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Upgrading mainland Europe's oldest iron suspension footbridge

Wissekerke castle park in Belgium contains mainland Europe's oldest remaining iron suspension bridge (1824). In 1989, after years of neglect, the Kruibeke town council bought the castle, park and finally, in 2006, the bridge. The Architectural Engineering Lab of the Vrije Universiteit Brussel (æ-lab) was consulted to put the refurbishment on the right lines and to check whether this bridge can stand the shift in function from private to public. This paper places the pedestrian bridge within the framework of 19th century bridge construction, determines its historical value, characterizes the used materials by metallographic methods combined with tensile and hardness tests, re-analyses the structure, proposes strengthening strategies and concludes with a renovation proposal that preserves all of the authentic elements, causes the least visual impact, is durable and guarantees continued public use.

1 Introduction

During the 19th century iron and steel were exploited to open up new horizons in bridge construction. The maximum span records for suspension bridges occurred in fast succession thanks to engineers such as *James Finley, Thomas Telford, Samuel Brown* and *Marc Seguin*.

Looking back at their impressive list of completed bridge projects, one has to conclude that most of the early 19th century suspension bridges are lost today. Some of them failed soon after they were built, some were destroyed by wind or water, some were bombed, others were dismantled for safety reasons or replaced while upgrading them to comply with new design standards.

Nowadays, the oldest remaining iron suspension bridges can be found in Great Britain. The Union (Chains) Bridge, built in 1820 by *Samuel Brown*, is the world's oldest remaining vehicular suspension bridge still open to (limited) vehicular traffic. Since most of the other long-span suspension bridges have disappeared, the smaller pedestrian bridges experience a gain in interest. In the United States, all the suspension bridges built before 1825 are lost, in Great Britain several early bridges remain [1] [2]. On mainland Europe the oldest bridges identified so far are the castle bridge in Wissekerke (Belgium), built in 1824, and the Kettensteg in Nuremberg (Germany), open to the public since 31 December 1824 [3]. The latter has been propped in the middle since 1931 as the original loadbearing capacity of the bridge (2 kN/m^2) is not sufficient according to modern standards.

The Wissekerke pedestrian bridge has been closed to the public since 1990 but will be restored in the near future. This paper discusses the historical context, the pathology, the material characterization, the structural assessment and the refurbishment proposal for this historical monument.

2 Historical value

In 1824 Viscount *Philippe Vilain XIIII* (1778–1856) put into practice plans to alter his castle Wissekerke at Bazel-Kruibeke, to turn the surrounding park into an English garden and to build a private bridge over the castle pond. He appointed the Brussels engineer *Jean-Baptiste Vifqu(a)in* (1789–1854) to design and carry out the structural calculations for the bridge. *J.-B. Vifquain* had graduated from the Ecole Polytechnique in Paris in 1814 and was widely known for his architectural and town planning work as well as for his hydraulic engineering projects. Since he frequently visited hydraulic works in Great Britain, he must have been aware of the English bridge construction expertise, which was different from the developments on the European mainland and in America.

The differences in the construction of suspension bridges relate to the main cable. In America *James Finley* used a catenary cable comprising individual chains linked to each other. In Great Britain the chains were replaced by so-called eye-rods, bars with a hole at the end, interconnected with bolts. From 1815 onwards, Sir *Samuel Brown* and *Thomas Telford* developed several suspension bridges with wrought iron eye-rods. In 1820 *Brown* built the Union Bridge and *Telford* finished the Menai Strait Bridge, with a span of 175 m, in 1826. In France the early bridge engineers adopted the catenary system, but they soon developed iron wire cables, which were stronger in tension.

The report of the French engineer *Claude Navier*, published in 1823, is a valuable source for understanding and evaluating the sequence of structural innovations. His report 'Rapport à Monsieur Bequey et Mémoire sur les Ponts Suspendus' covers all of the knowledge on suspension bridges available at that time [4]. Besides the theoretician *Claude Navier*, a more practically oriented Frenchman was experimenting with suspension bridges in France: *Marc Seguin* field-tested iron wire cables to build up the main cable of his suspension bridges. These wire cables were much

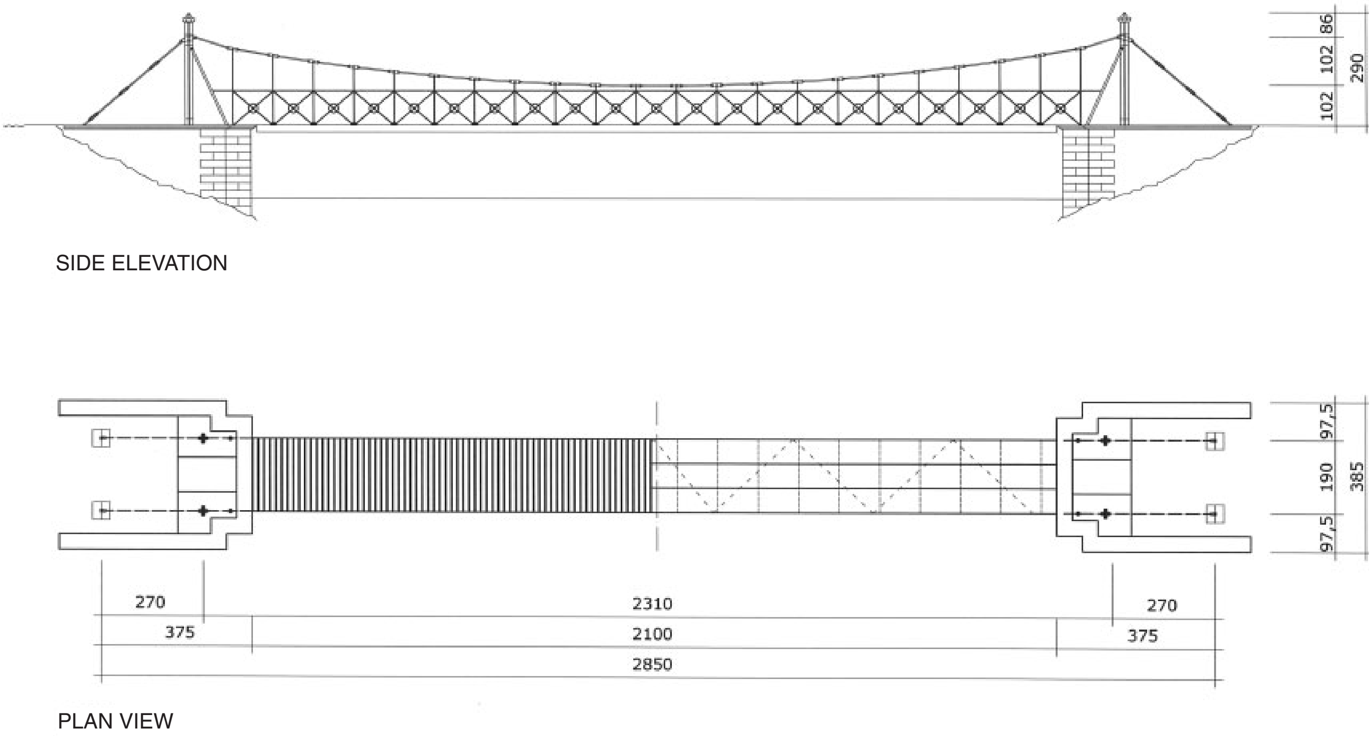

Fig. 1. Side elevation and plan of the historic suspension bridge in its current state

stronger than the eye-rods being used in Great Britain.

J.-B. Vifquain based the design details of the Wissekerke bridge on the English construction details (Fig. 1 and 2). Similar to the Union Bridge, *Vifquain* used eye-rods for the main chain of his bridge. Since extensive research has not revealed any remaining construction documents, archive pictures (Fig. 3 and 4) and a thorough analysis of the existing structure form the only possible basis for evaluating the authenticity of the various bridge elements.

Fig. 5 and 6 show the current state of the bridge. The bridge spans 23.1 m between the masts and has a deck width of 1.9 m. The suspension system is entirely symmetrical about the longitudinal bridge axis. At mid-span the suspension chain is 1.1 m above the deck and follows a catenary line up to 2.2 m above the deck at the ends of the bridge (i.e. the cast iron masts which are 2.9 m high). Each wrought iron suspension chain consists of individual eye-rods (1 m long, rectangular cross-section measuring 31 × 14 mm). These eye-rods and the vertical wrought iron hangers (rectangular cross-section 13 × 13 mm) which carry the deck are pinned together by means of connection plates (Fig. 7). Each suspension chain runs through the mast (Fig. 8) and is anchored to the abutment. The longitudinal stabil-

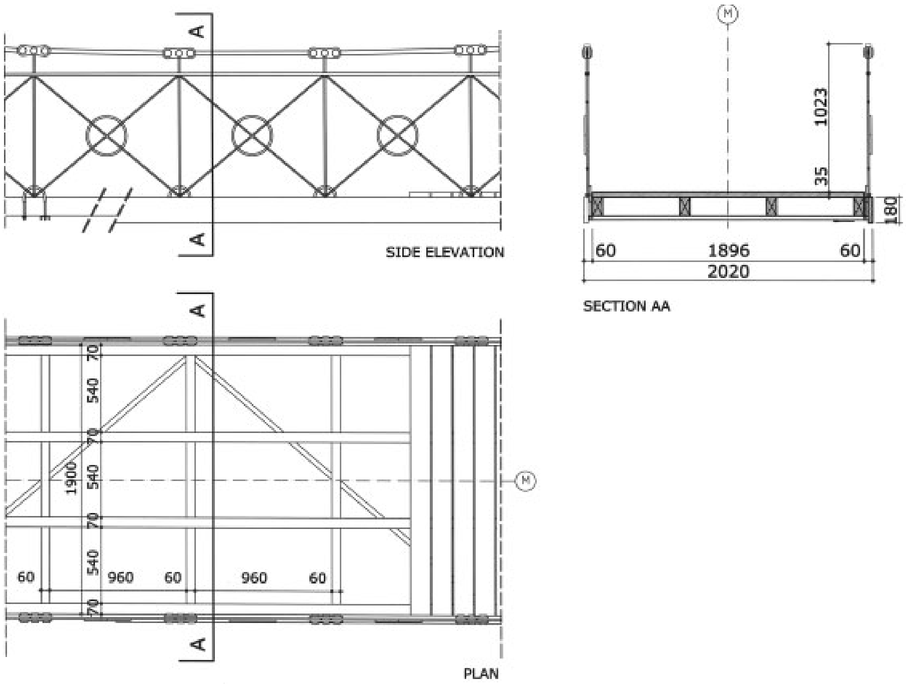

Fig. 2. Construction details of bridge deck and handrail in their current state

Fig. 3. Archive photo of the private suspension bridge at castle Wissekerke in 1905

Fig. 4. Archive photo of the Vilain XIIII family on the castle grounds in 1914 (courtesy of De Wilde, M.)

Fig. 5. *Current state of the suspension bridge (2003)*

Fig. 6. *View of the suspension bridge deck (2006)*

ity of the system is guaranteed by a strut and tie configuration fixed to the abutments. The transverse stability of the bridge is ensured by the mast portal frames on both banks and the wind bracing within the deck.

The current bridge deck consists of wooden boards fixed on four parallel beams along the longitudinal axis of the bridge. These beams are supported every metre by steel channel sections attached to the vertical hangers at their ends (Fig. 2). To analyse the connection between the vertical hanger and the channel section further, the wooden side board had to be partially removed. Fig. 9 illustrates how a hoop has been welded onto the vertical hanger and the diagonal bars of the railing. Bars with screw threads are welded to the hoop to attach the channel section with a bolt.

This connection of the bridge deck to the vertical hangers attracts our attention. Since U-bars could not yet be fabricated and the process of welding had not been invented in 1824, one can conclude that the bridge deck and the adjoining connections are not original [5]. Further inspection reveals that the hangers have been cut off in the past. The æ-lab team assumes that these hangers were originally fixed directly to the wooden beams. However, all other elements – the catenary cable, the portal masts and the railings – are authentic.

The way *J.-B. Vifquain* interwove the railing with the structural elements is remarkable for this bridge design. By forming diagonals in the railing, he stiffened the suspension bridge and reduced the movements induced by crossing pedestrians. This solution is not only very efficient from a structural point of view, but it leads to a very lightweight and elegant bridge.

3 Bridge pathology

By 1989 the last descendant of Viscount *Philippe Vilain XIIII* had left the castle. From that moment on Kruibeke council has invested in the purchase of the castle, the park and finally, in 2006, the bridge. The council opened the premises to the public in 1989. One year later, in 1990, the bridge – listed as a historic monument since 1981 – was closed to the public for safety reasons.

Currently, the bridge is in a very bad condition due to its exposure to the elements and lack of maintenance. The abutments have subsided, which has led to distortion of the deck and the metal railings (Fig. 7). All ironwork is corroded, several nuts and bolts are missing, four hangers are broken and one cast iron column shows a crack due to corrosion of the wrought iron suspension chain that passes through it (Fig. 8).

The investigation of the paint layers, which was carried out to reveal the original colour scheme of the ironwork, confirms the poor maintenance, even in early times. Fig. 10 shows the successive layers of paint on a column element (left) and a suspension eye-rod (right). On top of the undercoat of red lead there is a two-tone colour scheme. All the tension elements of the suspension cables, hangers and railings were dark blue, the compression elements, on the other hand, were dark green; oil-based paints were used for both. In the early 19th century, the bridge was repainted in these colours on a regular basis. This

Fig. 7. *Due to torsion of the bridge deck and corrosion, the vertical hanger has broken. The central bolt is not original (2003)*

Fig. 8. *Cast iron column with corrosion crack (2007)*

Fig. 9. *Construction detail of the connection of the hanger to the channel section, which became visible after removing the side board (2007)*

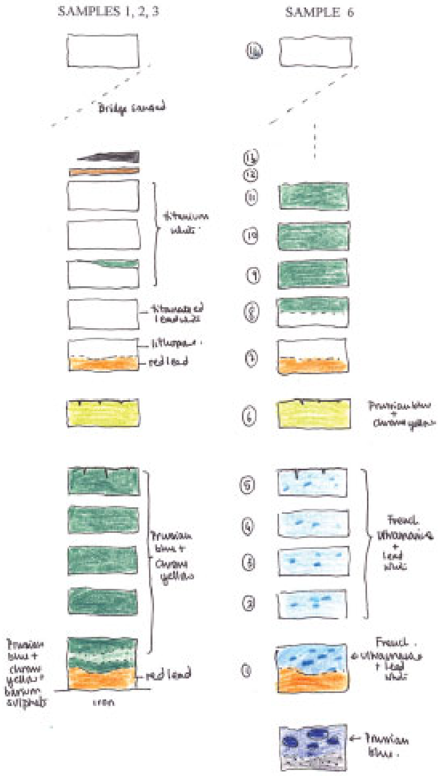

Fig. 10. Reconstruction of the layers of paint on the mast (left) and connector (right) [7]

Fig. 11. Analysing the layers of paint on an eye-rod connector: red lead, dark blue, green, white

two-tone scheme is confirmed by the grey tones of the archive photos (Fig. 3 and 4). The fifth layer is cracked and dirty, which indicates a long period of neglect. The investigation shows that after 1915 the entire bridge was painted bright green. The cracks in this layer reveal a period of neglect again. In the mid-20th century the ironwork was sanded, protected with red lead and the entire structure painted white. The following layer is two-tone again. The most recent white scheme dates from 1990 [6]. Due to the current refurbishment works in progress, the application of a new protective layer has been postponed and the iron elements continue to degrade very quickly (Fig. 6 and 7).

4 Material characterization

Since the Kruibeke council opened the park to the public, the status of the bridge has shifted from private to public. The structure does not fulfil the criteria of the applicable European and local Belgian codes of practice regarding bridge design. The Kruibeke authorities requested a recalculation of the loadbearing capacity.

4.1 Visual inspection

In the first instance, the materials were determined by visual inspection. The ornamented masts have a cruciform section, thick webs and a ground shaft. These characteristics all point in the direction of cast iron. Since the masts are loaded in compression, and since cast iron is very strong in compression, no further experiments are needed at this point.

The fine vertical hangers and eye-rods have a rectangular section, smooth surface texture and sharp corners. Taking into account the date and form, they consist of wrought iron. However, as the properties of wrought iron found in the literature are widely divergent, it is necessary to perform material tests to determine its strength and weldability.

4.2 Hardness and metallographic tests

From a structural point of view, the material tests on the wrought iron should be carried out on a structural element of the bridge such as a main chain or hanger. Unfortunately, this approach is not possible because, firstly, the main chains are essential elements for the bridge's strength and stability and, secondly, the cross-section of the hanger is too small (13 × 13 mm) to perform a representative tensile test. The horizontal bar of the railing (23 × 22 mm) is more suitable for a tensile test. However, the strength might differ from the iron used for the hanger. Nevertheless, a small sample of the broken vertical hanger and a sample of a broken horizontal handrail bar were taken as test samples. Comparison of additional hardness measurements and metallographic tests on both samples will confirm whether or not the results of the tensile tests on the horizontal bar might be extrapolated to the hangers.

The Vickers hardness measurements show that the hanger iron (130 HV 20) is stronger than the railing iron (109 HV 20). This is a typical phenomenon for rolled and hammered sections since forming a thinner section requires more work, and this shows up as a higher strength [5]. Applying the empirical relations to these results leads to a mean ultimate tensile stress of 434 N/mm^2 for the hanger iron and 364 N/mm^2 for the railing iron. Bearing these results in mind, together with the metallographic research, which indicates a similar type and purity of iron for both samples, the use of the tensile test results on the railing sample in the re-analysis leads to a safe approach.

4.3 Tensile test

The railing sample was sawn into three specimens (Fig. 12) and tested, leading to a mean ultimate tensile stress of 350 N/mm^2 (which correlates very well with the empirical value derived from the hardness measurements) and a mean yield stress of 257 N/mm^2 for a mean elongation of 17 % [8]. Since only three specimens were available, the lower 1 % percentile of the population (instead of the usual 5 %) was taken into account to convert statistically the test results into the characteristic strength (table 1).

4.4 Chemical analysis

A chemical analysis was carried out to test the wrought iron for weldability. The two prerequisites for weldability, namely a low carbon content C (0.01 %) and a low carbon equivalent value CE (0.027 %), are fulfilled (table 2). The low sulphur content S (0.008 %) indicates a low risk of hot cracks. Never-

Fig. 12. Three test specimens cut from a sample of wrought iron railing

Table 1. Conversion of the test results (yield stress, ultimate tensile stress and elongation) on three wrought iron rods to design strength fd according to the Eurocode

Wrought Iron	Tensile test			Design strength according to Eurocode				
	Rod 1	Rod 2	Rod 3	s	k	f_m	f_k	f_d
σ_y	259 N/mma^2	245 N/mm^2	268 N/mm^2	11.6	2.3	257 N/mm^2	230 N/mm^2	200 N/mm^2
σ_{UTS}	343 N/mm^2	357 N/mm^2	350 N/mm^2	7.0	2.3	350 N/mm^2	334 N/mm^2	290 N/mm^2
ε	(20) %	15.4 %	16.2 %	2.5	2.3	17.2 %	11 %	

Table 2. Chemical analysis of wrought iron rods [%]

Test specimen	C	Mn	Cr	Mo	V	Ni	Cu	CE	P	S
Rod 1	0.010	0.030	0.010	0.010	0.001	0.030	0.080	0.027	0.112	0.006
Rod 2	0.010	0.010	0.010	0.010	0.001	0.040	0.030	0.021	0.016	0.006
Rod 3	0.010	0.020	0.010	0.010	0.001	0.050	0.200	0.034	0.281	0.011
Mean	0.010	0.020	0.010	0.010	0.001	0.040	0.103	0.027	0.136	0.008

theless, special welding equipment with covered basic electrodes will be needed since the high phosphorous content (0.136 %) leads to a brittle weld seam. In general, butt welding is preferred to fillet welding for wrought iron elements because the presence of slag strings along the working axis increases the risk of failure by lamellar tearing [5].

This material study concludes that the strength of the wrought iron comes close to modern steel S235 and that the elements are weldable under special conditions.

5 Structural re-analysis

Historical research shows that 19th century engineers hardly performed any structural analyses for the main cables or chains and that if analysis methods were applied, they yielded results that were not completely correct. On top of that, connections were not calculated, but proof-tested on site [9].

When re-analysing the bridge's loadbearing capacity with the Eurocodes in mind and taking into account the derived maximum design stress of 200 N/mm^2, the main chain and the connections are able to carry an imposed variable load of no more than 0.4 kN/m^2 on the bridge deck. When comparing this to the imposed load of 5.0 kN/m^2 required according to the standard for public pedestrian bridges, it is clear that even with severe strengthening, the original structure will never be able to carry the required loads. Even if the authorities would agree to a reduced imposed load for this historical monument, e.g. 3 kN/m^2, increasing the strength of the damaged bridge to this level is too optimistic.

6 Structural design

Based on the historical bridge research (section 2), one can conclude that all elements apart from the current bridge deck (built up with channel sections and wooden beams) are authentic. Installing a new structural deck to carry all the imposed loads between the existing historic suspension structure upgrades the bridge to a public bridge while maintaining all the authentic historic elements. This option was preferred to the possibility of closing the bridge to public and restoring it as an architectural object for viewing only.

Opening the bridge to the public inevitably involves the creation of an additional new structure to make the structure carry the higher imposed variable loads (5 kN/m^2) and exhibit an appropriate dynamic behaviour. Several strengthening strategies were worked out: adding supports, positioning a structure underneath the deck, fitting a new structure within the original deck and suspending the deck with cable stays.

The Wissekerke council and the Belgian Royal Commission for Monuments and Sites preferred the third option, where a new steel box girder with timber deck replaces the former non-authentic timber deck. The original deck depth is determined by the timber side board merely 180 mm high. Ideally, the new box girder should fit within this height so that it is almost invisible to pedestrians crossing the bridge and persons viewing from a distance. A steel box girder (Fig. 13) that has a tapered cross-section with a structural depth of 180 mm at the sides and 500 mm on the central axis satisfies all ultimate limit and serviceability states as well as the dynamic behaviour criteria. The lowest point of this varying cross-section lies in the bridge's own shadow.

The steel box girder carries a wooden deck imitating the original wooden deck and is connected at its sides through a sliding connection to the original suspension structure which will be restored. A series of numeric analyses demonstrated that every other type of connection (e.g. hinged or fixed) between original and new structures would transfer a portion of the variable loads into the original structure, resulting in material stresses exceeding the established limits (670 N/mm^2 > 200 N/mm^2). However, to ensure the out-of-plane stability of the original bridge, this sliding connection is an absolute necessity.

Although the girder looks like one continuous structural element with a support at each end, the structural behaviour of the proposed solution does not correspond with this (Fig. 14). Engineering consultants Ney & Partners, appointed in 2007, split the girder into three unequal pieces in the lon-

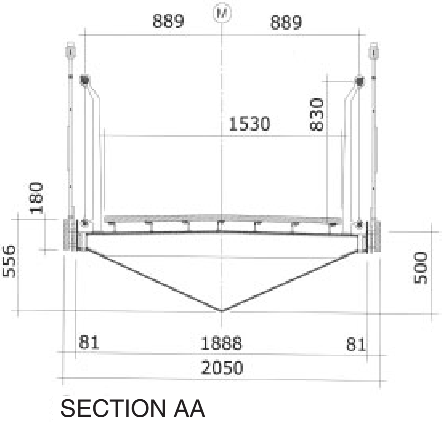

Fig. 13. Section through the new steel box girder and historic suspension bridge [10]

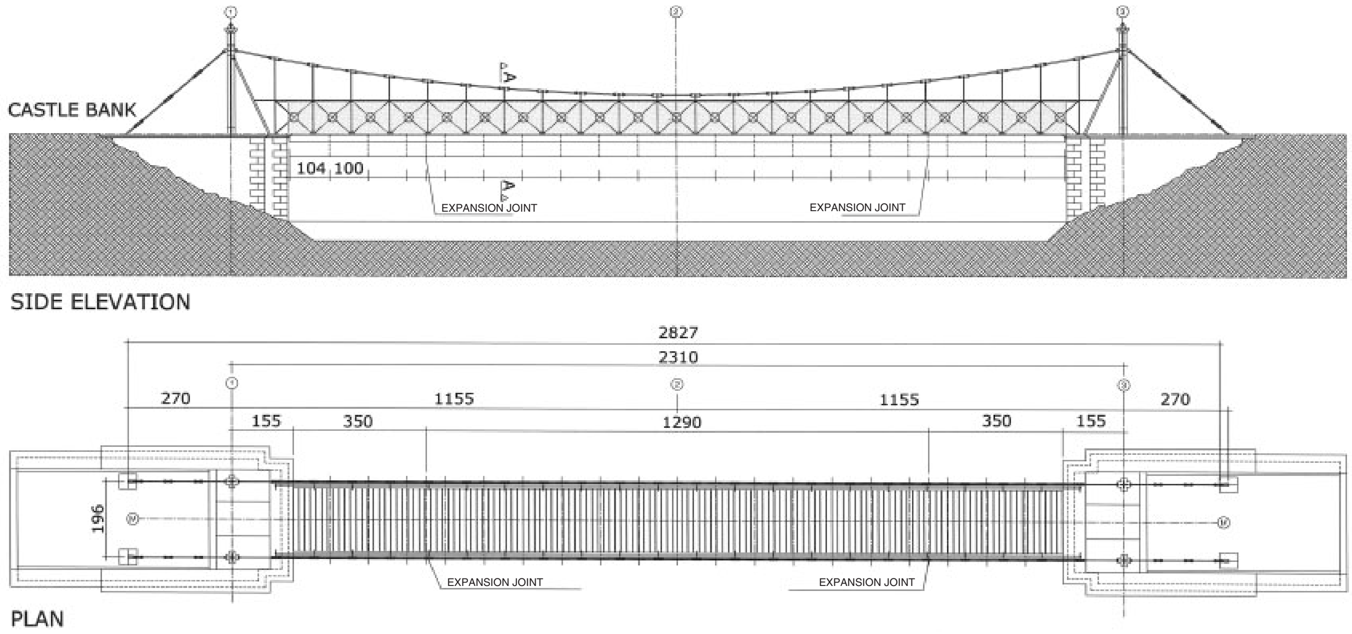

Fig. 14. Side elevation of the upgraded suspension bridge with new steel box girder [10]

gitudinal direction to reduce the internal forces and thus the depth of the box girder, and to ease the transport of the girder element to the site. The two outer pieces are cantilever box girders 3.5 m long with fixed supports at the abutments. Between these two cantilever box girders there is a 13 m long box girder, which is supported by the neighbouring cantilever elements and connected by means of sliding bars that transfer shear forces and allow for thermal movement of the box girder via the expansion joint.

The resulting shallow box girder is compact, hardly visible, easy to maintain and durable because it is completely enclosed and only needs anticorrosion treatment on the outside.

7 Conclusion

The pedestrian bridge at castle Wissekerke is mainland Europe's oldest remaining iron suspension bridge. Since the last descendant of Viscount *Vilain XIIII* left the castle in 1989, the castle park with the historic suspension bridge has been open to the public, leading to a shift in function from private to public. Although the historic iron is of good quality, the authentic bridge cannot carry the present-day imposed loads due to the structural concept and the slender dimensions of the elements used.

To upgrade the bridge, a new, barely visible steel box girder will be placed between the existing suspension bridge elements, replacing the non-authentic former bridge deck, preserving all of the available original material and guaranteeing the future usability of the public park and this remarkable 23 m span suspension bridge.

Acknowledgements

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