinge. Many of Robert Maillart's bridges became a Swiss heritage site of national significance.

The three-hinged bridges in reinforced concrete became truly popular in the first half of the 20th century. After the Second World War a few three-hinged bridges made of prestressed concrete were constructed. The first example is Grande Côte Bridge (Pont de la Grande Côte) (1960) in Le Lauzet-Ubaye, France, with a span of 101 m. The second example is Pennine Way Footbridge (1971) in Huddersfield, UK, with a span of 67.1 m and the shape of an arch without any columns above.

One of the possibilities for further development of three-hinged arch is the three-hinge frame. The first three-hinge bridge with triangular cell frames was constructed in 1982 in the lightweight concrete over the Sinigo River near Avelengo in the Province of Bolzano, Italy with a span of 125 m. But later cracks appeared in the bridge structure which was improved in 2008 by adding an additional truss below the original frame.

2.3. Glued laminated three-hinged arch bridges

A revival of the three-hinged arch bridges, this time made in glued laminated timber (glulam), occured during the last three decades. The earliest glued laminated three-hinged bridge is the Keystone Wye Interchange Bridge (1968) in Keystone, Wye, SD, USA, with a span of 47.2 m. This highway bridge is constructed with three parallel three-hinged arches where the road deck is supported by a number of glulam columns.

The glulam bridges come with a disadvantage as they require a considerable amount of maintenance. The Ernst Müller Bridge (Ernst-Müller-Brücke) (1987) in Hückeswagen, Germany had a span of 44.5 m. It was made as a through arch bridge where the deck was at the height of the arch springings. But this specific example of timber structure was not protected enough against the wood rot, so the bridge was first closed in 2006 and collapsed two years later.

The list of recent timber three-hinged arch bridges continues with the Eagle River Timber Bridge (1990), over the Eagle River, MI, USA where the structure is made only as two parallel arches with different spans of 23 m and 24 m.The span of the Hiraoka Bridge (also Hiroaka) (1993), where two parallel three-hinged glulam arches and the road deck above are connected with columns, is 45 m - the longest span of all Japanese timber arch bridges. The Wenner Bridge (Wennerbrücke) (1993) near Murau, Austria, shares the same span of 45 m, but it is made of four parallel three-hinged arches and the road deck is supported on each side of the arch by three rows of glulam columns and by two diagonal slabs above the base hinge. For some years it was the longest glulam three-hinge bridge in Europe. By the end of the century many small glulam three-hinged bridges were constructed across Europe. In Sweden, a number of road bridges were built: two examples are the Klockarbergsleden Bridge (1994) near Skellefteå with a span of 35 m, and the Margretelund Bridge (1994) near Stockholm with a span of 35 m. Both were designed as two simple arches with one column on each half of the arch. Two examples from Spain are bridges for pedestrians, both designed as a three-hinged through arch bridge. The first was built in Cangas de Onís (Puente peatonal de Cangas de Onís) with a span of 28 m, the second was constructed in A Pontenova with a span of 40 m. Another example of a through arch bridge is the pedestrian and bicycle Bonatti Bridge (Ponte Bonatti) (2001), built in the nature park near Barberino di Mugello, Italy, with a span of 67 m. In Germany a lot of wildlife crossings over the new highways were designed. Two examples are Wilmshagen Green Bridge (Wildbrücke Wilmshagen) (2004) with a span of 27.6 m and Wiesenhagen Wildlife Crossing (Wildbrücke Wiesenhagen) (2012) with a span of 32 m. Both are constructed as three-hinged arches with closed spandrel.

Table 3. *List of timber three-hinged arch bridges.*

Original name	Year	Material	Span [m]	Subtype
Keystone Wye Interchange (USA)	1968	glulam	47.2	open+vert.c.
Ernst-Müller-Brücke (D)	1987-2008	glulam	44.5	through arch
Eagle River Timber Bridge (USA)*	1990	glulam	23;24	open+vert.c.
Hiraoka Bridge (J)	1993	glulam	45	open+vert.c.
Wennerbrücke (A)*	1993	glulam	45	open+vert.c.
Klockarbergsleden Bro (S)	1994	glulam	35	open+vert.c.
Margretelund Bro (S)*	1994	glulam	35	open+vert.c.
Ponte Bonatti (I)*	2001	glulam	67	through arch
Robert 'Bob'C.Beach Bridge (USA)*	2003	glulam	43	through arch
Wildbrücke Wilmshagen (D)	2004	glulam	27.6	closed spand.
Wildbrücke Wiesenhagen (D)	2012	glulam	32	closed spand.
Herkimer Military Road (USA)	?	glulam	27	open+vert.c.
Puente peatonal Cangas de Onís (E)	?	glulam	28	through arch
Puente peatonal A Pontenova (E)	?	glulam	40	through arch

3. TYPES OF THREE-HINGED ARCH BRIDGES

According to Fernández Troyano [1] there are three types of bridges depending on the position of the deck relative to the arch: a deck arch bridge (upper deck), a half-through arch bridge (intermediate deck), and a through arch bridge (upper arch).

3.1. The upper deck three-hinged arch bridge

In the three-hinged deck arch bridge, or upper deck bridge, the deck is above the arch. As shown in below, these bridges can be further classified by the structure connecting the arch and the deck.

3.1.1. The trussed deck three-hinged arch bridge

The oldest subtype of the three-hinged structures is the trussed deck three-hinged arch bridge. It was used in the second half of the 19th century for metal bridges only. The first such bridge was the Unterspree Bridge in Berlin (1865) (Fig. 1). Later three-hinge arch bridges of this subtype all have similar structure, but the diagonals were turned in the opposite direction.

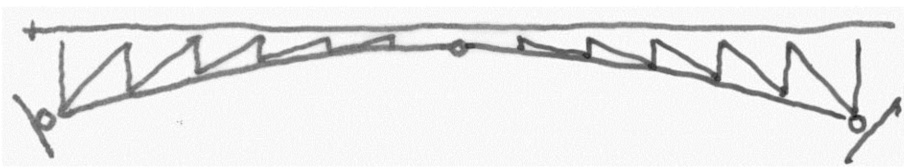

Fig. 1. *The trussed deck three-hinged arch bridge (Unterspree-Brücke, 1865, Berlin).*

3.1.2. The closed spandrel three-hinged arch bridge

The second subtype is the three-hinged arch bridge where the deck is above the arch and the spandrel space is filled with the material. This was the marginal subtype at the end of the 19th century when the engineers tried to build three-hinged arch bridges in new materials. Engineer Karl von Leibbrand created the first tamped concrete three-hinged arch bridge in Munderkingen over Danube (1893) (Fig. 2), and architect Theodor Fischer designed Luitpold Bridge, the oldest three-hinged stone bridge in Munich (1901).

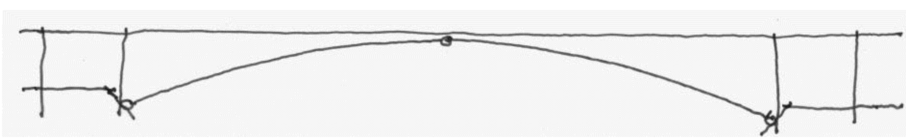

Fig. 2. *The closed spandrel three-hinged arch bridge (Donaubrücke, 1893, Munderkingen).*

3.1.3. The open spandrel three-hinged arch bridge

The open spandrel three-hinged arch bridge was the main subtype at the beginning of the 20th century when the period of concrete three-hinged arch bridges began. At that time, three bridges of a different material was made, but with the same structural logic. The spandrel space is open and the deck of the bridge is supported by columns above the three-hinged arch where columns are either vertical, diagonal, or have vaults. The Alexandre III Bridge (1900) in Paris, is the first example with vertical columns. The oldest example of the bridge where the columns have vaults at its top end is Dragon Bridge (1901) in Ljubljana (Fig. 3), made of the reinforced concrete using Melan System. The only example with diagonal columns is the bridge in Le Veurdre across Allier River (1910), France, constructed by Eugène Freyssinet in reinforced concrete (Fig. 4).

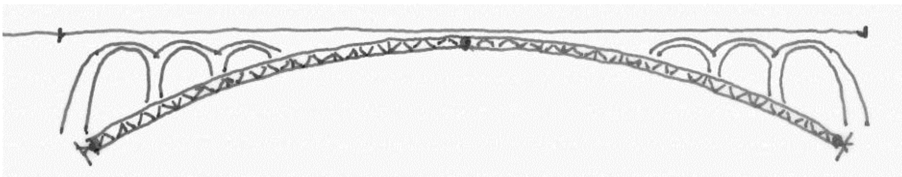

Fig. 3. *The open spandrel three-hinged arch bridge with vaults (Zmajski most, 1901, Ljubljana).*

Fig. 4. *The open spandrel three-hinged arch bridge with diagonals (Pont du Veurdre, 1910).*

This subtype is the most widely used and has many variations. The master of this subtype was Swiss engineer Robert Maillart whose open spandrel three-hinged arch bridges made in reinforced concrete are not only structural but also architectural achievements (Fig. 5).

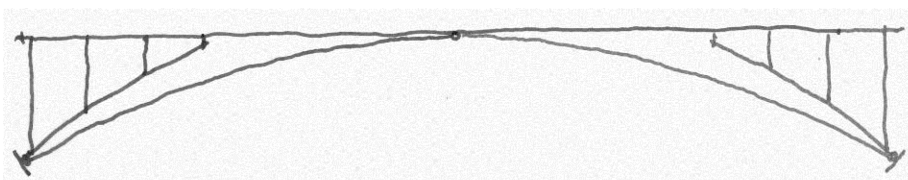

Fig. 5. *The open spandrel three-hinged arch bridge with columns (Salginatobelbrücke, 1930).*

3.2. The half-through three-hinged arch bridge

The second type, depending on the position of the deck to the arch, is a half-through arch bridge, where the deck is at an intermediate height between the springings and the crown of the arch. Therefore the deck is suspended from the arch with suspenders, usually made of metal cables. The first notable example of the three-hinged half-through arch bridge is the Austerlitz Viaduct over the Seine River in Paris (1904), designed by French engineers Maurice Koechlin, Fulgence Bienvenüe, Louis Biette and architect Jean-Camille Formigé (Fig. 6).

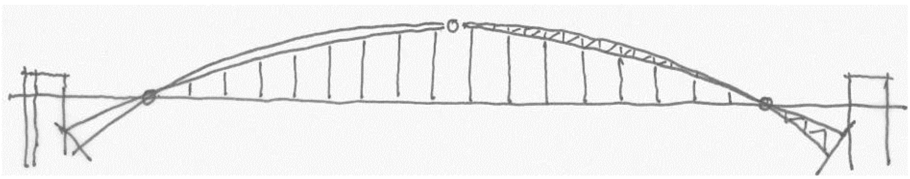

Fig. 6. *The half-through three-hinged arch bridge (Viaduc d'Austerlitz, 1904, Paris).*

3.3. The through three-hinged arch bridge

The last type is a through arch bridge, or upper arch, where the deck is at the height of the arch springings. Generally the deck is suspended from the three-hinged arch with cables. One of the last examples of the through three-hinged arch bridge is the glued laminated Bonatti Bridge (2001) near Barberino di Mugello in Tuscany, Italy (Fig. 7).

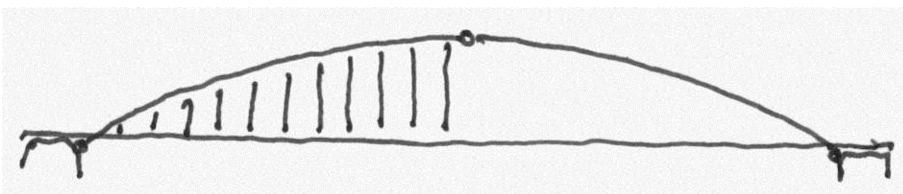

Fig. 7. *The through three-hinged arch bridge (Ponte Bonatti, 2001, Barberino di Mugello).*

4. DISCUSSION AND CONCLUSIONS

As far as the building material is considered, the list of 70 examined three-hinged arch bridges contains 25.7 % metal, 54.3 % concrete and 20 % timber bridges. As not all three-hinged arch bridges can be included in this study these numbers might only be considered as a raw estimation about how many three-hinged arch bridges were made using each material.

Although the periods of metal and concrete three-hinged arch bridges somewhat overlap, it is evident from Tables 1 and 2 that the most important metal three-hinged arch bridges were made before 1914 while the most significant and architecturally remarkable concrete ones were constructed between 1900 and 1940. More precisely, 12 of 18 metal bridges considered were made before 1914 and 30 of 38 concrete bridges were made between 1900 and 1940. As shown in Table 3, the timber, a material of the third period which starts in 1968, becomes especially popular in 1990s and remains so until today - only 2 out of 14 bridges included in this overview were made before 1990. The timber became popular only when the glued laminated timber was improved to sustain the impacts of the exterior environment.

The classification according to the bridge type (and subtype) as described in Section 3 is shown in the rightmost column of Tables 1, 2 and 3. Of all three-hinged arch bridges listed there are 59 deck arch bridges (7 trussed, 17 closed spandrel and 35 open spandrel), 5 half-through and 6 through bridges. Hence, the deck arch bridge is the dominant type of a three-hinged arch bridge regardless of the arch material: 78 % of metal, 95 % concrete and 64 % timber bridges are deck arch bridges. Furthermore, the most architecturally impressive three-hinged bridges, e.g., Maillart bridges, are deck arch bridges: compared to other (sub)types the open spandrel deck arch bridge allows significantly more design possibilities. This makes the open spandrel subtype (50 % of all included bridges) the most popular type during all three periods and in every construction material (7 metal, 21 concrete and 7 timber bridges).

Finally, some of the bridges seem to be based on the three-hinged arches, but in fact they are not. Two such examples are the Mirabeau Bridge (Pont Mirabeau) (1896) in Paris, with three spans of 34 m, 96.5m and 34 m, and the Viaur Viaduct (1902), the first large steel bridge in southern France, with multiple spans of 95 m, 220 m and 95 m. Both bridges are actually two balanced cantilevers joined in the middle by a hinge, although they both look like arch bridges. Likewise, the Bir-Hakeim Viaduct (Pont de Bir-Hakeim) (1905) in Paris is a continuous beam bridge with hinges, and the Asopos Viaduct near Lamia in central Greece built in 1908 and demolished in 1943 was a three-hinged rigid-frame bridge with inclined legs.

The classifications of other three-hinged structures like three-hinged frame systems and three-hinged three dimensional structural systems remain research issues.

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