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Restoration and strengthening strategies for 19th century iron pedestrian suspension bridges

S. Adriaenssens & B. Verbeeck
Department of Mechanics of Materials and Constructions, Vrije Universiteit Brussel, Brussels, Belgium

I. Wouters & M. de Bouw
Architectonic Engineering Sciences, Vrije Universiteit Brussel, Brussels, Belgium

ABSTRACT: The history of mainland Europe's oldest suspension bridges dates back to the beginning of the first half of the 19th century. The two World Wars as well as continued renovations to these bridges make that the earliest suspension bridges in central Europe (Belgium, France and Germany) can only be physically documented by decorative private suspension bridges. Mainland Europe's second oldest surviving suspension bridge (1824, Wissekerke, Belgium) is used to illustrate a particular restoration and strengthening approach used to make these bridges comply with current concepts of safety. The initially private pedestrian bridge spanning 20.5 m across the castle's moot, is at present part of a public park. Due to ill-maintenance and deterioration over decades as well as a function shift (from private to public), the bridge does not fore fill the current European norm for pedestrian bridge design. Two options offer themselves: the bridge is closed to the general public (with limited private access), restored and kept as an "architectural" object or the bridge is strengthened ensuring maximum public utility with minimum loss of authenticity. Six different strengthening strategies are briefly presented. These strategies include the addition of extra support to reduce the span, the addition of a structure under the deck (e.g. beams, truss, arch), the addition of a structure in the deck (e.g. pre-stressing cables, girder), the addition of a structure above the deck (e.g. truss along hand rail), strengthening of the suspension cable and finally strengthening through cable stays. The architectural and engineering advantages and disadvantages of these strategies are highlighted. One option is selected on the basis of maximum public use, (and compliance with current European Norms), optimal preservation, least visual impact and easy future maintenance. This strategy preserves and restores most of the authentic elements (being the cast iron mast, the wrought iron suspension chain, the back stay and the railing) and replaces the structurally inadequate non authentic deck with a closed steel box girder with timber deck. In this solution the suspension structure thus solely carries its own weight and temperature influences. The new girder designed for strength, stiffness, dynamics and carries dead loads and live loads laid down in the European Norms. Based upon this representative case study, general conclusions are given for restoration and strengthening strategies for 19th century iron pedestrian bridges.

1 INTRODUCTION

The iron suspension bridge of the Wissekerke castle in Kruibeke-Bazel was designed and constructed in 1824 by the Belgian engineer J.B. Vifquain (1789–1854) (see figure 1). Almost 160 years later, in 1981, the Belgian Royal Commission for Monuments and Landscapes classified this bridge due to its industrial-archeological value. In 2006 the castle, the park and bridge were bought from the Vilain VIIII family by the Kruibeke Village Council and opened to the public. The ill-maintained and deteriorated bridge did not comply with the current concepts of safety and was therefore closed to the public. A restoration and strengthening study was undertaken by the Vrije Universiteit Brussel, Brussels to upgrade this historical bridge. Key features in this study are the renovation of all authentic elements, strengthening with minimal visual impact, easy maintenance and future durability.

2 STRUCTURAL SYSTEM OF THE AUTHENTIC BRIDGE

The suspension bridge over the moot of Wissekerke's castle spans 20.5 m between the abutments and has a deck width of 2 m (see figure 2). The suspension system is doubled up and is entirely symmetrical about the longitudinal bridge axis . At the middle of the span, the suspension chain has a central height of 1.1 m above the deck and follows a catenary line up to 2.2 m

Figure 1. Period photograph of the Wissekerke iron suspension bridge, Belgium (1824, J.B. Vifquain).

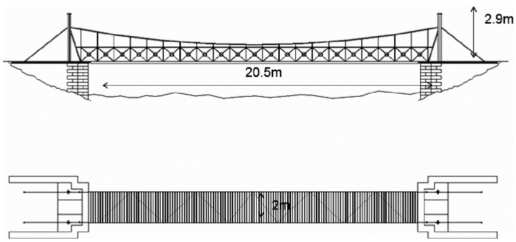

Figure 2. Elevation and plan of the authentic suspension system.

above the deck at bridge's extremities (being the cast iron masts which themselves have a height of 2.9 m). The wrought iron suspension chain cable consists of individual plates (1 m length, rectangular cross-section of 31 mm × 14 mm) that are pinned together with a connection to the railing. The chain goes through the masts and is anchored to the abutment. The longitudinal stability of the system is guaranteed by a strut and tie configuration fixed to the abutment. The transverse stability of the bridge is ensured by the mast portal frame. No information is available about the abutments. This study did not consider the bridge foundations.

3 INITIAL STRUCTURAL ANALYSIS AND DESIGN THEORY

Although no records have been found in the castle's archives about the bridge's structural design and analysis, this paragraph places the bridge in its historical context. The origins of the iron suspension bridges are found in the UK, France and USA in the beginning of the 19th century. In 1801 James Finley (USA) patented the first suspension bridge employing iron chains. Although Finlay built many small span suspension bridges, none older then 1824 have survived. In 1820 Samuel Brown (UK) constructed the first 132 m large span and still surviving suspension bridge for vehicular traffic across the River Tweed (Schultiz et al. (2000)). Within Europe, the UK was ahead in suspension bridge design. The engineer responsible for the design and construction of the Wissekerke bridge, J.B. Vifquain travelled often to the UK and must have been familiar with the emergence of this new bridge typology. In 1821 and 1823 the French government sent C. Navier to England to study and document the early suspension bridges (Billington et al. (1993)). Navier's research resulted in the first theoretical treatise on the history and theory of suspension bridges "Rapport et mémoire sur les ponts suspendus" (Navier (1823)). Although James Bernouilli (1691) was the first to develop the theory of the catenary and Nicholas Fuss (1794) of the parabolic cable, it was Navier who extended the theory of the unstiffened parabolic cable to include the effects of variable loads. It has been suggested that J.B. Vifquain acquainted with the early UK suspension bridges, must have studied Navier's newly developed theory and designed and constructed the Wissekerke suspension bridge in 1824. In 2006, 182 years later, the bridge as well as the surrounding park and castle became public property of the Kruibeke Village Council. At that moment, the bridge was badly deteriorated due to ill-maintenance and undergoes a function shift from private to public use. The structure does no longer fore fill the criteria laid down in the following prevalent European and local Belgian codes regarding bridge design:

- prEN 1991-2 Euro Code 1: Actions on structures – Part 2 – Traffic loads on bridges
- NBN B03-101 Belasting van Bouwwerken: Wegbruggen

4 SIX STRENGTHENING STRATEGIES

4.1 *General approach*

Being the second oldest suspension bridge in mainland Europe, this bridge proved to be of great historical value. In this context the Belgian Royal Commission for Monuments and Landscapes decided that two routes were possible for this structure: the first option consists of closing the bridge to the public and restoring it to its initial state, the second option was pressed upon by the Village Council and involves the strengthening of the bridge for public use with minimum loss of authenticity.

Opening the bridge to the public unavoidably involves the creation of an additional or new structure to make the structure carry higher imposed variable loads (500 kg/m^2 instead of the calculated 10 kg/m^2) and exhibit a appropriate dynamic behavior.

4.2 *Strengthening strategy 1: addition of an extra support*

The first strategy consists of adding 850 mm high isostatic steel beams to make up the new substructure

Figure 3. Strengthening Strategy 1: addition of extra supports.

Figure 4. Strengthening Strategy 2: addition of a structure under the deck.

spanning 20.5 m across the castle's moot. The structural depth is visually unacceptable but could be dimished by adding extra supports as was done for the chain suspension bridge in Nürnberg, Germany. This strategy is constructionally easy but distracts of the initial innovative nature of the authentic bridge that spans the water without intermediate supports (see figure 3).

4.3 *Strengthening strategy 2: addition of a structure under the deck*

The additional structure is positioned underneath the deck and is not visible while crossing the bridge (see figure 4). However from a distance (e.g. from the castle) the structure is rather visible and distracts from the initial structure. A few systems lend themselves to this type of structure:

- Trusses (Warren, Pratt or Vierendeel) have a certain degree of transparency, have higher structural efficiency than plain beams through their increased structural depth. The configuration of the trusses could be chosen so that the diagonals are in rhythm with the existing hand railing pattern. When following the moment-line, the truss increases its structural depth towards the middle of the span.
- By inverting the catenary shape of the suspension chain cable, one obtains the ideal compression arch under vertical downward load. From a visual point of view, this arch shape perfectly complements the catenary cable (as its mirror image). The bridge's initial structure reflected in the water, becomes the strengthening structure.

4.4 *Strengthening stratgey 3: addition of a structure within the initial deck height*

The initial deck height is determined by the timberside board that has a height of only 180 mm. Ideally the new structure should fit within this height to be almost invisible to the pedestrian crossing the bridge and to the spectator at a viewing distance (see figure 5).

Figure 5. Strengthening Strategy 3: addition of a structure within the initial deck height.

- A ribbon bridge with limited sag could theoretically fit within this small structural depth. However the poor soil conditions and the high foundation cost make this option rather unattractive.
- An steel box girder that has a cross-section with a structural depth of 180 mm at the sides to an increased structural height of 500 mm at the central axis, satisfies all ultimate limit and all serviceability states as well as the dynamic behaviour criteria. The lowest point of this variable cross-section lies in the bridge's shade. This shallow box girder is compact, hardly visible, maintenance friendly and durable as it is completely closed and only needs anti-corrosion treatment on the outside of the girder.

Figure 6. Strengthening Strategy 4: addition of a structure above the deck.

Figure 7. Strengthening Strategy 6: strengthening with cable stays.

4.5 *Strengthening strategy 4: addition of a structure above the deck*

Positioning the truss structure above the deck respects the clear height (see figure 6). This new structure could also serve as the new hand rail that satisfies the imposed load case of 1 kN/m (height 1.10 m). The downside of this design option however is that this strategy is highly visible. Since the bridge is mainly seen at an angle, the authentic suspension system imposed onto the truss appears as very heavy.

4.6 *Strengthening strategy 5: strengthening of the suspension cable*

Preliminary calculations indicate that the suspension chain cable is the weakest link in the authentic structure. By adding a second chain or cable the initial chain could be strengthened. From a constructional point of view, it is rather difficult to firstly get the forces from the vertical suspension elements into the new cable and to secondly integrate the new cable into the existing structure. The current suspension chains run through the masts where no space is available for an extra structural element. Seen the current cracks in the mast head, it is not advisable to add additional axial load to the masts.

4.7 *Strengthening strategy 6: strengthening with cable stays*

The new bridge deck structure could be cable stayed. This strategy makes a clear distinction between the initial bridge and the new added structure. Cable stayed bridges are rather transparent. The masts for the cable stay could be positioned symmetrically or asymmetrically (see figure 7), on both banks, straight or skew. This system needs a strong anchorage system and would be difficult to implement in the overgrown bank with poor soil conditions.

4.8 *Preferred strengthening strategy*

The addition of shallow box girder in the height of the bridge deck turns out to be the most positive strengthening strategy for this suspension bridge. Its main advantages are its minimal visual and disruptive impact, its ease of maintenance and its durable character.

5 STRUCTURAL DESIGN OF STEEL BOX GIRDER WITHIN INITIAL DECK HEIGHT

Based on the above mentioned design proposal to increase the bearing capacity of this public bridge to current European Codes, the inauthentic deck and substructure are replaced by a symmetric steel box girder. This girder provides the bridge with the required bearing capacity, stiffness and dynamic behaviour. The steel box girder carries a wooden deck and is connected at its sides through a sliding connection with the initial suspension structure that will be restored and where necessary restorated. The cross-section of the girder has a maximum central height of 500 mm that tapers to the sides to 180 mm (being the initial height of the timber side board). This girder is considered as a fixed beam that allows horizontal movement on one abutment (to allow for dilatation). The considered load cases are self weight, superimposed dead load, variable load (5 kN/m^2), wind load and temperature influences. The load combinations are carried out according to EN 1990:2002. The steel quality is S 355 J2G3 (Fe 510). Since the box girder is shallow the main design criteria is its dynamic behaviour. The girder design with fixed supports ensures that accelerations felt by the pedestrians walking in rhythm, are limited to avoid resonance with the bridge's own frequencies. The own frequency of the bridge was found to be 5.4 Hz. According to NBN B 52-001 this frequency is outside the danger zone and therefore no additional measures need to be

taken to avoid resonance. To satisfy the deflection limit the girder is slightly pre-cambered.

At the sides the authentic suspension and new structure are connected through a series of sliding connections (in the vertical and the longitudinal direction). A series of computational analyses demonstrated that every other type of connection (e.g. hinged or fixed) between the initial and added structure would transfer a portion of the variable loads into the initial structure, resulting in material stresses exceeding the acceptable limits (670 N/mm^2 >200 N/mm^2). To ensure the out-of plane stability of the initial bridge, this sliding connection is an absolute necessity.

An additional hand rail is designed to satisfy the stability and safety requirements. The hand rail structure consists of a steel frame filled with a fine stainless steel net. Its vertical members follow the rhythm of vertical suspension elements of the initial bridge. The frame is fixed to the box girder. The authentic suspension system now only carries its self weight and temperature influences.

6 CONCLUSION

This study demonstrated that restoring suspension bridges either reduces the structure to a sculptural architectural artefact or needs a substantial engineering study to make the system compliant with the current codes for bridge design. Strengthening strategies vary from banal structure additions (extra supports) that deviate from the ingenuity of the initial system to very visible systems that aesthetically complement (or in a worse scenario dominate) the initial structure. However from a conservational, architectural and engineering point of view, the strategy that is most subtle, has least visual impact, renovates all authentic parts, guarantees easy maintenance and durability seems to be the most preferred one.

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