CAST IRON ARCH BRIDGES – PART OF THE WORLD HERITAGE

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SUMMARY

Cast iron arch bridges were built in the late 18th and early 19th century across Europe. After the famous Iron Bridge in the Ironbridge Gorge in Coalbrookdale in England, being now part of the UNESCO world heritage, many cast iron bridges followed and substituted timber bridges. A series of cast iron bridges has been built in central Europe, in Laasan, Breslau, (now Wrocław), in Berlin, Potsdam, Bad Muskau and Schwerin. The paper gives an overview about the current state of some remaining cast iron arch bridges, typical damage cases, material properties and rehabilitation. Most of the old cast iron arch bridges serve as pedestrian bridges. Some of these bridges have been strengthened to increase the traffic load. Different rehabilitation measures as substitution of parts of the bridges and strengthening using Carbon Reinforced Polymers (CFRP) are discussed.

Keywords: *Arch Bridges, cast iron, materials parameter, rehabilitation.*

1. INTRODUCTION

The first cast iron arch bridges were built in the late 18th and early 19th century across Europe. Most people know that the Coalbrokedale bridge in the Ironbridge Gorge near Telford in England, which was the first of all iron arch bridges. The Ironbridge is part of the UNESCO world heritage embracing the iron gorge valley with the first blast furnace nearby. A second bridge was erected as a 1:4 copy - following the general design of the Coalbrookdale bridge - in the Wörlitz parks Germany, few years later, not made of cast but of wrought iron. The park is also listed as UNESCO world heritage site. A series of cast iron bridges has been designed and erected across central Europe. The paper gives an overview about the damaged and remaining cast iron arch bridges in Europe.

The majority of the surviving old cast iron arch bridges serve nowadays as pedestrian bridges. None the less, some of these bridges have been refurbished to allow the increase of the traffic load. Materials investigation of an old cast iron arch bridge in Germany using standardized specimens is exemplarily presented in this paper. Different rehabilitation measures as substitution of parts of the bridges and even strengthening by means of Carbon Reinforced Polymers (CFRP) are discussed. Further strengthening measures are adding arches made of modern cast iron or steel.

2. DEVELOPMENT OF NEW MATERIALS IN THE 18TH CENTURY

2.1. The English industrialization process in the 18th century.

Due to the development of new technologies for the production of iron in blast furnaces the industrialization process came onto a new level Abraham Darby I used coke for the cast iron production. Coke increased the temperature in the blast furnace and allowed the production of larger amounts of molten iron with only few impurities. The hot molten iron was cast in sand moulds, another invention of the Darby family. The invention of casting in open sand moulds allowed the production of large cast arches. Bridges were composed to replace timber bridges, mainly crossing rivers or canales.

3. CAST IRON ARCH BRIDGES AND THEIR CURRENT DESTINY

3.1. Iron Bridge at Coalbrookdale

The first cast Iron bridge (Fig. 1) in the world ever, personally visited in 2015 [1], was designed by Thomas Pritchard in 1775 built by Abraham Darby III in 1777-1779. The construction of the bridge was result of the industrial development in the iron gorge in the 18th century. Growing industrialisation requires more transport of raw material and goods. The bridge spans 30.62 m (100 ft) over the river Severn. The height is 45 feet from the support, i.e. 55 feet from the water level. The roadway is 7.31 m (10 yards). Fife parallel cast iron arches have a weight of almost 380 t. The connections of this early cast iron construction remind us timber connections as faucet joints and some bolted connections with square-head bolts (Fig. 2). The original roadway consisted of cast iron plates, now covered with an asphalt layer.

The upper surface of the arches is characterised by evaporating gases from the cast iron during the cooling process and shows still unevenness (Fig. 2). A table next to the bridge explains: The bridge was intended to be an advertisement for the skills of the Coalbrookdale ironmasters [1].

Fig. 1. *Iron bridge in the iron gorge.*

Fig. 2. Raw upper surface of the arches cast in open sand moulds.

3.2. Arch Bridge Lasaan

The first cast iron arch bridge on the European mainland was built in Laasan, now Łażany, Poland. The bridge was cast by the engineer John Baildon in Malapane foundry (now Ozimek, Poland) in 1794. In 1796 the bridge was taken into service (see Fig. 3, [2]). The bridge was not destroyed because of insufficient materials properties, ageing or corrosion, but collapsed in the end of World War II by overload.

3.3. First cast iron Bridge in Berlin

The first cast iron arch bridge in Berlin was built in 1796 as first iron bridge (Fig. 4, [3]). In difference to later cast iron bridges, the arch bridges were positioned on a masonry abutment. The cast iron arch was located between the old and new museum on the museum island. The cast iron arch bridge (Fig. 4) was replaced already after almost 30 years before the Old Museum was built (1825- 1830). Almost all cast iron bridges were crossing rivers or channels in gardens.

Fig. 3. First cast iron bridge on the European mainland in Laasan, 1796 (today Łażany)[2].

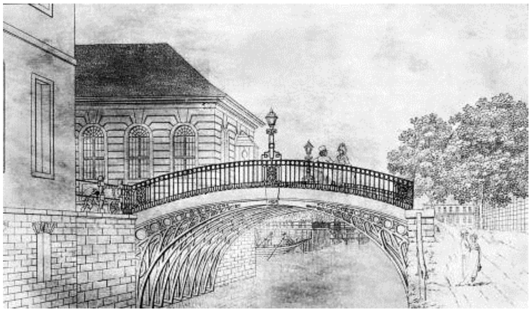

Fig. 4. *First cast iron bridge in Berlin 1796, drawing ~1800. (replaced in 1825), [3].*

3.4. Bridges in the Berlin-Charlottenburg castle park

3.4.1. High bridge

The Hohe Brücke (High bridge, Fig. 5) in red colour is bridging a 11.4 m wide canal in the Charlottenburg castle park. The bridge consists of four arches located on a masonry abutment. The bridge in Coalbrookdale was not decorated with elements that are not necessary for the load carrying capacity.

Fig. 5. *Castle bridge in the castle garden in Berlin-Charlottenburg.*

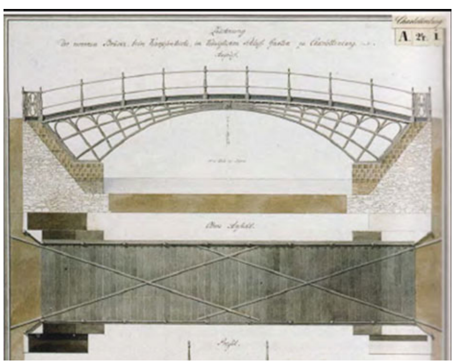

Fig. 6. *Drawing of the castle bridge in Berlin-Charlottenburg [4].*

The bridge was also cast in the Malapane (today: Ozimek, Poland) foundry. The drawing of the bridge was provided by the Wroclaw University of Technology, Poland, found in the archives of the former Oberbergamt Breslau. The drawing (Fig. 6) represents the state "As –built" and was drawn about 20 years after the bridge was built [4].

3.4.2. Iron arch bridge

Besides the more commonly known famous high bridge, a second arch bridge is bridging the canals in the Charlottenburg castle park. Five parallel arches with a more massive cross section form a relative flat arch. The arches of both bridges in the castle are simply located on the embankment. The drawing [5] was prepared in 1806, thus the bridge was probably built in 1806 or earlier. Dimensions on the drawing are given in Rhenish foot.

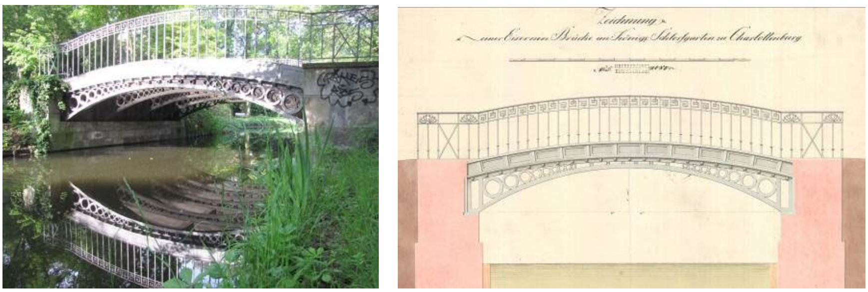

***Fig.** 7. Second existing iron bridge in the Charlottenburg castle park, photo and drawing [4] (provided by Wroclaw University of technology).*

3.5. Spanish Town in Jamaica

The earliest cast iron arch bridge in the Western Hemisphere is located in Spanish town in Jamaica, as reported by the worlds Monument Fund [5]. The bridge was designed by the English engineer Thomas Wilson and cast by Walker&Co, the Walker ironworks company in England.

***Fig. 8**. Earliest cast iron arch bridge (left) in the Western Hemisphere in Spanish town, Jamaica, with corroded surface (right), [6], Photo (2010): by courtesy J. Pheasant.*

The bridge was shipped from West Yorkshire to Jamaika in parts. There, the four arches of the bridge were assembled and fitted with cast iron frames for completing in 1801. The bridge spans 25 m over the Rio Cobre. The weight of the cast iron structure is 87 ton. Jamaican authorities, supported by the Friends of the Gregorian Society in Jamaica (FGSJ) contributed to rescuing the bridge from badly damaged abutment walls after heavy tornado, The bridge abutments have been repaired[6]. None the less, the cast iron arch on a photo [6] taken in 2010 (see Fig. 8) is heavily corroded.

3.6. Bad Muskau castle park

The bridge in the Bad Muskau castle park (Fig. 9) was probably built in 1820. It is not reported, precise when and where the bridge was cast. Some decades ago, the bridge abutments, made of stone, were replaced by concrete abutments with a masonry surface cover. Fortunately, no deterioration is visible in the concrete structure. As the six arches are clamped in the concrete abutment, there is only one transverse stiffener in the vertex of the arches and relatively thin wind bracings in the level of the upper chords riveted to the upper chords of the cast iron arches.

Fig. 9. *Bridge structure during rehabilitation works in 2014.*

Fig. 10. *Transverse stabilization in the vertex of the arch.*

In 2014, BAM was assigned to investigate the bridge material and to carry out materials testing as tensile tests, metallography and if possible nondestructive testing [7]. Nondestructive testing by radiography did not reveal any cracks in the specimens taken from a statically nonrelevat region of the arch. For further details see chapter 4.

3.7. Schwerin castle park

In the 18th century a garden around the Schwerin castle; Germany, was designed in baroque style. Later, in the 19th century, the garden was rearranged in a Landscape garden. Five historic The Schwerin castle garden bridges were probably built between 1850 and 1860. The last rehabilitation was carried out in 2001 by Binder [8]. The bridges were rehabilitated by substituting damaged cast iron arches by new cast arches cast in Poland. About 80 % of the arches were reused, cracks were partly repaired by hammer peeing. None the less, the rehabilitation was a good reason for the investigation of old cast iron material with lamellar graphite.

Fig. 11. *Schwerin castle garden bridge.*

Fig. 12. *Schwerin castle garden bridge.*

J. Alex [9] analysed the old grey cast iron material of the bridges and proposed a material model for plane stress (2D). Regarding mechanic parameters he reports a ratio between tensile and compression strength of lamellar cast iron between 24 and 33 %, both with non-linear materials behaviour. Besides iron (2-5%) and oxygen, silicium, mangan, phosphor and sulfur form metal alloy. Silicium enhances the graphite precipation of and contributes to the solidification in a stable system. Mangan is responsible for the creation of cementite, reducing the graphite formation. Phosphor reduces the ductility and sulphur weakens the grain boundaries due to deposite of iron sulfites along the boundaries [9].

4. CAST IRON MATERIAL

4.1. Mechanic-technological Parameters

The cast iron bridge and the landscape in the German Fürst-Pückler Park in Bad Muskau are listed as national heritage. For rehabilitation it was necessary to know more details about the mechanic-technological parameters of the old material. The mechanic parameters will be the basis for static calculation and the rehabilitation concept. Cores were taken of statically low loaded cross sections, see Fig. 13 and tensile test specimens were produced acc. to the sketch in Fig. 14.

Fig. 13. *Core drilling at Bad Muskau cast iron arch [7].*

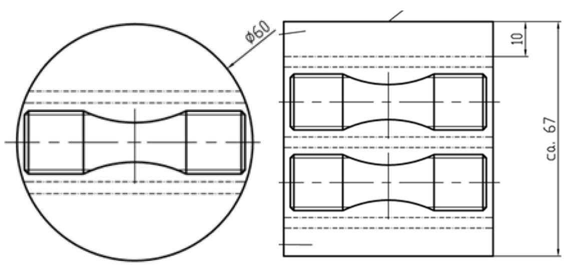

Fig. 14. *Tensile test specimen distribution in the cast iron drill core, Ø60 mm, t =67 mm [7].*

4.2. Tensile tests

The tensile strength is more precise with a large diameter. This was the reason for planning small speciemns with a diameter of 100 mm. The specimens and the tension direction were oriented in span direction of the arch. The results are presented in Tab. 1.

Table 1. *Tensile strength of the historic cast iron.*

Beam number	Specimen	Tensile strength in Rm in MPa	
		Single values	Mean values
2	2B	148	146
2	2C	144	
3	3B	170	163
3	3C	156	

The tensile tests of the lamellar cast iron were carried out acc. to EN 1561.

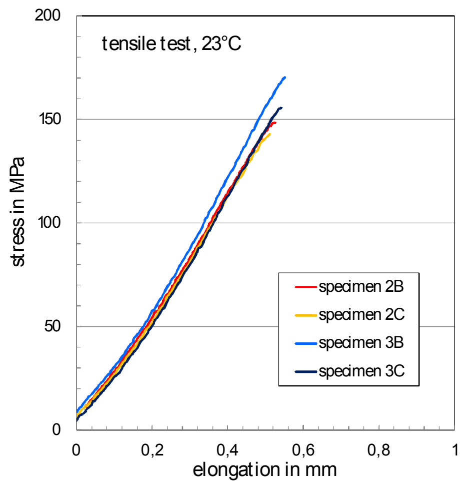

Fig. 15. *Tensile test without necking and local strains.*

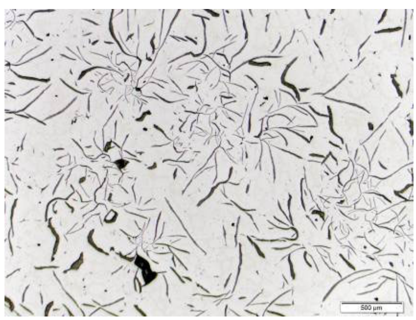

Fig. 16. *Metallography of the cast iron material after embedding and polishing the surface.*

4.3. Compression strength

The compression test specimens were taken from the areas in the drilled cores from arch 2 and 3 that were remaining besides the tensile test specimens. From each specimen, we produced four small compression test cylinders. The compression test specimens were oriented perpendicular to the beam direction. We assume an arch production in a horizontal direction and intended to get an integral value between the lower and upper surface of the cast iron. The height of the cylinders was 16 mm; the mean diameter was 8.49 mm. The test was carried out with a strain rate of 310^{-4} 1/s (velocity 0.005 mm/s). The tests were stopped at different compression conditions due to observation of the deformations in each state. The calculation of the flow curves based on the one-dimensional stress conditions was performed according to [11] until load maximum.

$$K_f = \sigma_w = \sigma_{tech}(1-e) = F/A\ (1-\Delta h/h_0) \quad (1)$$

$$\varphi = ln\ (1-\varepsilon_{tech}) = ln\ (h/h_0) = ln(h_0-\Delta h)/h_0 \quad (2)$$

where is $\varepsilon = \Delta h/h_0$.

The results are presented in Tab. 2. Figure 17 and 18 show the stress – deformation (shortening) curves. The compression strength (the compression curve) maxima are between 513 and 552 MPa. Figure 18 shows the flow curves until the load maximum.

Table 2. *Proof and compression strength of the historic cast iron.*

Beam and specimen number		Geometry after test			Compression strength		Proof strength	
		Height [mm]	Diameter [mm]	Diameter [mm]	Total strain	Value [MPa]	$R_{p0,1}$ [MPa]	$R_{p0,2}$ [MPa]
2	62	15,20	8.62	8.96	0.060	513	266	299
3	51	15.09	8,67	8.87	0.055	550	286	325
2	61	14.48	8.63	9.66	0.065	525	273	306
3	52	13.90	8.67	11.4	0.056	552	281	321

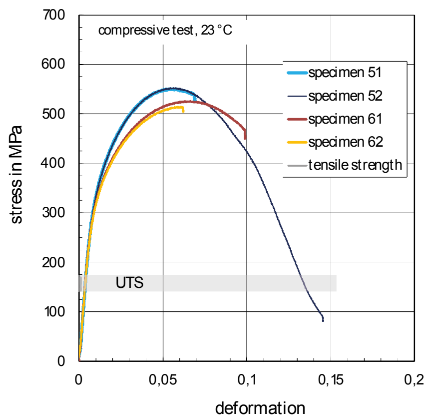

Fig. 17. *Technical stress-deformation curves with the tensile strength R_m for comparison.*

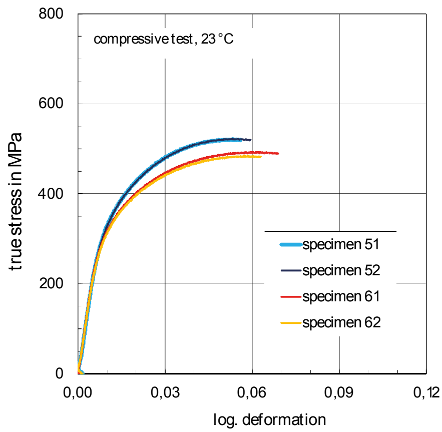

Fig. 18. *Flow curves determined until load maximum of technical stress-deformation curves Fig. 17.*

Fig. 19. *Compression test cylinders before (left), during (middle) and after the test (right).*

The mean values of the tensile stress are 159 ± 11 MPa and for the compression strength 533 ± 20 MPa. The ration between compression to tensile strength is 3.3 : 1. This correlates with the literature, where the tensile to compression strength ratio is usually reported to be between 3:1 and 4:1. With increasing strength, the ratio shifts downwards.

Nowadays, cast iron having a microstructure with lamellar graphite (EN 1561) is classified as EN-GJL 150 (Tensile Strength: 150-250 MPa, Compression strength: 600 MPa). In the materials sheet for EN-GJL-150, the youngs modulus is given as 78-103 MPa. The tensile strain of modern cast iron with lammelar graphite reaches a tensile strain between 0.3 and 0.8 %.

4.4. Metallography

The historic grey cast iron has a lamellar microstructure. A carbon content between 2.9 % and 5 % is regularly distributed flake-like in the material microstructure. The test report about the material of a cast iron arch, BAM-9.1/918 (2014) presents the microstructure of the old cast iron. Fig. 16 [7] shows the regular distributed lamellar graphite. In [9], Alex explains the rule of the lamellar graphite being responsible for the notch effect during tensile test. A second factor increasing the severity of the notch effect is high content of phosphate (> 0.05 %) causing with iron and carbon the creation of Steatite. Thus, the tensile strength is low compared to the compression strength.

5. REPAIR AND STRENGTHENING

5.1. Adding further elements or substitution of a number of elements

On possibility for strengthening old cast iron bridges is adding new arches between the old cast iron arches. Photos 20 and 21 show three additional arches located between the old cast iron arches to strengthen the bridge e.g. for fire brigades or vehicles for gardening.

Fig. 20. *Four original cast iron arches and three later added arched beams [8].*

Fig. 21. *Schwerin castle garden bridge during rehabilitation [8].*

If the damage of parts of cast iron bridges was too severe, cross sections have been strengthened, substituted one single or more elements in an arch bridge structure to keep the bridge in use. As result, the old bridge can take over the pedestrian and eventually bicycle traffic. Few of the old bridges, e.g. the historic Tickford bridge, as reported by Triantafillu in [13], strengthened with CFRP wraps, can take over even road traffic.

5.2. Reinforcement with CFRP

One of the bridges built more than 200 years ago, is the Tickford Bridge over the river Lovat in Newport Pagnell, England. The design was made by Henry Provis of Paddington, modified by Thomas Wilson. The bridge consists of six compound arched circular trusses spanning over 17.68 m (58 ft) and transversal diaphragm beam. The Walker iron works used dowels and keys instead of bolts. The bridge was repaired in 1900 and 1976 and carries road traffic until now [13].

The bridge was strengthened by wrought iron plates to the centre bays in 1900. In 1976, a reinforced concrete deck was placed on plastic foam. Later, the load carrying capacity was increased by adding CFRP-laminates. In case of a complicated geometry strengthening was carried out in situ with wet lay-up, which was vacuum-consolidated and cured under elevated temperatures. The bridge was strengthened with 14 layers of carbon fibre fabric, applied to the three largest spandrel rings and the lower main chord in a very short time period. The reinforcement was not thicker than 10 mm. Then, the bridge was repainted in a way the appearance remains the same than before strengthening [13].

6. CONCLUSION

To guarantee the safety of existing bridges or constructions made of the 200 years old material, a recalculation must proof the sufficient load carrying capacity und current load. The reassessment of the cast iron material is more demanding due to the non-linear behaviour of the old cast iron under loading. A material model for the recalculation of the old cast iron was found in [9]. Although the historic cast iron bridges look back to 200 years of service they can be reassessed despite their nonlinear behaviour. Some can be strengthened even for heavy traffic. Tests confirmed the nonlinear behaviour of tensile and compression and the tensile to compression strength ratio of 3:1 (i.e. between 3:1 and 4:1).

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