Unraveling the design of end-of-the-19th-century riveted connections in Belgium

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UNRAVELING THE DESIGN OF END-OF-THE-19TH-CENTURY RIVETED CONNECTIONS IN BELGIUM

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Keywords
Metal construction, riveted connections, design methods, Belgium, L. Lemaître, JW. Schwedler.

Abstract
The appraisal of existing riveted metal structures generally involves the understanding of their connection details. Unfortunately, it is tough to decipher how historical riveted connections were designed given the obsolescence of the hot-riveting technique. The design of riveted connections has to be analyzed to support the structural assessment and potential interventions. Practicing engineers, architects and heritage care specialists need to gain insight into the original design philosophy of the connection details to preserve both the service life and heritage value of iron and steel structures. Therefore, we unraveled the design of riveted connections by referring to historical literature and carrying out on-site surveys. This paper reveals the design philosophy of structural riveted connections of the end of the nineteenth century in Belgium.

Belgian educator-engineers mainly referred to the findings of French, German and English investigators but two to three decades after their original publication. From the 1880s onwards, the design philosophy of riveted connections took the geometry, the strength and the applied loads into account. However, rules of thumb and simple derivations of the 1850-60s still influenced the design markedly. The study of a built connection detail confirmed that practical matters impacted the as-built geometry of riveted connections. End-of-the-19th-century design methods are delicate to analyze since they combine both empirical and analytical considerations. The study of historical design methods allows to perform overall appraisal procedures of existing riveted structures with more confidence and can contribute towards more suitable remedial works.

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INTRODUCTION

In the foreseeable future, a growing number of historical metal structures will require remedial works. Maintenance, repair and strengthening interventions aim to preserve their state and extend their service life. The appraisal of load-bearing metal structures usually includes their connections. Between the 1840s and 1940s, rivets were the primary fastener used to fabricate these connections through a technique called hot riveting (Jacomy 1983). The hot-riveting technique consists in the heating of iron or steel rivets prior to their driving – installation process. Each white-hot rivet was put in a rivet hole to be driven either by hand or with the help of a riveting machine to connect two or more plates/sections together.

Unfortunately, renovation projects involving the hot-riveting technique come with numerous theoretical and practical issues. In particular, the understanding of the layout of construction details, their original design and underlying theoretical developments is often a difficult task. Yet, it is an essential step as methods of structural assessment require knowledge of the geometry of the connection details. Insights into the original design of riveted connections allow, among others, to clarify their actual layout, identify geometrical parameters non-destructively, and reveal potential design errors.

Therefore, we reviewed historical literature to understand the original design of riveted connections. In particular, we referred to handbooks, treatises and manuals written by Belgian educator-engineers of the end of the nineteenth century. We performed on-site surveys on an existing riveted structure and studied the as-built geometry of a connection detail.

The research presented in this paper unravels the design philosophy of structural riveted connections of the end of the nineteenth century in Belgium. First, the major breakthroughs of French and German investigators who influenced Belgian educator-engineers are discussed. Second, a connection detail of the 1888 Brussels Cinquantenaire Park north hall (Belgium) is re-designed based on former design methods in an attempt to highlight their actual implementation.

DESIGN OF STRUCTURAL RIVETED CONNECTIONS

Current knowledge on the structural behavior of riveted connections results from the genesis and progressive evolution of the theory of riveted connections that occurred during the two past centuries. In the 1830-40s, the prominent experiments performed/supervised by William Fairbairn and Edwin Clark in the UK laid the foundations of the theory of riveted connections, which in turn influenced engineers and theoreticians on an international scale for decades. The large amount of experiments that were subsequently carried out underlines the intense desire of 19th- and 20th-century investigators to get a clear insight into the structural behavior of riveted connections and their failure modes (de Jonge 1945). The results of those experiments characterizing the behavior of riveted connections at ultimate were prerequisites necessary to their design.

The evolution of the design methods of riveted connections is characterized by a balance of power between science and technique. The technique – riveting teams' experience and practices in the shop/on the job site – conditioned first the design philosophy formulated by engineers and theoreticians. Over a period of almost 100 years (1850s–1940s), technique progressively interacted with science – experimental results, ultimate strengths – to develop more accurate methods that were the forerunner of today's standards.

The design of a riveted connection involves a large number of parameters dealing with geometry, strength and applied loads. Those parameters were not, however, simultaneously taken into account within the evolution of the design methods. Prior to the 1880s, the design of riveted
connections resulted merely from geometrical considerations. Parameters needed in a design such as the rivet shank diameter \( d \), the number of rivets \( n \) and the rivets pattern were empirically deduced. A major change in design philosophy occurred at the end of the 19th century. From the 1880s onwards, the design involved the geometry, the strength and the applied loads. The load-bearing capacity of the rivets was eventually related to the magnitude of the applied loads. The rivet shank diameter \( d \) was, however, still deduced by using the empirical formulas peculiar to the period prior to the 1880s. End-of-the-19th-century design methods are delicate to assess since they combine the introduction of more accurate theoretical insights with the use of older commonly used statements and their inconsistencies. (Collette 2014)

**Louis Lemaître’s empirical formula**

Between the 1840s and 1870s, the design of structural riveted connections was based on the methods peculiar to the field of industry that had introduced the hot-riveting technique, namely boilerwork. Boilerwork had laid the foundation for the traditional craftsmanship of hot riveting. The technical know-how had been successively handed down from one boilermaker to another (Jacomy 1983). The design resulted solely on the experience of a given boilermaker. Rules of thumb became publicly spread through the publication of some manuals from the 1840s onwards, such as the manuels Roret (Jullien and Valerio 1846). Riveting practices and techniques of renowned boilermakers had a powerful impact on the design of riveted connections, as experience was synonymous with reliability and seriousness (Jacomy 1983).

In 1856, the French boilermaker Louis Lemaître who originated from La Chapelle-Saint-Denis near Paris published a design table that provided the rivet shank diameter and rivet pitch to be adopted for a range of plate thicknesses (Fig. 1) (Lemaître 1856). The rivet pitch is the distance between the axes of two adjoining rivets (see Fig. 4). By publishing the proportions of riveted connections he commonly used in his shop, Lemaître marked an important milestone within the evolution of the design methods of iron and steel riveted connections.

<table>
<thead>
<tr>
<th>ÉPAISSEUR DES TOLES en millimètres.</th>
<th>DIAMÈTRE DU CORPS DES RIVETS en millimètres.</th>
<th>ÉCARTLEMENT DE CENTRE EN CENTRE en millimètres.</th>
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Figure 1: French boilermaker Lemaître broke new ground in 1856 with his design table providing the rivet shank diameter (centre) and rivet pitch (right) based on the plate thickness (left) (Lemaître 1856).
The widespread use of Lemaître's rules of thumb was possible thanks to the mathematical translation made by Aîné Armengaud the following year in 1857 (Armengaud 1857). Based on Lemaître's table, Armengaud suggested an empirical formula for the rivet shank diameter \( d \) that was valid for any plate thickness \( e \) (Eqn. 1) (Armengaud 1857). This relationship better known as Lemaître's empirical formula predominantly influenced Belgian educator-engineers and theoreticians of the decades that followed (Dechamps 1888; Aerts 1911; Nachtergal 1937).

\[
d = 1.5e + 4 \text{ [mm]}
\]  

(Eqn. 1)

In a design, the plate thickness \( e \) was the starting point of the whole geometry of riveted connections. It allowed to define the rivet shank diameter \( d \) through the \( d/e \) ratio, which can be derived from equation 1. In turn, the rivet shank diameter \( d \) was the geometrical parameter that prevalently conditioned the rivets pattern from the 1840s onwards, and allowable loads calculations from the 1880s onwards (Collette 2014). The \( d/e \) ratio was a convenient pre-design criterion that fundamentally influenced all the design methods of riveted connections between the 1840s and 1940s (Dechamps 1888; Leman 1895; Combaz 1897; Nachtergal 1937).

**Johann Wilhelm Schwedler's method: towards an analytical approach**

The philosophy of end-of-the-19th-century design methods was primarily analytical since the allowable stress design model was effectively implemented and the number of rivets needed per force transmission \( n \) was calculated. Paradoxically, these methods were combined with simple derivations related to the rivets pattern. The theory of the German engineer Johann Wilhelm Schwedler was one of those derivations commonly used by Belgian engineers from the 1880s onwards.

Schwedler broke new ground with his semi-analytical approach dedicated to design riveted connections (de Jonge 1945). Notably published in the issues N°47 and 48 of the *Wochenblatt herausgegeben von Mitgliedern des Architekten - Vereins zu Berlin* in November 1867 (Schwedler 1867a; Schwedler 1867b), Schwedler's discussions dealt with the structural behavior of riveted connections – friction and shear, the joining typologies as well as the rivets pattern (de Jonge 1945). His analyses laid the foundation of numerous subsequent theoretical investigations, even up to the 1940s. Unfortunately, the theoretical inaccuracies and simplifying assumptions inherent to the semi-analytical design methods formulated by the end of the 1860s – like the one of Schwedler – contributed to hold up further progress for a long time (de Jonge 1945).

Until the beginning of the 20th century, numerous Belgian educator-engineers, among others, referred to the convenient theory developed by Schwedler to arrange rivets (Dechamps 1888; Leman 1895; Combaz 1897; Aerts 1911). Schwedler's theory relied on an easy-to-use graphical method that defined the rivets pattern and spacing by means of geometrical considerations. He conceptually subdivided the plates of a connection into several strips of equal width \( s \). Each strip had a loop that surrounded each one rivet (Fig. 2). Schwedler assumed a uniform distribution of the loads within the strips and that the joint behaved in pure shear.

Schwedler's principle belonged to the category of semi-analytical design approaches based on the method of equivalent bearing areas. It presumed that the allowable tensile load of a strip was equaled to the allowable shear load of the rivet it surrounded. Because of theoretical inconsistencies dealing with the shear-tension ratio, the strip width \( s \) depended solely on geometrical parameters, that is, the \( d/e \) ratio.
Equation 2 states the width strip $s$ as a function of the rivet shank diameter $d$ and the plate thickness $e$. The factor $\propto$ equaled to one for the plates of splices in single shear and the outer plates of splices in double shear, and equaled to two for the inner plates of splices in double shear. Being very convenient to use in a design, the value of $d/e$ equals two was often used by practicing engineers as it allowed to simplify the expression of the parameter $s$. (Dechamps 1888)

$$s = \propto \frac{\pi d}{8} \cdot \frac{d}{e} \quad \text{(Eqn. 2)}$$

End-of-the-19th-century design methods improved the design philosophy of riveted connections but revived at the same time inappropriate reasoning by referring to the past theories of the end of the 1860s. The investigations evidenced the recurring presence of a non-negligible time lag – about two to three decades – between the development of new design models and their actual influence on Belgian educator-engineers. Superficial literature reviews, pragmatic considerations – i.e., language barriers, combined with a reluctance to change the methods established so far may explain the delay of transnational theoretical transfer.

**CASE STUDY: 1888 BRUSSELS CINQUANTENAIRE PARK HALLS**

At the request of Belgian King Leopold II, a large-span exhibition hall was designed in 1887 and built in 1888 for the International Gathering of Science and Industry hosted in Brussels at the Cinquantenaire Park (jubilee park). Today the north hall’s principal roof covers an area measuring some 46 m by 170 m (151 ft by 558 ft). It consists of two-hinged, lattice arches with vertical piers of 11 m high (36 ft), and is made of wrought iron (Fig. 3, top left). The building belongs to
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the *Galerie des Machines* typology (machinery hall), a kind of iron and glass building that appeared many world fairs in the second half of the 19th century. Added to the Brussels heritage list in 2004, the north hall is used today as an aviation museum. (Collette 2012)

**Description of the connection detail**

The studied connection detail is part of the bottom-chord member of the lattice arches near their apex (Fig. 3, top left). The bottom-chord member is a built-up section made of flat plates and angles riveted together. This connection detail ensures the continuity of the chord members of the large-span lattice arches in the longitudinal direction (Fig. 3, bottom left).

The geometry and dimensions of the connection detail are shown on figure 3, right. This layout was drawn based on the 1887 original plans made by *Société Cockerill* (Seraing, Belgium), the load-bearing structure manufacturer, and recent on-site surveys (Cockerill 1887). This connection is a butt splice – triple riveted double butt joint – as it connects two plates in the same plane with the use of gusset plates. The continuity of the 250-mm-wide inner plate (9 13/16 in) having a thickness of 10 mm (3/8 in) is ensured by two diamond-shaped gusset plates of that same thickness (Fig. 3, right). The gusset plates are 160 mm wide (6 5/16 in) and transfer the loads through six rivets per force transmission. The nominal shank diameter of the rivets is 16 mm (5/8 in) and the diameter of their round heads equals 28 mm (1 1/8 in).

Figure 3: The connection detail is in the bottom-chord member of the lattice arches, near their apex (left). Cross section (top right) and plan view (bottom right) of the connection detail (authors' collection).
The connection detail is a zigzag-riveted connection given the staggered layout of the rivets. Zigzag-riveted connections were assumed to be stronger than chain-riveted connections since such joining typology ensured a more uniform distribution of the loads (Dechamps 1888; Combaz 1897). The fact that JW. Schwedler advised the arrangement of rivets in zigzag (Fig. 2) and the impact of his theory on Belgian educator-engineers might explain this observation (Dechamps 1888; Leman 1895). Because of the diamond shape of its gusset plates, the connection detail embodies a specific configuration that is the convergent type. Convergent zigzag-riveted connections were – erroneously – considered as an optimal choice and approved by a vast majority of engineers on an international scale (Collette 2014).

**As-built geometry versus end-of-the-19th-century design methods**

It follows from equation 1 that the theoretical nominal shank diameter of the rivets $d$ corresponds to 19 mm (3/4 in) for a plate thickness $e$ of 10 mm (3/8 in). The fact that the rivets are subjected to double shear may explain the lower actual value of $d$, which is 16 mm (5/8 in) (Fig. 3, right) (Dechamps 1888). Three shank diameters were used on the load-bearing structure of the Brussels halls: 16, 18 and 20 mm (5/8, 11/16 and 13/16 in, respectively) (Cockerill 1887).

The connection detail was re-designed based on the graphical method of Schwedler, considering the plate thickness $e$ and rivet shank diameter $d$ of the as-built geometry. The calculation of $s$ allows to define the rivets pattern and the geometry of the gusset plates. The width of the strips $s$ surrounding each a rivet equals 10 mm, that is, around 3/8 in (Eqn. 2, Fig. 2). The total width of the inner plate is then adapted to match the one of the gusset plates. The theoretical design of the connection detail obtained is compared to its as-built geometry on figure 4.

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**Figure 4:** The theoretical design of the connection detail is in line with its as-built geometry, considering the practical matters that rounded up/down the values of the rivet pitch $p$, rivet lap $l$ and edge distance $v$ (authors' collection).
The theoretical total width of the gusset plates is only 6% or 9 mm (3/8 in) larger than their actual width (169 mm instead of 160 mm) (Fig. 4). However, the tighter rivets pattern leads to a total gusset plate length that is 17% shorter than the as-built geometry. Rational and practical matters linked to rivet driving should be also taken into account when comparing the two configurations (i.e., available space needed to satisfactorily drive a rivet). For instance, theoretical values of the edge distance $v$ and rivet lap $l$ were typically rounded up to at least 20 and 25 mm (13/16 and 1 in), respectively, to ease the fabrication of built-up sections (Collette 2014). In particular, the distance between transverse rivet rows would be enlarged in practice given the tight theoretical rivets pattern (Fig. 4). Furthermore, the distance between the two inner transverse rivet rows – three rivets each – of 48 mm would be rounded up to 50 mm. Taking these practical considerations into account, the total length of the gusset plates would almost approximate the actual length of 270 mm (Figs. 3 & 4). Also, the "practical" total width of the gusset plates may be around 180 mm (7 1/16 in), that is, 12.5% larger than their as-built geometry. In any case, the actual design of the riveted connections of the Brussels halls is safe, as a result of the conservative approach and high safety factors of former design methods (Collette 2014).

CONCLUSIONS

This paper addressed the design philosophy of end-of-the-19th-century riveted connections in Belgium. The study aimed to provide insights into the theory, original design and layout of structural riveted connections. The content of historical Belgian literature was investigated and the influence of foreign investigators was highlighted. The geometry of a connection detail dating back from 1888 was surveyed and confronted with contemporary design methods.

Prior to the 1880s, the design leant solely on geometrical considerations. From then on, the allowable stress design method has been actually implemented, taking the geometry, the strength, and the applied loads into consideration. Nevertheless, the prevalent pre-design criterion introduced by Louis Lemaître in 1856, which is the $d/e$ ratio, still played a major role in a design. The more accurate philosophy of end-of-the-19th-century design methods was not fully implemented because of the delayed diffusion and long-lasting impact of earlier theories and their inconsistencies. The graphical design method developed by Johann Wilhelm Schwedler in 1867 was reported by Belgian educator-engineers. Moreover, the re-design of the studied connection detail does indicate that its as-built geometry is in line with Schwedler's method, considering practical considerations that modified the final design. Although being recommended at the time, the configuration of convergent zigzag-riveted connections acts as a stress-raiser towards the rivets of end rows. Consequently, the state of these rivets may be thoroughly inspected on site. To further this research, investigations on different joining typologies of connection details as well as other Belgian riveted structures could be analyzed.

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