Frankfurt project: Overview of cast-iron bridge design (18^{th}-19^{th} centuries)

October 27, 2020

1 Introduction

The aim of this project is to identify any construction patterns used in early iron construction that could have both structural and aesthetic value for modern bridge design. This literature review will focus on the evolution of cast-iron and its use within bridge engineering, since it's first use on The Iron Bridge in Shropshire, England in 1779 (Miller, 2015).

2 Cast iron

Before the eighteenth century, cast-iron was used very rarely for structural applications, before two innovations allowed it to be available in 'large quantities and at lower cost' (Swailes & Marsh, 2005). These innovations were the switch to coke instead of charcoal as the blast furnace fuel, and more powerful steam engines to provide air to the furnaces.

Whilst cast iron is characteristically strong in compression, it is weak and brittle in tension. This is why many influential engineers such as Thomas Telford used cast iron members primarily in compression; mostly avoiding its use in bending or tension members (Gagg & Lewis, 2011). This fact explains why, at least initially, many cast-iron bridge designs adopted features used in masonry structures. Whilst cast-iron was sometimes used for beams, they were designed with heavily asymmetric sections with enlarged lower flanges as shown in Figure 1.

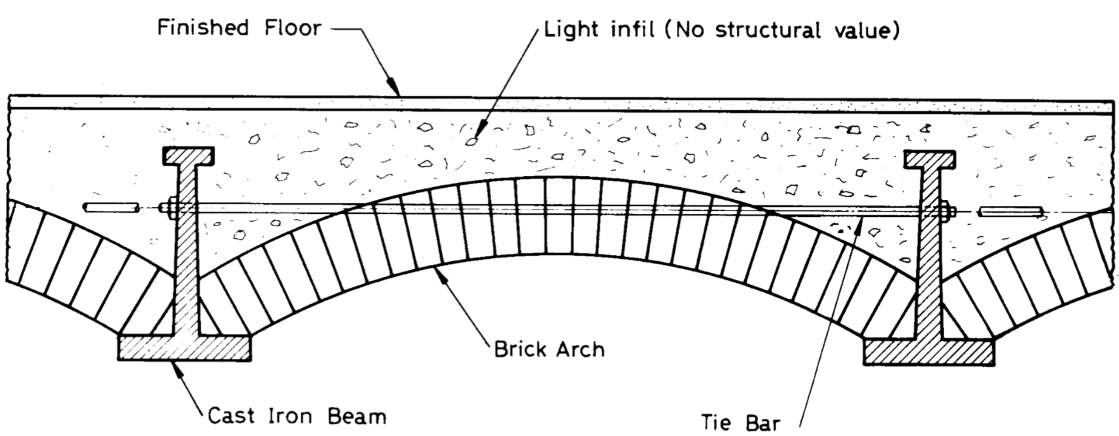

Figure 1: Barrel vault construction showing asymmetric cast iron beams with enlarged lower flanges to compensate for cast iron's lack of tensile strength (Bates, 1984)

3 The Iron Bridge

The Iron Bridge (Figure 2) in Shropshire, England, constructed in 1779, was the world's first iron bridge and went on to inspire the more widespread use of structural ironwork (Miller, 2015). The idea for the bridge was inspired by the new blast furnace at Coalbrookdale and was conceived by the Architect Thomas Farnolls Pritchard.

Figure 2: General view of the bridge in 2014 (Miller, 2015)

Whilst undoubtedly iconic, the structural form with concentric circular cast-iron arches is flawed as evidenced by its long history of repairs and alterations (outlined by Miller, 2015). Due to a lack of knowledge or confidence in the material, the structure was vastly over-designed leading to excessive structural redundancy (Miller, 2015 and Gagg & Lewis, 2011). The semicircular form results to the arch producing a relatively small amount of horizontal thrust at the supports and thus provided 'little resistance to the aggressive earth pressure it encountered' (Paxton, 2007). The combination of excessive redundancy and the lack of resistance against horizontal pressure meant that the structure was incapable of easily accommodating any movements, leading to a 'myriad of full fractures' (Gagg & Lewis, 2011). More recently, the arch springings have been strut apart by the installation of a 'concrete slab across the river bed' (Miller, 2015).

An interesting feature of The Iron Bridge is that due to its novelty, the workers building the bridge were not familiar with iron and therefore used joining techniques typical to carpentry, such as dovetail and shouldered joints (English Heritage, 2020). This can be evidenced in the connections of the radial elements connecting the three arch ribs shown in Figure 3. Whilst these radial elements are nice architectural touches Figure 4 demonstrates that, along with much of the structure, they offer little structural value with the innermost arch rib being noticeably more stressed than the other members.

Swailes & Marsh (2005) states that the iron spandrel rings seen in The Iron Bridge that sit between the outermost arch rib and the vertical members were 'copied' from the 'weight-relieving barrel rings' of the stone arch bridge at Pontypridd shown in Figure 5. However, whilst the weight-relieving rings in a stone arch have a clear structural value of reducing the pressure at its crown, the value of iron rings as structural members in The Iron Bridge is less clear. Despite this, iron rings were present in many structures after the construction of The Iron Bridge, commonly within bridges as iron rings forming the spandrels between arch ribs and decks of bridges (Examples include: Old Wearmouth Bridge, Sunderland (1796); Tickford Bridge, Buckinghamshire (1810); Pont Du Carrousel, Paris (1834); Exeter Iron Bridge, Exeter (1835); Triana Bridge, Sevilla (1852)).

Figure 3: Details of the radial elements used on The Iron Bridge, showing the use of carpentry joints (English Heritage, 2020)

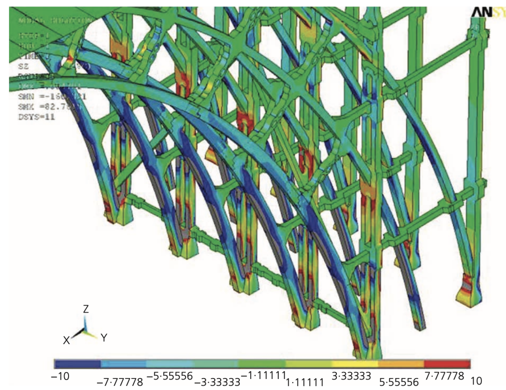

Figure 4: Isometric plot showing frame stresses from one of the load cases considered by Miller (2015)

Figure 5: Drawing of the bridge at Pontypridd opened in 1756 (The National Library of Wales, 2020)

4 Use of rings in bridge spandrels

4.1 Thomas Wilson

The designer of the Wearmouth Bridge is unknown, but according to Grace's Guide (2018) it is probable that it was Thomas Wilson. After the criticism of The Iron Bridge's semi-circular design, the Wearmouth Bridge used a segmental arch form of about 65 degrees (James, 2015). A prominent feature of Wilson's cast-iron bridge designs is the use of cast-iron circles diminishing from the haunches to the crown of the arch as shown in Figure 6 also present in some of his other bridges such as Tickford Bridge, Buckinghamshire and the Spanish Town Bridge, Jamaica. According to James (2015) the benefits of these circular spandrels over rectilinear framing were that they were 'relatively easy to fit and capable of accepting considerable distortion without snapping'. This type of spandrel can be observed in the design of many cast-iron bridges including: East Bridge, Dundee (1804); Pont Saint-Thomas, Strasbourg (1841); Puente de isabel II, Sevilla (1852)).

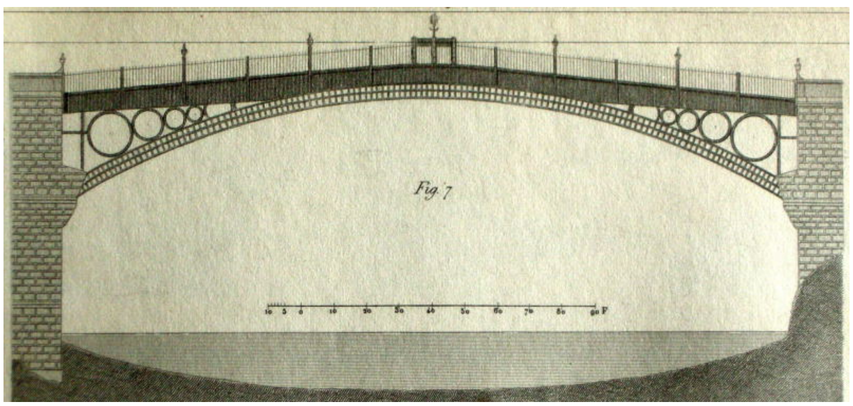

Figure 6: Drawing of 1796 Wearmouth Bridge (Grace's Guide, 2018)

Unlike the arch ribs used on The Iron Bridge, where the design simply evoked the voussoirs of a masonry arch, Wilson's bridges used cast-iron voussoirs as shown in Figure 7 held together by wrought-iron straps. James (2015) argues that this was inspired by the French engineer Armand Vincent de Montpetit, who proposed this type of arch rib in 1779. This was because France did not have the facilities to cast large half-ribs this was alongside their distrust of cast-iron due to its brittle nature and hence a greater reliance on wrought-iron which was more difficult (technically and economically) to cast on large scales.

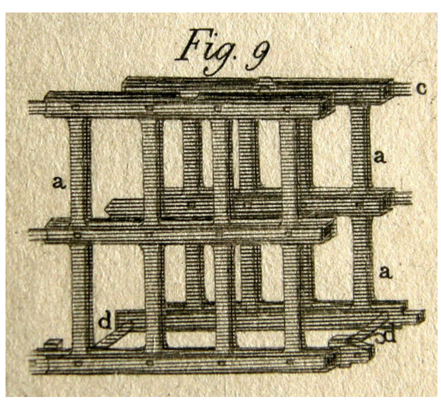

Figure 7: This figure shows a pair of cast-iron voussoir panels of the Old Wearmouth Bridge connected by transverse ties (Grace's Guide, 2018)

5 Thomas Telford's iron bridges

Thomas Telford was a pre-eminent civil engineer of the eighteenth, and early nineteenth centuries and was elected the first ever president of the Institute of Civil Engineers. Paxton (2007) states that Telford's work on cast-iron bridges influenced bridge design to the extent that by 1830, 10 out of 19 bridges exceeding 32m in span in the world (18 of which were in Britain) were either inspired by or designed directly by him.

Telford's first use of cast-iron was in aqueducts such as those at Longdon-on-Tern and Pontcysyllte, however these structures have little aesthetic interest and thus not relevant to this project. His first cast-iron bridge design was the construction of a bridge at Buildwas, Shropshire where the old stone bride was destroyed in a flood in 1795. This was the first iron-bridge constructed following the success of The Iron Bridge nearby, yet Telford believed he could improve upon the the design. He introduced segmental arches with substantial abutments, instead of the semicircular ones used on The Iron Bridge which he argued 'offered little resistance to the aggressive earth pressure it encountered'. The design included three inner ribs, in conjunction with suspending ribs either side of the bridge deck as shown in Figure 8. (Paxton, 2007).

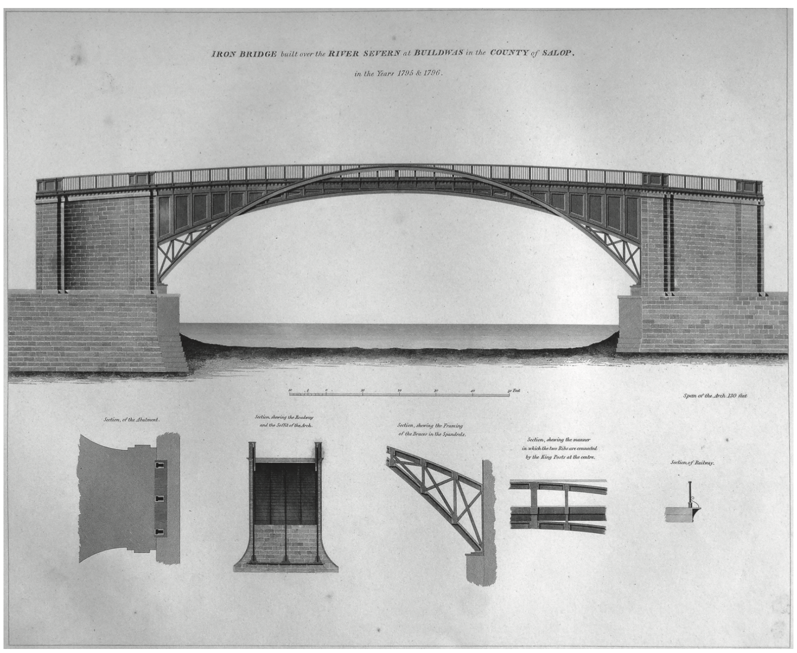

Figure 8: Drawings of Telford's Buildwas Bridge constructed in 1796 (Shrewsbury & Newport Canals Trust, 2020)

The bridge was a clear success and improvement upon The Iron Bridge, spanning 9.1m wider despite having less than half as much iron (185 compared to 385 tonnes) (Engineering Timelines, 2020). Writing about the design of his bridge Telford wrote:

'I made the arch 130 feet span. The roadway rested on a very flat arch calculated to resist the abutments if disposed to slide inwards as at Coalbrookdale, while the flat arch was itself sustained and strengthened by an outer arched rib on each side of the bridge springing lower than the former and also rising higher thus introducing more of the principle of timber trussing than of masonry. The back of each abutment is in a wedge shape so as to throw off laterally much of the pressure of the earth' (Engineering Timelines, 2020)

Despite the engineering success of the bridge, the contribution of the suspending ribs has been questioned with Paxton (2007) calculating that the bearing ribs would have been adequate to support the loads without them. Paxton argues that Telford was also aware of this, as this feature never appeared in any of his future cast-iron bridge designs.

The next development of Telford's bridge design was the Bonar Bridge as shown in Figure 9, and 'proved the first of a genre with 'lozenge'-or diamond-shaped lattice spandrels of which eight bridges exceeding 32m were erected by 1830' (Paxton, 2007). Paxton gives the following as improvements over its contemporary cast-iron bridges:

- Deep, but narrow rectangular ribs, with piercings between spandrel loading points to create triangular openings.
  - This demonstrated Telford's awareness that 'the strength of a simply supported rectangular beam increased with the square of its depth'. This minimised any bending stresses that could lead to cracking of the cast-iron.
  - The piercing in these locations reduced the cross-sectional area of the rib by about a half, whilst keeping the stresses within safe limits.
- The ribs were designed as the only element transferring the thrust to the abutments. Using this, Paxton used a graphical method to determine the thrust line of the rib, finding it to lie within its middle third, thus reducing the likelihood of bending stresses.
- The lozenge-lattice spandrel members were of a cruciform cross section which was 'much more efficient in strength terms' than circular or square sections. bridge ironwork acts as one huge frame in addition to the parts being designed to act separately.

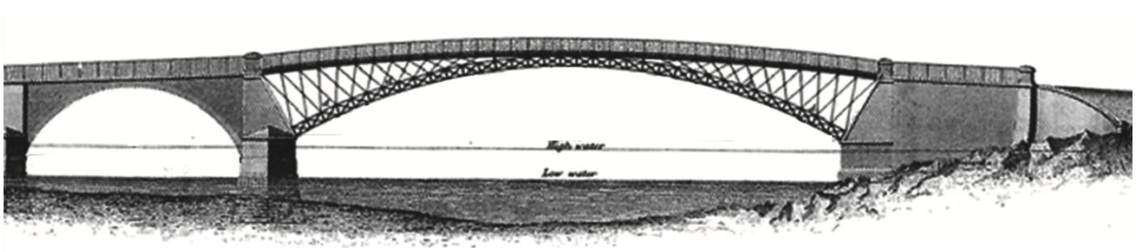

Figure 9: Bonar Bridge (1812) had a main span of 46m and was the first of this style of Telford's bridge with the lozenge-lattice panels (Paxton, 2007)

The next development of Telford's Bonar genre was to rotate the lozenge-lattice spandrels vertically into a more structurally efficient orientation as can be seen in Figure 10 depicting the Mythe Bridge.Not only have the Bonar genre of Telford's cast-iron bridges been undoubtedly successful and influential (with many standing to this day) Paxton (2007) gives an excellent description of their aesthetic value:

'Attractive visual features of Telford's Bonar genre are, in general, the Palladian cruciform elevation of the slender ribs, the gently curved parapet line and the gossamer-like slenderness of the lozenge spandrels.'

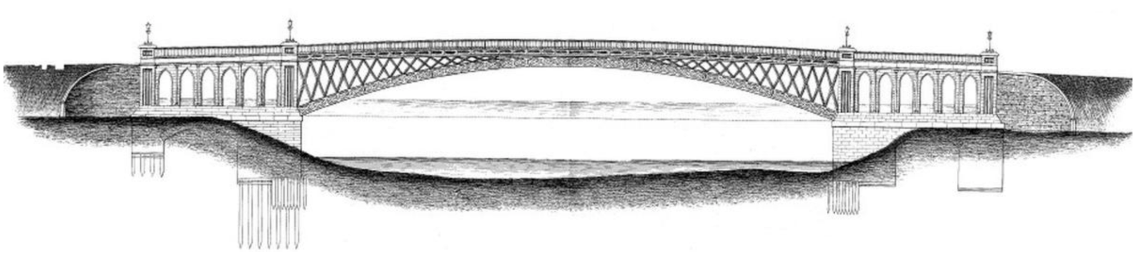

Figure 10: Mythe Bridge over the Severn at Tewkesbury (1826) is the longest span of the Bonar genre (Structurae, 2020)

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