Vrije Universiteit Brussel

FACULTY OF ENGINEERING
Department of Architectural Engineering

# RIVETED CONNECTIONS IN HISTORICAL METAL STRUCTURES (1840-1940)

## HOT-DRIVEN RIVETS:
## TECHNOLOGY, DESIGN AND EXPERIMENTS

QUENTIN COLLETTE

Thesis submitted in fulfilment of the requirements for the award of the degree of
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SUPERVISORS: PROF. INE WOUTERS
ASS. PROF. STEPHANE SIRE

ir.quentin.collette@gmail.com

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Rue Guillaume Stocq 42
B-1050 Brussels
Tel.: +32 (0)2 646 90 90
Fax: +32 (0)2 646 90 00
E-mail: info@abceurope.be

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# SUMMARY

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*.

The inspection, structural assessment and intervention strategy of existing riveted connections raise numerous theoretical and practical challenges for decision-makers and workmen – i.e., riveting teams. It is tough to decipher how they were fabricated and designed given the obsolescence of hot riveting. In addition, the inadequacy of available literature makes their structural assessment delicate. Ultimately, hot riveting is a technique hard to master and for which specialists barely exist. Engineers, architects, heritage care specialists and riveting teams all need support when appraising and renovating riveted connections. Which materials and techniques were used to fabricate them? What can be learned from their design? Which parameters affect their structural behaviour?

In an attempt to answer those questions, we reviewed international historical literature to unravel the original technology and design of riveted connections. In particular, we discussed the evolution of the riveting technology by referring to historical patents (1830-1940). To examine the actual use of former techniques and design methods, we assessed the geometry and microstructure of dismantled riveted connections. We also performed shear tests on simple configurations of connections – for which we managed the fabrication – to assess their structural behaviour before and after intervention.

This study provides information relevant for the appraisal of historical riveted connections. It assesses a wide range of parameters that may qualitatively or quantitatively affect their structural behaviour. The research output can help decision-makers and riveting teams. It focuses on standard configurations of riveted connections fabricated through the hot-riveting technique between the 1840s and 1940s in France and Belgium. The study relies on a multidisciplinary approach that brings historical, technological, analytical and experimental results together. The first two parts of the study relate to the technology and design of riveted connections, respectively. The technological part unravels rivet manufacture and installation while the design part discusses the geometry, theory and design methods. The third part reviews the findings of the two previous ones by means of experimental investigations. A closing chapter provides the reader with assessment tools and

intervention recommendations intended for engineers, architects, heritage care specialists as well as riveting teams.

The technology and design of riveted connections evolved markedly between the 1840s and 1940s. The expansion of metal construction required the mechanization of rivet manufacture and installation. Wrought iron was gradually replaced by steel from the 1880s onwards but the use of steel rivets depended on the development of convenient riveting machines. In the 19th century, rivets could be installed either by hand or with a machine. Portable riveting machines supplanted hand riveting from the 1910s onwards. Machine riveting has a positive influence on the structural behaviour of riveted connections. The design of riveted connections was merely empirical before the 1880s and became analytical from then on. Riveted connections were usually oversized because of a high safety level and practical constraints.

Given the major changes in technology and design, appraising the connections of riveted structures built in 1880s–1920s calls for additional care. The analysis of the geometry permits to identify the rivets used and the results of past experiments allow to estimate their load-bearing capacity. Hence, the amount of destructive tests can be reduced. The investigations showed that the strength of wrought-iron rivets complies with present standards. When the structural assessment necessitates the installation of new rivets, the guidelines provided by the study help decision-makers limit the impact of the intervention.

Although further research should be conducted on the theory of riveted connections and the shear behaviour of complex joining configurations for instance, the study adds to our knowledge on historical riveted connections. It contributes towards the preservation of both the heritage value and the service life of historical riveted structures for the decades, and hopefully centuries, to come.

# SAMENVATTING

In de nabije toekomst zal een toenemend aantal historische metalen structuren gerenoveerd moeten worden. Het onderhouden, herstellen en versterken van deze structuren hebben als doel hun levensduur te verlengen. De evaluatie van dragende metalen structuren omvat ook een studie van de verbindingen. Tussen de jaren 1840 en 1940 waren klinknagels het meest gebruikte verbindingsmiddel voor het construeren van verbindingen door de zogeheten *techniek van het warm klinken*.

De inspectie, structurele analyse en interventiestrategieën van bestaande geklinknagelde verbindingen gaan tegenwoordig gepaard met talrijke theoretische en praktische uitdagingen voor het hele renovatieteam, gaande van historici, architecten en ingenieurs tot de werklieden die de verbindingen op het terrein klinknagelen. Inzicht krijgen in hun fabricage en ontwerp is complex gezien de techniek van het warm klinken in onbruik geraakte. Bovendien zorgen de beperkingen van beschikbare literatuur voor moeilijke structurele analyses. Ten slotte is de techniek van het warm klinken moeilijk aan te leren en bovendien zijn er weinig deskundigen. Ingenieurs, architecten, monumentenzorgers en klinknagelploegen hebben nood aan ondersteuning bij de evaluatie en renovatie van geklinknagelde verbindingen. Welke materialen en technieken werden voor de fabricage van geklinknagelde verbindingen gebruikt? Welke nuttige informatie kan men uit hun geometrie afleiden? Welke parameters beïnvloeden hun structurele gedrag?

Om die vragen te beantwoorden hebben we de oorspronkelijke technologie en het ontwerp van geklinknagelde verbindingen bestudeerd door het raadplegen van internationale historische literatuur. In het bijzonder hebben we de evolutie van de techniek van het warm klinken aan de hand van historische patenten besproken (1830-1940). Om de werkelijke toepassing van voormalige technieken en ontwerpmethodes in kaart te brengen, hebben we de geometrie en microstructuur van geklinknagelde verbindingen onderzocht in het labo. Daarenboven hebben we afschuiftesten van eenvoudige configuraties van verbindingen uitgevoerd om hun structurele gedrag voor en na interventie te analyseren.

Dit onderzoek levert relevante informatie voor de evaluatie van historische geklinknagelde verbindingen. Het bestudeert een groot aantal parameters die het structurele gedrag kwalitatief of kwantitatief kunnen beïnvloeden. De onderzoeksresultaten kunnen zowel de raadgevende- als de uitvoerende renovatie- en restauratie experten ondersteunen. De studie legt zich toe op eenvoudige configuraties van geklinknagelde verbindingen die door de techniek van het warm klinken in Frankrijk en België gefabriceerd werden. Passend bij een multidisciplinaire aanpak worden historische, technologische, analytische en experimentele resultaten

samengebracht. De eerste twee delen van de studie hebben betrekking op de technologie en het ontwerp van geklinknagelde verbindingen. Het technologische deel ontrafelt de productie en installatie van klinknagels terwijl het ontwerpluik de geometrie, theorie en ontwerpmethodes belicht. Het derde deel maakt een kritische analyse van de twee vorige mogelijk, dankzij experimenten. De studie wordt afgerond met evaluatie-instrumenten en interventie-aanbevelingen voor zowel ingenieurs, architecten en monumentenzorgers als klinknagelploegen.

In de periode 1840-1940 zijn de technologie en het ontwerp van geklinknagelde verbindingen sterk geëvolueerd. Zo vereiste de groeiende ontwikkeling van ijzeren en stalen constructies een mechanisering van de klinknagelproductie en -installatie. Smeedijzer werd vanaf de jaren 1880 geleidelijk door staal vervangen maar het gebruik van stalen klinknagels hing af van de ontwikkeling van geschikte klinkmachines. In de negentiende eeuw konden klinknagels zowel handmatig als machinaal geklonken worden. Draagbare klinkmachines vervingen het handmatig klinken vanaf de jaren 1910. Het machinaal klinken heeft een positieve invloed op het structurele gedrag van geklinknagelde verbindingen. Hun ontwerp was voor de jaren 1880 enkel empirisch en werd analytisch sindsdien. Door het hoge veiligheidsniveau en praktische redenen werden geklinknagelde verbindingen meestal overgedimensioneerd.

De evaluatie van verbindingen van geklonken structuren gebouwd in de periode 1880-1920 eist bijzondere aandacht gezien de snelle evolutie van hun technologie en ontwerp. De studie toont hoe men door een grondige analyse van de geometrie van de verbindingen, samen met de interpretatie van eerder uitgevoerde experimenten, tot een inschatting van de gebruikte klinknagel en het daaruit afgeleide draagvermogen kan komen. Het aantal destructieve proeven, nodig voor de karakterisering van de verbinding, kan dus verminderd worden. Verder werd aangetoond dat de weerstand van smeedijzeren klinknagels voldoet aan de huidige normen. Indien toch, om structurele redenen, nieuwe klinknagels nodig zijn, worden richtlijnen gegeven hoe de impact van een renovatie in elke stap van het proces, van ontwerp tot uitvoering, verkleind kan worden.

En hoewel er nog verder onderzoek nodig is naar bijvoorbeeld de theorie van geklinknagelde verbindingen en het gedrag in afschuiving van complexe verbindingsconfiguraties, levert deze studie al een belangrijke bijdrage tot het begrip van geklinknagelde verbindingen. Zo draagt de studie bij tot het verlengen van zowel de levensduur als de historische waarde van het erfgoed zodat het bewaard kan blijven voor de komende decennia en, hopelijk, eeuwen.

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# II DESIGN

# III EXPERIMENTS

# ABBREVIATIONS

| | |
|---|---|
| AAM | Archives d'Architecture Moderne |
| ABS | Association Belge de Standardisation |
| AFNOR | Association Française de Normalisation |
| ARCH | Architectural Engineering (dept. of VUB) |
| BI | British Imperial |
| BPD | Belgian Patent Database |
| BPDM | Belgian Patent Database on Metallurgy |
| BPDRT | Belgian Patent Database on the Riveting Technology |
| CH | Chapter |
| CHST | Centre d'Histoire des Sciences et des Techniques (dept. of ULg) |
| CPTC | Chicago Pneumatic Tool Company |
| DIN | Deutsches Institut für Normung |
| DPMA | German Patent and Trade Mark Office (DEPATISnet) |
| DR-D-BJ | Double Riveted Double Butt Joint |
| DR-D-LJ | Double Riveted Double Lap Joint |
| DR-S-BJ | Double Riveted Single Butt Joint |
| DR-S-LJ | Double Riveted Single Lap Joint |
| DTC | Dardelet Threadlock Corporation |
| EC | Eurocodes |
| EN | European Standard |
| EPO | European Patent Office (Espacenet) |
| FF | French Francs |
| HML | Hagley Museum and Library |
| INPI | Institut National de la Propriété Industrielle |
| JFAC | John F. Allen Company |
| LBMS | Laboratoire Brestois de Mécanique et des Systèmes (dept. of UBO) |
| LCC-WT | Lansing Community College – Welding Technology |
| MeMC | Mechanics of Materials and Constructions (dept. of VUB) |

| | |
|---|---|
| MB | Moniteur Belge |
| MIAT | Museum over Industrie, Arbeid en Textiel |
| NAB | National Archives of Belgium |
| NACE | National Association of Corrosion Engineers |
| NBN | Belgian Bureau for Standardization |
| NMBS/SNCB | National Belgian Railway Company |
| OPRI | Belgian Office for Intellectual Property (FPS Economy) |
| RP | Réserve Précieuse (ULB’s library) |
| RSBI | Recueil Spécial des Brevets d’Invention |
| SB | Sustainable Bridges |
| SD | Standard Deviation |
| SETE | Société d'Exploitation de la Tour Eiffel |
| SI | Système International |
| SR-D-BJ | Single Riveted Double Butt Joint |
| SR-D-LJ | Single Riveted Double Lap Joint |
| SR-S-BJ | Single Riveted Single Butt Joint |
| SR-S-LJ | Single Riveted Single Lap Joint |
| TR-D-BJ | Triple Riveted Double Butt Joint |
| TR-D-LJ | Triple Riveted Double Lap Joint |
| TR-S-BJ | Triple Riveted Single Butt Joint |
| TR-S-LJ | Triple Riveted Single Lap Joint |
| UBO | Université de Bretagne Occidentale (University of Brest) |
| UCL | Université catholique de Louvain |
| ULB | Université Libre de Bruxelles |
| ULg | Université de Liège |
| USPO | United States Patent Office |
| UBS | Ultimate Bearing Strength |
| USS | Ultimate Shear Strength |
| UTS | Ultimate Tensile Strength |
| VUB | Vrije Universiteit Brussel |
| WA | Watertown Arsenal |

# SYMBOLS

| | |
|---|---|
| $a$ | number of shear plane(s) per rivet |
| $d$ | nominal rivet shank diameter |
| $d_{driven}$ | driven rivet shank diameter |
| $d_{hole}$ | rivet hole diameter |
| $D$ | head diameter |
| $e$ | plate thickness (ply) |
| $f$ | ultimate strength |
| $f_b$ | ultimate plate bearing strength |
| $f_s$ | ultimate rivet shear strength |
| $f_t$ | ultimate plate tensile strength |
| $f_{ur}$ | ultimate tensile strength of a driven rivet |
| $F_b$ | ultimate plate bearing load |
| $F_t$ | ultimate plate tensile load |
| $F_s$ | ultimate rivet shear load |
| $F_s$ | shear load (CH7) |
| $F_{s,y}$ | yield shear load (CH7) |
| $F_{s,u}$ | ultimate shear load (CH7) |
| $g$ | grip length |
| $G$ | gage |
| $h$ | head depth |
| $l$ | rivet lap |
| $L$ | applied load |
| $n$ | number of rivet(s) per force transmission |
| $p$ | rivet pitch |
| $P_{allow}$ | allowable load per rivet of the joint in shear/bearing |
| $P_b$ | allowable plate bearing load |
| $P_s$ | allowable rivet shear load |
| $P_{s,tot}$ | allowable shear load of the connection |

| | |
|---|---|
| $P_t$ | allowable plate tensile load |
| $P_{t,strip}$ | allowable strip tensile load |
| $R$ | head radius of curvature |
| $R$ | allowable stress (CH5) |
| $R_b$ | allowable plate bearing stress |
| $R_s$ | allowable rivet shear stress |
| $R_t$ | allowable plate tensile stress |
| $R_{t,strip}$ | allowable strip tensile stress |
| $s$ | safety factor |
| $s$ | strip width (CH5) |
| $u$ | elongation |
| $u_y$ | elongation at yield |
| $u_u$ | elongation at ultimate |
| $v$ | edge distance |

# INTRODUCTION

STATE OF THE ART

AIMS AND SCOPE

METHODOLOGY

SOURCES

THESIS OUTLINE

Commuting from San Francisco to the North Bay (Santa Rosa) by crossing the Golden Gate Bridge, reading a book on the Berlin underground, or enjoying the view of Paris from the top of the Eiffel Tower; millions of people have been doing such activities (Fig. 0-1). However, it is a given that those daily activities are only made possible insofar as the structural integrity of these historical metal constructions is guaranteed. In particular, the millions of rivets that were needed to erect these structures constitute a key parameter today. While most of the commuters and visitors remain unaware, the subject is of concern to governmental agencies, road and railway authorities, heritage care authorities as well as to private companies tackling both heritage and safety issues. Historic preservationists, architects and structural engineers involved in the appraisal of existing load-bearing metal structures are faced with challenging issues today and in a foreseeable future.

Figure 0-1: We are daily confronted with historical riveted structures, (left) commuters crossing the Golden Gate Bridge (Nathan Holth, HistoricBridges.org) and (right) visitors inaugurating the Eiffel Tower in 1889 (SETE 2010)

For civil engineering construction, especially for bridges, strength assessment has to address fatigue, seismic and damage analyses as well as changes in traffic conditions. With regard to building construction, the structural appraisal is strongly linked to preservation strategies conducted on industrial and exhibition halls, department stores, railway stations, etc. These applications of riveted structures all require regular inspection and maintenance, and some of them remedial works – repair, strengthening or replacement. The perennial character and/or adaptive re-use of these constructions is one of the central challenges our society is faced with, given the present and future demographic, socio-economic, and environmental pressures.

Today numerous barriers have to be overcome when dealing with the repair or strengthening of existing riveted connections. Being the predominant joining technique between the 1840s and 1940s, hot riveting conditioned the development of iron and steel load-bearing structures. Unfortunately, the bridge and building construction communities have steadily forgotten the know-how regarding the

complex, and now largely obsolete, riveting technology. Nowadays, the hot-riveting technique is expensive and time-consuming. Moreover, very limited information on the design and installation of rivets is available in literature. In addition, it is difficult to accurately predict the actual strength and stiffness of riveted connections, as the quality of riveting is variable. All these reasons explain why, today, rivets are generally replaced by bolts.

> "It is often difficult to carry out a repair using new rivets, as nowadays there is limited remaining experience of the technique. (...) Rivets are usually replaced with high strength friction grip bolts, or proprietary fasteners such as Huck bolts, or tension control bolts." (Tilly et al. 2008, 129–130)

Such remedial works may be considered inappropriate when the riveted connections of an existing structure are an integral part of its heritage value. Therefore, the hot-riveting technique has been re-introduced in renovation practice. The recent rehabilitation of the 1888 north hall of the Brussels Cinquantenaire Park (Belgium) and the 1881/1910 Hays Street bridge in San Antonio (TX, USA) are some fine examples (Fig. 0-2). Unfortunately, renovation projects involving the hot-riveting technique come with numerous issues, for example: the understanding of the layout of construction details and their original design, the identification of the rivet shank diameter, the removal of rivets without damaging the plates, the determination of the adequate shank length to satisfactorily drive new rivets, the driving technique itself, etc. Furthermore, only a few experienced riveting teams – called *riveting gangs* – per country are still able to drive rivets today. Paradoxically, this situation generates highly competitive markets in which practical and technological tricks become "confidential", to the detriment of the sharing of knowledge and know-how.

Figure 0-2: Remedial works carried out on riveted connections of historical metal structures. 2010 renovation of the horizontal trusses (top-left) of the Brussels Cinquantenaire Park's north hall (bottom-left) and 2009 strengthening of the floor beams (top-right) of the Hays Street bridge (bottom-right) (Sparks 2010, 70, 73)

As a consequence, there is a need to study historical riveted connections in order to pinpoint the presence of phenomena affecting their structural behaviour both qualitatively and quantitatively, and to guide actual renovation practices. More fundamentally, a global approach supporting the preservation of the historical significance of the built heritage must be developed, since remedial works should be less intrusive.

Parameters such as the original design and technology used should be taken into account when appraising riveted structures. Given the wide range of iron and steel grades and member classes available at the time, the identification of material properties is a difficult task on its own. Yet, it is an essential step as from on-site low-level appraisal to detailed numerical analysis, methods of structural assessment all require basic knowledge of material properties. 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. With regard to the riveting technology, a better understanding of how rivets were manufactured and installed provides qualitative information on the structural behaviour of riveted connections, and can reveal the origin of potential defects that may detrimentally affect their sustainability.

# 1 STATE OF THE ART

The study of structural riveted connections is not new. As early as in the spring of 1838, the British William Fairbairn had supervised experiments conducted by Eaton Hodgkinson on the strength of wrought-iron plates and riveted connections (Fairbairn 1850); other investigations then followed (Clark 1850; Flint 1892)[1]. Material characterization studies of wrought iron were implemented in both Europe and the US. Engineers and institutions such as Kirkaldy in 1858-61 (UK) or the Watertown Arsenal in the 1880-90s (US) conducted experiments to appraise the mechanical properties of wrought iron, as it was a prerequisite for the design of load-bearing structures and their riveted connections (Bowman and Piskorowski 2004; O'Sullivan and Swailes 2009). Investigations on the behaviour of both the basic material and riveted connections were key preconditions for the development of the theory and design methods of these connections. Test results were then spread through handbooks and design guides intended for student and practicing engineers and architects, as no standards were available yet. At the beginning of the 20th century but more predominantly in the 1930-40-50s, a second pool of original research was carried out, mainly in the US, and especially in the Midwestern US – Illinois, Michigan, and Ohio (Landon 1927; Wilson and Oliver 1930; Cox and Munse 1952). It focused on the shear behaviour of steel riveted connections and the tensile behaviour of undriven and driven steel rivets. These experiments were aimed at assessing the influence of a range of parameters on the structural behaviour of riveted connections such as the steel grade, the joint geometry, the driving technique and the quality of riveting. As for 19th-century experimental investigations, the test results were discussed and confronted with each other (Graf 1941; Schenker, Salmon, and Johnston 1954).

In literature, most of the studies conducted have belonged to the research field of structural engineering. During the first half of the 20th century, the overall research approach related to very detailed analyses discussing the influence of the design and the technology of steel riveted connections on their structural behaviour. The concern in literature peculiar to these last two decades focused, however, on other distinctive topics. The characterization of the fatigue behaviour of existing riveted connections has been the most investigated topic, especially in the field of bridge engineering. The interest shown originates in the assessment of the remaining fatigue life and potential ways to extend it, the identification of critical details, and the need for remedial work recommendations (DiBattista, Adamson, and Kulak 1998a; Imam,

[1] According to the American engineer A.E. Richard de Jonge, the Committee of the Franklin Institute of the State of Pennsylvania (US) had been the first to carry out experiments on riveted connections in 1837. However, the small size of the tested specimens had led to results that could not provide a good basis for general construction (de Jonge 1945, 11–12).

Righiniotis, and Chryssanthopoulos 2007; Larsson 2009; Åkesson 2010; de Jesus et al. 2011; Heinemeyer and Feldmann 2011; Pipinato, Pellegrino, and Modena 2012). Analytical, numerical and experimental research campaigns were carried out to achieve these objectives. In some cases, static evaluations were done but merely as preliminary analyses. Few full static investigations of riveted connections were conducted during the past decades (D'Aniello et al. 2011; Jost 2012; O'Sullivan 2013). Some analyses were also dedicated to the seismic behaviour of riveted connections (Roeder, Leon, and Preece 1994; Sarraf 1996; Gebreyohaness, Clifton, and Butterworth 2012). The focus of almost all of the above studies rests on 20th-century riveted connections made of steel, and only few investigations deal with wrought-iron riveted connections, e.g., de Jesus et al. (2011), O'Sullivan (2013). Additionally, some of those investigations aim to discuss or improve the content of the current standards, for static evaluation (Kulak, Fisher, and Struik 2001; D'Aniello et al. 2011; Jost 2012) as well as for fatigue evaluation (DiBattista, Adamson, and Kulak 1998b; Pipinato et al. 2009). Such approaches are in line with a general observation commonly admitted, that is, the presence of both theoretical and practical inadequacies and lacking information within available standards (DiBattista, Adamson, and Kulak 1998a; de Bouw et al. 2009; Åkesson 2010; D'Aniello et al. 2011). Structural appraisal and renovation guidelines have been developed and published in the form of technical reports to partially fill this gap (SB 2007a; SB 2007b; SB 2007c; Kühn et al. 2008; Tilly et al. 2008).

All in all, the research studies conducted in the field of structural engineering – factually – discuss the experimental and/or numerical results found at the level of the overall behaviour of the connections of a given – group of – structure(s). They often neglect the potential influence of parameters at the level of the joints themselves such as the driving technique used, quality of riveting, geometry of driven rivets, presence of visible and invisible defects, etc. Given the obsolescence of the riveting technique, we may have forgotten the value-added of carrying out more refined and exhaustive studies, as it was done during the first half of the 20th century for instance. An awareness and clear understanding of these parameters and their impact on the structural behaviour can be obtained by investigating the original design and technology of riveted connections.

Next to structural engineering, a few other research fields have directly or indirectly dealt with the analysis of historical riveted connections, for example: industrial archaeology and history of technology (Jacomy 1983; Jacomy 1998; Simmons 1997; Truijens 2001), history of structural engineering (de Jonge 1945; Leslie 2010), and history of materials science (Hooper et al. 2003). Construction history approaches are, however, undeservedly under-represented. The research philosophy of the field of construction history can be interpreted as follows: the conducted investigations aim

to give an answer vis-à-vis current issues by trying to understand how and why a structure was built in a certain way. A multidisciplinary approach and methodology can be used to reach this goal – e.g., archival research, literature review, in situ research, experiments. Unfortunately, multidisciplinary research linking the appraisal of historical riveted connections to their original design and technology is almost absent.

## 2 AIMS AND SCOPE

The present thesis positions itself in the research field of construction history and innovatively brings historical, technological, analytical and experimental approaches together to principally serve the fields of structural engineering and heritage preservation. This multidisciplinary research contributes to add to our knowledge on the structural behaviour of iron and steel riveted connections. It attempts to answer the following questions that still remain partially open:

- Which materials and techniques were used to fabricate riveted connections?
- What can be learned from the original design of riveted connections?
- Which parameters affect the structural behaviour of riveted connections?

The study aims to provide information relevant for the appraisal of the structural integrity of historical riveted connections. A wide range of parameters that may affect their behaviour is investigated and their impact pinpointed. Those parameters range from the rivet bar used for rivet manufacture to the type of tools applied for driving rivets, and include the geometry, theory, strength and design of riveted connections, among others. The thesis output is in line with standard appraisal approaches applied to historical metal structures (Fig. 0-3).

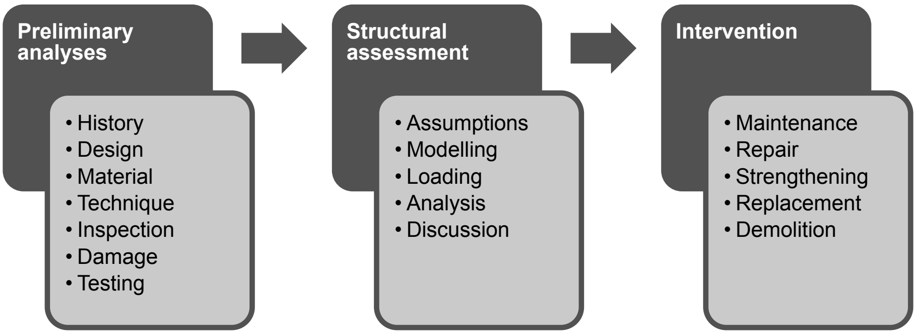



Figure 0-3: Simplified schematic overview of the appraisal procedure of existing metal structures, the study provides input to both preliminary analyses and intervention strategies

It constitutes an input for practicing engineers, architects and historic preservationists when dealing with the structural assessment and intervention strategy of existing riveted connections. With regard to the intervention strategy, the study contributes to the field of heritage preservation by providing recommendations that stimulate adequate and less-intrusive interventions in the form of assessment tools and intervention recommendations. The present work attempts to help those decision-makers involved in the appraisal of riveted connections and emphasizes parameters and phenomena to which more attention should be paid. As a consequence, the contribution of the study hinges mainly on preliminary analyses conducted prior to any structural assessment, but also on the last step, that is, the intervention strategy itself (Fig. 0-3).

The study focuses on riveted connections in the field of load-bearing iron and steel construction. Five main scopes apply to the study. Firstly, the focus of the thesis will be on rivets installed through the hot-riveting technique, as the cold-riveting technique was not suitable for structural work. Secondly, the period investigated covers just over a century, starting in the 1840s and ending in the 1940s. This period corresponds to the heyday of structural riveted connections in iron and steel construction (Jacomy 1983, 12). Thirdly, the analyses primarily relate to the French and Belgian context. Pragmatic considerations and practical constraints – e.g., sources and material availability, language barriers – justify this geographical focus. Fourthly, standard joining configurations of riveted connections are studied, namely splice joints[2]. As emphasized by Cox and Munse (1952, 3), fundamental knowledge on "basic" typologies is needed before any understanding of more complex and realistic ones. Fifthly, the thesis scopes out the static behaviour of riveted connections. Nevertheless, the thesis results are an input for fatigue assessment as well.

## 3 METHODOLOGY

Historical riveted connections are investigated by means of a multidisciplinary and global approach covering almost every step having an impact – direct or indirect – on their structural behaviour (manufacture, geometry, design, and installation). A tripartite methodology is used to implement such approach. Each step of the methodology is embodied by a main part in the thesis. Interacting with each other, these parts are as follows: technology, design, and experiments.

[2] See chapter 1, section 3, for more information.

## PART I – TECHNOLOGY

The technology of structural riveted connections is investigated in Part I. The focus of this part lies primarily on the understanding of the whole riveting process, and the development and progressive mechanization of the technology over time. Rivet manufacture and rivet driving are the two main topics discussed.

The relevance of analyzing the riveting technology is twofold. First, the riveting technology influences the geometry, design and structural behaviour of riveted connections. The significance of these effects is accentuated by the fact that technological processes evolved considerably during the 19th century. Rivet manufacture conditioned the mechanical properties of the fabricated rivet on the one hand, and the geometry of its head on the other hand. Rivet driving impacted significantly on the structural behaviour of riveted connections – i.e., frictional, shear and bearing strengths. Second, the study of the riveting technology and its progressive mechanization over time provides insights into the causes of defects and damages that can be identified on existing iron and steel riveted structures. Actually, rivet manufacture and driving are responsible for the majority of those defects. The analyses of Part I also support the investigations conducted in Part II and Part III.

Technological developments of rivet manufacture and driving are first studied through the content of traditional literature. Since the evolution of the riveting technology involved trans-national technology transfers, international literature is referred to, in addition to French and Belgian publications. Second, the analyses are enriched and completed by the content of historical Belgian patents (1830-1940). Patents reveal precise information – valuable texts and drawings – about the working of the machines and the main technical issues of the time. A database on the riveting technology was set up to facilitate data processing. Studying the Belgian patent data sheds light on international technological development thanks to its large number of patents and patentee's nationalities.

The main contribution of Part I lies in the comparison between the content of literature and patents on the one hand, and the set-up of a patent database dealing with the riveting technology on the other hand. A selection of patents was digitized, and quantitative and qualitative analyses were carried out.

## PART II – DESIGN

The design of structural riveted connections is the second main topic addressed by the thesis. The original geometry of the rivets and the main joining typologies are first presented. Then, the theory conditioning the design is discussed and alimented by the results of experiments conducted within the period covered by the study (1840s-

1940s). Finally, the design philosophy and content of the main categories of design methods are investigated.

Analyzing the design of historical riveted connections supports every step of the overall appraisal procedure shown on figure 0-3: the preliminary analyses, the structural assessment, and the intervention itself. The understanding of the geometry of rivets and the design principles of riveted connections promotes, to some extent, on-site appraisal of existing riveted structures by means of non-destructive techniques. In addition, insights into the theory of riveted connections and how they were assumed to behave help us decipher the actual configurations of the construction details on site. Failure modes, simplifying assumptions and theoretical inconsistencies reveal valuable information on the original design. The – almost forgotten – main findings of the extensive experiments conducted in the first half of the 20th century bring to light the essential influence of key parameters on the structural behaviour. Knowing the presence of those parameters and their effects, the structural assessment of an existing riveted structure can be performed with a higher level of confidence. In addition, it guides the renovation practices of present intervention strategies by valorizing the conclusions and recommendations resulting from past experiments.

Part II uses predominantly the content of French and Belgian sources to investigate the geometry and design of riveted connections. The design principles are put into an international context, as they primarily relied upon prevalent theories and test results spread on an international scale[3]. Moreover, international literature is also referred to, rather for confrontation and validation purposes.

The main contribution of Part II is twofold. On the one hand, the evolution of the geometry, theory and design of riveted connections is drawn up through the content of French and Belgian sources, and enriched by international literature. On the other hand, the learning-from-the-past approach described above allows to apprehend the overall appraisal procedure of historical riveted connections with more confidence (Fig. 0-3).

## PART III – EXPERIMENTS

Experimental investigations are conducted in Part III with the idea of completing the study by confronting theory with practice. The core philosophy of Part III scopes out two complementary aspects that both contribute to support present appraisal procedures. First, it (in)validates the content of historical literature on the technology of riveted connections and their design. Second, it assesses the structural behaviour

[3] In the main, these prevalent theories and test results originated from the UK, France, Germany and the US.

of standard splice joints under shear loading. Experiments are conducted on both dismantled and fabricated riveted connections. The design, manufacturing and driving techniques, quality of riveting, and mechanical properties under static loading of riveted connections are the parameters studied.

The actual implementation of the content of historical literature is verified to assess the relevance of the analyses described in Part I and Part II. Actually, the configuration of the built riveted connections may not specifically meet the theory. In addition, the research approach promotes a critical review of the whole design of historical riveted connections that is experimentally assessed – from the shank diameter used to the parameters of strength that directly affected the design. While the design methodology is appraised in Part II, the values of strength on which it is based are investigated in Part III, among others. Finally, the experiments carried out attempt to study the influence of today's renovation practices on the structural behaviour of historical riveted connections.

Part III focuses on end-of-the-19th-century riveted connections made of wrought iron. The decades at the end of the 19th century constitute a key transition period, since they are characterized by major changes in both material use – i.e., switch from wrought iron to steel – and techniques – i.e., switch from hand to machine riveting. Limited information on the microstructure and mechanical properties of wrought-iron riveted connections – their rivets and plates – is available in today's literature (SB 2007c; de Jesus et al. 2011). The design and shear behaviour of wrought-iron riveted connections under static loading remain little known to this day. Actually, available research focusing on these topics dates back to the second half of the 19th century (Clark 1850; Frémont 1906).

The geometry and metallography of hot-driven rivets dismantled from four French and Belgian wrought-iron structures (1880s-1890s) are analyzed to reveal their original design and technology, and appraise their quality of riveting. The content of French and Belgian sources that are contemporary to the investigated period is referenced. Regarding the investigations on the shear behaviour, the former techniques and design methods addressed in Part I and Part II were revived to fabricate wrought-iron riveted specimens. Present renovation practices were used for the fabrication of their repaired equivalents. The shear test results are discussed and confronted with historical literature.

Three main features characterize the contribution of Part III. The confrontation of the results derived from experiments with the content of historical literature is the first feature. The second point of interest consists in the fabrication of wrought-iron riveted specimens in accordance with the techniques, materials and design principles of the time. Finally, the assessment of the quality of riveting and shear behaviour of the

riveted specimens, in the same way as engineers did in the 19th century such as E. Clark (UK), C. Frémont (France) or W. Fairbairn (UK), is the third feature.

# 4 SOURCES

A detailed overview of the sources used throughout the study is provided below. Five main types of sources were referred to: historical patents, (hand)books and standards, papers, theses and reports, and riveted structures themselves.

## 4.1 HISTORICAL PATENTS

Within the framework of research on construction history, the patent record can be used to investigate when inventions were introduced, what problems were considered important, and how technologies changed over time. Belgium and its extensive patent data were chosen to analyze the inventiveness of the riveting technology between 1830 and 1940. Patents were investigated from the 1830s onwards as it corresponds to the independence of Belgium. A patent is defined as a form of intellectual property that grants an exclusive monopoly to its holder – the *patentee* – for using and protecting an invention (material, technique, machine, etc.) during a defined period, called the *patent term*. Before being granted and enforced, the applicant – the inventor himself or his assignee – had to file a patent's application that contained an administrative section (e.g., patent's title, date, applicant's name) and a descriptive section (aims, detailed description and claims), generally with illustrations (drawing, plan)[4]. Unfortunately, historical Belgian patents registered before 1984 cannot be consulted online[5]. From research in the National Archives of Belgium (NAB), a database of around 180 patents dealing with the riveting technology was set up (BPDRT)[6]. Patents were selected based on their title from inventories – compilation of all the granted patents – available at the Belgian Office for Intellectual Property (OPRI): *Catalogue des brevets d'invention* (1830-1854) (Dujeux 1842) and *Recueil spécial des brevets d'invention* (1854- ) (RSBI). Each patent was then encoded and described by a list of parameters, notably a topic and a subtopic. The use of filters – e.g., time period, inventor, topic – eases search queries within the database. Finally, a stratified sample was selected and 120 patents were fully digitized at the NAB and OPRI. To determine how long a patent was maintained,

[4] Additional information on historical patents such as the patent type, the patentee's nationality and profile or technology transfer is provided in chapter 2, sections 1.2.2 and 2.3.2.

[5] See online databases Espacenet of the European Patent office (EPO) and DEPATISnet of the German Patent and Trade Mark Office (DPMA).

[6] The exhaustiveness, representativeness and reliability of the database was validated through a confrontation with two patent databases of the historian Arnaud Péters containing more than 10.000 Belgian patents (BPD 2007; BPDM 2011).

publication lists of abandoned patents[7] provided by the appendices of the *Moniteur Belge* (MB)[8] were consulted at the *Réserve Précieuse* (RP) library of the *Université Libre de Bruxelles* (ULB).

For in-depth analyses of a given invention, the content of Belgian patents was compared to other similar patents registered in other countries such as France (*Institut National de la Propriété Industrielle* (INPI)) or the US (*United States Patent Office* (USPO)).

## 4.2 (HAND)BOOKS AND STANDARDS

The second category of sources chiefly includes handbooks, books, and standards. On the whole, they are relevant for the understanding of the design of historical riveted connections, that is, Part II of the study.

For the period prior to 1950, the majority of these sources are books dealing with the strength of materials and the design of iron and steel structures in general. The extensive experimental investigations conducted by Frémont in 1906 stands out of the pool of available books since it was one of the only study that was fully dedicated to riveted connections (Frémont 1906). Actually, in the vast majority of the cases, the topic of riveted connections is one of the subjects approached in these books. Those are handbooks (Laissle and Schuebler 1871; Dechamps 1888; Aerts 1911; Barberot 1911), some of them are teaching handbooks (De Vos 1879; Leman 1895; Twelvetrees 1900; Jacquemain 1946), providing applied knowledge and practical information on the geometry, theory and design of riveted connections. However, two main drawbacks go together with these sources, namely the absence of references to built structures and the disregard for the topic of the riveting technology. In a more recent past, some books dealing with structural riveted connections within one of their chapters were published, for both design purposes (Rumpf 1964; Kulak, Fisher, and Struik 2001) and appraisal purposes (Bussell 1997; Tilly et al. 2008).

In the 20th century, standards were also published such as the reports of the *Association Belge de Standardisation* (ABS)[9] in Belgium (Gérard 1923; ABS 1941), and their content, discussed by contemporary authors (Nachtergal 1937). To a lesser extent, present standards such as the Eurocodes (EC) are referred to as they support today's practicing engineers for the structural assessment of riveted structures.

[7] Forfeiture owing to non-payment for instance.

[8] Belgian government publication.

[9] Better known today as the *Belgian Bureau for Standardization* (NBN), the ABS was found in 1919 in Belgium (HML 2013).

## 4.3 PAPERS

Papers – journal and conference papers – embody the third category of sources that were referred to. They contain detailed information on the static – and later on fatigue – behaviour of riveted connections, which was generally revealed by means of experiments.

Before 1950, journal papers dealing with the above topic can be found in the following publications, e.g.: *Philosophical Transactions of the Royal Society of London* (Fairbairn 1850), *Annales des Ponts et Chaussées* (Considère 1885), *Annales des Travaux Publics de Belgique* (Cuvelier 1901), *Transactions of the American Society of Civil Engineers* (Flint 1892; Schmitt 1901; Hrennikoff 1934), *Engineering News-Record* (Blackelock 1924; Davis, Woodruff, and Davis 1939), etc. As mentioned in section 1, some papers addressing the fatigue behaviour of riveted connections were published during the last decades. These papers are to be found in journals such as: *Engineering Structures*, *Structure and Infrastructure Engineering, Canadian Journal of Civil Engineering*, *Journal of Constructional Steel Research*, *Steel Construction*, etc.

In addition, some papers dealing with fatigue assessment were published in the proceedings of international conferences, e.g.: *Nordic Steel Construction Conference*, *Structural Analysis of Historic Constructions*.

## 4.4 THESES AND REPORTS

The fourth category of sources comprises master theses, doctoral theses, reports, calculation notes and renovation records. They constitute an input in the three main parts of the study – i.e., technology, design, experiments. Most of these documents are unpublished. Referring to the content of unpublished documents was essential for this study as they often look at past publications in a new light, unlike literature that generally deals with more recent and contemporary publications.

Before 1950, these sources are basically reports or master theses summarizing the results of experimental investigations conducted at American universities for the major part, as mentioned in section 1 (WA 1883; Landon 1927; Wilson and Oliver 1930; Wilson and Thomas 1938; Cox and Munse 1952). In a more recent past, reports dealing with the appraisal and rehabilitation of historical riveted structures were commissioned, among others, by railway authorities[10] and research centres[11]. Master and doctoral theses have also broached the topic of riveted connections for a

[10] E.g., *National Belgian Railway Company* (NMBS/SNCB).

[11] E.g., the European Commission's *Joint Research Centre* (JRC) and *Sustainable Bridges* research project (SB), the *Joint Transportation Research Program* (JTRP) at the Indiana Department of Transportation and Purdue University.

variety of issues during the last decades, in both Europe (Jacomy 1983; Larsson 2009; O'Sullivan 2013) and the US (Hooper 2003; Jost 2012). Finally, calculation notes and renovation records of existing riveted structures made by engineering offices and building agencies – e.g. the *Belgian Buildings Agency* – provided valuable information as well.

## 4.5 RIVETED STRUCTURES

The riveted structures themselves are the fifth category of sources. Information embodied in existing riveted connections, their design and materials, is essential to better understand historical structures. Riveted samples were required for the geometrical and metallographic investigations performed in Part III.

The hot-driven rivets analyzed were dismantled from the following four French and Belgian wrought-iron structures (1880s-1890s): Louhans bridge (1883, Louhans, France), Lambézellec bridge (1893, Brest, France), Cancale pier (1897, Cancale, France), and Brussels Cinquantenaire Park halls (1888, Brussels, Belgium).

## 5 THESIS OUTLINE

As introduced in section 3 above, the spinal column of the thesis is composed of three main parts, namely: **PART I – Technology**, **PART II – Design**, and **PART III – Experiments** (Fig. 0-4). Each main part contains one or more thematic chapters abbreviated as *CH* from now on. Analyses conducted in the body of each chapter aim to answer a selective list of starting questions.

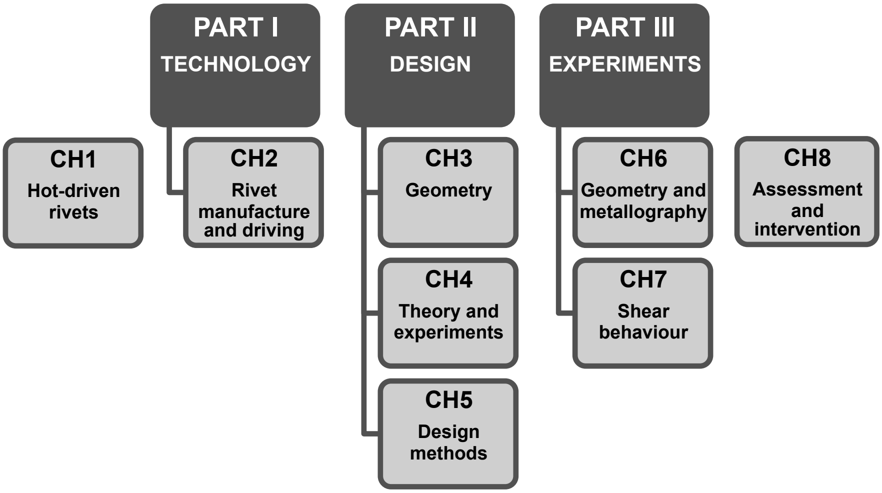



Figure 0-4: Outline of the thesis' main parts and chapters

**Chapter 1** provides background information for the three main parts of the study. After a factual definition of the components of a riveted connection and the hot-riveting technique, the context and development of rivets as a structural fastener in the field of iron and steel construction are presented.

**Chapter 2** reveals steps involved in the overall riveting process (1840s-1940s). Embodying the first part of the study, which is the riveting technology, the two main aspects addressed are rivet manufacture – rivet material, manufacturing techniques – and rivet driving – perforation of the plates, rivet heating, driving techniques. The mechanization of rivet manufacture and driving and its evolution over time is drawn based on literature and historical patents.

**Chapter 3** introduces the second main part of the study – the design – by analyzing the geometry of riveted connections. At the level of the rivet itself, standard shank diameters as well as the proportions of the rivet heads are studied. At the level of the riveted connections, the different types of splice joints and their layout are presented. Rivets pattern and spacing provide background information for the failure modes and empirical design methods discussed in CH4 and CH5, respectively.

The second chapter of Part II deals with the theory of riveted connections that conditioned their design. **Chapter 4** reviews the results of past experiments and pinpoints the influence of parameters – including the ones discussed in CH2 and CH3 – on the structural behaviour of riveted connections. Chapter 4 provides the material necessary for the results discussion of the experiments carried out in Part III (CH6 and CH7).

The design methods of riveted connections are addressed in **chapter 5**. They are merged into four categories, that is, empirical methods, semi-analytical methods, analytical methods, and standards. The same framework is applied to each category of design methods for their discussion: philosophy and assumptions, methodology, and rivets pattern and spacing.

In an attempt to (in)validate the content of historical literature on both the technology and design of riveted connections, experimental investigations are performed on dismantled wrought-iron rivets and riveted connections in Part III. **Chapter 6** qualitatively assesses the geometry and metallography of wrought-iron rivet samples (1880s-1890s). Geometrical investigations include the plate thickness, the driven diameter of the rivet shank and the head proportions. Metallographic investigations focus on the grain flow in the shank and the rivet heads as well as on slag area percentages.

After having checked the effective implementation of the former techniques and design principles on historical samples, these techniques and principles are valorized to fabricate wrought-iron riveted specimens for the experimental programme of the next chapter. **Chapter 7** quantitatively assesses the shear behaviour of fabricated wrought-iron single lap joints (2013). The discussion of the shear behaviour is enriched by investigations conducted on the quality of riveting. Involving today's materials and techniques, the influence of remedial works on the shear behaviour of wrought-iron riveted specimens is studied.

Closing the study, **chapter 8** provides a selective list of assessment tools and intervention recommendations in the form of tables, timelines and guidelines. These tools were developed based on the results gathered from Part I, Part II, and Part III. They contribute to help decision-makers involved in the appraisal of riveted connections, and emphasize parameters and phenomena to which more attention should be paid.

After presenting the general conclusions and further research perspectives, a translation dictionary and glossary assist the reader in clarifying a list of key concepts used throughout the study. Finally, a digital copy of the patent database related to the riveting technology and used in CH2 is added in appendix.

# CHAPTER 1

# THE HEYDAY OF STRUCTURAL HOT-DRIVEN RIVETS (1840-1940)

**Chapter 1 provides necessary background information for the three parts of the study. Riveted connections and their rivets are first defined. Then, the introduction and development of the hot-riveting technique is discussed. Finally, structural applications of riveted connections are analyzed.**

**Chapter 1 aims to answer the following questions:**

*How did riveted connections condition the field of iron and steel construction?*

*Which are the structural applications of rivets?*

# 1 DEFINITION OF RIVET

A rivet consists of a first **rivet head**[1] – called manufactured head or **shop head** – formed by crushing the end of the cut segment of a cylindrical bar iron or steel called **rivet shank**. Rivet manufacture could be a manual or mechanical operation conducted on the job site or in the shop, either through the cold- or hot-forming technique. Geometrical parameters defining a manufactured or **undriven** rivet are the rivet shank diameter $d$, the head diameter $D$, the **head depth** $h$ and the head radius of curvature $R$ (Fig. 1-1). The rivet head in the form of a spherical cap – the **round head** – was the most common one for structural applications.

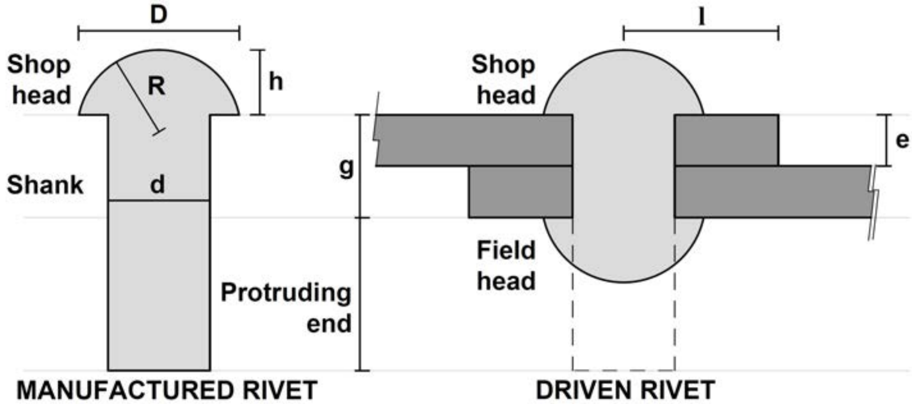



Figure 1-1: Geometrical parameters defining a rivet (left) and a riveted connection (right)

As broached in the introduction, the study scopes out the hot-riveting technique. Hot riveting means that the rivet is heated before being installed, i.e., **driven**. Hot riveting involved three steps. First, the plates to be joined were generally subpunched or pre-drilled. Undersized rivet holes to be widened were then reamed or re-drilled in the shop or field once the plates were hold together by installation bolts to guarantee a secure fit. Then, the forge boy – the **rivet stoker** – heated the rivet in a small **furnace** until it took on a **cherry-red** to **white-hot** colour (950 °C to 1100 °C). The **rivet passer** could toss the hot rivet to the **rivet catcher** who caught the rivet with **tongs** and put it in the rivet hole. The final step is the rivet driving itself, that is, **upsetting** the rivet shank in the rivet hole and form the field head. Prior to driving, the **holder-on** (person) had to **buck up**[2] the rivet on the shop side with a **holder-up**

[1] French and Dutch translations of terms in bold are provided at the end of the study. Technical terms are also shortly defined in a glossary, see the translation dictionary and glossary.

[2] To hold in place.

(tool). The **riveter(s)** could then form the second rivet head – the **field head**[3] – on the **protruding shank** end of the rivet (Fig. 1-2, top). Rivet driving was manually and later mechanically operated. With **hand riveting**, the field head is formed with a hand-held hammer – a **riveting hammer** – equipped with a **rivet snap** at its end (kind of die) (Fig. 1-2, bottom). With **machine riveting**, the rivet is driven by a riveting machine fed by steam, hydraulic or pneumatic energy. Depending on the riveting technique used, the rivet is thus either **hand-driven** or **machine-driven**[4]. The team generally composed of the rivet stoker, the rivet passer, the rivet catcher, the holder-on, and the riveter(s) is called **riveting gang**. Riveting could only be done in wrought iron and later steel materials.

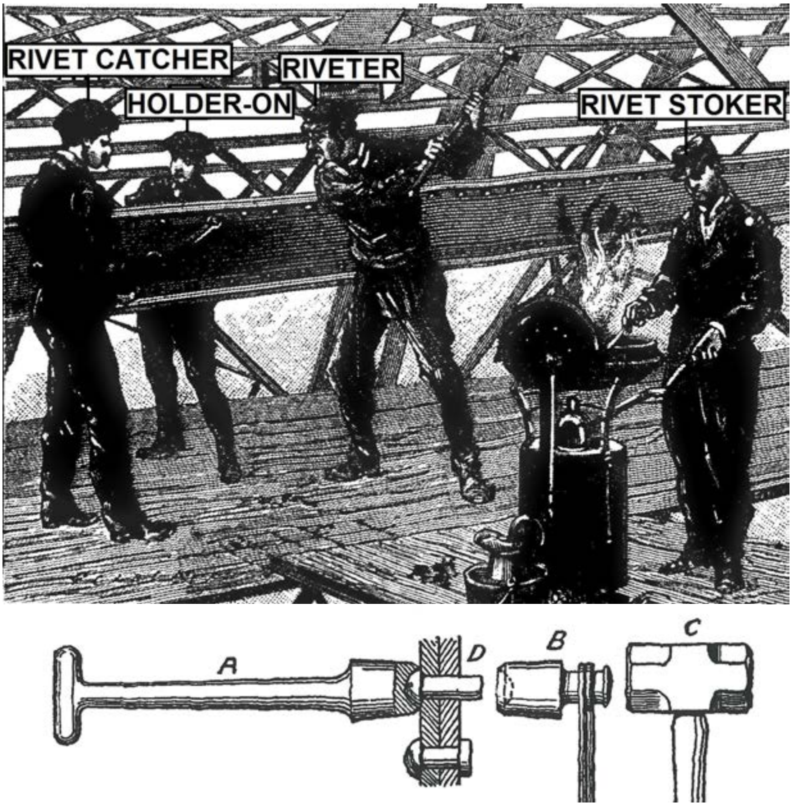



Figure 1-2: (Top) Members of a riveting gang and (bottom) riveting set of hand riveting: (A) the holder-up, (B) the rivet snap (+ tongs), (C) the hand-held riveting hammer, and (D) the rivet being driven (Tissandier 1889; Lineham 1902, 285)

[3] The terminology of "shop head" and "field head" are strictly used to distinguish the first from the second rivet head. Under no circumstances these terms provide any information whether if the rivet heads are manufactured/driven in the shop or in the field, that is, on the job site.

[4] Hand-driven rivets thus don't mean that rivets are driven by a hand-operated machine (e.g., portable air hammer). This configuration falls into the scope of machine-driven rivets (portable and fixed riveting machines).

Unlike cold riveting, hot riveting has significant positive influence on the slip resistance of the connection at the level of the faying surfaces. The frictional strength is provided to the connection by the lateral compression – the **clamping force** – applied by the rivet heads to the plates tightened to one another, called **plies** (layers) (Fig. 1-1). The clamping force is induced by the cooling of the hot rivet that shrinks longitudinally. The **grip length** $g$ is the total thickness of the joint, that is, the sum of each plate thickness $e$ (Fig. 1-1). Provided that shear forces induced by the loads applied on the connection don't exceed the frictional strength of the faying surfaces, the connection is slip-resistant and the rivet, a friction-type fastener. Once the frictional strength is cancelled, the connection belongs to the bearing-type category. The plates are brought into bearing against the rivet shank, and the loads, transferred by shearing of the rivet via single or multiple shear plane(s). Deformations of the rivet shank, the rivet hole and/or the plies then take place. Failure occurs according to one or a combination of the following failure modes: rivet shear, plate bearing (rivet hole), and tension of the plate net cross-section.

# 2 ADVANCES IN FABRICATION

Focused on iron and steel construction between the 1840s and 1940s, the study discusses first the preceding technologies developed for boilerwork and shipbuilding industries.

## 2.1 BOILERWORK AND SHIPBUILDING

The widespread use of the hot-riveting technique is closely related to the development of the Industrial Revolution. Major discoveries and technological developments in mining and metallurgy, transportation, energy supply, machinery, etc., had to be materialized and manufactured. The field of boilerwork was the first to introduce the hot-riveting technique at the beginning of the 19th century. The use of rivets as fastener was a necessity given the limited size of iron plates available at the time. Boilers of steam engines and later locomotives were fabricated through riveting. Secondly, the shipbuilding industry resorted to the hot-riveting technique to respond to the growing expansion of the maritime traffic and commercial exchanges. (de Jonge 1945, 11–14; Jacomy 1983, 11)

> "The most intense development of riveted joints took place in connection with the development of boilers and iron ships, and it can hardly be wondered at that the main part of the literature of these early years [1837-1866] deals, almost exclusively, with these two fields." (de Jonge 1945, 14)

As stated by de Jonge, the two fields of boilerwork and shipbuilding are the birthplace of the hot-riveting technique. Those fields will predominantly determine both the

technology and the design of riveted connections for structural applications, that is, Part I and Part II of the study, respectively.

## 2.2 IRON AND STEEL CONSTRUCTION

Symbolizing the societal mutations generated by the Industrial Revolution, the design of the 1779 cast-iron Coalbrookdale bridge in Ironbridge (UK) might testify to a fundamental change: the progressive substitution of wood with iron as a structural material (Cossons and Trinder 2002; de Bouw 2010). The important total joint thickness of the connections in wooden construction had made the use of rivets as a structural fastener inappropriate so far – e.g., shank buckling, wood splitting (Truijens 2001, 47). Wrought iron was used on a large scale as a structural material from the 1840s onwards. According to O'Sullivan (2013), the mass production of rolled wrought-iron structural sections – e.g., angle shapes, plate irons – was facilitated by the development of the steam hammer and robust rolling mills in the early 1840s (O’Sullivan 2013, 44, 285).The material availability, affordable price (vs. wood) and enhanced ductility (vs. cast iron) of wrought iron were key preconditions for the development of the hot-riveting technique.

From the 1840s onwards, the construction of large-span wrought-iron bridges in the UK announced the early stirrings of a new joining era on an international scale: the use of riveted connections in the field of iron and steel construction (Jacomy 1983, 11; O’Sullivan 2013, 285). The emblematic Conway (1848) and Britannia (1850) tubular bridges both designed by William Fairbairn and the Royal Albert bridge (1859) designed by Isambard Kingdom Brunel are fine examples (Berridge 1970) (Fig. 1-3).

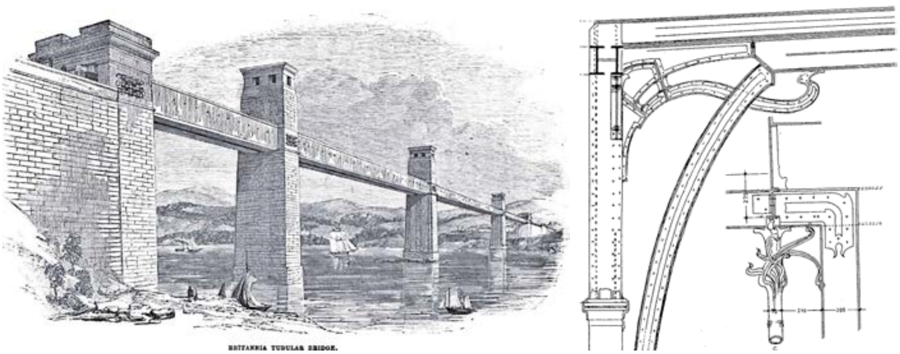



Figure 1-3: The riveting technology was applied in large infrastructure works as well as in private houses, (left) 1850 Britannia tubular bridge and (right) 1899 Victor Horta's *Maison du Peuple* (Williams 1852, 186; Horta)

Next to civil engineering applications such as railway, roadway and pedestrian bridges, riveted connections were also used for short- and medium-span structures such as railway stations and department stores. 19th-century architectural styles

such as Art Nouveau valorized the applications of hot riveting in private housing and public buildings (Fig. 1-3, right). The riveting technique allowed to concretize architects' expectations in terms of special experience, rationality, functionality, hygiene, aesthetic and ornamentation.

In the 1880s and more effectively at the turn of the century, steel became a standard building material that progressively replaced wrought iron (Bussell 1997, 37; de Bouw 2010, 73; O'Sullivan 2013, 286). For skyscraper framing for example, this switch from cast and wrought iron to steel took less than a decade in the US (Leslie 2010, 236).

## 2.3 RIVETS VS. BOLTS AND WELDING

Rivets were required to compensate the technical limitations of the rolling technique with regard to the span length of the sections. Rivets allowed to fabricate large load-bearing elements by connecting L-sections with flat plates for instance. They were often combined with bolts as they concern differentiated structural functions. Load-bearing elements were fabricated with rivets, either via shop or field riveting, and then assembled with bolts – or rivets – in the field. Unlike bolts, rivets can be considered as a permanent fastener, like welded connections. Bolts were privileged when dismantling was required but also for applications for which rivets were inappropriate, that is, when the grip length was too long or for connections between wrought and cast iron for instance. Rivets had, however, some advantages over bolts: material cheapness, improved stiffness of the connections, ability to compensate holes misalignment, etc. (Combaz 1897a, 2(3):110; Truijens 2001, 47; Leslie 2010, 248)

In the early 20th century, field riveting was still considered as an efficient and cost-effective joining technique (Leslie 2010, 249). As soon as the labour cost was an issue later on in the 20th century (Simmons 1997, 15), the overall cost of riveted connections became higher than for bolted connections. Bolts progressively earned the status of leading field fastener in the 20th century (Rumpf 1964, 562). After the Second World War, field riveting progressively fell into disuse (Morgan 1979, 124).

The introduction of the welding technique had also a negative impact on the use of rivets. The welding technique mainly developed in the shipbuilding industry during the Second World War as a way to increase vessels loading capacity – selfweight decrease of 15% to 20% – and easily make them watertight (Truijens 2001, 61–62). In iron and steel construction, early applications of the 1930s also related to the wish of using cost-effective building techniques. The hybrid fabrication of the Lanaye Vierendeel steel bridge in Belgium (1931) combining both shop welding and field riveting is a nice example (Espion 2012, 239). The welding technique became a strong competitor towards hot riveting as soon as its first technical issues such as the base metal quality or the temperature were solved. Numerous disadvantages were

then linked to the riveting technique, for example: higher selfweight – rivets and connecting plates, higher overall cost, cumbersome riveting equipment, noisy job, number of people needed, speed (Simmons 1997, 14; Truijens 2001, 62–63). From a structural point of view, the use of riveting and riveted connections proved, however, its superiority compared to the welding techniques, especially for structural work such as for bridge construction subjected to fatigue loading. Actually, large-scale fatigue tests performed on riveted and welded steel bridges in Germany, Russia, etc., in the 1920-30s underlined the superiority of the riveting technique (Bernhard 1929; Kühl 1934).

In spite of this, improvements in welding and hot-rolling techniques accentuated by economic and practical considerations led structural rivets on a slippery slope in the building sector from the 1930s onwards (Jacomy 1983, 12; Lemoine 1986, 77). Late applications of the riveting technique are observed, however, until the 1960s in Belgian railway bridge construction for instance (Truijens 2001, 62).

## 3 STRUCTURAL APPLICATIONS

Structural applications of hot rivets in iron and steel construction can be divided into two main groups depending on whether they aim to "fabricate/compose" or "assemble". The fabrication of built-up sections used as girders or columns is the first structural application. Assembling these girders and columns together in order to build a given structure – e.g., skeleton frame, portal frame – is the second type of application of hot rivets[5]. In general, built-up applications relate to shop riveting while assembly-type applications, to field riveting.

Typically, open and hollow built-up sections are mainly made of flat plates, angle shapes, L-sections, T-sections or U-sections connected together by rivets. First, large girders in bending were fabricated as built-up sections (Fig. 1-4, top). Later, also columns were built up in wrought iron and shortly later in steel, replacing cast-iron columns that steadily fell into disuse from 1880 onwards (Fig. 1-4, bottom) (Lemoine 1986, 43, 48; Leslie 2010, 248). Solid-webbed sections required rivets to ensure continuity in both longitudinal and transverse directions. In the transverse direction, the constituent plates and sections were connected by rivets to effectively fabricate the built-up section. In addition, web and chord members had to be extended in the longitudinal direction of the built-up section for large span lengths.

[5] These two structural applications will be abbreviated by "built-up type" and "assembly type" from now on, respectively.

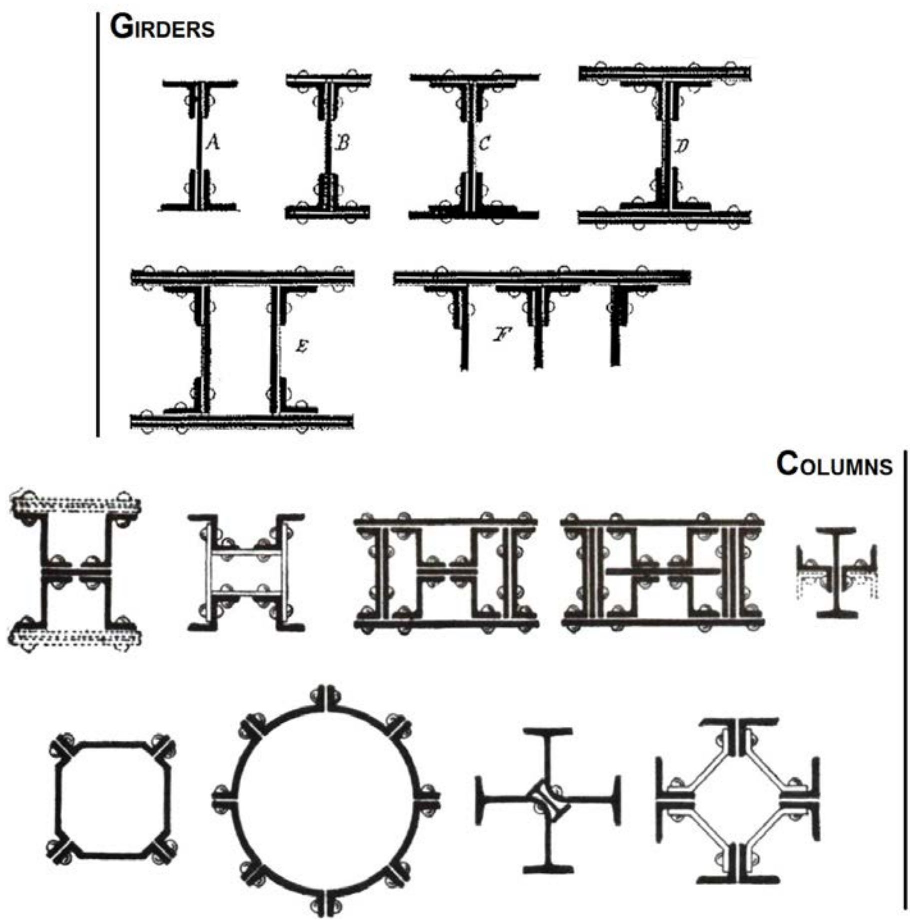



Figure 1-4: The fabrication of girders and columns are built-up applications of hot rivets (Combaz 1897b, 3(7):22; Freitag 1904, 198–99)

Assembly-type applications of rivets relate to the assembly of girders and/or columns, as standard bolts practices. This includes the construction of floors and, more generally, frames of load-bearing structures. Hinged, semi-rigid and rigid framing were obtained by using or combining seat angles, web angles and tee connections to assemble a beam to a column in building frames – i.e., beam-to-column connections (Rumpf 1964, 575–83) (Fig. 1-5, left). By replacing solid webs by a more or less sophisticated network of flat plates, angle shapes and L-sections, trusswork required the use of rivets to connect diagonals and vertical posts to chord members with or without **gusset plates** (Fig. 1-5, right). Trussed arches, girders and portal frames were used for both building construction and civil engineering construction. Trusswork for which chord members are built-up sections thus combines the two structural applications of rivets, that is, the built-up type – chord members' fabrication – and the assembly type – diagonals to chord members. Hence, the distinction

between those two structural applications is not always straightforward, especially when they are combined within the same structural typology such as for trusswork.

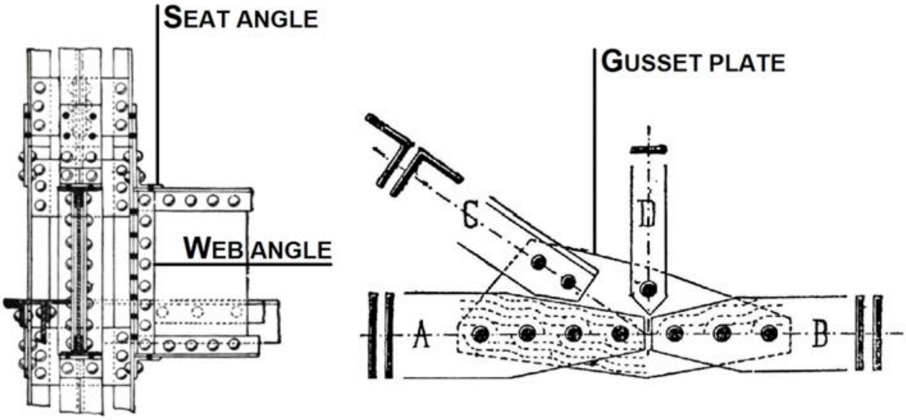



Figure 1-5: Beam-to-column (left) and trusswork connections (right) are two assembly-type applications of rivets (Freitag 1904, 215; Dechamps 1888, fig. 86)

A distinction is made between **splice** and perpendicular joints, regardless of the structural application of rivets. The distinction depends on the angle between the components to be connected. Splice joints basically connect two or more plates together in the same or parallel plane(s) either to ensure the continuity of built-up sections or for assembly matters. There are three main categories of splice joints: lap splices, butt splices and shingle splices (Fig. 1-6). Lap splices do not include any cover plate. Butt and shingle splices connect two or more plates together with one or two **cover plate**(s)[6]. The plates to be connected overlap with each other with shingle splices (Fig. 1-6).

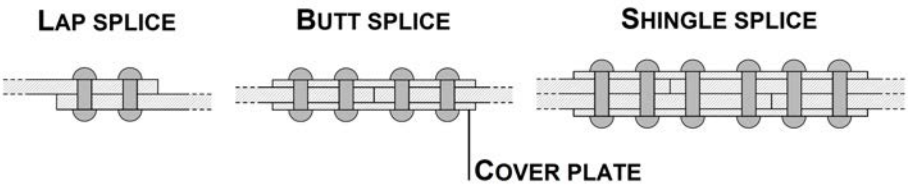



Figure 1-6: The arrangements of the plates and use of cover plates(s) allow to distinguish the different types of splice joints

Perpendicular joints generally involve two or more flat plates and/or built-up sections that are perpendicular to each other. These joints are most of the time constructed with the use of angle shapes, for example: web-to-flange connection (built-up type), beam-to-column connection (assembly type).

[6] Splices joints are further presented and discussed in CH3, section 3.

## 4 CONCLUSIONS – ESSENTIAL FASTENER

A rivet consists of a cylindrical metal shank and a head, generally round, at its end. Iron and steel plates and sections were connected together by rivets. The rivets were heated and then driven either by hand or with a riveting machine. This is called hot riveting. The hot-riveting technique allowed to introduce significant advances in fabrication in the field of iron and steel construction. The advantages of structural riveting – e.g., reliability, affordability, design possibilities – permitted the development of new girder and column shapes, construction details, etc., but also trusswork, rigid connections or self-bracing frames for instance. These innovations were a precondition for the widespread construction of both short- and large-span metal structures.

The description of the hot-riveting technique made at the beginning of the chapter underlined the different stages it involves. Hot riveting is a complex technique that experienced major evolutions over time. Part I of the study broaches the topic of the riveting technology, that is, rivet manufacture and rivet driving.

# PART I
# TECHNOLOGY

*Machine-riveting is now the rule, and hand-riveting the exception.*

(Twelvetrees, 1900, 91)

# PART I
# TECHNOLOGY

## CHAPTER 2
## RIVET MANUFACTURE AND DRIVING

**Chapter 2 embodies the technological part of the study. It aims to draw up the evolution of the riveting technology and understand how it was gradually mechanized over time. It addresses the two main steps of the hot-riveting technique, that is, rivet manufacture and rivet driving. Rivet manufacture discusses the rivet material and the manufacturing techniques. Rivet driving relates to the perforation of the plates, the heating of the rivets and the driving techniques. Literature reviews combined with patent analyses are used to investigate rivet manufacture and driving.**

**Chapter 2 aims to answer the following questions:**

*Which materials were used for rivet manufacture?*

*Why had the riveting technology been progressively mechanized?*

Technological challenges, cost efficiency, productivity, growing demand, improved labour conditions, etc., all these factors directly or indirectly stimulated manufacturers, technicians and engineers of the 19th and 20th centuries to mechanize and automate the riveting technology, that is, rivet manufacture and rivet driving. Over a period of more than one century (1830-1940), the technological processes evolved considerably, which impacted the design and the structural behaviour of riveted connections.

Technological developments of rivet manufacture and driving are first investigated through the content of historical literature, to be then enriched and completed by information provided by historical patents. As mentioned in the introduction of the study, the content of historical Belgian patents is valorized by the database that was set up (BPDRT). The database contains around 180 patents dealing with the riveting technology between 1830 and 1940.

A patent testifies to an act of invention. Invention, however, does not necessarily mean innovation. Only when a patent was commercialized and effectively used in practice could it be defined as an innovation: its quality, relevance and diffusion within the industry having been proved. No technical patentability requirements – e.g., novelty, relevance, quality, non-obviousness – had to be met in order to be granted a Belgian patent (Péters 2006). As a result, many patents were granted which were not effectively commercialized or used in the industry. In the absence of any other source of information, the patent term and international patenting are relevant parameters to assess the innovativeness of patented machine or technique (Inkster 2003, 182; de Favereau 2011, 364). A confrontation with other sources providing additional information allows to clarify these uncertainties. The manufacturing and driving techniques are analysed in sections 1.2 and 2.3, respectively, by systematically combining historical literature with patents. The patent database supports the quantitative and qualitative analyses conducted in sections 1.2.2 and 2.3.2.

## 1 RIVET MANUFACTURE

Rivet manufacture is defined as the process of transforming a cut segment of round bar iron or steel into a rivet. The manufactured rivet obtained – called **undriven** rivet – is made of a rivet shank and a shop head at its end (see Fig. 1-1, CH1). Different materials and techniques were used for rivet manufacture. The overall process conditioned the mechanical properties of the manufactured rivet on the one hand, and the final geometry of the shop head on the other hand (see CH3).[1]

[1] As a reminder, the analyses are fundamentally conducted in the viewpoint of the field of iron and steel construction.

## 1.1 RIVET MATERIAL

Until the end of the 19th century, round wrought-iron bars – called bar iron – had been the typical base metal chosen for rivet manufacture. More precisely, a specific type of structural bar iron of better quality was used, which is rivet iron. A material of superior quality was required given the thermo-mechanical treatments induced by rivet heating and driving. As emphasized by O'Sullivan, rivet – and bolt – iron can be considered as a separate structural component type, because of their differentiated material properties compared to bar iron and other member classes (O'Sullivan 2013, 160, 290–91). Actually, both strength and ductility of rivet iron was higher, on average, than for bar iron, plate iron and other sections (angles, tees, etc.) (Fairbairn 1850, 681; Twelvetrees 1900, 60). Like bolt iron, rivet iron was subjected to further hot workings that refined the slag inclusions, which improved its mechanical properties (O'Sullivan 2013, 288).

At the turn of the 20th century, the choice of the base metal was the subject of many discussions and debates as steel became available, next to wrought iron (Van Drunen 1892, 250). Educator-engineers commonly advised to use rivets having slightly lower or at the most the same mechanical properties as those of the plates to be joined (Leman 1895, 197; Combaz 1897, 2(3):115). This general statement can be explained by the fact that the design of riveted connections was based on failure modes[2]. To connect wrought-iron plates together, it was generally recommended to use wrought-iron rivets (Combaz 1897, 2(3):116). As a result, the design philosophy of wrought-iron riveted connections was not in line with the actual mechanical properties of rivet and plate irons. Actually, French and Belgian educator-engineers may have disregarded the difference in mechanical properties between rivet irons and plate irons due to theoretical inaccuracies[3]. To connect steel plates together, several features in iron and steel construction peculiar to the transitional period 1880-1900 discredited steel rivets in favour of wrought-iron rivets. Firstly, the widespread use of steel as a structural material had to face with economic considerations, wrought iron being a cheaper material[4]. Secondly, the turn of the century was directly related to a major technological evolution substituting hand with machine riveting. Steel rivets had to be machine-driven due to the more accurate installation technique they required (Leman 1895, 197). Given the narrow range of driving temperatures for

[2] The plate bearing failure mode, that is, the crushing of the rim of the rivet hole by the rivet shank due to high bearing stresses, explains why rivet material should not be stronger than plate material (see CH5, section 4.1 for further details).

[3] See CH5 for more information.

[4] For example, the French *Galerie des Machines* of 1889, originally supposed to be made of steel, was constructed with wrought iron eventually for reasons of cost: 0,41 FF/kg (FF, French francs) for steel against 0,30 FF/kg for wrought iron (Vierendeel 1902, 220; Crosnier Leconte 1989, 164–95).

which steel rivets could be properly installed, the driving time had to be reduced. Some countries such as Russia even forbade the use of steel rivets to connect steel plates together (Leman 1895, 198). The mature development of riveting machines was a prerequisite for the use of steel rivets. Finally, well-settled construction culture and habits slowed down the switch of rivet material. In countries allowing the use of steel rivets, a lot of practicing engineers were not always enthusiastic about it. Hence wrought-iron rivets could be used until the 1900s (Frémont 1906, 104; Van der Veen 1919, 70). From the 1890s onwards, the construction of large-scale steel structures in France and the UK progressively reconciled engineers with structural applications of steel rivets:

> "Toutefois, il est probable que les grandes constructions en acier exécutées récemment en France et en Angleterre modifieront les idées à ce sujet et que les ingénieurs, montrant alors plus de confiance, généraliseront l'emploi des rivets d'acier dont ils utiliseront plus complètement la résistance." (Leman 1895, 198–99)

In the 20th century, rivet bars made of steel and later high-strength steel were used for rivet manufacture (Nachtergal 1937, 248; Rumpf 1964, 558). In most countries such as the US, the UK or Germany, it was typically advised to use a rivet material of the same or somewhat lower strength than the steel plates to be joined (Schenker, Salmon, and Johnston 1954, sec. I–4; Rumpf 1964, 558).

The table below provides the range and mean values of ultimate tensile strength (UTS) and elongation at failure for rivet iron (i.e., wrought iron), rivet steel and rivet high-strength steel (Tab. 2-1)[5]:

Table 2-1: UTS and elongation at failure of rivet irons, steels and high-strength steels

| RIVET BAR | ULTIMATE TENSILE STRENGTH (RANGE \| MEAN) (MPa) | ELONGATION AT FAILURE (RANGE \| MEAN) (%) |
|---|---|---|
| Rivet iron | 320 - 410 \| 365 | 17 - 36 \| 26,5 |
| Rivet steel | 330 - 450 \| 390 | 22 - 28 \| 25 |
| Rivet high-strength steel | 460 - 600 \| 530 | 18 - 20 \| 19 |

The mechanical properties with regard to rivet iron were deduced from recent literature that compiled and compared test data mainly originating from historical sources on an international scale (Bowman and Piskorowski 2004, 20, 35–36; O'Sullivan 2013, 128, 161). Bowman and Piskorowski (2004) based their analyses on David Kirkaldy's data (Glasgow, UK, 1858-61) and Commander Lester A. Beardslee (US, 1879). O'Sullivan (2013) produced a database of tensile test records on wrought

[5] The figures provided for rivet iron are solely indicative and by no means substitute actual mechanical properties obtained by experiments. They only give an idea of the scope of wrought iron material properties to be expected. Other figures may be found outside the above ranges, given the high scatter of the results.

iron material properties merging both historical test data – e.g., A.H. Emery's tests at Watertown Arsenal, US, 1880s-90s – and modern test data – e.g., Edinburgh Post Office, 1866. These figures corroborate the test results of other contemporary experiments conducted by K. Styffe (Sweden), T. Telford (UK) and Captain S. Brown (UK) for instance (Fairbairn 1850, 681; Twelvetrees 1900, 60).

As for rivet iron, a sufficiently ductile material was a main requirement for rivet steel. Low-carbon steel or mild steel were the typical rivet materials chosen. Other varieties such as manganese, silicon or nickel steel were used to a minor extent. In contrast with wrought-iron bars, the material properties of rivet steel and rivet high-strength steel were more uniform and very few variations are to be observed between various countries such as Belgium, France, Germany, Spain, the UK, the US, Canada (Tab. 2-1) (Leman 1895, 197; Frémont 1906, 143; Wilson and Oliver 1930, 8; Schenker, Salmon, and Johnston 1954, sec. I–2; Rumpf 1964, 558).

## 1.2 MANUFACTURING TECHNIQUES

Based on rivet iron or steel, the rivet could be manufactured either via cold or hot forming. Between 1830 and 1940, the manufacturing techniques of the shop head evolved from manual operations on the job site to mechanically mass-produced rivets in the shop. Rivet manufacture experienced a mechanization in the mid-19th century to meet the social and economic mutations of the time. It rationalized and standardized the many different shapes and dimensions of rivets. Improvements in the working of rivet-making machines were a necessity to solve technical issues affecting the quality of rivet manufacture.

### 1.2.1 MECHANIZATION OF RIVET MANUFACTURE, LITERATURE REVIEW

Prior to 1850, in the field of boilerwork, rivet manufacture was a manual operation and no standardization of rivet dimensions was implemented (i.e., shank and head diameter). The production was custom-made and mainly carried out on the job site. Blacksmiths crushed the end of a cut segment of rivet iron by using a kind of cast-iron anvil called "bombarde" (Fig. 2-1). They quickly crushed the white-hot end via a percussion process by hammering and then finished the work by **riveting over** with a rivet snap to form the shop head. One workman could reach an output of 100 kg manufactured rivets on a daily basis. Productions made in small shops were still to be found as late as in the 1880s, as in Paris for instance. From 1850 onwards, the urgent need to increase production to meet the rising demand led to the progressive mechanization of rivet manufacture, given the growing rise of iron and steel construction. (Frémont 1906, 2–3; Jacomy 1983, 18)

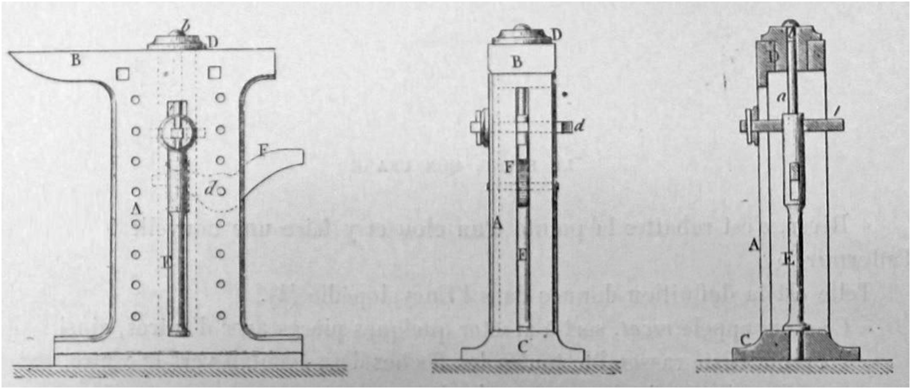



Figure 2-1: Cast-iron anvil used by blacksmiths for rivet manufacture (Frémont 1906, 2)

The development of rivet-making machines used for structural building and civil engineering applications originated from boilerwork. As early as in 1836, the Paris boilermaker Antoine Durenne broke new ground by inventing one of the first rivet-making machines based on the similar working of one of his previous punching machine tools (Fig. 2-2). Durenne basically replaced the punch by a rivet snap. This time the shop head was formed through a continuous pressure rather than a percussion-based working. Durenne's manufacturing machine was a multifunctional device able to produce rivets but also bolts, nails, etc. Shortly later, the same type of punching machine tools also inspired the design of riveting machines like the one developed by W. Fairbairn in 1838 (see section 2.3.1). (Frémont 1906, 4; Jacomy 1983, 90)

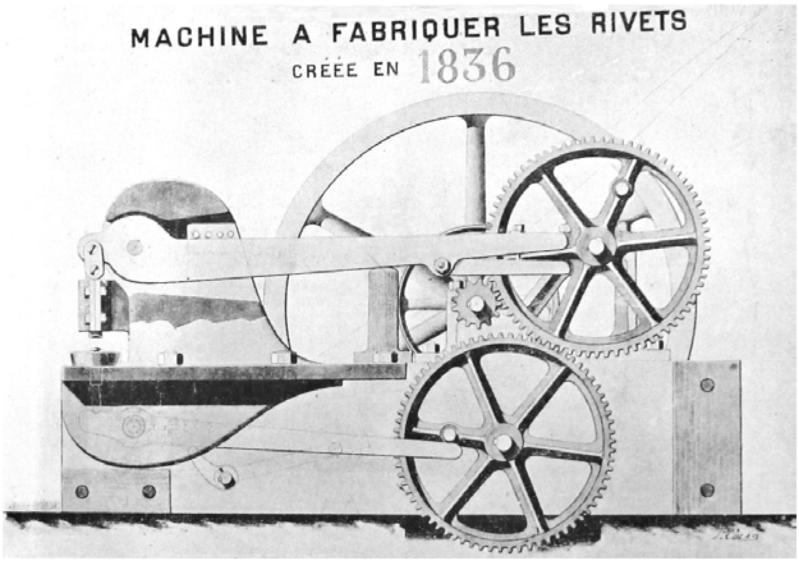



Figure 2-2: Antoine Durenne's rivet-making machine (Paris, 1836) (Frémont 1906, 4)

The first rivet-making machine designed specially for the manufacturing of rivets and bolts was invented, however, by the British Haley in 1855. Haley's machine could reach an output of 1.000 kg of rivets per day[6]. On the occasion of the London world fair of 1862, de Bergue from Manchester already presented a rivet-making machine for mass production. De Bergue's machine could achieve an average daily output of 2.000 rivets per hour. (Frémont 1906, 4)

The specific manufacturing machines developed from the second half of the 19th century onwards clearly were aimed at solving the main technical issues of the time. These improvements dealt in particular with the supply of rivet iron/steel and the ejection of manufactured rivets. Intended to increase output, these rivet-making machines allowed to reduce the needed labour as well as the level of workmanship. In addition, it allowed the many different shapes and dimensions of rivets peculiar to the period before 1850, to be standardized and the variety reduced. At the end of the 19th century, on-site manufacturing had been gradually replaced by the opening of large shops specialized in mass-produced rivets. (Frémont 1906, 3; Jacomy 1983, 18–20)

### 1.2.2 MECHANIZATION OF RIVET MANUFACTURE, BELGIAN PATENT DATA

Patents are a remarkable archival source for the analysis of innovations linked to riveting technology. In particular, they provide precise information – valuable text and drawings – about the working of the machines, their inventors and the international diffusion of their patent(s), which is not to be found in literature. Studying the patented topic and type, the patent content, the profession and nationality of the inventor provides an understanding of the peak-periods, important players (inventor/company), technological challenges, improvements and evolution of techniques, international technology transfers, etc. The large number of patents granted in Belgium, and its attractiveness to foreign inventors, made it exceptional (Saiz Gonzales 2003, 246). Regardless of the field of industry, almost 75% of patents were granted to persons and corporate entities from outside Belgium. This amount was also higher, on average, than in neighbouring countries (de Favereau 2011). As a consequence, the Belgian patent data sheds light on international technological development.

This section addresses the topic of manufacturing techniques through a three-level approach: quantitative analysis, qualitative analysis, and case study. The quantitative analysis of patents (1830-1940) highlights the inventive climate on an international scale whereas the qualitative study deals with technical descriptions and the record

[6] This may correspond to roughly 3.500 to 7.000 rivets, depending on their dimensions.

of modifications to inventions. The case-study level is focused on one given machine that attracts attention.

### QUANTITATIVE ANALYSIS

Within all the patents of the database dealing with the macro topic "rivets", the two most important subtopics are the manufacturing and the driving techniques, with respectively 32% and 33% of the patent registrations. Although equivalent in terms of relative importance, these two subtopics were prominent at different times. An interesting observation is the presence of two peak periods: from 1851-1870, about manufacturing techniques, and from 1891-1910, regarding driving techniques (Fig. 2-3).

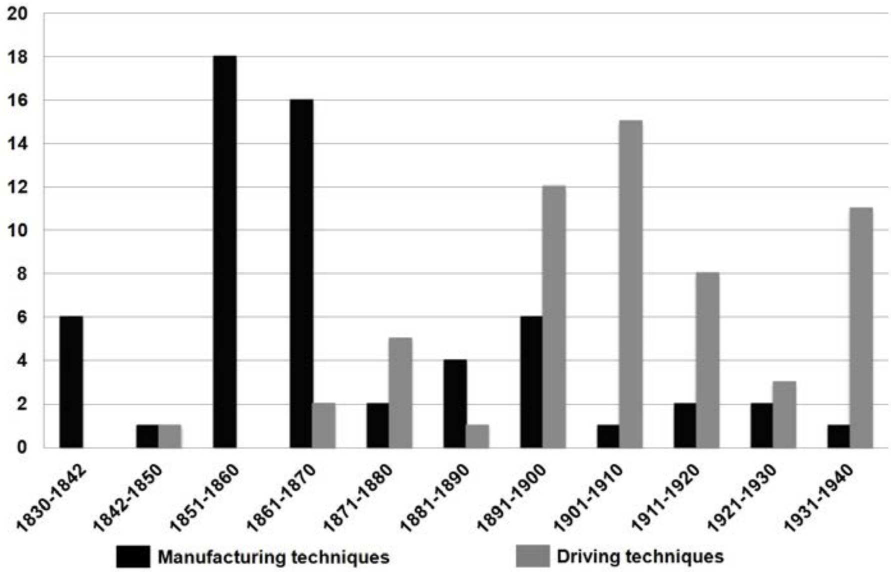



Figure 2-3: Change in number of patents for the two main subtopics of manufacturing and driving techniques registered at OPRI between 1830 and 1940 (BPDRT 2010)

The period 1851-1870 reflects a strong inventive activity that is almost exclusively dedicated to rivet-making machines. Indeed, these patents account for as much as 87% of all the patents listed in the database. This first peak period matches the content of historical literature discussed in the previous section 1.2.1. In the database, the first patent addressing the subtopic of manufacturing techniques is the importation patent registered by the British James Vardy for "appareils mécaniques pour la fabrication de boulons, de clous, de rivets, etc." (Vardy 1838). Vardy patented it in 1838, that is, two years after A. Durenne's machine[7]. (BPDRT 2010)

[7] J. Vardy patented the same rivet-making machine in other countries such as in France one year later (Vardy 1839).

Three patent types were available from administrative point of view. A patent was called an *invention* when it was first applied for in Belgium, irrespective of the patentee's nationality. When the invention or improvement had already been granted a patent in another country, the applicant had to apply for an *importation* patent. Finally, an *improvement* patent was used to refer to an improvement of an existing Belgian patent (invention or improvement). Although the invention patent was the standard model defined by Belgian laws, the improvement patent played a major role as it allowed to grant key innovations based on existing techniques. The importation patent was the economic and industrial leverage used by the different countries engaged in fierce competitions towards the status of the most industrialized country of the world. As a consequence, the importation patent type represented the privileged tool of international technology transfers. (Caron 1984, 101–17)

Figure 2-4 shows the change in patents for manufacturing techniques classified by patent type. The presence of a peak period in the 1850s-1860s, and more precisely between 1856 and 1870, is very clear. A large proportion of importation patents, counting for 36%, characterizes the period 1856-1870. Since a foreign inventor – i.e., non Belgian – could register an invention patent as well, this figure must be revised upwards. Actually, slightly more than 50% of the patents were granted to foreign inventors coming from the UK, the US and France in the main. Improvement patents seem to be under-represented within the whole period 1830-1940 (Fig. 2-4). Again, this factual observation camouflages a totally different reality. As underlined by de Favereau, some invention and importation patents could be entitled "Improvements/modifications for..." (de Favereau 2011, 44). Hence the study of patent titles revealed that half of the patents deal with improvements between 1830 and 1940. (BPDRT 2010)

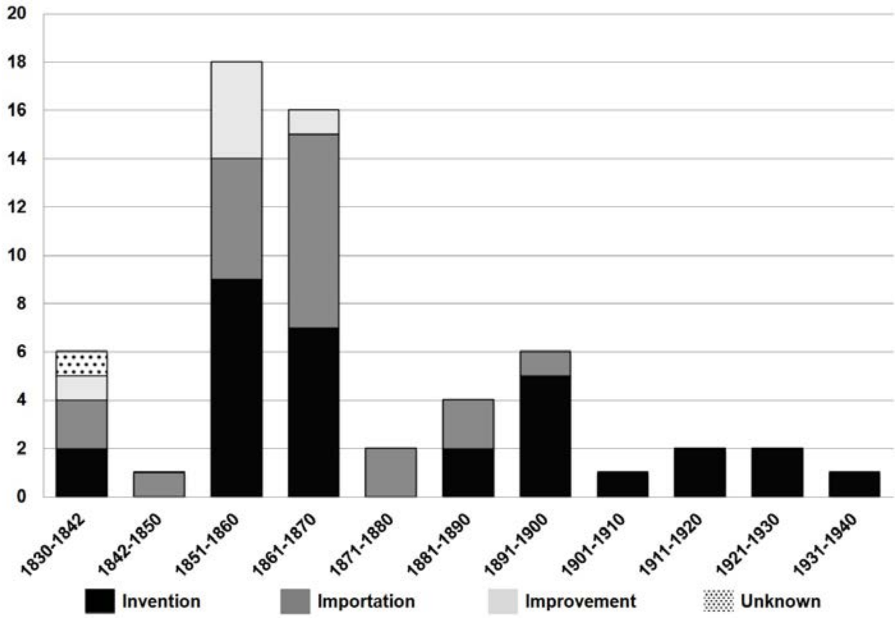



Figure 2-4: Number of patents for the subtopic of manufacturing techniques classified per patent type (invention, importation, improvement or unknown; 1830-1940) (BPDRT 2010)

The strong inventive activity of 1856-1870 was partly due to the institution of the Belgian law of 1854. Before 1854, the applicant could choose one of the three patent terms available – 5, 10 or 15 years – with the application fee increasing with the term, and the entire fee had to be paid as of the application date. Then in 1854, under new legislation, terms and payment procedures changed: the new law spread out the payment of the registration fee, and added an unusual, and long, patent term of 20 years. To maintain the validity of his patent, the patentee had to pay each year a patent annuity that progressively increased over time: a sum of 10, 20, 30 etc. Belgian francs was due for the first, second, third year etc. Thanks to its flexibility, the new legislation contributed to a democratization of invention, generated a considerable increase of patent registrations, and stimulated technology transfers. It attracted many foreign inventors, that is, 50% between 1856 and 1870. The low number of patents peculiar to the 20th century is explained by the substitution effect generated by the second main subtopic, which are the driving techniques[8] (Figs. 2-3 & 2-4). (de Favereau 2011, 30–42)

Like Durenne's device (section 1.2.1), the majority of the rivet-making machines patented (80%) were multifunctional in that they allowed the production of two or more fastener types: rivets, bolts, screws, nails, nuts, plugs, cramps, etc. Nevertheless, the most encountered machine type combined rivet and bolt

[8] See section 2.3.2.

manufacture, accounting alone for half of the patents dealing with rivet-making machines between 1830 and 1940 (BPDRT 2010).

### QUALITATIVE ANALYSIS

The descriptive section of patents reveals the patentee's profession and the detailed working of the rivet-making machine down to the smallest detail. Indirectly, it also provides information on the technical issues of the time and, consequently, the aims and claims of the inventions.

Regardless of their nationality, most of the patentees were self-employed workers between 1830 and 1854, namely technicians, mechanicians, or mechanical engineers. From the middle of the 19th century onwards, "worker-inventor" patentees declined in number, supplanted by researchers and scientists employed by companies (BPDRT 2010). This change and emergence of a more institutionalized research was likely due to the increasing complexity and sophistication of the inventions (Péters 2006; de Favereau 2011).

Belgian patentees contributed towards the mechanization of rivet manufacture. The inventors Auguste Boin and Jean-Baptiste Fondu who notably registered patents between 1855 and 1859 in Charleroi[9] are some nice examples. A. Boin developed rivet-making machines based on the cold-forming technique. Some of his patents were maintained for a longer than average term. For instance, the annuities of his invention patent N°1.656-1.671 had been being paid for ten years (MB 1865; BPDRT 2010). In fact, Boin's property right had been transferred to the company *Société Ve Lambert et Ce*. This patent's long term, combined with the interest shown in it by a company, are good indications of innovativeness. With regard to J.-B. Fondu, he was a mechanical engineer who patented – among others – multifunctional manufacturing machines (i.e., rivets, bolts, nuts). His ironwork shop was renowned for the quality of the products fabricated, even outside Belgium. This is evidenced by the silver medal he won at the world fair held in 1878 in Paris (Adan et al. 1878).

The working of rivet-making machines generally included three steps: cutting a segment of rivet iron or steel for the rivet shank, forming the shop head, and ejecting the manufactured rivet. In most cases, these steps were simultaneously operated on different rivets in production; to each of them corresponded one of the three manufacturing stages. This was achieved by means of a rotating round plate called "porte-clouières" on which multiple openings or "clouières" received each a rivet shank either to be cut, crushed or ejected. Actually, the rotation of the round plate allowed to bring each rivet in front of peculiar parts of the rivet-making machine devoted to a given manufacturing stage (Fig. 2-5) (BPDRT 2010):

[9] Charleroi is a city of the Hainaut province located in the Walloon Region of Belgium.

1. **Cutting the rivet iron/steel**. The rivet iron or steel to be cut was inserted in the machine. Rivet-making machines either worked via the cold-forming or the hot-forming technique, and some of them could even combine these two processes. With the hot-forming technique, the end of the rivet iron/steel was first heated and then cut to create the rivet shank, to be ready for the second manufacturing stage.
2. **Forming the shop head**. One end of the rivet shank was brought in front of a rivet snap similar to the ones used for rivet driving. The shop head was formed thanks to the action of the rivet snap that crushed the rivet shank end via a continuous pressure.
3. **Ejecting the manufactured rivet**. Once the rivet was manufactured, a cylindrical ejection rod pushed the rivet out of the machine. Some machines working by hot-forming were equipped with a water cooling system to avoid overheating of the machine parts – an important issue – and to facilitate the ejection of the rivet.

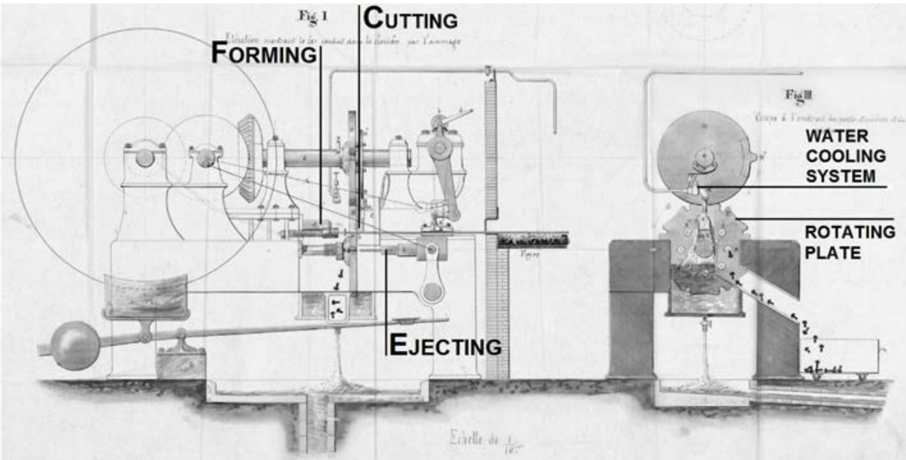



Figure 2-5: Importation patent N°14.529 of J.V. Gauthier for a rivet- and bolt-making machine (Gauthier 1863)

Hence, compared to manual manufacturing techniques, most of the rivet-making machines not only formed the shop head but also mechanized the cutting of the rivet iron/steel as well as the ejection of the manufactured rivet. While the fundamental purpose of these machines was to mechanize manufacture, the presence of technical, practical and economic issues inherent in the development of rivet-making machines had to be solved as well. All in all, the pool of factors justifying the invention of these machines can be merged into four main pools of concerns:

- **Performance**. For reason of cost-efficiency, the mechanization of rivet manufacture allowed to decrease the labour needed and to increase output via mass production.
- **Working**. The improvement of the working of rivet-making machines was a main concern of these technical inventions. It dealt with every manufacturing stage, for example: cutting of the rivet iron/steel, overheating control of machine parts (hot-forming technique), crushing process, phasing of the manufacturing stages, long-term robustness.
- **Quality**. The quality of manufacture was essential as it directly impacted the shape of the rivet. Improvements in quality were the following: non-deterioration of the rivet shank, regularity of the shop head without any defect (e.g., lip surrounding its base), symmetry of the rivet, etc.
- **Flexibility**. User-friendly devices went together with mechanization: standardization of machine parts matching different shank diameters, easily interchangeable parts, easy handling, enhanced automation, etc.

CASE STUDY: J. LE BLANC & A.J. VINCENT'S RIVET-MAKING MACHINE (1872)

The rivet-making machine of Jules Le Blanc and Auguste Jean Vincent was chosen as case study to illustrate an example of clear innovativeness[10]. Firstly, their machine was patented on an international scale (France, Belgium, US). Secondly, it was exhibited at the Paris world fair of 1889 and its manufacturer was granted an award. Finally, their innovation had been widely used in large shops producing rivets in different countries such as France, Belgium or the UK. For the present case study, such additional information was obtained by referring to the content of exhibition catalogs and official journals of international exhibitions. In line with the tradition established by national and international exhibitions, world fairs marked the European innovation landscape from the mid-19th century onwards (Plum 1977; Schroeder-Godehus and Rasmussen 1992; Aimone and Olmo 1993; Adriaenssens 2001). Awarded inventors and manufacturers were a strong sign of technological breakthrough and commercial success. According to Moser, awards were granted to the most efficient and innovative machine tools, which directly provides a way of measuring their intrinsic quality (Moser 2005).

The success story of J. Le Blanc and A.J. Vincent's rivet-making machine originated from the patent N°93.667 registered on 28 December 1871 in France for "un système

[10] Obviously, numerous other rivet-making machines broke new ground and experienced a successful commercialization, for example: J. Vardy (UK), A. Boin (Belgium), V.H. Laurent (France), F.A. Saÿn (France), etc.

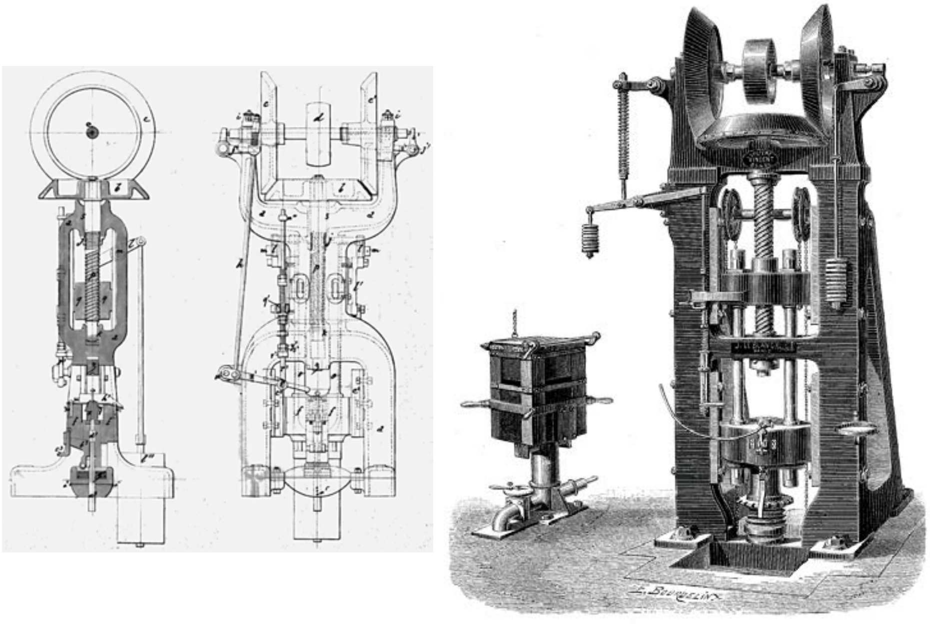
de machine à fabriquer les rivets, les boulons, les couverts en métal et autres pièces à frapper". J. Le Blanc was a French manufacturing engineer who owned a construction shop in Paris, 52 rue du Rendez-Vous, and built the machine. A.J. Vincent, the designer of the machine, was mechanical engineer. Less than one year later, on 3 October 1872, they patented their machine in Belgium with the importation patent N°31.291 (Fig. 2-6, left) (Vincent and Le Blanc 1872). In 1876, they registered a patent N°181.453 entitled "machines for making bolts, rivets, &c." in the US for which the patent system was particularly closed to foreign inventors at that time (Allen 1875; Inkster 2003, 182). In the descriptive text of these patents, they highlighted the technical improvements and superiority provided by the machine, especially compared to contemporary devices of the time:

> "Le but atteint par l'emploi de ce moyen mécanique est de la plus haute importance, car il remplace avec avantage réel, tous les genres de balanciers et de découpoirs employés dans les diverses industries et spécialement dans la fabrication des rivets, (…), où la vis monte et descend avec la charge nécessaire du balancier proprement dit ou du volant destiné à lui imprimer son coup." (Vincent and Le Blanc 1872)

In 1889, Le Blanc and Vincent had the opportunity to exhibit their rivet-making machine at the Paris world fair within the class N°53 on machine tools, part of the main category VI on tools and mechanical industrial processes (Fig. 2-6, right). Actually, the machine they exhibited in 1889 was an improved model derived from its previous versions patented in the 1870s. The construction shop J. Le Blanc won a silver medal for its contribution to the Paris world fair, which corresponds to the third level of prize[11]. (Kreutzberger and Monin 1893, 2:65–67)

As for the patented versions, Le Blanc and Vincent's exhibited a machine called "système Vincent" – Vincent system – that was a multifunctional device manufacturing rivets but also bolts, cramps, etc. The range of applications was wide as it concerned iron and steel construction but also boilerwork, shipbuilding, etc. In most cases, the machine manufactured fasteners via the hot-forming technique, together with a small furnace (Fig. 2-6, right). In contrast with rivet-making machines working with a rotating round plate, the Vincent system crushed the end of pre-cut segments of rivet iron one by one, according to a vertical axis. Here the shop head was formed thanks to a linear reciprocating motion bringing the heated top-end of a rivet shank in front of a fixed rivet snap. The reciprocating motion was generated by the bi-directional rotation of a large vertical screw (Fig. 2-6). The workman intervention was limited to supply cut segments of rivet iron to the machine as the manufactured rivets were automatically ejected. (Vincent and Le Blanc 1872; Kreutzberger and Monin 1893, 2:65–67)

[11] This prize level corresponds to the 40% most innovative and efficient machine tools belonging to the class N°53 (Ply (Le commandant) 1891, 5).



MACHINE A FRAPPER LES RIVETS, SYSTÈME VINCENT

Figure 2-6: J. Le Blanc and A.J. Vincent's rivet-making machine patented in Belgium on 03/10/1872 (left) and its improved model exhibited in 1889 (right) (Vincent and Le Blanc 1872; Kreutzberger and Monin 1893, 2:66)

The technical improvements claimed by Le Blanc and Vincent and reported by official journals of the world fair are heading in the same direction as the trends observed at the level of the whole patent database (Vincent and Le Blanc 1872; Kreutzberger and Monin 1893, 2:65–67). Firstly, the machine allowed to mechanize and automate some manufacturing stages, namely forming the shop head and ejecting the manufactured rivet. Secondly, the easy regulation – without dismantling – of the compressive force crushing the shank end enhanced its flexibility. However, the range of fitting shank diameters and lengths was not unlimited for a given Vincent system, which explains why five machine types were available to take this into account. Thirdly, the handling of the machine didn't require any high muscular effort of the workman. Last, but by no means least, it allowed to reach an average output ranging from 1.200 to 1.800 manufactured rivets per hour.

## 2 RIVET DRIVING

Rivet driving can be defined as the installation process of fastening plates with rivets. To every driven rivet belongs a rivet shank with a shop and a field head clamping two or more plies (see Fig. 1-1, CH1). Prior to the driving stage, the plates had to be perforated, and the rivet, heated. Different mechanized driving techniques were

developed in the second half of the 20th century, replacing the first techniques operated by hand.

> "J'ai toujours été frappé de la grande importance que les ingénieurs attachent, avec raison d'ailleurs, à la bonne exécution du rivetage, dans la construction des ponts comme dans la fabrication des chaudières, et j'ai généralement constaté la négligence des ouvriers dans l'exécution de ces rivetages." (Frémont 1906, 138)

As stated above by Frémont in 1906, structural engineers and workmen members of riveting gangs had contradictory priorities regarding the execution of rivet driving. In particular, his statement points out the existence of unfortunate riveting practices that could detrimentally affect the quality of riveting[12].

## 2.1 PERFORATION OF THE PLATES

The perforation of plates was the subject of the most controversial debates within the evolution of the riveting technology. W. Fairbairn was the first to highlight the influence of plate perforation on the strength of riveted connections as early as in 1838 (Fairbairn 1850, 699). Later in the 1860s-1870s, it led to a major debate opposing two schools of thought: punching versus drilling. While the former advocated the punching technique because of its cheapness and reliability – no plate weakening, the latter were in favour of drilling and contended that the strength of punched plates could be reduced by 20% and more. (de Jonge 1945, 13)

The effects of punching and drilling had been addressed through experiments on unriveted perforated plates in tension and riveted connections in shear, especially in Germany, the UK, France, and shortly later in the US[13]. The protagonists of punching such as W. Fairbairn (1873) or H. MacColl (1875) concluded that the strength of connections with punched holes was not necessarily lower than those with drilled holes. These erroneous results might be explained by inaccurate measuring instruments. Then, the topic had been more thoroughly investigated, particularly in France, by renowned engineers such as J. Barba (1875) or A. Considère (1885) who proved the negative impacts of the punching technique on the mechanical properties of plates as a result of strain hardening. (de Jonge 1945, 13, 66–68, 82)

Strain hardening took place in a narrow zone around the punched hole near its edge, on an annular area ranging from 2 to 4 mm wide, depending on the material quality and – to a lesser extent – the plate thickness (de Jonge 1945, 67, 82). However, the

[12] The quality of riveting primarily depends on the (un)successful character of the execution of the driving operation – e.g., driving temperature, driving time, skills of the riveter. The topic of the quality of riveting is addressed in CH6, CH7 and CH8 in detail.

[13] These experiments and their results are addressed in CH4, section 3, to assess the influence of the perforation technique on the structural behaviour of riveted connections.

impact of strain hardening decreased strongly beyond the first millimetre, as it was reported by educator-engineers of the time:

> "D'après les expériences de M. Barba, la zone de métal altéré par l'écrouissage ne dépasse pas un millimètre d'épaisseur autour du trou par le poinçonnage, quand les tôles n'ont pas plus de 10 millimètres d'épaisseur; elle est un peu plus étendue, suivant M. Considère, quand les tôles sont plus épaisses." (Dechamps 1888, 127)

The above issue was closely related to the importance of using ductile material for riveted connections, as it was stressed by turn-of-the-20th-century educator-engineers (Leman 1895, 177; Frémont 1906, 81; Zwiers 1916, 47; Van der Veen 1919, 65).

All in all, structural, practical and economic matters came together to condition the use of the various perforation techniques available. Those are summarized below:

- **Drilling**. From a structural point of view, everyone agreed that drilling was the best perforation technique. It provided better results and didn't weaken the plates. It was even possible to drill multiple holes simultaneously. However, full drilling was too expensive, because of the tools and amount of labour it required. As a consequence, the full drilling technique was rarely used. (Dechamps 1888, 127; Leman 1895, 178; Combaz 1897, 2(3):110)
- **Punching**. Punching was the easiest, fastest and cheapest perforation technique (Combaz 1897, 2(3):110; Leman 1895, 178). The tapering form of the rivet holes – truncated cone shape – consequent to punching was favourable to a good **upset** of the shank in the hole while being driven (Aerts 1911, 24). Nevertheless, the technique was not recommended due to its structural and practical drawbacks: strain hardening of the plate material, risk of hole misalignment if not properly perpendicularly done, surface condition of the rim of the hole, etc. Different techniques could cancel the plate deterioration. Annealing or drilling out an annular width of 1 mm by reaming was sufficient to restore the original ductility of the base metal (de Jonge 1945, 82). It was also important to check the surface condition of the rim of the punched hole as the punching technique could damage the base metal (Van der Veen 1919, 71–72).

- **Punching and annealing**. Annealing could cancel the detrimental effect of strain hardening. However, the method was not recommended in practice, given its localized action that could lead to hole misalignments, and thus a potential difficult driving. (Dechamps 1888, 127)
- **Subpunching and reaming**. The combined action of punching and drilling was considered as the best compromise between those two individual perforation techniques. The overall installation cost of subpunching and reaming was higher than full punching but lower than full drilling. First the rivet hole was subpunched to a diameter that was 2 or 3 mm smaller than the final hole diameter wished. Then the remaining 2-3 mm of the undersized hole were drilled out by reaming. Reaming was the most practical and economic method chosen to remove the strain-hardened area surrounding punched holes (de Jonge 1945, 82). In addition, reaming allowed to adjust potential hole misalignments[14]. Consequently, combining subpunching and reaming was the most recommended method for plate perforation. In the 20th century, the subpunching stage had been progressively replaced by pre-drilling, as today's practice. (Dechamps 1888, 127; Van Drunen 1892, 246–48; Leman 1895, 178; Frémont 1906, 77–78; Aerts 1911, 24)

To insert the heated rivet in the rivet hole, the hole diameter had to be slightly larger than the rivet shank diameter $d$. Basically, the rivet shank was upset by the driving operation, and filled the rivet hole laterally. In some cases – for short grip lengths and/or machine riveting – the shank upset could also compensate misaligned holes by filling the gaps.

The hole diameter $d_{hole}$ was a function of the shank diameter $d$. The recommended difference in diameter was generally expressed as follows (Eqn. 2-1):

$$d_{hole} = d + \begin{cases} 1 \text{ to } 2\ mm, & SI\ units \\ 1/16\ in, & BI\ units \end{cases} \tag{2-1}$$

For countries using SI units, the hole diameter had to be 1 to 2 mm larger, on average, than the shank diameter (Leman 1895, 178; Combaz 1897, 2(3):10; Van der Veen 1919, 69; Nachtergal 1937, 246). The value of 4 mm acted as upper-bound value for large shank diameters, i.e., 24-25 mm (Barberot 1888, 365–66; Twelvetrees 1900, 76). An average hole-shank diameter difference of one sixteenth of an inch

[14] According to Van der Veen, the allowable misalignment between two holes should not exceed 5% of their diameter (Van der Veen 1919, 70). The topic is further discussed in CH8, section 1.1.2.

was recommended in countries using imperial units (Rumpf 1964, 562; Newman 2001, 118). To give an example, in order to drive a rivet that is 22 mm in diameter, the rivet hole would be subpunched or pre-drilled at 21 mm and widened by reaming until 23,5 mm (Aelterman 2013).

## 2.2 RIVET HEATING

Once the plates were perforated, the rivets could be heated prior to the driving operation. Rivet heating was, like rivet driving, fundamentally based on the know-how and experience of riveting gangs. Different systems were available, namely fixed and portable devices fed by charcoal, coke and fuel, and later by gas and electricity. The rivets had to be uniformly heated through their entire length. A direct contact of the rivets with the combustible substance was not recommended. Traditional charcoal forges weren't the best technique as they heterogeneously heated – and often burned – the rivet shank by concentrating the heat on its end. According to Frémont, reverberatory furnaces – such as the one developed by the French boilermaker Louis Lemaître – were the only way to easily ensure an homogeneous heating temperature (Fig. 2-7, left) (Frémont 1906, 136). Most of the portable reverberatory furnaces invented afterwards were based on Lemaître's fixed version. In practice, however, small portable and lightweight coke and charcoal forges, and other derivative versions supplied by fuel, etc. – available by the end of the 19th century – were more convenient and privileged by rivet stokers (Fig. 2-7, centre). (Van Drunen 1892, 254; Frémont 1906, 136–38)

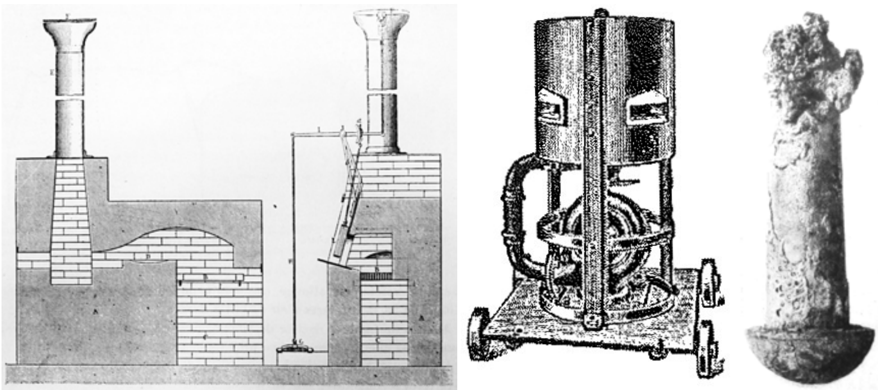


Figure 2-7: (Left) reverberatory furnace developed by L. Lemaître in La Chapelle-Saint-Denis near Paris in 1845, (centre) portable forge fed by coke, (right) rivet shank end deliberately burned to shorten its length (Frémont 1906, 136–37; Champly 1929, 15:102)

The heating temperature was a critical parameter requiring a careful attention. First, it impacted the strength and the shrinkage of the rivet itself, if heated too high and/or for too long **soaking times**. Secondly, it conditioned the driving temperature, that is,

the temperature of the rivet just before being driven. If the heating temperature was too low and/or the process too slow[15], the driving temperature could be too low[16] as well and the driving stage, consequently more difficult[17]. Thirdly, it influenced the structural behaviour of riveted connections.[18] (Frémont 1906, 87, 108; Vermes 2007, 2)

The assessment of the temperature attained in the rivet was based on its colour and external appearance. The surface of the rivet had to be glossy and sweating, possibly with small sparks. The rivet was ready to be driven when it had reached a cherry-red to white-hot colour, depending on the material of the rivet bar. These colours correspond to the temperature range of ca. 950 °C to 1100 °C[19]. Rivets manufactured from rivet iron were cooked when they took on a bright orange to yellow/white-hot colour. The minimal heating temperature of steel rivets was reached when they had a cherry-red colour, but they were also generally driven while being white-hot. (Combaz 1897, 2(3):109; Rumpf 1964, 562; Jacomy 1983, 24–25; Vermes 2007, 2)

Overheating rivets to ease driving was, unfortunately, common practice for rivet stokers disregarding the structural behaviour of the connections. Some of them even thought that overheating could be beneficial to the rivets:

> "Cette habitude de chauffer à température très élevée leur [rivet stokers] fait brûler beaucoup de rivets, plus soucieux qu'ils sont de diminuer leur peine que de conserver la qualité du métal; certains ouvriers croient même qu'ils améliorent ainsi le métal, "en le soudant à lui-même", comme ils disent." (Frémont 1906, 137)

Even more appalling, another unfortunate habit consisted of burning the end of rivet shanks being too long, as a convenient way to shorten their length, instead of using rivets having the proper dimensions (Fig. 2-7, right) (Frémont 1906, 137).

When the rivets were taken out from the furnace, calamine deposits had to be removed by firmly shaking them against a hard surface. Put every three to five rivet holes, temporary installation bolts guaranteeing a secure fit by holding together the plates to be connected could be then removed stepwise for rivet driving. (Aelterman 2013)

[15] A slow process relates to the time spacing between the removal of the rivet from the furnace and the start of the driving operation that is too long.

[16] The rivet undergoes a temperature decrease by radiation (ambient air).

[17] The compressive force needed to drive a rivet is inversely proportional to its driving temperature.

[18] The influence of the heating temperature on the structural behaviour of the connections is discussed in CH4, section 3.

[19] I.e., 1750 °F to 2000 °F.

## 2.3 DRIVING TECHNIQUES

Like manufacturing techniques, driving techniques experienced numerous major evolutions, especially between 1850 and 1910. In addition to manageability matters, the mechanization of rivet driving consisted of three main technological innovations regarding the energy supply of the riveting machines developed: steam energy, hydraulic energy, and pneumatic energy[20]. The first fixed steam riveting machines were cumbersome, expensive and couldn't carry out every driving operation. Some connections still required hand riveting. In the 1870s, portable devices supplied by hydraulic energy were developed. Portable pneumatic machines finally ousted the hand riveting technique at the turn of the 20th century.

While the first riveting machines fitted for structural work date back from the 1850s, their mature development and widespread use occurred from the 1880s onwards, stimulated by the breakthrough of steel as a structural material and the obsessive search for cost savings. Inventions of new riveting machines and improvements in the working of existing ones were a major concern between 1895 and 1910, as it will be revealed by historical patents.

### 2.3.1 MECHANIZATION OF RIVET DRIVING, LITERATURE REVIEW

The field of boilerwork introduced the hot-riveting technique but also the first riveting machine. In 1838, the British engineer and boilermaker W. Fairbairn developed the first riveting machine supplied by steam energy, based on the working of contemporary punching machine tools. His device could drive one rivet every 8 seconds, that is, a working rate 10 to 12 times higher than hand riveting. Shortly later in 1844, French boilermakers developed steam riveting machines that improved the technical and economic drawbacks of Fairbairn's first generation machines. Those were L. Lemaître and the Schneider brothers (Le Creusot) who exhibited both their machines at the 1844 national exhibition in Paris[21]. On the occasion of the construction of the Conway tubular bridge (1848), Garforth who originated from Dukinfield, UK, invented in 1847 the very first riveting machine fitted specially for structural work (Fig. 2-8). The frame of his machine was simple and the working, innovative since the piston was horizontally powered. Later in 1876, the manufacturers Pusey & Jones from Wilmington, DE (US), proposed a machine fitted for the fabrication of built-up sections. Their device constituted one of the last major

[20] A timeline that graphically summarizes the evolution of the mechanization of the driving techniques is provided in CH8, section 1.4.

[21] Lemaître also registered an invention patent for ten years that same year in Paris for a punching and rivet-driving machine. The main feature was the tight fit of the plates to be connected prior to rivet driving, that is, one of the biggest issue of the machines of the time (Lemaître 1844). In addition, Louis Lemaître broke new ground regarding the first design methods of riveted connections, as it will be seen in CH5, section 2.2.

improvements made to steam riveters, before three decades of technological stagnation. Based on the cam-lever principle, steam riveting machines fell into disuse at the beginning of the 20th century. (Jacomy 1998, 37–40)

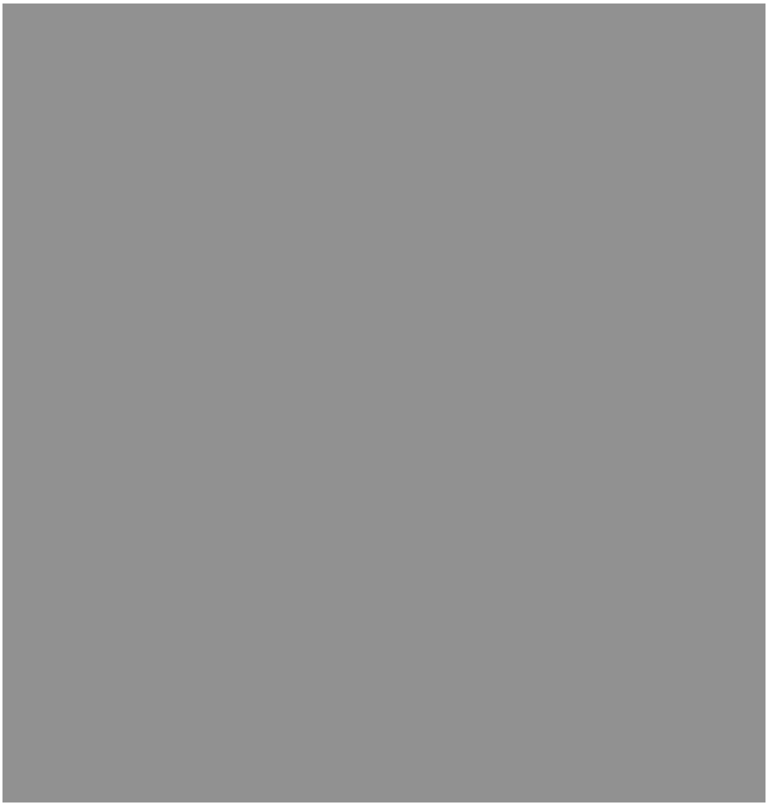


Figure 2-8: The first riveting machine fitted for structural work was invented by Garforth in 1847 (UK) (Grace's Guide 2007)

On the occasion of the 1862 London world fair, de Bergue et Cie presented a riveting machine for which the working was based on a connecting rod/crank system. This new generation of machines exerted a short-term pressure on the shank end to form the field head. As for steam riveters, the development of these riveting machines came to a halt by around 1880. (Jacomy 1983, 102)

The use of hydraulic energy was the key innovation that marked the development of 19th-century riveting machines. Inspired by the working of steam machines involving the action of a pressurized fluid, hydraulic riveting machines were used from the 1860s onwards. In 1865, London engineer Ralph Hart Tweddell invented the first hydraulic device that was a fixed model. Derived from his fixed machine, Tweddell developed a portable version five years later, built by the manufacturers Fielding & Platt from Gloucester, UK. Hydraulic riveters developed in the 1880s, together with the introduction of machines in the form of clamps – called jaw riveters – that allowed

to reach places of difficult access. Given the complexity of hydraulic machines and their related equipment needed, they were not particularly used in the field of iron and steel construction. By the end of the 19th century, no major improvements in the working of hydraulic machines were added. Hydraulic riveters were progressively supplanted by another, cheaper, technological wave: the pneumatic transmission. (Jacomy 1983, 105–112; Simmons 1997, 5–6)

In 1875, the American manufacturer John F. Allen form New York broke new ground by applying for the first time the principle of compressed air to portable riveting machines. He developed several portable machine tools to meet different applications – e.g., built-up sections for bridge construction, boilerwork. Allen improved his design and proposed an innovative machine that was exhibited at the 1878 world fair held in Paris. As with hand riveting, his device separately implemented two functions: holding the shop head by compression and upsetting the shank to form the field head by percussion. In a sense, while steam and hydraulic riveters formed the field head by compression, Allen reintroduced, similarly to hand riveting, the percussion system thanks to the pneumatic transmission. Due to technical issues regarding related equipment – i.e., compressors, piping – that still had to be overcome, the widespread use of pneumatic machines was, however, delayed. (Jacomy 1983, 112–16; Simmons 1997, 5–6)

Before the introduction of the last major technological breakthrough of air hammers, hybrid riveting machines combining multiple transmission systems were developed, mainly between 1880 and 1925. The French engineer Delaloë invented several hybrid machines that did not require additional equipment, contrary to Tweddell's hydraulic systems for instance (Ply (Le commandant) 1891, 218). In charge of an iron and steel construction shop, Delaloë proposed alternative machines from 1886 onwards. Substituting hand riveting on the job site at the same time, he also combined electric and hydraulic energies to build both fixed and portable hybrid riveting machines (Fig. 2-9). (Jacomy 1998, 117–19)

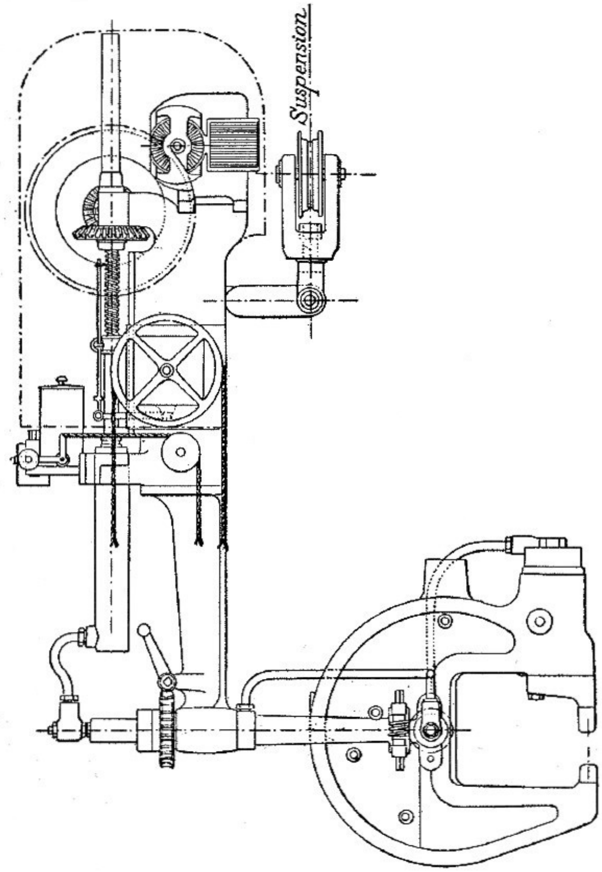



Figure 2-9: Portable version of Delaloë's hybrid riveting machine called "electric **riveter**", that is, a portable hydraulic riveting machine supplied by an electric motor (Maugas 1900, 170–71)

The last step within the mechanization of the driving techniques was the introduction of a very convenient type of pneumatic riveting machines: air hammers. During the 1880s, American inventors adapted compressed air to light machine tools that were easy to handle. Pneumatic hammers could be traced back to several riveting machines patented at the end of the 19th century by Joseph A. Boyer and Pierre Chouteau from St. Louis, MO (US). In 1899, Boyer introduced an improved model called "Boyer long-stroke riveting hammer" that could drive one rivet every six to seven seconds (Fig. 2-10). Manufactured by the Chicago Pneumatic Tool Company (CPTC), Boyer's air hammers allowed to speed up the driving process and reduce the size of the riveting gang to three men. More fundamentally, an experienced and skilled riveter was no longer needed. In the US, workmen were initially wary of air hammers because of the kick of the hammer, the vibrations and the risk of deafness. Given the economic benefits, builders exerted major pressures on workers, which explains why the technique underwent a fast development in the US. In Europe,

reactions were even more mixed, hand riveting being a European expertise. Labour organizations were first opposed to the use of air hammers. The workers claimed the better quality and precision of hand riveting, and trusted more cumbersome pneumatic riveting machines characteristic of the first generation models (e.g., J.F. Allen). On the occasion of the 1900 Paris world fair, the Chicago Pneumatic Tool Company aggressively advertised on Boyer's hammer, which was awarded a gold medal. Boyer's air hammer came into general use in Europe from 1910 onwards eventually. Though slightly improved by Boyer himself and other inventors, the basic working of this hammer used to condition machine riveting practices during decades. For a given range of shank diameters, different models were used depending on the rivet material and the space available to carry out rivet driving. (Simmons 1997, 9–17; Jacomy 1998, 49–50)

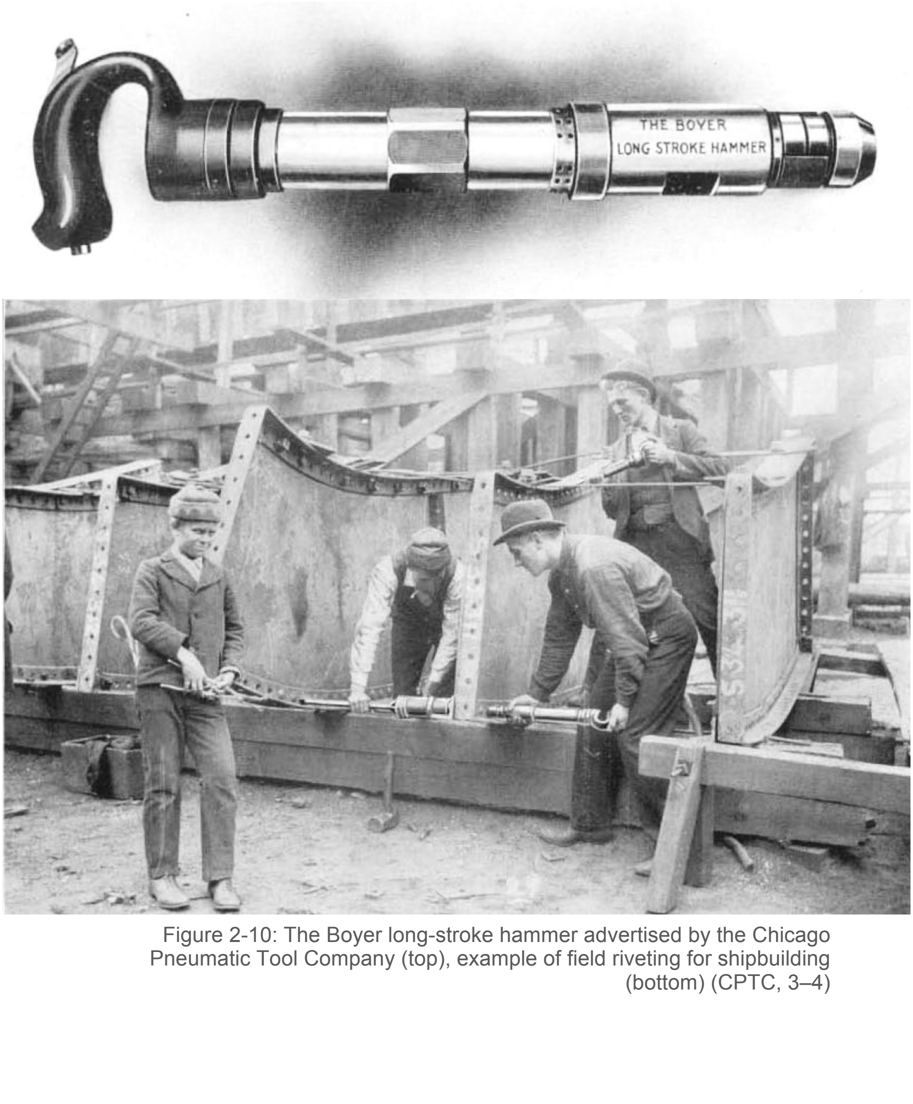



Figure 2-10: The Boyer long-stroke hammer advertised by the Chicago Pneumatic Tool Company (top), example of field riveting for shipbuilding (bottom) (CPTC, 3–4)

Air hammers or "long-strokes" were labour-saving devices that eased field riveting, in addition to shop riveting. They sounded the death knell for hand riveting at the beginning of the 20th century. Nothing much has changed since then in today's riveting practices, as it will be seen in chapter 7. Similar air hammers are used to drive rivets but also for other purposes thanks to their multifunctional features (e.g., rivet removal with a rivet buster, **pack rust** removal).

### 2.3.2 MECHANIZATION OF RIVET DRIVING, BELGIAN PATENT DATA

#### QUANTITATIVE ANALYSIS

The quantitative analysis of historical Belgian patents conducted in section 1.2.2 underlined the presence of a second peak period in patent registrations that occurred between 1891 and 1910 (Fig. 2-3). Contrary to the period 1856-1870 that almost exclusively dealt with manufacturing techniques, the second peak period is characterized by patent registrations that increased for a variety of subtopics: improvements for rivet-making machines, joining typologies, rivet removal, heating systems, etc. Counting for 50% of the patents, the subtopic of driving techniques was the most investigated topic, more precisely between 1896 and 1910. (BPDRT 2010)

Figure 2-11 shows patents for driving techniques, registered between 1830 and 1940, classified according to the three categories invention, importation and improvement. Two main trends can be observed. The intensity of the inventive climate from the 1890s onwards on the one hand, and the predominance of invention patents on the other hand.

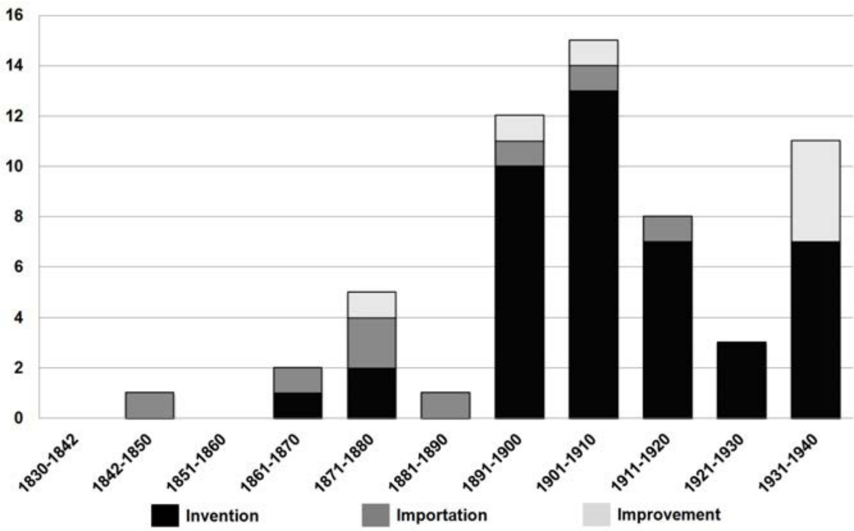



Figure 2-11: Number of patents for the subtopic of driving techniques classified per patent type (invention, importation or improvement; 1830-1940) (BPDRT 2010)

Although the first riveting machine fitted for structural work had been invented by Garforth in 1847, there is a clear time-lag with the patenting intensity on driving techniques that started 40 years after. This fact is related to the actual development and use of riveting machines during the decades around the turn of the 20th century, as emphasized by the literature review in the previous section. In addition, the period before 1890 was strongly dominated by inventions and improvements related to manufacturing techniques.

With regard to the patent type, the vast majority of the patents granted between 1896 and 1910 belonged to the invention type, accounting for 84% of the registrations (Fig. 2-11). The under-representation of importation patents doesn't reflect, however, the influence of foreign inventors. Actually, more than half of the patents of the period 1896-1910 were owned by foreign inventors coming from the US but also the UK, Germany and France. The financial and legal incentives offered by the Belgian patent system stimulated international technology transfers explaining this trend (de Favereau 2011, 265–66). Improvement patents were also in the minority in 1830-1940 (Fig. 2-11). However, most of the patents in that period mainly concerned improvements for the working and additions of new components to existing riveting machines. (BPDRT 2010)

The patent research validates the introduction dates of the main technological evolutions experienced by the driving techniques during the second half of the 19th century, discussed in section 2.3.1. In the database, the first patent granted for a hydraulic riveting machine is the invention patent N°20.682 registered by the German Oscar Fallenstein in 1866 (Fallenstein 1866). This corresponds to the period when R.H. Tweddell started his investigations on hydraulic transmission from 1865 onwards. The first patent having explicitly addressed the topic of pneumatic riveting machines in the database was granted to the American John F. Allen on 30 December 1876, who was the pioneering inventor of pneumatic transmission[22]. All in all, the technological breakthroughs of pioneering inventors discussed in the previous section are also to be found in the Belgian patent data, for example: 1847 importation patent of Garforth (UK), 1872 importation patent of Tweddell (UK), 1876 invention and 1877 improvement patents of Allen (US), etc. (BPDRT 2010)

[22] See section 2.3.1.

### QUALITATIVE ANALYSIS

The working of riveting machines was accurately detailed in the descriptive section of historical patents. As with hand riveting, patents revealed that the basic working of riveting machines was based on two main steps: bucking up the heated rivet on the shop side (holder-on function) and upsetting the rivet shank in the rivet hole to form the field head (upset function) (Fig. 2-12):

1. **Holder-on function**. Prior to the driving stage, the heated rivet to be driven was inserted in the rivet hole and bucked up by a holder-up device. Depending on the working of the riveting machine, the holder-up device could be either a part of the riveting machine or a separate tool. For jaw riveters, the holder-on function was naturally integrated in the frame of the riveting machine, as the holder-up end of the jaw acted as a stop to counteract the pressure applied by the machine in order to drive the rivet. For portable pneumatic hammers, the holder-on function was a separate tool that held the shop head in place by compression for example (pneumatic holder-up). Once the shop head was securely bucked up, the shank end could be upset.
2. **Upset function**. The upset function of the riveting machine consisted of crushing the shank end to upset the shank in the rivet hole. This operation was carried out through a continuous pressure (hydraulic transmission) or a series of repeated blows (pneumatic transmission). Once the field head was formed, the riveting machine was moved in front of the adjacent rivet hole to repeat the driving operation.

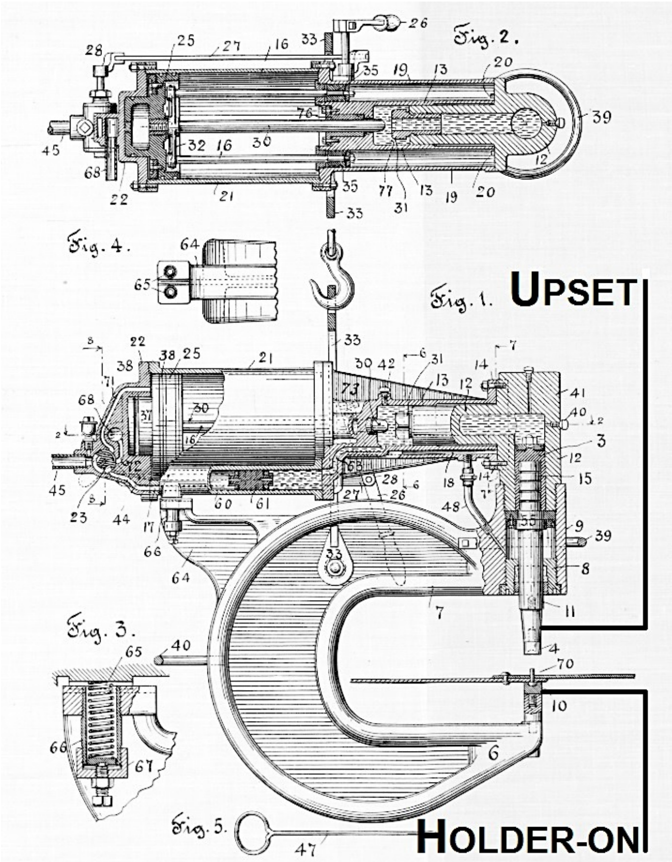



Figure 2-12: Portable pneumatic jaw riveter invented in 1901 by mechanical engineer John A. Carlisle from Philadelphia, PA, US (Carlisle 1901)

Compared to hand riveting, machine rivet driving strongly increased the speed of the driving operation by upsetting the shank and forming the field head in only a few seconds. The inventive climate related to driving techniques almost exclusively dealt with the driving operation itself. The two preliminary steps namely plate perforation and rivet heating still needed, however, direct human interventions. While some improvements concerned manageability and comfort matters, most of the modifications solely focused on technical and constructional issues (BPDRT 2010):

- **Secure fit of the plates**. While the first riveters were invented by the end of the 1830s, these first generation machines presented numerous technical imperfections during the three decades that followed. The fit tightening of the plates before the driving operation was one of the biggest issues. The subject was crucial in order to avoid loose rivets and thus any decrease in frictional strength.

- **Manageability and comfort**. For shop riveting and even more for field riveting, a sufficient manageability of the machines had to be ensured. Actually, this was the second main issue of the first generation machines. Numerous developments dealt with portable, compact and lightweight devices. The flexible use of riveting machines was also of concern regarding the handling of the upset system in front of the shank end, variable grip lengths, etc. Finally, the comfort of workmen operating the riveting machines was taken into account, e.g.: less noisy devices, additional components cushioning the blows of air hammers.
- **Holder-on system**. The holder-on function focused inventors' attention, as it is the prerequisite operation before the driving stage. Whatever the driving technique – jaw riveters, air hammers, etc., new systems were developed and improvements, added to existing models, to adequately hold the shop head against the outer ply of the connection in fabrication.
- **Upset system**. The overall working of the riveting machines was simplified and improved, especially their frame and assembly. Devices fitted for peculiar applications were developed as well, to fabricate specific built-up sections for instance. The setting and adjustment of the pressure applied by riveting machines to drive rivets was also investigated. Finally, numerous improvements were related to the cylinder-piston systems and the valves for the admission and exhaust of pressure.

CASE STUDY: JF ALLEN'S RIVETING MACHINES (1876 & 1877)

The portable pneumatic riveting machines of John F. Allen were chosen as case study to illustrate technical advances that marked the mechanization of rivet driving in more details. Firstly, J.F. Allen patented numerous riveting machines but also drilling machines, air compressors, etc., in different countries such as in the US, Canada, Belgium or the UK (EPO 2011; DPMA 2011). Secondly, some of his devices were exhibited at world fairs, and their technological innovations, reported in contemporary literature such as *The Engineer* ("Allen's Pneumatic Rivetting Machines" 1878).Thirdly, trade catalogs proved that his company delivered riveting machines to international customers who were particularly satisfied with their design, working and price, as emphasized by the Vice President of the McClintic-Marshall Construction Co. on August 18th, 1902 (Pittsburgh, PA, US):

> "Regarding your Riveters, beg to say that we have a large number of your horse shoe Riveting Machines, both at our Pittsburgh and Pottstown plants. The design and workmanship of these machines is of the best, and we prefer your machine to any other make that we have used." (JFAC 1904, 7)

Established in 1872, the John F. Allen Company (JFAC) based in New York, 372 Gerard Avenue, manufactured riveting machines fed by pneumatic transmission for boilerwork, shipbuilding and structural applications. The first riveting machine developed by J.F. Allen around 1875 was a jaw riveter. The frame form of jaw riveters allowed to reach many difficult places to carry out the driving operation. Although energy-efficient, its technical imperfections made it only suitable for small-span structural work and other applications that didn't require a high riveting quality unlike bridge construction and boilerwork. He then improved the working of his first generation devices and invented very sophisticated pneumatic machines for which the holder-on and upset functions were separately implemented, as for hand riveting. (JFAC 1904; Frémont 1906, 28–30)

On 17 February 1875, Allen applied for a patent N°168.314 at the United States Patent Office for a riveting machine having such innovative working (Allen 1875). More than one year later, on 30 December, 1876, he registered the same machine in Belgium with the invention patent N°41.097 (Fig. 2-13, left) (Allen and Roeder 1876). Although the main claim concerned the working of the valves, the design of the pneumatic machine was, however, the most important innovation. The plates to be connected physically separated the device into two stand-alone parts. The bottom part acted as a holder-up to buck up the shop end side of the heated rivet (Fig. 2-13, left). The holder-on system was a holder-on bar attached to an installation bolt passing through the adjoining right rivet hole. The upper part of the machine could then drive the rivet via the upset system (Fig. 2-13, left). Here a vertical cylinder operated the piston equipped with a rivet snap at its bottom end. Repeated blows formed the field head by percussion. One year after, on 16 July 1877, Allen adapted the working of his pneumatic machine and registered an improvement patent N°42.520 in Belgium (Fig. 2-13, right) (Allen and Roeder 1877). Two main improvements were introduced. The use of an automatic valve – combined with an additional valve – to avoid any pressure return in the cylinder on the one hand (Fig. 2-13, right, (A)), and a mechanical process intended to move the whole riveting machine on the other hand. The sliding foot $J'$ allowed to readily adapt the device to all distances of the rivet holes from each other (Fig. 2-13, right, (B)). In addition, the holder-on system was improved, and the overall size and selfweight of the machine, reduced. Actually, the Belgian improvement patent was consequent to the American

copy N°194.396 registered three months before, on 3 April 1877, to improve the original US patent N°168.314 (Allen 1877).[23]

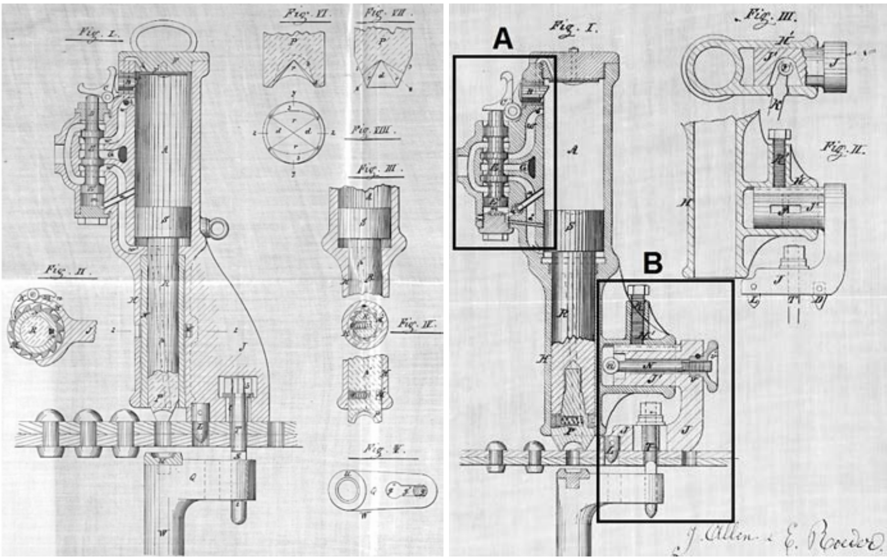



Figure 2-13: Patents registered in Belgium by J.F. Allen together with H.E. Roeder for a pneumatic riveting machine: (left) 1876 invention patent N°41.097 and (right) 1877 improvement patent N°42.520 (Allen and Roeder 1876; Allen and Roeder 1877)

The riveting machine was, among other models, exhibited at the 1878 Paris world fair ("Allen's Pneumatic Rivetting Machines" 1878). Like the Vincent system discussed in section 1.2.2, Allen's pneumatic riveting machine was built in France by the French manufacturer Jules Le Blanc (Jacomy 1983, 115). The machine was fitted for a wide range of applications such as shipbuilding and structural work (e.g., fabrication of built-up sections for bridge construction), but more predominantly for boilerwork, as shown in figure 2-14. The John F. Allen Company also developed various devices tailored only to structural work such as jaw riveters (all-around applications), compression lever riveters equipped with an angle lever (built-up sections), lattice riveters for trusswork – i.e., limited available space (JFAC).

[23] In most cases, inventors who registered a large number of patents simultaneously protected their technique in different countries – Belgium often included – by adding small changes and/or by deliberately fragmenting one given invention into multiple applications.

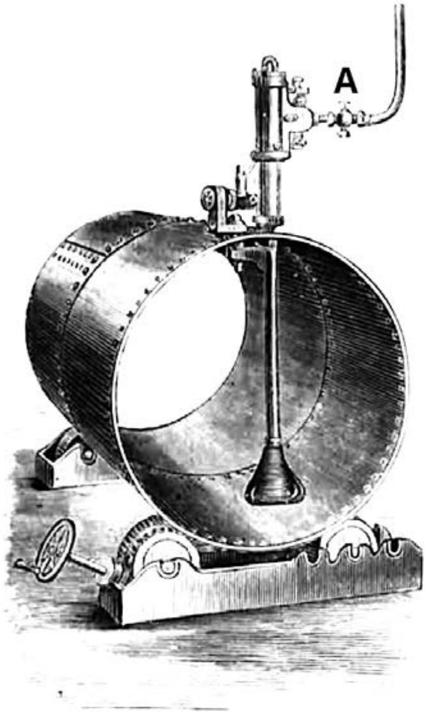



Figure 2-14: Allen's riveting machine exhibited at the world fair held in Paris in 1878, the attendant pressed the button A to link the riveter to the air reservoir for the driving operation (“Allen’s Pneumatic Rivetting Machines” 1878, fig. 7)

The pneumatic riveting machines developed and manufactured by the John F. Allen Company were the precursor of hand-held air hammers. These devices further improved the system combining the holder-on and upset functions separately, being operated by the pneumatic holder-up and the air hammer, respectively.

# 3 CONCLUSIONS – THE IDEAL OF MECHANIZATION

Socio-economic and technical factors conditioned the development of the riveting technology between 1830 and 1940. Moreover, construction culture and habits could act as a major decision-making leverage to support or discredit a given new technological advance. Rivet driving more predominantly influenced the quality of riveting than rivet manufacture, the potential defects originating from the latter being more easy to check and to detect than the ones generated by the former.

Based on the analyses conducted, the two starting questions formulated at the beginning of the chapter are answered below.

The material used for rivet manufacture was of superior quality and had to be sufficiently ductile for rivet driving on the one hand, and for serviceability matters on the other hand. The first rivet irons made of wrought iron were progressively substituted by rivet steel – later rivet high-strength steel – at the turn of the 20th century. A high scatter of the mechanical properties of rivet iron was observed. Hence, the change in base metal induced, on average, an increase in UTS together with a slight decrease in elongation at failure. In general, educator-engineers recommended to use rivets having slightly lower or at the most the same mechanical properties as those of the plates to be joined.

The actual mechanization of the riveting technology developed in two tiers: rivet manufacture between the 1850s and 1880s and rivet driving between the 1880s and 1900s. Rivet-making machines permitted to increase output needed to support the growing development of riveted connections in iron and steel construction. Simultaneously, the mechanization of rivet manufacture allowed to rationalize the geometrical and dimensional variety of rivets peculiar to the period before 1850. The development and widespread use of riveting machines was closely related to the acceptation of steel as a structural material at the end of the 19th century, as broached in chapter 1, section 2. The switch from hand to machine riveting was made possible by overcoming multiple technical barriers, especially with regard to the energy supply, the transmission, and the working of the devices, but also their manageability and portability. Paradoxically, as underlined by Jacomy (1983), the frenetic search to mechanize rivet driving led only to the automation of the driving operation itself; the two preliminary steps namely plate perforation and rivet heating still needed, however, direct human interventions.

In addition to the riveting technology, the design of historical riveted connections allows to reveal key information within the appraisal of their structural integrity. The design of riveted connections is the scope of the next part of the study. To introduce the topic, the next chapter – CH3 – unravels the geometry of rivets and riveted connections.

# PART II
# DESIGN

*The latter [best methods of riveting] is a practical and highly important inquiry, as great difference of opinion exists amongst engineers and others, as to the form, strength and proportions of rivets, and the joints of which they form an essential part.*

(Fairbairn, 1850, 678)

# PART II
# DESIGN

## CHAPTER 3
## GEOMETRY

**The geometry of riveted connections is the scope of chapter 3. It promotes a better understanding of the original layout and proportions of riveted connections, and how they evolved over time. The analyses focus on the dimensions of rivets – rivet shank and heads – and standard joining typologies of splice joints. The investigations are based on the content of French and Belgian literature. The findings highlight key parameters that influenced the geometry of riveted connections.**

**Chapter 3 aims to answer the following questions:**

*What are the proportions of rivets? Did they evolve over time?*

*What are the differences between the types of standard splice joints?*

*Which parameters condition the geometry of riveted connections?*

The geometry of riveted connections and their rivets is the first main input parameter that intervened in their design, in addition to their strength in tension, shear and bearing. Geometrical considerations were a key point in a design, since it impacted on both the fundaments of the theory of riveted connections and the design methodology itself[1]. Unravelling the geometry of riveted connections consequently helps us decipher the construction details of existing iron and steel structures. Moreover, it provides information that is useful when appraising the structural integrity of these load-carrying structures on site.

First, the geometry of rivets themselves – rivet shank and heads – is analyzed to add to the knowledge on their proportions, and how they may have evolved over time. Second, the main joining typologies of standard splice joints are investigated in an attempt to understand why they were used and which were their distinctive features. As mentioned in the introduction of the study, the content of historical French and Belgian literature is used to achieve these objectives. In addition, international literature is referred to, rather as a matter of contextualization.

## 1 RIVET SHANK

A manufactured rivet that is not yet driven is characterized by a rivet shank and a shop head (see CH1, Fig. 1-1). The rivet shank is defined by two geometrical parameters, which are the shank diameter and the shank length.

For structural applications, shank diameters ranging from 13 to 26 mm were available (Tab. 3-1). On the market, shank diameters were obtainable in almost every millimetre – even and uneven – and decimal values existed too (e.g., 19,5 mm, 22,5 mm). Practical, economic and structural concerns restricted, however, the variety of shank diameters effectively used in the shop as well as on the job site. For a given riveted structure, the number of different shank diameters was roughly limited to three in order to rationalize the amount of tools involved in rivet driving (Nachtergal 1937, 246). Moreover, shank diameters below 16 mm were barely used for structural safety reasons. For countries using SI units such as France and Belgium, the even diameters of 16 mm, 18 mm, 20 mm, 22 mm and 24 mm were the most usual ones in practice (Tab. 3-1). (Dechamps 1888; Scharroo and Bertholet 1911; Nachtergal 1937; Jacquemain 1946; Kienert 1949; Drouet)

Table 3-1: The standard shank diameters used for structural applications are mentioned in bold

| SHANK DIAMETER $d$ (mm) |
| --- |
| 13 - 14 - **16** - **18** - 19 - **20** - **22** - **24** - 25 - 26 |

[1] As it will be seen, respectively, in the two next chapters of Part II, namely CH4 and CH5.

In a design, at the micro-level of a riveted connection, the shank diameter $d$ was deduced from the thickness $e$ of the plates to be connected (Fig. 1-1). For a given plate thickness, the $d/e$ ratio allowed the shank diameter $d$ to be identified. This geometrical ratio was a convenient pre-design criterion that fundamentally influenced all the design methods of riveted connections, as it will be seen in detail in chapter 5, section 2. (Dechamps 1888, 132; Leman 1895, 186; Combaz 1897, 2(3):114; Nachtergal 1937, 252)

With regard to the shank length, it includes the grip length $g$ of the connection to be fabricated and the protruding shank length needed to form the field head (Fig. 1-1). While the grip length was obviously known, the identification of the protruding shank length was, however, delicate and difficult to predict accurately with confidence (Frémont 1906, 141–42). Actually, the protruding shank length had to be tested and adjusted since it depends on the plate perforation technique, the driving technique and the geometry of the rivet snap. An adequate identification of this length was essential to avoid the presence of defective rivet characteristics, such as a lip around the field head, that could detrimentally affect the sustainability of riveted connections (Twelvetrees 1900, 89)[2]. Despite everything, educator-engineers provided practical rules of thumb to approximately define the total length of the rivet shank (Eqn. 3-1) (Dechamps 1888, 129; Barberot 1888, 366; Leman 1895, 178; Nachtergal 1937, 245). More refined formulae were available as well. In particular, they take the number of plies constituting the grip into account – e.g., increment of 1 mm per faying surface – as well as other parameters such as the perforation technique or the drilling technique (Nachtergal 1937, 246). According to Nachtergal (1937), machine-driven rivets required a longer protruding shank than hand-driven rivets, given the more efficient upset of the shank in the rivet hole. In the same idea, the protruding shank length had to be more important for punched holes, being cone-shaped, compared to drilled holes (Nachtergal 1937, 246).

$$Shank\ length = g + \begin{cases} 1{,}25\ d \\ 1{,}5\ d \end{cases} \tag{3-1}$$

From a structural point of view, two main requirements had to be satisfied with regard to the geometry of the rivet shank. First, an upper-bound value of the shank diameter $d$ corresponding to a given plate thickness $e$ had to be ensured – thanks to the $d/e$ ratio – to avoid the crippling of the plates (Dechamps 1888, 132). Second, the contribution of the grip length $g$ within the total shank length had not to exceed an average value of ca. 10 cm to 15 cm for two reasons (Eqn. 3-1) (Dechamps 1888, 128; Van Drunen 1892, 250; Combaz 1897, 2(3):109). On the one hand, it could

[2] A kind of collar surrounding the bottom of the head, see CH8, section 1.1.1, for more information.

imply non-uniform contact conditions between the shank and the rim of the rivet hole along the grip length (Chateau 1866, 2:182; Aerts 1911, 25). One the other hand, since the magnitude of the longitudinal shrinkage of the shank once driven is – among others – a function of the grip length, the rivet yield strength had not to be reached, as a result of a too high inner prestressing of its shank (Dechamps 1888, 128; Van Drunen 1892, 250). More fundamentally, a too large longitudinal shrinkage could also pop off the rivet head(s) and thus cancel the frictional strength of the connection. Consequently, it was recommended to replace rivets by bolts in the presence of – some of – the above situations.

## 2 RIVET HEADS

The 19th century is characterized by a large formal and dimensional variety of rivets heads. Technological, economic and structural considerations led to a rationalization of the forms and dimensions of the rivet heads at the turn of the 20th century.

Three main types of rivet head shapes were available: round, countersunk and coned heads (Fig. 3-1). However, the round head was the most common one in the field of iron and steel construction.

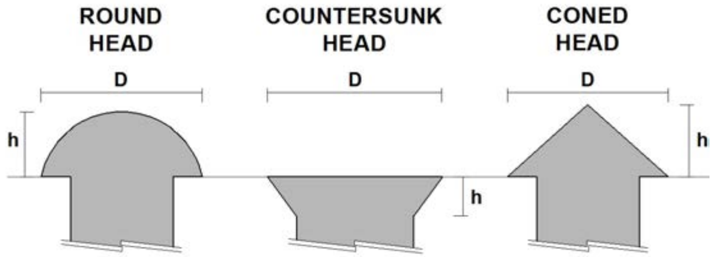



Figure 3-1: The round head (left), countersunk head (centre) and coned head (right) were three head shapes commonly available (head diameter $D$ and head depth $h$)

The riveting technology conditioned the geometry of the rivet heads, as discussed in chapter 2. While rivet manufacture determined the geometry of the shop head, the field head shape resulted from the driving operation[3]. Hence, the proportions of the shop and field heads were not necessarily the same, since the rivet snap used for rivet manufacture could differ from the one used for rivet driving. The mechanization of the manufacturing process allowed the many different shapes of shop head characteristic of the period before 1850, to be standardized and the variety reduced. Actually, given their expensiveness and complex manufacturing, particular shapes of shop head were "naturally" ousted from the market (Jacomy 1983, 54). Regarding the field head, the development of rivet machines and their intrinsic working generated

[3] See CH2, section 1 and section 2 on rivet manufacture and rivet driving, respectively.

the progressive dominance of the round head, to the detriment of the coned head for instance (Jacomy 1983, 57). In addition, 19th-century educator-engineers discredited the use of coned heads for structural reasons:

> Quant aux rivets à tête conique, il convient de les rejeter, attendu qu'ils ont une résistance inférieure à celle des rivets à tête hémisphérique. (Combaz 1897, 2(3):121)

Concerning the dimensions of the rivet heads, the broad dimensional diversity peculiar to the 19th century had been channelled and rationalized through standards from the 1920s onwards. (Jacomy 1983, 52)

## 2.1 METAMORPHOSIS OF THE ROUND HEAD

The geometry of a round rivet head – shop head or field head – is defined by three parameters: the head diameter $D$, the head depth $h$ and the head radius of curvature $R$ (see CH1, Fig. 1-1). The ratios between these geometrical parameters were not constant but changed progressively over time. By the end of the 19th century, together with the development of the strength of materials, the selfweight and cost of riveted connections became a prior concern. Studies on ways to reduce their average weight and cost were carried out. From that point of view, the head depth $h$ was one of the parameters investigated. These studies led to the metamorphosis of the shape of the round head.

By the 1920s, the round head made room for two derived improved shapes: the round snap head and a more flattened version, the **button head** (Fig. 3-2). For a given head diameter $D$, the round snap head had a higher head depth $h$, that is, a more hemispheric shape. Also called *en goutte de suif*, the lighter button head was characterized by its lower head depth given its two radiuses of curvature.

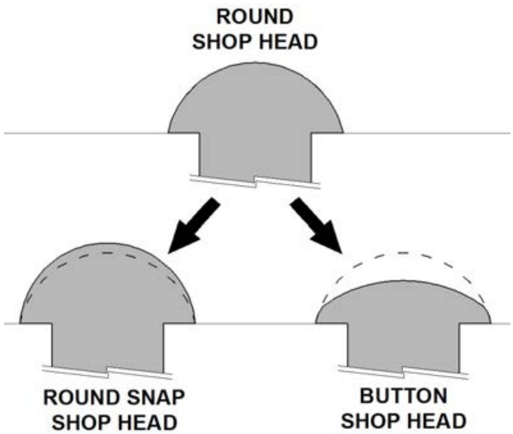



Figure 3-2: The original round head evolved into the round snap head (left) and the button head (right)

The results of quantitative analyses focused on the $h/D$ ratio confirm the metamorphosis of the round head into one of its followers, namely the round snap head. The dot charts shown on figure 3-3 give the values of the $h/D$ ratio calculated based on the geometry of rivet heads mentioned in French and Belgian literature published between 1873 and 1953.

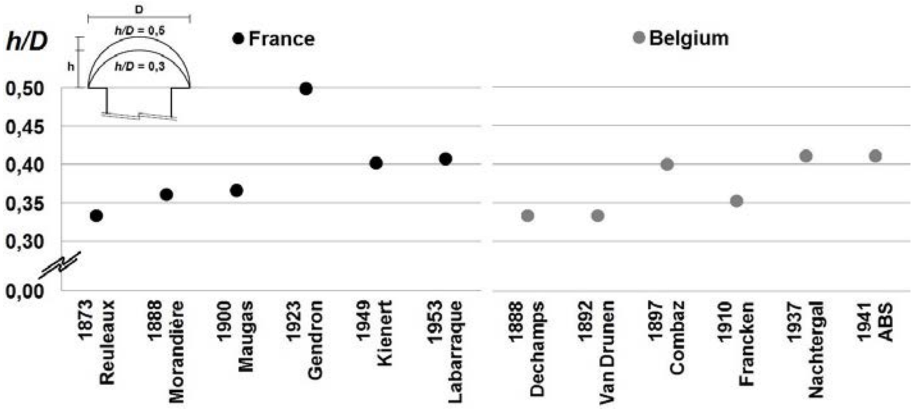



Figure 3-3: The content of French and Belgian literature reveals the progressive increase of the $h/D$ ratio over time

In both countries, the evolution of the $h/D$ ratio gives evidence of increasing head depths for a given head diameter (Fig. 3-3). Between 1870 and 1900, the $h/D$ ratio approximates the value of 0,37. Around the mid 20th century, this ratio averages the value of 0,41. The morphological transition occurred primarily between 1900 and 1920; regardless of some high values prior to 1900 that are comparable to the almost hemispheric shape peculiar to the 20th century. From the 1940s onwards, the $h/D$ ratio remained practically constant, in accordance with the progressive decay of riveted connections in iron and steel construction.

## 2.2 SHOP HEAD PROPORTIONS

In historical literature, the three parameters defining the geometry of the shop head – head diameter $D$, head depth $h$, and radius of curvature $R$ – are all expressed as a function of one parameter: the shank diameter $d$. Basically, it means that rivets of various dimensions are geometrically affine for a given head type such as the round head. Therefore, it underlines the presence of dependence relations between the shank diameter of a rivet and the geometry of its shop head. Since the shank diameter depends on the plate thickness, on-site measurements of the geometry of shop heads may allow to trace back to the nominal shank diameter on the one hand, and the plate thickness on the other hand (Eqn. 3-2)[4].

[4] This assumption will be (in)validated by means of experimental investigations in CH6.

$$Plate\ thickness\ e \xrightarrow{d/e} Shank\ diameter\ d \xrightarrow{\begin{cases} D/d \\ h/d \\ R/d \end{cases}} \begin{cases} Head\ diameter\ D \\ Head\ depth\ h \\ Radius\ of\ curvature\ R \end{cases} \qquad (3\text{-}2)$$

As a result, the proportions of the shop head can be assessed through the $D/d$, $h/d$ and $R/d$ ratios (Eqn. 3-2). The evolution over time of the $D/d$ and $h/d$ ratios of round shop heads is depicted on the dot charts of figure 3-4. These values were calculated based on the content of French and Belgian literature published between 1873 and 1953. The dot charts give evidence of the almost constant value of the $D/d$ ratio in both France and Belgium (Fig. 3-4, top). Regarding the $h/d$ ratio, the observed downward trend has to be linked with the progressive emergence of the round snap head, as noticed in the previous section (Fig. 3-4, bottom). Hence, the content of historical French and Belgian literature reveals two main rough ratios of $D/d$ and $h/d$, respectively equalling $5/3$ and $2/3$. The $R/d$ ratio was then geometrically deduced from the two previous ones. Knowing $D$ and $h$, the radius of curvature $R$ was easily calculated and also expressed as a function of $d$.

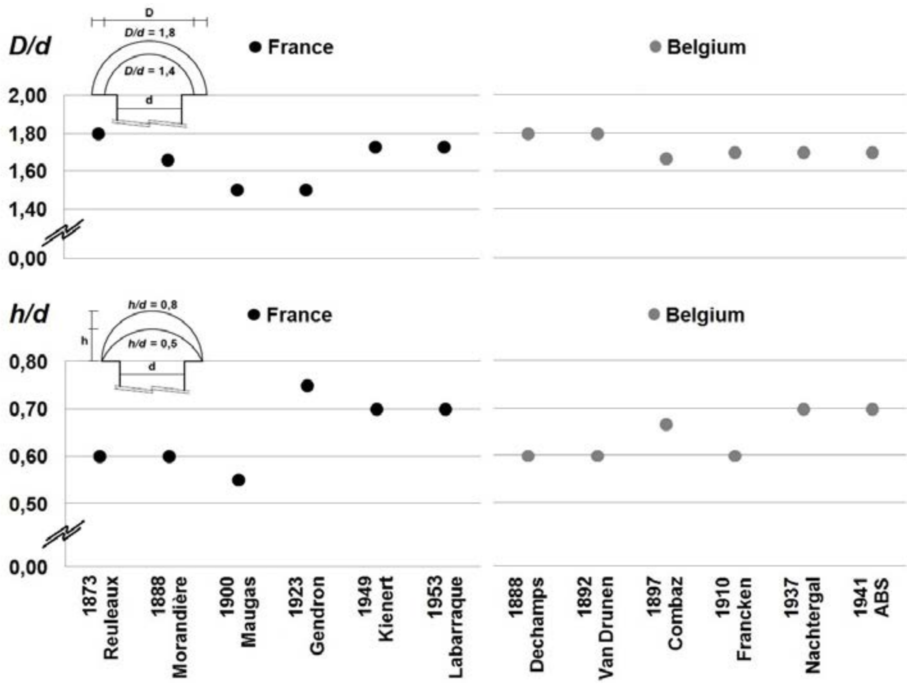



Figure 3-4: Almost constant values of the $D/d$ ratio (top) together with increasing values of the $h/d$ ratio (bottom) between 1873 and 1953 in France and Belgium

Based on the above analyses, table 3-2 provides the average head diameters $D$ and head depths $h$ of round shop heads in absolute values for the five standard shank diameters $d$ commonly used in practice (see Tab. 3-1). Provided that rivet driving is properly executed, the original proportions of the shop head should remain constant after the driving operation.

Table 3-2: Head diameter $D$ and head depth $h$ of round shop heads based on the five standard values of shank diameter $d$

| **SHANK DIAMETER $d$ (mm)** | **ROUND HEAD** | |
|---|---|---|
| | **HEAD DIAMETER $D$ (mm)** | **HEAD DEPTH $h$ (mm)** |
| 16 | 27 - 28 | 11 |
| 18 | 31 | 12 |
| 20 | 34 | 13 - 14 |
| 22 | 37 - 38 | 15 - 16 |
| 24 | 41 | 17 |

## 2.3 FIELD HEAD PROPORTIONS

While the study of the shop head proportions revealed the geometrically affinity of rivets as a result of their manufacturing stage, the same is not necessarily true for the field head. The original proportions of the field head are linked to two main aspects interacting with each other: the geometry of the rivet snap used to drive the rivet on the one hand, and the quality of riveting on the other hand.

For both hand-driven and machine-driven rivets, the rivet snap tool that equipped the end of a hand-held or air hammer – respectively – determines the shape of the field head. The field head diameter $D$, head depth $h$ and radius of curvature $R$ will correspond to the diameter, depth and curvature of the inner rim of the rivet snap provided that a satisfactory quality of riveting is ensured.

If the quality of riveting is insufficient, the presence of defects will affect the shape of the field head[5]. For instance, a protruding shank length that is too short or too long will make the field head unfilled or generate a lip around it, respectively. The ability of the riveter to properly drive a rivet and consequently form the field head also influences its proportions. When a rivet is badly driven, the field head can show an unsymmetrical and/or irregular shape.[6]

Hence, the shape and proportions of the field head may differ from the ones of the shop head of a given rivet. Therefore, the dependence relations of equation 3-2 may not apply for the field head, and consequently relate to the shop head only, assuming

[5] The topic of the quality of riveting is addressed in CH6, CH7 and CH8.

[6] For more information on damaged rivets, see CH8, section 1.1.

that the latter is properly bucked up during the driving operation[7]. Indirectly, this observation raises the issue of the distinction between the shop and the field head ends when appraising the structural integrity of an existing riveted structure on site[8].

# 3 JOINING TYPOLOGIES

Together with the geometry of rivets, the analysis of the main joining typologies of riveted connections help us understand their original design and reveal potential design errors. The joining typology impacted the overall layout of riveted connections – rivets pattern and spacing – and thus their stiffness, structural behaviour, and failure mode. Within the design methodology of a riveted connection, the joining typology had to be chosen before its final geometry could be empirically or analytically defined, similarly to the plate thickness $e$. Hence, the joining typology to be used was a strategic choice.

## 3.1 LAP AND BUTT SPLICES

As stated in the introduction, the study focuses on standard joining typologies of splices joints. While lap splices connect plates directly together, butt splices connect plates with the help of one or two cover plate(s)[9]. Splice joints are based on the overlap principle: an overlap zone between two or more plates is necessary to transmit the loads through the rivets.

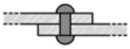
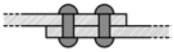
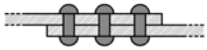
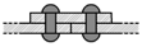
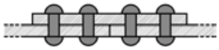
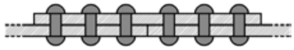
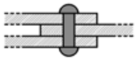
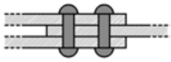
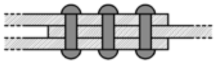
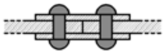
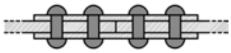
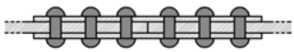
Depending on the number of rivet rows, a distinction is made between a single, double, or triple overlap for respectively one, two, or three rivet rows per force transmission. These joints are single riveted, double riveted or triple riveted, respectively (Tab. 3-3, column headings). The number of plates to be joined at each force transmission determines the stress state of the rivet(s). Connecting two plates corresponds to single shear whereas it is double shear when three plates are joined. In the former case, the rivet shank is loaded via one shear plane while in the latter case, two shear planes per rivet have to bear loads (Tab. 3-3, line headers 'Single' and 'Double'). As a result, for a given loading case, half of the amount of rivets is needed under double shear in comparison with a single shear connection.

[7] A holder-up tool that is too small can distort the original shape of the shop head.

[8] The topic will be investigated in CH6.

[9] As a reminder, splice joints basically connect two or more plates together in the same or parallel plane(s), see CH1, section 3.

Table 3-3: Overview of the main configurations of splice joints under single or double shear, that is, single, double or triple riveted single/double lap or butt joints, and their abbreviation[10]

| | | SINGLE RIVETED | DOUBLE RIVETED | TRIPLE RIVETED |
|---|---|---|---|---|
| SINGLE | LAP JOINT |  SR-S-LJ |  DR-S-LJ |  TR-S-LJ |
| | BUTT JOINT |  SR-S-BJ |  DR-S-BJ |  TR-S-BJ |
| DOUBLE | LAP JOINT |  SR-D-LJ |  DR-D-LJ |  TR-D-LJ |
| | BUTT JOINT |  SR-D-BJ |  DR-D-BJ |  TR-D-BJ |

In the absence of connecting plates – cover plate or gusset, splice joints will be subjected to out-of-plane deformations as a result of the bending moment produced by eccentrically applied loads. Consequently, the presence of unwanted forces – e.g., bias tension – in the overlap zone of these asymmetric joints can pop off the rivet heads and collapse the joint. Double and, even more, triple riveted joints are less affected by this phenomenon than single riveted joints (Tab. 3-3). Engineering writers recommended using single or double butt joints, called *assemblage à plat-joint* and *assemblage à chaîne* (Novat 1900, 193), that is, splice joints with one or two cover plate(s), respectively. In particular, considered as an optimal solution, double butt joints were often installed because of their doubly symmetric geometry (Tab. 3-3). This joining typology was known by engineers to be stronger, which justified the extra labour cost for installing the cover plates. Actually, for a given loading case, double butt joints would be likely to fail at higher stresses and strains than lap joints. (De Vos 1879, 1:98; Leman 1895, 196; Combaz 1897, 2(3):116–17; Aerts 1911, 34)

The vast majority of the authors advocated using the same thickness for the cover plate and joined plates in a single butt joint. For double butt joints, generally the cover plates were half the thickness of the plates to be joined (Tab. 3-3). (De Vos 1879, 1:98–99; Leman 1895, 192–93; Aerts 1911, 34; Jacquemain 1946, 60–61)

[10] The configurations of splice joints are labelled as RR-B-JT where RR stands for rivet row(s) (SR: single riveted; DR: double riveted; TR: triple riveted), B refers to the shear behaviour (S: single shear; D: double shear) and JT, to the joining typology (LJ: lap joint; BJ: butt joint).

> "On calcule les dimensions transversales [of the cover plates] de façon à ce que leur section nette soit au moins égale à la section nette des tôles interrompues au même point." (Novat 1900, 198)

From a more analytical point of view, it means that the total net section of the cover plate(s) – single and double butt joints – had to be at least equalled to the total net section of the joined plates, as stated by Novat (1900).

## 3.2 CHAIN- AND ZIGZAG-RIVETED CONNECTIONS

When lap or butt splice joints involved a large number of rivets – multiple rivet rows having each more than one rivet, the designer could opt for either *chain riveting* or *zigzag riveting*. The rivets of chain-riveted connections are arranged according to a uniform network of parallel rows while they are staggered for zigzag-riveted connections (Fig. 3-5). In historical literature such as handbooks or manuals, zigzag-riveted connections were assumed to be stronger than chain-riveted connections since such joining typology ensured a more uniform distribution of the applied shear loads (Dechamps 1888, 134; Combaz 1897, 2(3):119; Aerts 1911, 34). The prevalent theoretical investigations conducted by the German engineer JW. Schwedler in 1867, and their major impact on educator-engineers, might explain this observation. Advising the arrangement of rivets in zigzag, the convenient design method developed by Schwedler was actually referred to by various authors (Dechamps 1888, 132; Leman 1895, 188; Aerts 1911, 39)[11].

[11] The topic is further addressed in CH5, section 4.3.

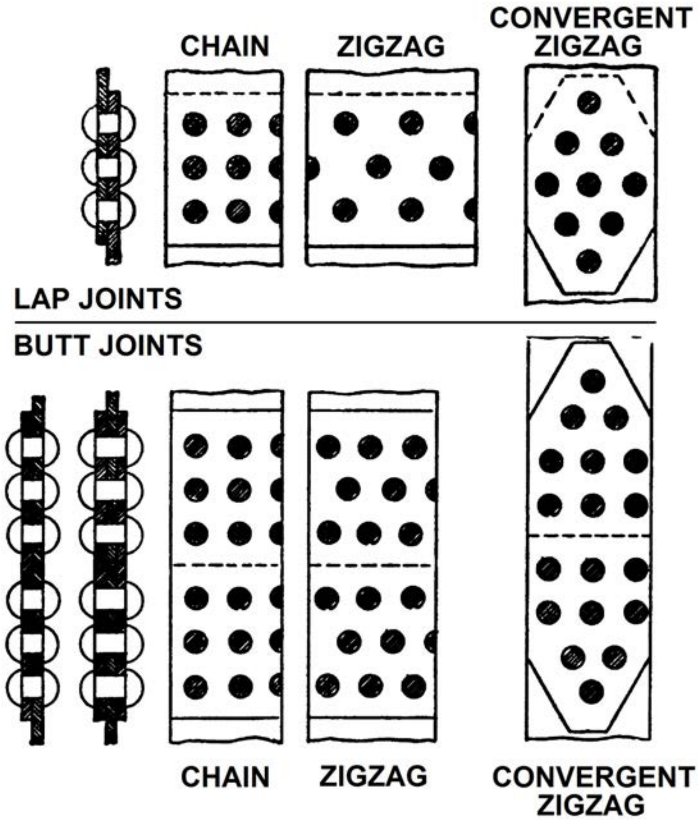



Figure 3-5: Triple chain- and zigzag-riveted single lap joints (top), and triple chain- and zigzag-riveted butt joints (bottom) (adapted from Twelvetrees 1900, 95–96)

In particular, a specific configuration of zigzag riveting was approved by a vast majority of authors on an international scale, which is the convergent type (Twelvetrees 1900, 95, 96; Van der Veen 1919, 81; Jacquemain 1946, 55). Considered as an optimal choice, convergent zigzag-riveted connections are lap splices or butt splices characterized by diamond-shaped rivet lap ends or cover plates, respectively (Fig. 3-5). The outer rows of lap and butt splices belonging to the convergent type certainly maximize the plate net sections as only one rivet hole was perforated. At the same time, they concentrate, however, a non-negligible amount of the applied shear loads on one single rivet per force transmission. This observation emphasizes on theoretical misunderstandings and/or simplifying assumptions that may have primarily focused on one failure mode, namely the tensile failure of the plate net section, rather than on rivet shear (Jacquemain 1946, 55)[12].

[12] The main types of failure mode are discussed in CH4, section 2.2.

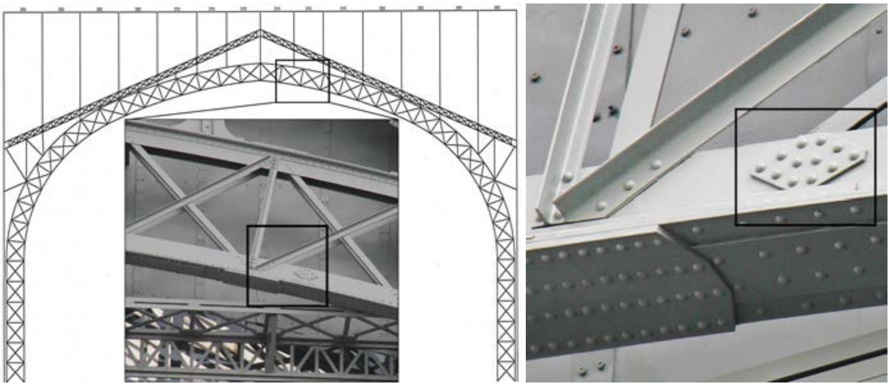


Figure 3-6: Zigzag-riveted connections belonging to the convergent type (right) were used for the fabrication of the chord members of the trussed arches of the 1888 Brussels Cinquantenaire Park halls (left)

Convergent zigzag-riveted connections are to be found on the top- and bottom-chord members of the trussed arches of the Brussels Cinquantenaire Park halls for instance (Fig. 3-6, right). Figure 3-6 shows also multiple-riveted butt splices having large cover plates used at the nodes of the truss to ensure the continuity of the chord members, which are built-up sections. At these nodes, the T-sections and L-sections of the vertical posts and diagonals are connected to the chord members by means of three rows of rivet(s) subjected to single shear, that is, triple riveted single lap joints (Fig. 3-6, Tab. 3-3).

## 3.3 RIVETS PATTERN AND SPACING

When the joining typology – lap or butt splices – was chosen, three geometrical parameters had to be defined in order to complete the arrangement of rivets, and thus the overall layout of the connection. These three parameters are the following: the rivet pitch $p$, the rivet lap $l$ and the edge distance $v$ (Fig. 3-7). The rivet pitch $p$ is the distance between the axes of two adjoining rivets. In ordinary riveted connections, the rivets were usually arranged in rows of even pitch (Twelvetrees 1900, 97). The rivet lap $l$ refers to the length of the end side of the (cover) plate, and the edge distance $v$, to its edge side (Fig. 3-7).

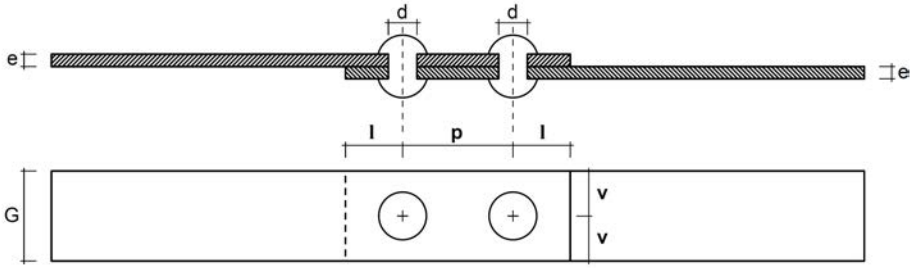



Figure 3-7: The pattern of rivets is defined by three geometrical parameters, the rivet pitch $p$, the rivet lap $l$ and the edge distance $v$ (double riveted single lap joint)

Similarly to the geometry of the shop head discussed in section 2.2, the rivet pitch, rivet lap and edge distance were all stated – in most cases – as a function of the shank diameter $d$ (Eqn. 3-3) (Dechamps 1888, 133–36; Combaz 1897, 2(3):115; Novat 1900, 193; Aerts 1911, 43–50; Scharroo and Bertholet 1911, 75; Kienert 1949, 81–82).

$$Plate\ thickness\ e \xrightarrow{d/e} Shank\ diameter\ d \xrightarrow{\begin{cases} p/d \\ l/d \\ v/d \end{cases}} \begin{cases} Rivet\ pitch\ p \\ Rivet\ lap\ l \\ Edge\ distance\ v \end{cases} \qquad (3\text{-}3)$$

The three above geometrical parameters influenced the design methodology of riveted connections, in particular the empirical methods, and conditioned their failure modes, as it will be seen in the two next chapters (CH4 & CH5).

## 4 CONCLUSIONS – PREDOMINANT SHANK DIAMETER

The content of French and Belgian literature was used in the present chapter to analyze the geometry of riveted connections. It allowed to reveal the usual considerations regarding standard splice joints as well as the proportions of rivets and their evolution over time.

The geometrically affinity of the shop head underlines that its proportions depend on the shank diameter $d$, as a result of rivet manufacture. Although available in even, uneven and decimal numbers, rivet shanks of 16 mm, 18 mm, 20 mm, 22 mm and 24 mm in diameter were commonly used in practice. The three main ratios – $D/d$, $h/d$ and $R/d$ – defining the geometry of the shop head remained almost constant over time. They are equalled to 1,69, 0,65 and 0,86, respectively, for round shop heads, that is, the most usual head shape for structural applications. Yet, between 1900 and 1920, the shape of the round head became more hemispheric – higher $h/d$ ratio of the round snap head, and a more flattened derivative was also introduced, which is the button head. Fundamentally, the proportions of the field head are also geometrically affine but here the shank diameter $d$ may not be necessarily a reliable

parameter to assess. Actually, the geometry of the field head depends on rivet driving and its quality (presence of potential defects).

Concerning the joining typologies, the difference between lap and butt splices lies in the use of cover plate(s). Regardless of their higher cost, double butt splices were considered as an optimal choice given their doubly symmetric geometry. The overall layout of existing riveted connections is worth to be appraised on site as it may act as stress raisers on some of their rivets – e.g., convergent zigzag-riveted connection.

The plate thickness $e$ is the starting point of the whole geometry of riveted connections, since it determines the shank diameter $d$ through the $d/e$ ratio. Nevertheless, we should keep in mind that the practical value of this ratio effectively implemented in a design might differ from its theoretical equivalent, given practical and economic constraints linked to the rationalization of the amount of needed tools for instance. Then, the shank diameter $d$ is the geometrical parameter that prevalently conditions the proportions of the shop head as well as the arrangement of rivets. As a consequence, the shop head's proportions[13] and the rivets pattern may allow to reveal the nominal shank diameter of driven rivets on existing riveted structures by a non-destructive way.

As for the structural behaviour, the riveting technology, etc., some of the above considerations on the geometry of riveted connections – e.g., joining typologies, rivets pattern – conceal and result from the main findings of experiments. The next chapter (CH4) addresses the topic of the theory of riveted connections through an analysis of the test results of 19th- and 20th-century experiments.

[13] Provided that the shop head can be identified (see CH6).

# PART II
# DESIGN

## CHAPTER 4
## THEORY AND EXPERIMENTS

**The development of the theory of riveted connections is addressed in chapter 4. The topic constitutes as a prerequisite towards the understanding of the design methods of historical riveted connections. The aim of chapter 4 is twofold. First, it attempts to reveal how 19th-century engineers perceived the ultimate shear behaviour based on failure modes. Second, it pinpoints the parameters that have an influence on the shear behaviour. The results of 19th- and 20th-century experiments conducted by acknowledged British, American, French and German investigators are reviewed to achieve these objectives.**

**Chapter 4 aims to answer the following questions:**

*How were riveted connections assumed to behave under static loadings? Did it evolve over time?*

*What are the average ultimate strength values found by experiments?*

*Which parameters influence the shear behaviour?*

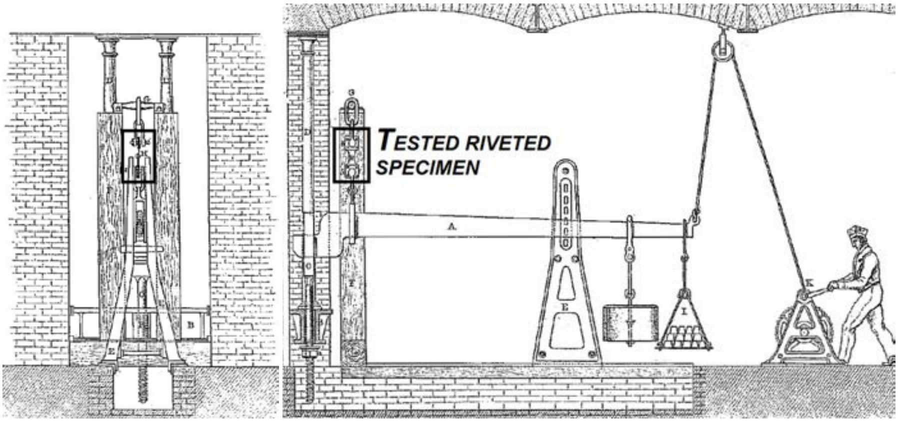



Figure 4-1: Testing machine used by W. Fairbairn in 1838 in a 5 storey high building to carry out an extensive shear tests campaign (adapted from Fairbairn 1850, 679)

Launched in the spring of 1838, the extensive shear tests campaign conducted by Eaton Hodgkinson under William Fairbairn's supervision (UK) gave initial impetus to the development of the theory of riveted connections (Fig. 4-1). Some disastrous explosions of steam boilers stressed the need to investigate the strength of riveted connections and their constituting plates. Those accidents attracted the attention of investigators on the structural behaviour of riveted connections that proved to be the weakest part of riveted tanks and boilers. (de Jonge 1945, 11)

Next to their geometry that was addressed in the previous chapter (CH3), the strength of riveted connections is the second main input parameter that intervened in their design. Experimental investigations allowed the ultimate strengths of riveted connections and their failure modes to be revealed. Such information was needed to define the design stresses of the plates in tension/bearing and the rivets in shear/bearing[1]. Hence, the analysis of the theory of riveted connections is a prerequisite to understand their design, and consequently decipher original construction details of existing riveted structures that are appraised. Moreover, the main findings of past experiments bring the influence of key parameters on their structural behaviour to light, and may guide today's renovation practices.

This chapter broaches the topic of the theory of riveted connections. The overall structural behaviour of riveted connections is first briefly presented based on today's knowledge. Then, a literature review focuses on the understanding of the behaviour of standard splice joints under static loadings by engineers of the time. The evolution of the theory of riveted connections is discussed, namely the strengths and failure modes. Finally, the impact of parameters on their structural behaviour dealing with both the technology and the design is assessed by reviewing the results of 19th- and

[1] The topic is the subject of the next chapter (CH5).

20th-century experiments. The discussions are based on experiments mainly performed in the UK and the US, that is, the countries in which the first large-scale tests took place (de Jonge 1945, 13)[2].

## 1 STRUCTURAL BEHAVIOUR

The load-bearing capacity of standard splice joints involves their frictional, shear, and bearing strength. Unfortunately, a thorough understanding of the structural behaviour of riveted connections is not yet reached to this day (Gasparini and Simmons 1997, 137). In spite of extensive research performed in the 19th and 20th century on the topic, today's standards rely on simplistic rules of thumb regarding how rivets behave in shear. The most common simplifying assumptions are as follows (EC 2005, 24–25, 27, 29):

- The rivet shank complete fills the rivet hole after driving;
- The contribution of the frictional strength is neglected;
- Riveted connections behaves in pure shear/bearing;
- The applied loads are uniformly distributed within the rivets of a given joint.

For single riveted splice joints[3], every rivet may theoretically take up an equal share of the applied load, leaving actual considerations of rivet driving[4] aside. In any case, this is not true for multiple riveted splice joints comprising more than one rivet(s) row per force transmission. Here the rivets of the outer rows will yield and fail before the full shear capacity of the rivets of the inner rows is reached. This sequential failure of rivets progressing from the outer rows of the joint inward is better known as *unbuttoning* (Rumpf 1964, 568).

As introduced in chapter 1, section 1, the fictional strength of the joint is provided thanks to the hot-riveting technique. The frictional strength results from the clamping force of the rivet that squeezes the connected plies (Fig. 4-2, top-left). The plies are subjected to transverse compressive stresses, and more fundamentally, to a complex triaxial stress state in the vicinity of the rivet hole (Fig. 4-2, right) (Åkesson 2010, 25). The inner prestressing state of the rivet is induced by its longitudinal shrinkage, as it cools after driving. The residual clamping force depends on, among others, the grip length, the driving technique, the driving temperature and the quality of riveting

[2] From the 1890s onwards, experimentations were also conducted in other countries, particularly in Germany (e.g., C. Bach, G. Barkhausen in 1892; A. Seydel in 1908; P. Müller in 1909) and France (e.g., A. Considère in 1886; M. Dupuy in 1894-95; M. Rabut in 1892; C. Frémont in 1906).

[3] That is, lap and butt splices having one rivet(s) row per force transmission, see CH3, section 3.1, for more information.

[4] I.e., holes misalignment and clearances, quality of riveting, etc.

(Kulak, Fisher, and Struik 2001, 28). The magnitude of the clamping force is highly variable and increases for longer grips (Wilson and Thomas 1938, 10–11).

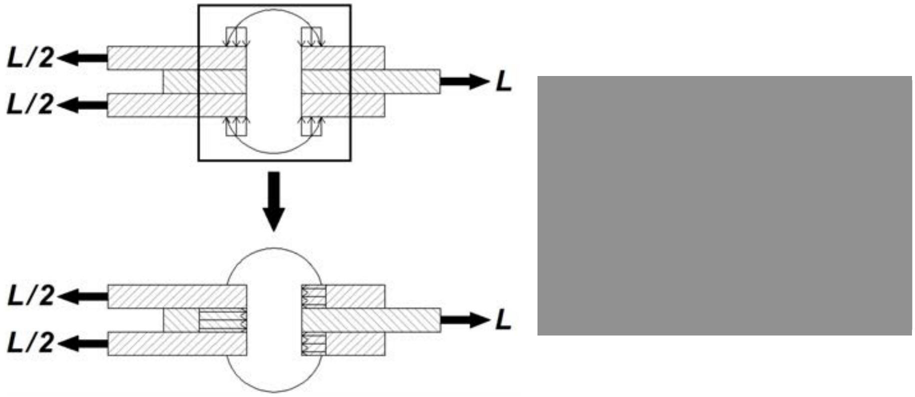



Figure 4-2: The plies are brought into bearing against the rivet shank when the frictional strength is overcome (top-left to bottom-left), (right) simplified distribution of the transverse compressive stresses within the plies induced by the clamping force (Åkesson 2010, 26)

Similarly to high-strength bolts, the frictional strength resulting from the clamping force prevents the joint to slip into bearing. The joint is slip-resistant for shear loads of moderate magnitude. The joint behaves as a friction-type fastener until the external tensile loads applied on its constituting plates exceed the frictional strength of the faying surfaces. Once the loads overcome the frictional strength, the joint belongs to the bearing-type category. The plies are brought into bearing against the rivet shank, and the loads, transferred by shearing of the rivet(s) via single or multiple shear plane(s) (Fig. 4-2, bottom-left).

Deformations of the rivet shank and/or the plies occur. The rivets of symmetric joints such as double lap and butt splices are theoretically subjected to pure shear. Asymmetric joining typologies of splice joints show, however, secondary stresses inducing out-of-plane displacements, given the eccentricity of the loads from the centroid of the joint. Such joining configurations increase the potential detrimental effect(s) of rivet manufacture and driving – if present – on the load-bearing capacity of rivets in comparison with rivets in pure shear (Cox and Munse 1952, 28). For increasing shear loads, the joint behaves elastically until the yielding of either the rivet shank or one of the plates takes place. Collapse of the joint occurs according to one or a combination of the following failure modes: rivet shear, plate tension (net section) and plate bearing (rivet hole on the plate's lap side). Typically, asymmetric splice joints develop combined failure modes (D’Aniello et al. 2011, 522).

Nowadays, in static design, rivets are considered as shear-type fasteners. The frictional strength of the riveted connections to which they belong is neglected within

the calculations, given its variable and unpredictable features. Hence, riveted connections are assumed to behave either in pure shear or bearing (EC 2005, 27).

## 2 GENESIS OF THE THEORY

Current knowledge on the structural behaviour obviously results from the genesis and progressive evolution of the theory of riveted connections that occurred during the two past centuries. The fundaments of the static theory experienced major evolutions between the 1840s and 1920s, and raised long-lasting debates within the engineering world (de Jonge 1945). In the 1830-40s, the prominent experiments performed/supervised by W. Fairbairn and E. 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 behaviour of riveted connections (de Jonge 1945, 47). The results of those experiments characterizing the behaviour of riveted connections at ultimate were prerequisites necessary to their design – empirical, semi-analytical and analytical methods, as it will be seen in the next chapter (CH5).

This section addresses the topic of the theory of riveted connections. The main theoretical models and their evolution over time are first investigated to understand how riveted connections were assumed to behave under shear loading. Then, the main types of failure modes are presented since they prominently impacted on the design methods. For each failure mode, average values of the corresponding ultimate strength of standard configurations of wrought-iron and steel splice joints are given and discussed. Providing insights into the theory of riveted connections permits to reveal the fundaments on which historical design principles were based, and consequently better understand the construction details of existing riveted structures today.

### 2.1 FRICTIONAL, SHEAR AND BEARING STRENGTHS

Between the 1840s and 1890s, divergent interpretations arose from the discussion of the results of experiments performed on riveted connections to assess their shear behaviour. These theoretical models led to major quarrels and debates within the engineering world until the turn of the 20th century.

The first theoretical considerations regarded structural rivets as behaving either in pure friction or pure shear. From the 1880s onwards, they were then considered as pure shear-type fasteners. From the beginning of the 20th century onwards, the

bearing strength of riveted connections was taken into account eventually, next to their shear strength, as with today's standards.

### 2.1.1 EVERLASTING QUARREL BETWEEN THE PROTAGONISTS OF FRICTION AND SHEAR

The most important debate of the theory of structural riveted connections arose from the construction of the Conway (1848) and Britannia (1850) tubular bridges in the UK – the largest-span bridges of the world at that time. Both bridges were designed by W. Fairbairn under the direction of Robert Stephenson. Due to a quarrel between Fairbairn and Stephenson concerning the design of these bridges, they each published their own book to assert their differing points of view and theories. (de Jonge 1945, 12)

On the one hand, Fairbairn published the results of the extensive shear tests campaign carried out in 1838 by Hodgkinson whom he supervised (Fairbairn 1850). Fairbairn and Hodgkinson postulated that the strength of riveted connections was provided by shear only. The fact that their theory relied on the behaviour *at ultimate* explains why rivets are considered as a pure shear-type fastener. Actually, the frictional strength has to be first exceeded before the plate can be brought into bearing and thus shear the rivets.

On the other hand, Stephenson asked Edwin Clark – his resident engineer – to write the book that summarized the results of his experiments (Clark 1850). Clark and Stephenson's theory considered, however, rivets as a friction-type fastener. Here the frictional strength at the faying surfaces is assumed to be sufficient to take up the shear loading applied on the connections *in service* (i.e., at working loads).

These two opposing theories led to two major schools of thought – friction-type vs. shear-type fastener – in the engineering world on an international scale[5]. This theoretical quarrel lasted for the decades to come. (de Jonge 1945, 12)

### 2.1.2 SHEAR-TYPE FASTENERS AS A RULE

From the 1880s onwards, the controversy between the friction and the shear theories progressively disappeared. Most of the theoreticians agreed that a combined action of the frictional and shear strengths contributed to the overall structural behaviour of a riveted connection. In practice, however, they were strictly considered as shear-type connections in France and Belgium (Dechamps 1888, 130–31; Leman 1895, 184–5; Novat 1900, 194–5), but also – more fundamentally – on an international scale (Waddell 1891, 91; Twelvetrees 1900, 117; Van der Veen 1919, 72). The frictional strength was neglected for two main reasons.

[5] In Germany, for instance, the educator-engineer C. Bach who promoted the friction theory in his 1890s-1900s publications was against JW. Schwedler's theory (1867) in favour of shear (Aerts 1911, 42; de Jonge 1945, 93, 96).

First, the shear strength of the connections was the key parameter to consider, since the design was primarily based on their behaviour at ultimate and failure modes, as it will be seen in chapter 5. Actually, the fact that the frictional strength did not affect the structural behaviour at ultimate was a known phenomenon (Flamant 1897, 287–88; Twelvetrees 1900, 114):

> "Even if this state of things exists [the frictional strength of a joint], the inference must not be drawn that the ultimate strength of a joint is in any way increased thereby." (Twelvetrees 1900, 114)

Nevertheless, educator-engineers and theoreticians of the time were aware of the sufficient contribution provided by the frictional strength to the overall shear behaviour of the connections in service (Novat 1900, 194; Desarces 1913, 17). This was, for example, emphasized by Desarces in 1913:

> "Nous voyons que l'adhérence suffit pour assurer la transmission des forces et qu'elle devrait servir de base dans le calcul de résistance des lignes de rivets. Pourtant, dans la pratique, [...] on considère une ligne de rivets comme devant travailler uniquement au cisaillement." (Desarces 1913, 217)

Second, the complexity and extreme variability of the effect of friction on the structural behaviour headed in the same direction as the above reason. A large number of parameters that conditioned the magnitude of the frictional strength – e.g., grip length, surface condition at the faying surfaces, driving technique and time, quality of riveting – were difficult to assess and predict (Leman 1895, 182–84; Frémont 1906, 52).

Hence, neglecting the frictional strength of riveted connections subjected to shear loading was a conservative approach. It provided an additional safety margin since it potentially tended to relieve rivets from shearing stresses.

### 2.1.3 BEARING-TYPE CONNECTIONS: SHEAR AND BEARING STRENGTHS

Within the evolution of the theory of riveted connections, the bearing strength was experimentally investigated after the frictional and shear strengths. In 1858, JH. Latham (UK) seems to be the first to draw attention to the bearing pressure, that is, the pressure applied by the rivet shank on the rim of the plates' rivet holes and vice versa. He was later followed by other investigators such as H. Gerber in 1865 (Germany), AV. Kaven in 1868 (Germany), etc. In particular, in 1869, WC. Unwin (UK) stressed the fact that Fairbairn (1850) had omitted to discuss the influence of the bearing pressure on the shear behaviour of the tested riveted specimens. (de Jonge 1945, 12, 60, 62, 64)

Typically, excessive bearing pressure could result from insufficient care in defining the $d/e$ ratio in a design. This is evidenced by the fact that the ultimate bearing load

that a plate can withstand is notably a function of the bearing area, which is the product of the plate thickness $e$ multiplied by the shank diameter $d$ (Tab. 4-2). Hence, for a given plate thickness, the cross section of a rivet will increase more rapidly than the bearing area will do for increments in shank diameter. (Twelvetrees 1900, 113)

As it will be seen in chapter 5, in a design, the notion of bearing strength was taken into account from the beginning of the 20th century onwards in France and Belgium[6]. This period corresponds to the progressive development of standards. As a consequence, educator-engineers and theoreticians did not directly include the bearing strength into their design methodology, given the time lag with the experiments performed during the previous decades. From then on, structural riveted connections have belonged to the bearing-type category involving both the shear strength of the rivet(s) and the bearing strength of the plates constituting them. Present standards are based on this theoretical model since they treat riveted connections as shear/bearing joints (EC 2005).

## 2.2 FAILURE MODES

The different failure mechanisms of splice joints subjected to shear loading were revealed by the experiments performed in the 19th century. Engineers' understanding and interpretation of the failure modes fundamentally influenced the design methodology of riveted connections. The (in)accurate theoretical assumptions they made conditioned the dimensions of the rivets, their number and pattern. As a result, it impacted on the final geometry and layout of riveted connections, and consequently the whole riveted structure itself.[7]

In general, historical French and Belgian authors reported on four main types of failure modes that are given and described in table 4-1 (De Vos 1879, 1:96; Dechamps 1888, 131; Flamant 1897, 288–90; Novat 1900, 195; Aerts 1911, 35–36; Jacquemain 1946, 49). To almost each of these failure mechanisms correspond parameters on the geometry and strength of riveted connections impacting their design (Tab. 4-1). The crushing of the plies constituting the grip was avoided through geometrical considerations only, namely the $d/e$ ratio. The tearing of the plates depended on the rivet pitch $p$ and edge distance $v$ as well as on the ultimate tensile strength (UTS) of their net section. With regard to the crushing of the rivet hole or shank, it is the rivet lap $l$ and again the $d/e$ ratio that were taken into account for the geometry. Since the pressure applied by the rivet shank on the rivet hole was generally of concern, the ultimate bearing strength (UBS) of the plates was

[6] The notion of bearing strength was introduced earlier in the design methods in the US for instance. Authors such as JAL. Waddell referred to the bearing strength in as early as 1891 (Waddell 1891, 90).

[7] See CH5 for further details.

considered at the design stage from the beginning of the 20th century onwards. For a given shear behaviour of the rivets – either single or double shear, their bearing capacity obviously depends on their ultimate shear strength (USS) and the shear plane(s) area resulting from the shank diameter $d$.

Table 4-1: The main failure modes of riveted connections influenced parameters dealing with both their geometry and strength

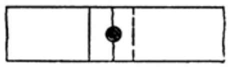
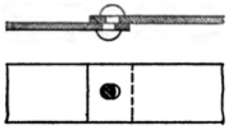
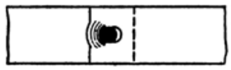
| FAILURE MODES | | DESIGN | |
|---|---|---|---|
| TYPE | DEFINITION | GEOMETRY[8] | STRENGTH |
| Grip crushing | The plies of the grip are transversally crushed by the bottom surface of the rivet heads. | $d/e$ | / |
| Plate tearing | The plates are torn along the lines of rivets. | $p$ & $v$ | Ultimate plate tensile strength (UTS plate) |
| Plate/shank crushing | The rim of the rivet holes is crushed by the pressure applied by the rivet shank and vice versa. | $l$ & $d/e$ | Ultimate plate bearing strength (UBS plate) |
| Shank shearing | The rivet shank is sheared by the plies in tension. | $d$ | Ultimate rivet shear strength (USS rivet) |

The $d/e$ ratio characterizing the first failure mode was a prevalent geometrical parameter that conditioned the design of all riveted connections, regardless of the design method used[9]. The three last failure modes directly influenced, however, the design principles taking also the strength of riveted connections into account (Tab. 4-1). The strength of riveted connections was primarily based on plate tension (net section), rivet shear (shank) and plate bearing (lap side). The failure mechanisms and formulae of the ultimate load of the plate in tension, rivet in shear and plate in bearing mentioned by historical French and Belgian literature are given in table 4-2 for a single riveted single lap joint subjected to shear loading (De Vos 1879; Combaz 1897; Flamant 1897; Novat 1900; Nachtergal 1937). Those formulae were reported by international literature too (Waddell 1891; Twelvetrees 1900; Zwiers 1916; Van der Veen 1919).

[8] See CH3, Fig. 3-7, for the definition of the geometrical parameters.

[9] See CH5 for further details.

Table 4-2: Failure mechanism and ultimate load withstood by a single riveted single lap joint in plate tension, rivet shear and plate bearing

| FAILURE MODE | PLATE TENSION | RIVET SHEAR | PLATE BEARING[10] |
|---|---|---|---|
| |  (Twelvetrees 1900, 98) |  (Twelvetrees 1900, 98) |  (Twelvetrees 1900, 98) |
| Ultimate load[11] | $F_t = (G-d)ef_t$ | $F_s = \pi \frac{d^2}{4} f_s$ | $F_b = def_b$ |

*Where: $F_{t/s/b}$ is the ultimate plate tensile/rivet shear/plate bearing load per unit gage, $f_{t/s/b}$, the ultimate plate tensile/rivet shear/plate bearing strength and $G$, the **gage**.*

The ultimate loads of the plate in tension, rivet in shear and plate in bearing are stated as a function of the plate/rivet geometry[12] and the ultimate strengths[13] (Tab. 4-2). Note that the terminology mentioned in historical literature is inappropriate since it assumed that the strength of one given element – rivet or plate – characterized the overall strength of the connection. Obviously, a combined action of both rivets and plates account for the behaviour of the connection. Nonetheless, this terminology is used from now on in accordance with the content of historical literature.

Each of these strengths is separately addressed in one of the three following sections (2.2.1, 2.2.2 and 2.2.3). Average values of the UTS plate net section, USS rivet shank and UBS plate lap of wrought-iron and steel splice joints are given[14]. Retrieved from Twelvetrees (1900), the figures summarize the results of shear tests campaigns carried out in the second half of the 19th century in the UK by acknowledged engineers such as W. Fairbairn, D. Kirkaldy, B. Stoney, D. Greig & M. Eyth, etc. Average values of $f_t$, $f_s$ and $f_b$ are provided since these parameters did not significantly evolve over time for a given material. As a reminder, the UK, together with the US, was a major seat of research regarding the characterization of the overall shear behaviour of riveted connections in the 19th century (de Jonge 1945, 20). The discussions focus on three parameters that were intensely debated within

[10] In the interests of clarity, the original terminology – the crushing strength – is replaced from now on by its equivalent in application nowadays, namely the bearing strength (EC 2005).

[11] The formulae relate to the standard joining typology of the single riveted single lap joint involving one single rivet. They also apply, however, for single riveted single lap and butt joints having more than one rivet in a row by considering a unit **gage** length.

[12] Plate net section $(G-d)e$, rivet shear plane area $\pi\, d^2/4$, plate bearing area $de$.

[13] UTS plate net section $f_t$, USS rivet shank $f_s$, UBS plate lap $f_b$.

[14] The plates and rivets of wrought-iron/steel splices are both made of wrought-iron/steel.

the theory of riveted connections, namely the joining typology, the material and the perforation technique[15].

### 2.2.1 PLATE TENSILE FAILURE

Basically, the failure mode of plate tension depends on the perforation technique as well as the mechanical properties inherent to the plate material. However, other parameters such as the joining configuration and rivet driving have also an important impact on the behaviour of wrought-iron and steel splices subjected to shear loading.

The perforation of the plates could negatively impact on their strength and ductility. The different techniques used for plate perforation, their advantages and drawbacks, were presented in chapter 2, section 2.1. The topic was the most controversial debate within the evolution of the riveting technology opposing two schools of thought: punching versus drilling. The protagonists of punching such as W. Fairbairn (1873) or H. MacColl (1875) erroneously concluded that the tensile strength of wrought-iron plates having punched holes was not necessarily lower than those with drilled holes (Fairbairn 1873; MacColl 1875). Conversely, H. Sharp's tensile tests carried out in 1868 showed that annealing could overcome the plate weakening induced by punching (Sharp 1868). In his book in 1875, J. Barba notably investigated the deterioration of the base metal made of mild steel – newly developed at *Creusot* and *Terre-Noire* – due to punching by means of experiments (Barba 1875). He found that strain hardening mainly occurred in only a narrow area near the edge of the punched hole, on an annular zone of ca. 1 mm wide. Annealing the plates could, however, cancel the plate deterioration. According to Barba, rivet heating was insufficient to anneal the hardened area of punched plates (de Jonge 1945, 62, 67, 82). In 1885, A. Considère concluded from his tests that the loss of strength of punched plates ranged from 20% – wrought iron, extra soft steel – to 35% – hard steel, depending on the material quality (Considère 1885, 739–40). In the main, the average loss of ductility could reach 20%, and even up to 50% according to Kirkaldy (1876) (O'Sullivan and Swailes 2009, 263).

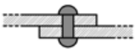
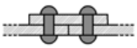
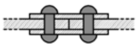
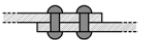
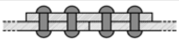
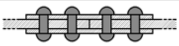
The loss of plate tensile strength resulting from the punching technique was partially compensated by the positive effect of the thermo-mechanical treatments induced by the hot-riveting technique – i.e., combined action of rivet heating and driving. Actually, test results summarized by Twelvetrees revealed that the UTS of the plate net section $f_t$ of wrought-iron splices is generally lower than the UTS of the plate material in its unperforated state – and thus unriveted – by ca. 15% (Twelvetrees 1900, 110). For splice joints made of steel, the values of $f_t$ approximate or even exceed the UTS of the plate material, presumably because of the driving technique

[15] The importance of those key parameters was revealed by the analyses of CH2 and CH3.

used (i.e., machine riveting for steel rivets vs. hand riveting for wrought-iron rivets). In addition, the positive impact of the hot-riveting technique on the shear behaviour was even more pronounced for small plate thicknesses and $G/d$ ratios (Twelvetrees 1900, 111; Schenker, Salmon, and Johnston 1954, II–23)[16].

Table 4-3 provides average UTS values of the plate that failed in tension $f_t$ – net section – and having generated the collapse of lap and butt splices subjected to shear loading. These are single riveted and double riveted single or double lap and but joints made of wrought iron or steel, and for which the plates were perforated according to the punching or the drilling technique.

Table 4-3: Average ultimate plate tensile strength $f_t$ (net section) of lap and butt splices subjected to shear loading, wrought-iron/steel splices with punched/drilled rivet holes (Twelvetrees 1900, 111–12)[17]

| JOINING TYPOLOGY[18] | ULTIMATE TENSILE STRENGTH OF THE PLATE NET SECTION $f_t$ (MPa) | | | |
|---|---|---|---|---|
| | WROUGHT IRON | | STEEL | |
| | PUNCHING | DRILLING | PUNCHING | DRILLING |
|  SR-S-LJ | 250 | 260 | 370 | 410 |
|  SR-S-BJ | 250 | 260 | 370 | 410 |
|  SR-D-BJ | 260 | 275 | / | / |
|  DR-S-LJ | 260 | 275 | 370 | 400 |
|  DR-S-BJ | / | / | / | / |
|  DR-D-BJ | / | / | 370 | 400 |

The figures given in table 4-3 are in line with the above discussions regarding the perforation technique: the UTS plate net section $f_t$ is lower for splice joints having punched holes. The negative effect of punching is, however, more moderate for wrought-iron splices.

Next to the hot-riveting technique, the joining typology has also an influence on the parameter $f_t$, especially for riveted connections made of wrought iron. Here asymmetric configurations of single riveted lap and butt splices (i.e., SR-S-LJ and

[16] See section 3.2 for more information on the $G/d$ ratio.

[17] The missing figures correspond to values that were deliberately not provided for matters of statistical representativeness or because of lacking information (i.e., absence of tests).

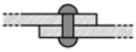
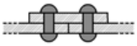
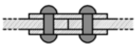
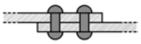
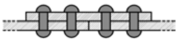
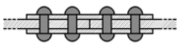
[18] See CH3, Tab. 3-3, for detailed explanations on the labels.

SR-S-BJ) failed at lower $f_t$, for both punched and drilled rivet holes (Tab. 4-3). Contrarily, double riveted joints – though asymmetric – and butt joints with two cover plates showed slightly higher values of $f_t$, which is in accordance with the discussions suggested in chapter 3, section 3.

### 2.2.2 RIVET SHEAR

Average USS values of the rivet shank $f_s$ that generated the collapse of lap and butt splices under shear loading are given in table 4-4. The figures relate to the same joining typologies as the ones discussed in the previous section.

Table 4-4: Average ultimate rivet shear strength $f_s$ (shank) of lap and butt splices subjected to shear loading, wrought-iron/steel splices with punched/drilled rivet holes (Twelvetrees 1900, 106, 108)

| JOINING TYPOLOGY | ULTIMATE SHEAR STRENGTH OF THE RIVET SHANK $f_s$ (MPa) | | | |
|---|---|---|---|---|
| | WROUGHT IRON | | STEEL | |
| | PUNCHING | DRILLING | PUNCHING | DRILLING |
|  SR-S-LJ | 260 | 250 | 320 | 300 |
|  SR-S-BJ | 250 | 230 | 300 | 290 |
|  SR-D-BJ | / | / | / | / |
|  DR-S-LJ | 260 | 250 | 330 | 320 |
|  DR-S-BJ | 260 | / | 330 | / |
|  DR-D-BJ | 260 | 250 | 330 | 320 |

The above figures reveal three main aspects. Firstly, while the values of $f_s$ of wrought-iron splice joints approximate their $f_t$, the same is not true for steel splices (Tabs. 4-3 & 4-4). Regarding the latter, the average $f_s$ is markedly lower than $f_t$. The larger variations in mechanical properties between plate and rivet irons compared to plate and rivet steels might explain this observation[19]. Secondly, a slight advantage of the punching technique over the drilling technique is evidenced (Tab. 4-4). It highlights the fact that the detrimental effect of punched holes being neither reamed nor re-drilled may not affect the behaviour of splice joints when they fail in rivet shearing. The slight increase in $f_s$ of wrought-iron and steel joints having punched

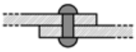
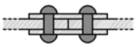
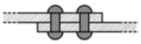
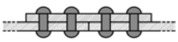
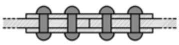
[19] As noticed in CH2, rivet irons benefitted from a better quality – both strength and ductility – than plate irons. This may compensate the difference between the USS of the rivet shank and the UTS of the plate net section.

holes may originate from the larger shear plane area resulting from the truncated cone shape characteristic of punched holes. Thirdly, although not predominant, the influence of the joining typology is in line with the observations of the previous section. Double riveted lap and butt splices perform slightly better than single riveted ones (Tab. 4-4). Actually, the higher stiffness provided by the larger number of rivet rows – twice as high as for single riveted splices – conceal out-of-plane displacements of the connections. It consequently reduces the additional bias tension within the rivets, known to be detrimental to their shear behaviour (Cox and Munse 1952).

### 2.2.3 PLATE BEARING

Similarly to sections 2.2.1 and 2.2.2, table 4-5 gives average UBS values of the plate that failed in bearing $f_b$ – lap side, causing the collapse of lap and butt splices subjected to shear loading.

Table 4-5: Average ultimate plate bearing strength $f_b$ (lap side) of lap and butt splices subjected to shear loading, wrought-iron/steel splices with punched/drilled rivet holes (Twelvetrees 1900, 113)

| JOINING TYPOLOGY | ULTIMATE BEARING STRENGTH OF THE PLATE LAP $f_b$ (MPa) | | | |
|---|---|---|---|---|
| | WROUGHT IRON | | STEEL | |
| | PUNCHING | DRILLING | PUNCHING | DRILLING |
|  SR-S-LJ | 410 | 410 | 550 | 550 |
|  SR-S-BJ | 410 | 410 | 550 | 550 |
|  SR-D-BJ | 550 | 550 | 690 | 690 |
|  DR-S-LJ | 410 | 410 | 550 | 550 |
|  DR-S-BJ | 410 | 410 | 550 | 550 |
|  DR-D-BJ | 550 | 550 | 690 | 690 |

For both lap and butt splices, neither the perforation technique nor the number of rivet rows per force transmission seem to influence the ultimate bearing strength of the plate $f_b$ against the bearing pressure applied by the rivet shank on the bearing area $de$. The shear behaviour conditions, however, the values of $f_b$. Splice joints in double shear – i.e., SR-D-BJ and DR-D-BJ – perform better that joints subjected to single shear (Tab. 4-5). This observation can be explained by the negative influence

of asymmetric configurations of lap and butt splices behaving in single shear on their bearing capacity at ultimate.

As a result, analyzing the ultimate strengths of lap and butt splices corresponding to the three major failure modes considered at the time – plate tension, rivet shear and plate bearing – allowed to underline three main notices. First, the perforation technique influences the shear behaviour at ultimate of wrought-iron and steel splice joints failing in plate tension ($f_t$). Second, the values of $f_s$ stressed the fact that it is the actual shank diameter of the rivet shank – driven configuration – that conditions, among other parameters, the behaviour at ultimate of splices joints failing in rivet shearing. This consideration brings us back to the importance of the diameter of the rivet hole $d_{hole}$ (see CH2, Eqn. 2-1). Thirdly, the symmetric feature of lap and butt splices seems to have a positive impact on $f_b$, that is, when the crushing of the plate is responsible for the failure of these joints.

The behaviour at ultimate embodied by $f_t$, $f_s$ and $f_b$ defined the design of riveted connections, as it will be seen in the next chapter (CH5).

## 3 IN-DEPTH STUDY OF PARAMETERS

The previous section discussed the shear behaviour at ultimate and typical failure modes of wrought-iron and steel riveted connections. The prevalent experiments characterizing the overall shear behaviour – plate tension, rivet shear, plate bearing – of standard splice joints were primarily conducted in the 19th century. In the main, they focused on the effect of basic parameters such as the joining typology, the material and the perforation technique. These fundamental investigations laid the groundwork for more detailed experimental programmes that were progressively launched from the 1900s onwards through more systematic, extensive and accurate approaches. Those experiments were aimed at assessing the stress distribution within the plates and rivets under static loading as well as the influence of rivet manufacture and driving on the shear behaviour of riveted connections. (de Jonge 1945, 13–49)

The present section discusses the influence of rivet manufacture and driving on the shear behaviour of riveted connections, based on a literature review. The strength and ductility of driven rivets are compared to the undriven configuration. The many discussions and contradictory historical results pinpoint the difficulty to determine key parameters that influence the overall shear behaviour of riveted connections. Nevertheless, this section attempts to give a coverage of the majority of the effects impacting their behaviour (i.e., material, geometry and technology). The results of

20th-century experiments[20] and recent literature are referred to. As the most extensive experimental investigations on standard splice joints under static loadings were performed in the US and France, the section focuses mainly on research originating from those two countries (Frémont 1906; Wilson and Oliver 1930; Cox and Munse 1952; Schenker, Salmon, and Johnston 1954).

Valorizing the main findings of past experiments brings the influence of key parameters on the structural behaviour of riveted connections to light. Such approach contributes to guide today's renovation practices. In addition, the conclusions drawn directly support the investigations conducted in the chapters of Part III (CH6 & CH7).

## 3.1 STRENGTH AND DUCTILITY OF DRIVEN RIVETS

The thermo-mechanical treatments induced by rivet manufacture and driving transforming a cut segment of rivet bar into a manufactured rivet, and eventually a driven rivet, modify the strength and ductility of the base metal (i.e., rivet iron or steel). Figure 4-3 gives a schematic overview of parameters that condition the strength and ductility of rivets in their driven configuration. These parameters[21] can be merged into five groups, which reflect the decisions to be taken in the subsequent phases from design to execution of a riveted connection: material, manufacture, geometry, heating and driving (Fig. 4-3).

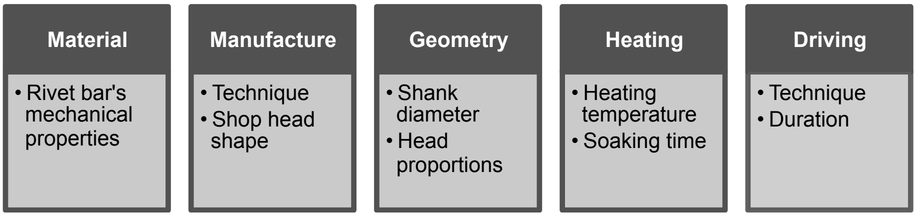



Figure 4-3: Five groups of parameters have an influence on the strength and ductility of driven rivets

Firstly, the strength and ductility of a driven rivet obviously depends on the rivet bar from which it originates. Secondly, the manufacturing technique – hot vs. cold-formed, machine type, etc. – as well as the quality of manufacture determine the shop head shape and strength. Thirdly, the proportions of the driven rivet, its shank and heads, have an effect on its strength. Finally, rivet driving – rivet heating and the

[20] Note that the discussions rely on available published and unpublished test results found in literature and grey literature, respectively. This notice is relevant given the non-negligible amount of confidential experiments conducted in the 20th century and recent past on the topic. In the main, these investigations were – and still are – commissioned by steel construction companies specialized in the hot-riveting technique, national railway companies, etc., given the high competitiveness of this niche market (Aelterman 2013).

[21] Non-exhaustive list.

driving operation itself, to be more precise – influences the strength and ductility of rivets.

Although these phenomena were known, neither 20th-century design methods[22] nor present standards have effectively taken them into account so far (EC 2005; D'Aniello et al. 2011). Nevertheless, the topic should be of concern to practicing engineers appraising the structural integrity of existing riveted connections. Actually, the shear behaviour of riveted connections depends, among others, on the shear capacity of driven rivets. In its turn, the ultimate shear capacity of driven rivets results from their USS, itself directly conditioned by the final UTS after driving (Cox and Munse 1952, 22–23; Schenker, Salmon, and Johnston 1954, I–2, 28).

The effect of parameters related to the above five aspects is discussed below (Fig. 4-3):

RIVET BAR'S MECHANICAL PROPERTIES

As noticed by Schenker, Salmon and Johnston (1954) on 20th-century rivet steels, the intrinsic material properties of the base metal are the most prevalent parameter conditioning the UTS – and consequently USS – of driven rivets:

> "The basic properties of the material of which the rivets are made are of prime importance in determining the characteristics of the finished rivets [driven configuration]. No other single factor can produce such a wide range of ultimate rivet strength values as variation of material." (Schenker, Salmon, and Johnston 1954, I–27)

The above statement applied even more for rivet irons. Although they were of the very best quality, wrought-iron bars used for rivet manufacture were characterized by important variations in material properties, as emphasized by the figures of table 2-1 (see CH2). The manufacturing process of wrought iron had a predominant influence on its quality. The quality was increased thanks to repeated hot workings – four to six workings were recommended – that refined the shape, the size and dispersion of the slag inclusions, together with improved mechanical properties. Insufficient or excessive workings could detrimentally affect the ductility. In addition, when wrought iron was worked at a too low temperature, the formation of coarse slag inclusions could initiate rivet failure under sufficient load. (Hooper et al. 2003, 1556, 1562; Tilly et al. 2008, 79; O'Sullivan and Swailes 2009, 261–62)

The material properties of steel and high-strength steel rivet bars were more homogeneous than rivet irons, especially in elongation at failure (see CH2, Tab. 2-1). Moreover, rivet steels and rivet high-strength steels used in various countries such as France, Belgium, Spain, Germany, Canada, the UK or the US had a very similar strength and ductility (Schenker, Salmon, and Johnston 1954, I–3).

[22] See CH5, sections 4 and 5.

Hence, large variations in USS and ductility of the driven rivets of historical wrought-iron structures are to be expected because of the differences in material properties of rivet irons[23]. Rivets made of steel and high-strength steel bars are significantly less concerned by this observation.

SHANK DIAMETER

Previous research underlined the relevance to make a distinction within the structural wrought-iron component types – e.g., plates, angles, bars – when assessing their mechanical properties because of the different degrees of working they had undergone (Bowman and Piskorowski 2004, 17; Sparks 2008, 452; O'Sullivan 2013, 160). Rivet iron was a material of superior quality with regard to the toughness. Though no relationship exists between the mechanical properties and the thickness of wrought-iron plates, the shank diameter of a given rivet iron impacted its mechanical properties (O'Sullivan 2013, 73). Tensile tests campaigns were conducted on rivet irons with diameters ranging from 50 mm down to 10 mm at the Watertown Arsenal in the 1880s-90s in the US (Watertown, MA)[24]. The results proved that the yield strength and the ultimate tensile strength (UTS) parallel to grain slightly increased for decreasing values of bar's diameters. O'Sullivan and Swailes (2009) suggest that the greater strength of small bar diameters may have been consequent to the higher amount of hot workings they experienced (O'Sullivan and Swailes 2009, 266–67).

American investigators – e.g., H. Cox and WH. Munse, JB. Kommers – and European investigators – e.g., S. Gallik, C. Frémont – of the 1900s, 1920s and 1950s made similar observations with regard to steel rivets. There appeared a small tendency, generally lower than 7%, for the UTS of steel rivets to increase with decreasing shank diameters (Cox and Munse 1952, 28). However, since the effect of the shank diameter was limited, it was believed that the strength and ductility of steel rivets could be considered as independent of size. (Frémont 1906, 106; Schenker, Salmon, and Johnston 1954, I–13)

[23] In general, the UTS of rivet irons ranges between 320 MPa and 410 MPa, and their elongation at failure, between 17% and 36% (see Tab. 2-1).

[24] The extensive tests campaign conducted at Watertown Arsenal established the US as a major player in the field of material testing on a world basis. Thanks to the accuracy and high testing capacities of the machine constructed by the Ames Manufacturing Company of Chicopee Falls under the supervision of Albert H. Emery, numerous tests were carried out, and the results, yearly published. (O'Sullivan and Swailes 2009, 265)

RIVET HEADS

Forming the shop and field heads via rivet manufacture and driving, respectively, modified the grain flow of rivet irons/steels being originally oriented in the longitudinal direction. Actually, a reorientation of the grain flow occurred at the head/shank interface and within the heads. For rivets manufactured and driven by a machine, this orientation within the heads goes up to 90° relative to the rivet shank[25]. For wrought-iron rivets, since both yield and ultimate tensile strengths perpendicular to grain are ca. 15% lower than parallel to grain[26], these regions can be considered as weaker within the rivet (Hooper et al. 2003, 1562; O'Sullivan and Swailes 2009, 269). In the 2000s, this observation was stressed by Hooper et al. (2003) who investigated the metallurgy of the wrought-iron rivets of the RMS *Titanic*:

> "This evidence [reorientation of slag inclusions] suggests that the process of forming the head [...] produced regions of significant reorientation of the slag extruded along the shaft [shank], and may have produced regions along the rivet's loading axis that have lower strengths." (Hooper et al. 2003, 1559)

The UTS of a rivet could be determined by the failure of one of its heads. Standard proportions of rivets, and in particular the $h/d$ ratio, guaranteed that such rivet failure would not occur under normal circumstances (Frémont 1906, 132). However, manufacturing and/or driving errors leading to a shop/field head depth being too small could reduce its UTS and initiate head failure when the inner prestressing of the rivet was too high and/or under accidental loads[27].

In France, Frémont (1906) performed tensile tests on driven steel rivets to assess the minimal head depth for which the rivet head would not pop off (Frémont 1906, 131–33). In the same idea, in the US, Wilson and Oliver (1930) compared the UTS of steel rivets having different field head depths and shapes driven by an air hammer (Wilson and Oliver 1930, 18–21). These tensile tests underlined the detrimental effect of small $h/d$ ratios on the tensile behaviour of steel rivets at failure (Fig. 4-4) (Frémont 1906, 131–33; Wilson and Oliver 1930, 18–21).

[25] For more information, see CH6, section 3 and Fig. 6-2.

[26] Up to 30% according to Bussell (1997) or Tilly (2008) (Bussell 1997, 60; Tilly et al. 2008, 9).

[27] Certainly, it would only affect the frictional strength of riveted connections though.

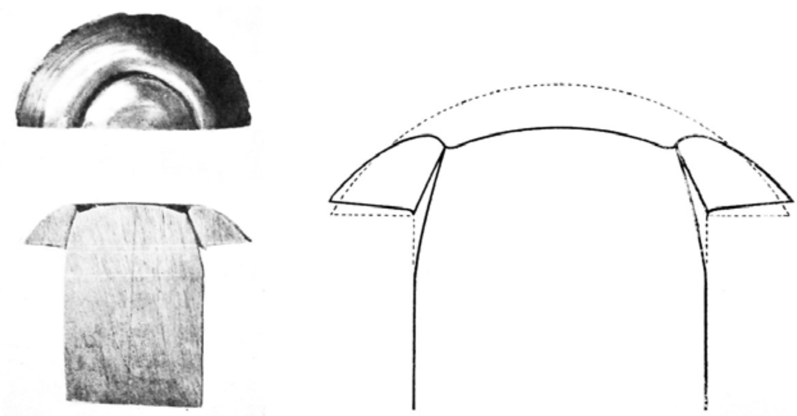


Figure 4-4: Round rivet heads with a too small $h/d$ ratio are responsible for the failure of steel rivets in tension (Frémont 1906, 133)

When remedial works require the hot-riveting technique, rivet heads – more fundamentally the field head – having insufficient head depths should be preferably removed to redo the driving operation.

#### HEATING TEMPERATURE

Until the 1900s, French engineers such as L. Molinos and C. Pronnier in 1857 or E. Simonot in 1901 believed that rivet heating reduced the ductility of *driven* rivets (Frémont 1906, 104). Quenching induced by the cooling of the rivets was, they stated, at the origin of these variations. In 1906, Frémont broke new ground by notably studying the influence of heating on *undriven* wrought-iron and steel rivets, regardless of the effect of rivet driving. Frémont did not record any noticeable influence, neither positive nor negative, on the yield strength, ultimate strength and elongation at failure of wrought-iron and steel undriven rivets heated at standard temperature (Frémont 1906, 107). In addition, he drew two essential conclusions on the impact of heating on the strength and ductility of rivets in their driven configuration, which is the one that actually matters. First, Frémont highlighted the increase in yield and ultimate strength of driven rivets heated at common-practice temperature, as a result of their longitudinal shrinkage. Second, he stressed the vicious effect of overheating that simultaneously increased the UTS and markedly decreased the ductility of driven rivets (Frémont 1906, 107–8)[28]. The experiments performed by Wilson and Oliver (1930) in the US were heading in the same direction as Frémont's findings regarding overheated/burned steel rivets (Wilson and Oliver 1930, 18).

[28] As discussed in CH2, section 2.2, overheating rivets to ease driving was, unfortunately, common practice for rivet stokers disregarding the structural behaviour of the connections.

Hence, the heating temperature has a positive influence on the strength and ductility of *driven* wrought-iron and steel rivets provided that they are not overheated (i.e., risk of brittleness).

#### SOAKING TIME

In 1930, Cox and Munse stressed the importance of the soaking time when assessing the strength of driven steel rivets:

> "In any analysis of the data, the soaking time must be taken into account because of its influence on the strength of the rivets." (Cox and Munse 1952, 12)

Their investigations revealed a slight decrease in UTS – ca. 5% – of driven rivets with increased soaking times ranging from 7 min to 25 min (Cox and Munse 1952, 14)[29]. Therefore, a follow-up of the length of soaking time of rivets is preferable.

#### DRIVING TECHNIQUE

In addition to its cost-effectiveness, the supersession of hand riveting by machine riveting went together with a positive impact on the frictional and shear strength of riveted connections, for a given quality of riveting[30].

The frictional strength was improved thanks to the more efficient tightening of the plies during the driving operation. On the one hand, the shop head was more firmly bucked up against the outer ply with a pneumatic holder-up tool compared to a hand-held one. On the other hand, riveting machines exerted higher compressive forces applied on the protruding shank end to form the field head.

The shear strength of rivets was markedly increased by the use of riveting machines. On average, machine-driven wrought-iron and steel rivets benefitted from an increase in yield and ultimate strength of 15% in comparison with the material properties of rivet irons/steels from which they originated (Frémont 1906, 107; Wilson and Oliver 1930, 8, 23, 24; Schenker, Salmon, and Johnston 1954, I–6)[31]. However, test results regarding steel rivets revealed a significant reduction in ductility once driven (Schenker, Salmon, and Johnston 1954, I–5, 6)[32]. Hence, this observation

[29] Cox and Munse tested steel rivets, 7/8 in (22 mm) in diameter, driven with an air hammer. Note that soaking times greater than 25 min were uncommon in standard shop and field practices (Cox and Munse 1952, 14).

[30] The quality of riveting – e.g., upset of the shank in the rivet hole – is not necessarily better for machine-driven rivets compared to hand-driven rivets, as it will be seen in Part III.

[31] Experiments – unpublished results – recently performed by M. D'Aniello in Italy confirm the main findings of the investigators of the first half of the 20th century.

[32] Loss up to 50% compared to the elongation at failure of rivet steels.

stresses the need to use a material of high ductility for the rivet bars, as it was emphasized by historical international literature[33].

Widely used between the 1880s and 1900s, hydraulic riveting machines induced a higher increase in UTS of driven rivets than pneumatic hammers. Moreover, they also better improve the overall structural behaviour of the connections (Simmons 1997; Jacomy 1998). Compared to the material properties of rivet steels, the UTS of rivets was increased by ca. 10% when driven with an air hammer, and by ca. 20%, with a hydraulic riveter[34]. Those figures were, however, characterized by a large scatter of the results regarding both driving techniques. The increase in UTS ranged from 5% to 18% with air hammers and from 8% to 35% with hydraulic riveters (Wilson and Oliver 1930, 23–24; Schenker, Salmon, and Johnston 1954, I–5, 6).

The quality of riveting could be improved by better working conditions (weather, installation facilities, etc.). This is particularly the case when comparing field heads driven by fixed hydraulic riveters in the shop with field heads driven by portable air hammers on the job site.

#### DRIVING TIME

From investigations performed in the 1940s and 1950s in the US on steel rivets, it would appear that usual driving times do not affect their strength. Nevertheless, RA. Hechtman's experiments seemed to reveal the negative effect of too long driving times on the strength of rivets. (Cox and Munse 1952, 14, 34; Schenker, Salmon, and Johnston 1954, I–5)

On the contrary, Frémont's findings underlined the positive influence of long driving times – i.e., 60 s – on the upset of the shank of rivets made of steel in the rivet hole (Frémont 1906, 75–77). As a better upset theoretically implies a larger shear plane area, this would be beneficial to the ultimate shear capacity of rivets. As a result, driving rivets until their field head is satisfactorily formed might be an advisable practice.

#### INTERMEDIATE CONCLUSIONS

To sum up, reviewing the main findings of 20th-century test results dealing with the strength and ductility of wrought-iron and steel driven rivets allows to draw intermediate conclusions. Expectably, the mechanical properties of rivet irons and steels used for rivet manufacture are the first – and most important – aspect defining

[33] See CH2, section 1.1.

[34] The figures relate to 25 tensile tests campaigns – ca. 6 tests per campaign – performed in the UK, the US and Canada between 1926 and 1952 on steel rivets driven either by air hammers or hydraulic riveters. The rivets were 16 mm to 28 mm in diameter and the grip length ranged from ca. 25 mm to 125 mm.

the strength and ductility of driven rivets. Secondly, decreasing shank diameters improve the USS of driven rivets – as a result of their increased UTS, especially for wrought-iron rivets. Thirdly, rivet heating and driving increase the USS of driven wrought-iron and steel rivets, even when overheated. However, overheating must be avoided since it markedly reduces the ductility of both wrought-iron and steel rivets. Regardless of the heating temperature, the driving operation detrimentally affects the ductility of steel rivets, which stresses the importance of using ductile materials for rivet steels. Fourthly, a $h/d$ ratio of the field head that is too small can lead to the head failure in case of secondary stresses, high clamping forces and/or accidental loads inducing an inner tensile state within the rivet.

## 3.2 SHEAR BEHAVIOUR OF RIVETED CONNECTIONS

So far, the investigations have addressed the strength and ductility of driven rivets by virtually isolating them from the connections to which they belong. Based on the above literature review, the following discussions pinpoint the influence of key parameters on the overall shear behaviour of riveted connections.

The shear behaviour depends on the geometry, the joining typology, and the rivets pattern and spacing, as noticed in the previous chapter. In addition, the hot-riveting technique and quality of riveting predominantly influence the shear behaviour of riveted connections[35]. Basically, the shearing capacity of a rivet shank relies primarily on its USS and shear plane(s) area.

The effect of the above parameters on the shear behaviour of riveted connections is discussed below:

### JOINING TYPOLOGY AND RIVETS PATTERN

The (a)symmetry of the joining typology, the presence of cover plate(s), the number of rivet row(s) per force transmission as well as the arrangement of rivets received attention of investigators as long as rivets had been used (Schenker, Salmon, and Johnston 1954, II–15).

As noticed in section 2.2, shear test campaigns notably conducted by acknowledged 19th-century British engineers on wrought-iron and steel splice joints revealed the slight better performances of multiple riveted splices under shear loading, regardless of the failure mode. In particular, multiple riveted double butt joints are an efficient joining typology. Hence, for a given number of rivets, the arrangement in line(s) of

[35] Note that the quality of riveting also affects the shear behaviour. Since, as far as the author knows, no experiments were conducted on that topic in the 20th century, it falls out of the scope of this section. However, qualitative and quantitative analyses of the effect of the quality of riveting are carried out in CH6 and CH7, and summarized in CH8.

rivets is preferable to the one in row(s) since it allows to use the plate net section to the fullest extent, in addition to the higher stiffness provided by such configurations[36]. Practical and economic constraints justified, however, to opt for multiple rivet lines and rows when a large number of rivets was required. Actually, arranging rivets in a large number of lines, each having a few rivets, would have not been efficient given the considerable waste of plate material.

In the 1860-70-80s, numerous experiments were conducted and/or discussed by British engineers such as E. Clark, W. Fairbairn, JH. Latham, WR. Browne or D. Kirkaldy on the arrangement of rivets by comparing chain with zigzag riveting. The results of these experiments were all in favour of chain riveting (de Jonge 1945, 51, 54, 56, 65, 69). As a consequence, the recommendations made by French and Belgian educator-engineers on that topic were heading in opposite direction, as noticed in chapter 3, section 3.2. The major impact of JW. Schwedler's breakthroughs may partially account for this observation (de Jonge 1945, 8). The inefficient configuration of convergent zigzag connections – approved on an international scale – was notably highlighted in 1939 by Davis et al. in the US. Their shear tests campaign proved that the recommendations commonly assumed in practice were wrong. Actually, their test results evidence that the use of fewer rivets in the end rows was ineffective and reduced the shear strength of riveted connections by ca. 10% (Davis, Woodruff, and Davis 1939).

Regarding the spacing of rivets, the tests performed by Davis et al. (1939) did not reveal any significant influence of the rivet pitch on the shear behaviour of steel riveted lap and butt splices (Davis, Woodruff, and Davis 1939).

G/d RATIO

The $G/d$ ratio is strongly linked to the key notion of joint efficiency. This notion was referred to in countries using BI units to compare the structural efficiency of different joining typologies on the one hand, and to design the riveted connections in practice. The efficiency of a riveted connection can be defined as its ultimate strength in tension, shear or bearing – depending on the failure mode – expressed as a percentage of the ultimate tensile strength of the unperforated plate material having the same cross-sectional area as the perforated plate of the connection (Fairbairn 1850, 695–96; Twelvetrees 1900, 122–24)[37]. An efficiency of 100% represents a configuration for which the strength would not be positively/detrimentally influenced

[36] "Row" refers to a transverse line of rivets.

[37] Though they differ in terminology, the notion of "net efficiency" later used by 20th-century authors like Schenker et al. (1954) is nothing else than a particular case of the "efficiency" discussed by Fairbairn (1850), Twelvetrees (1900), etc., corresponding to the plate tension failure mode (net section).

by the presence of a rivet hole[38]. The efficiency could even exceed 100% depending on the $G/d$ ratio, the plate material ductility and the perforation technique. This means that the UTS of the plate net section responsible for the failure of a splice joints under shear loading could be higher than the UTS of the unperforated plate material. Transverse stresses rose by the presence of the rivet hole may notably account for this phenomenon. In particular, small $G/d$ ratios positively influenced the efficiency of perforated plates under tension, and thus the shear behaviour of the connections at ultimate. (Schenker, Salmon, and Johnston 1954, II–19–23)

#### GRIP LENGTH

The grip length $g$ played a predominant role into the shear behaviour of riveted connections at ultimate. Thanks to their experiments performed in the 1930-50s, American investigators reported lower UTS and USS values of driven steel rivets for increasing grip lengths (Wilson and Oliver 1930, 21–22; Davis, Woodruff, and Davis 1939; Cox and Munse 1952, 23–24). An average decrease in USS of 10% was noticed for 125-mm-grip driven rivets in comparison with grips that were 25 mm long (Schenker, Salmon, and Johnston 1954, I–9–11).

This phenomenon originates from the better upset of the shank in the rivet hole for connections having shorter grips (Wilson and Oliver 1930, 22; Cox and Munse 1952, 24). While for short grips, the shank diameter in its driven configuration presumably equals the hole diameter, the same is not true for long grips. After driving, the rivet of a long grip may not completely fill the rivet hole, which explains its reduced shearing capacity[39].

As a result, riveted connections failing in rivet shearing perform better with shorter grip lengths. A small grip improves the upset of the shank in the rivet hole, which consequently increases its shear plane(s) area and shearing capacity.

#### SHANK UPSET

Three main parameters affect the upset of the shank in the rivet hole: the grip length, the driving temperature and the driving technique.

The geometry of the connection, notably the grip length, was a key parameter influencing the shear behaviour of riveted connections, as previously mentioned. Argued by sellers of riveting machines, the better upset of the shank in the rivet hole of machine-driven rivets was commonly admitted at the time (Frémont 1906, 52, 56). For short grips, this general statement was right, but for longer ones it needs to be

[38] A focused discussion of this phenomenon is developed in CH7, see section 4.3.1 for more details.

[39] See section dealing with the parameter SHANK UPSET.

nuanced. Tests carried out by Frémont (1906) on wrought-iron riveted connections with 100-mm-long grips highlighted the presence of an efficient upset and contact between the shank and the rim of the hole only near the field head, over a length of ca. 40 mm (Fig. 4-5) (Frémont 1906, 57–68). Actually, clearances were more likely to occur at the centre and shop head end of the rivet. The better upset of the shank near the field head end was also reported by American investigators on steel riveted connections from the 1920s onwards (Landon 1927; Wilson and Oliver 1930).

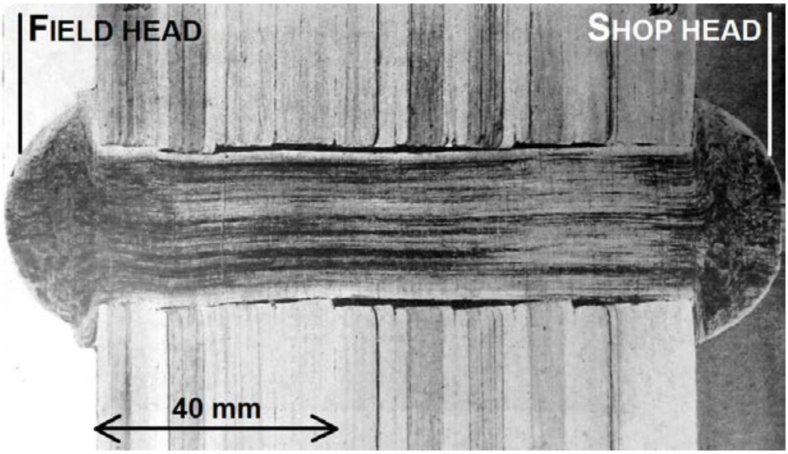



Figure 4-5: Better upset of the shank near the field head end of rivets having long grips; the rivet was driven with a JF. Allen's pneumatic riveting machine to fabricate a 100-mm-grip wrought-iron riveted connection (Frémont 1906, 60, 67)[40]

In addition, a driving temperature that is too low also affects the upset of the shank in the rivet hole, and made rivet driving more difficult. Next to the heat loss induced by radiation, the driving temperature was subjected to a second decrease in heat due to the contact with the cold plies (conductivity).

The driving technique influences the upset of the shank, and the overall stiffness of the connection. Machine riveting could better compensate installation errors – e.g., misaligned rivet holes, not sufficiently tightened plates – than hand riveting. However, the type of riveting machine – portable air hammer vs. powerful hydraulic riveter – seemed not to affect the shank upset (Frémont 1906, 58).

Since it conditions the shank diameter and the USS of the driven rivet, the upset of the shank in the rivet hole constitutes a prevalent parameter on the shear behaviour of riveted connections. Moreover, a shank that incompletely fills the rivet hole provides little contact bearing area. A non-full bearing along the grip length may thus lead to bearing and shear stress concentrations in service.

[40] See CH2, section 2.3, for more information on the riveting machines developed by JF. Allen.

INTERMEDIATE CONCLUSIONS

The above discussions permit to pinpoint two findings. Together with the strength and ductility of the plates and rivets, the joining typology and geometry of the connections condition first how the connections will behave. In particular, splice joints perform better for symmetric configurations and an increasing number of rivet rows. Second, the uniform upset of the shank in the rivet hole strongly influences the shear behaviour. A better shank upset can be obtained by limiting the grip length, driving rivets with riveting machines, and ensuring a sufficient driving temperature.

# 4 CONCLUSIONS – BEHAVIOUR NOT YET FULLY ELUCIDATED

The theory of riveted connections and its evolution over time was the scope of the present chapter. The overall shear behaviour of standard splice joints and their main failure modes was discussed. The review of the test results of 19th- and 20th century experiments allowed to highlight the effect of parameters linked to the materials, geometry and techniques on the behaviour of lap and butt splices subjected to shear loading.

Although the structural behaviour of wrought-iron and steel riveted connections under static loading was investigated as early as in the 1830s, the divergent theoretical models opposing friction to shear reconciled with each other only by the end of the 19th century. As its complex and variable behaviour was – and still is – difficult to predict, the frictional strength was eventually neglected by engineers and theoreticians who considered rivets as pure shear-type fasteners from the 1880s onwards. From the 1920s onwards, riveted connections were assumed to behave either in pure shear or bearing, similarly to the content of present standards.

The experiments that revealed the overall shear behaviour of splice joints were conducted in the 19th century. The analyses focused primarily on the influence of the joining typology, the material and the perforation technique on the behaviour of these joints at ultimate. Four main failure modes characterized the ultimate behaviour of lap and butt splices subjected to static shear loading: grip crushing, plate tearing, plate/shank crushing and shank shearing. The key parameters that conditioned all the design methods of riveted connections originated from the analysis of failure modes. These parameters deal with both the geometry and the strength of riveted connections. While the geometrical ratio $d/e$ was deduced from the first failure mode, the three last ones introduced – among others – each a main parameter of strength: the UTS of the plate net section $f_t$, the USS of the rivet shank $f_s$ and the UBS of the plate $f_b$ (lap side). In the main, the figures provided by tables 4-3, 4-4 and 4-5 evidenced the influence of the perforation technique on $f_t$, the hole diameter on $f_s$, and the joining typology on $f_b$.

The implementation of more systematic and detailed research campaigns was peculiar to the first half of the 20th century. Based on the test results of 19th-century investigations, they assessed the individual influence of a large number of parameters on the shear behaviour of standard wrought-iron and – more predominantly – steel splice joints. In the main, those parameters deal with rivet manufacture, rivet heating, rivet driving and the geometry of splice joints. Figure 4-6 pinpoints the parameters that have a positive or negative influence on the shear behaviour of wrought-iron and steel splices for a given joining typology, mechanical properties of the plate and rivet materials, and quality of riveting. It separately addresses the impact of parameters on each of the three ultimate strengths defining the behaviour of splices joints subjected to shearing, that is, plate tension $f_t$, rivet shear $f_s$, and plate bearing $f_b$.

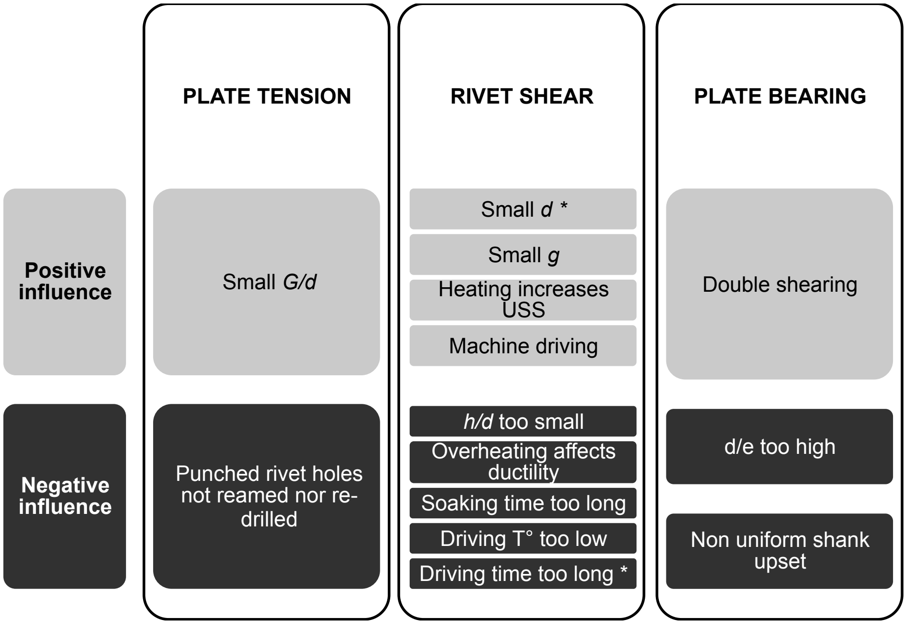



Figure 4-6: Parameters that positively (top) and negatively (bottom) influence the shear behaviour of riveted connections with regard to plate tension (left), rivet shear (centre) and plate bearing (right)[41]

Past investigators considered that the UTS of driven rivets was a good proxy for the determination of their USS. The results of tensile tests performed on driven rivets provide valuable information on the shear behaviour of riveted connections. They highlighted that machine riveting increases the USS of driven rivets by 10% with an air hammer and by 20% with a hydraulic riveter.

[41] The parameters for which the influence is limited are marked with an asterisk (*).

Both the geometry and the strength of riveted connections conditioned the fundaments of the design methodology of wrought-iron and steel riveted connections. The analyses carried out on these topics in chapters 3 and 4, respectively, support the investigations of the next chapter. Chapter 5 focuses on the design methods of historical riveted connections and their evolution over time.

# PART II
# DESIGN

## CHAPTER 5
## DESIGN METHODS

**Chapter 5 focuses on the design methods of historical riveted connections. Unravelling the former design principles contributes towards the understanding of the construction details of existing riveted structures. The investigations of chapter 5 aim to provide insights into the main categories of design methods used between the 1840s and 1940s in France and Belgium. Three subjects are addressed within each category: the design philosophy and assumptions, the design methodology and the arrangement of rivets. Handbooks, manuals, treatises and standards published by French and Belgian educator-engineers and standards institutes were consulted to reach this goal.**

**Chapter 5 aims to answer the following questions:**

*How were riveted connections designed?*

*How did the design methods evolve?*

*Which parameters conditioned the design eventually?*

# 1 INTRODUCTION

Borrowed from bolted connections, the fundaments of present ultimate limit state analyses of riveted connections result from the development and evolution of the design methods that occurred in the 19th and 20th century. Prior to 1850, the design principles relied solely on the experience and practices of iron boilermakers. Then, the growing number of riveted structures and their increasing span length required scientific approaches to build up a theoretical knowledge. Experiments were conducted to assess the structural behaviour of riveted connections and reveal their main failure modes. The test results supported the methods – rules of thumb, formulae – implemented by practicing engineers in a design.

The evolution of the design methods is characterized by a balance of power between science and technique. The technique – experience and practices in the shop and 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 – test results, ultimate strengths – to develop more accurate methods that were the forerunner of today's standards.

Analyzing the core philosophy of historical design methods contributes towards the understanding of the construction details of existing iron and steel riveted structures. It helps us decipher the as-built geometry of the connections through the theoretical models and design assumptions from which they originate. Moreover, former methods can give evidence of inappropriate design principles influencing the safety level of the connections. Hence, the study of historical design methods allows to apprehend overall appraisal procedures of existing riveted structures with more confidence and stimulate adequate remedial works.

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. The broad variety of methods can be merged within four main categories: empirical methods, semi-analytical methods, analytical methods, and standards (Tab. 5-1). The present chapter assesses the philosophy of historical design methods belonging to these four categories and draws their evolution over time. The discussions are based on the investigations conducted in the two previous chapters on the geometry and ultimate strengths of riveted connections. Each category of design methods is analyzed according to the same tripartite framework. First, the theoretical assumptions and overall philosophy on which the design is based are studied. Second, the design methodology is addressed and the main parameters determining

the final design are highlighted. Third, the rules defining the layout of riveted connections – rivets pattern and spacing – are provided.

Table 5-1: The four main categories of design methods addressed matters of geometry, strength and applied loads to different extent over time[1]

| CATEGORY | PERIOD[2] | GEOMETRY | STRENGTH $f_t$ | STRENGTH $f_s$ | STRENGTH $f_b$ | LOADS |
|---|---|---|---|---|---|---|
| Empirical | 1840s-1870s | ✖ | | | | |
| Semi-analytical | 1870s-1880s | ✖ | (✖) | (✖) | | (✖) |
| Analytical | 1880s-1920s | ✖ | ✖ | ✖ | (✖) | ✖ |
| Standards | 1920s-1940s | ✖ | ✖ | ✖ | ✖ | ✖ |

Analyses conducted in the present chapter scope out the French and Belgian context (1840s–1940s). Handbooks, treatises, manuals and standards published between the 1850s and 1940s in these two countries were consulted[3]. The design principles of splice joints subjected to single and double shear are assessed, in accordance with the scope of this study. The discussions address the methods that considered rivets as a shear-type fastener[4]. The research philosophy provides background information for detailed analyses related to specific design methods. However, the chosen research methodology is in line with the corresponding starting questions and focuses rather on the understanding of the overall philosophy of the design principles. Accordingly, such approach goes together with matters of rationalization that are peculiar to the presence of categories and rough time ranges (Tab. 5-1).

## 2 EMPIRICAL METHODS

The use of structural riveted connections gradually developed from the 1840s onwards, as noticed in chapter 1, section 2. Between the 1840s and 1870s, their design 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

[1] Note that the information provided by table 5-1 is simplified. It relates to the parameters that have a direct influence on the design of riveted connections. The discussions conducted in the sections of the chapter will reveal that the interactions between those parameters are more nuanced since some of them conceal, in a sense, the influence of others. The symbol (✖) means that the parameter in question was addressed but not taken into account eventually.

[2] Time periods are mentioned for matters of contextualization. They are approximative and overlap with each other since it would be irrelevant to provide accurate start and end dates.

[3] The design methods prior to the 1870s were barely published – e.g., L. Lemaître (1856), A. Armengaud (1857) – as they resulted from the experience and know-how of iron boilermakers and constructors. More recent literature such as the study of Jacomy (1983) was consulted to complete the overview.

[4] As noticed in CH4, section 2.1.2, the contribution of the frictional strength was eventually neglected by educator-engineers given its unpredictable feature.

the traditional craftsmanship of hot riveting. The technical know-how had been successively handed down from one boilermaker to another (Jacomy 1983, 63). 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* in France and Belgium (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, 63). Despite their practical approach, empirical rules of thumb played a key role within the evolution of the design methods.

Empirical methods were exclusively based on geometrical considerations (Tab. 5-1). Their content did not evolve significantly, contrary to the way they were expressed. The rules of thumb were replaced by design tables, which in turn were quickly translated into empirical formulae from the 1850s onwards, since the majority of boilermakers preferred the use of the latter (Jacomy 1983, 69).

## 2.1 PHILOSOPHY AND ASSUMPTIONS

Prior to the 1870s, the design of structural riveted connections depended on empirical formulae used in the field of boilerwork. Geometrical parameters exclusively conditioned the design of riveted connections, regardless of their strength and the loads applied on the plates (Tab. 5-1). Although the major breakthroughs of British and German investigators such as W. Fairbairn, E. Clark or JW. Schwedler were contemporary to this period (1840s–1870s), the design methods used in France and Belgium did not seem to have taken them into consideration so far. Nevertheless, the defects and/or explosions of steam boilers noticed by boilermakers may have influenced the rules of thumb they formulated. In a sense, these empirical methods conceal considerations on the strength of riveted connections.

## 2.2 METHODOLOGY

Though the empirical methods – tables and formulae – published around the mid 19th century were merely a pretext for an artificial convergence between science and technique, they allowed to define the design of riveted connection.

The design methodology generally involved three main steps. First, the type of splice joint to be used resulted from design choices, structural considerations – i.e., joint's stiffness – and practical constraints. Second, the shank diameter was deduced from the plate thickness either via rough ratios or empirical formulae. The diameter of the undriven rivet $d$ impacted on the design instead of the hole diameter $d_{hole}$ taken into account by present standards (EC 2005, 23, 27). Third, the arrangement of rivets

was defined. Usually, the number of rivets was not calculated but depended on the joining typology, the plates' width and the rivets pattern.

### THE d/e RATIO FATHERED FROM L. LEMAÎTRE'S DESIGN TABLE

The $d/e$ ratio played a predominant role within the evolution of the design methods between the 1840s and 1940s. It allowed to define the shank diameter $d$ based on the plate thickness $e$ in a very convenient way. This relationship influenced the design methodology as well as the rivets pattern and spacing, as noticed in chapter 3. Boilermakers commonly alluded to the main rule of thumb of equation 5-1 (Jacomy 1983, 68–69).

$$\frac{d}{e} = 2 \tag{5-1}$$

As revealed by the analyses of chapter 2, sections 2.2 and 2.3.1, the French boilermaker Louis Lemaître who originated from *La Chapelle-Saint-Denis* near Paris contributed towards the development of the riveting technology. Among others, he invented in 1844-45 an efficient reverberatory furnace to heat rivets and a steam riveting machine that improved Fairbairn's model (Frémont 1906, 19–20, 136–37).

One decade later, in 1856, he published a design table that provided the shank diameter and rivet pitch to be adopted for a range of plate thicknesses (Fig. 5-1) (Lemaître 1856, 7). This relationship between the shank diameter $d$ and the plate thickness $e$ was more refined than equation 5-1. 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.

| ÉPAISSEUR DES TOLES en millimètres. | DIAMÈTRE DU CORPS DES RIVETS en millimètres. | ÉCARTEMENT DE CENTRE EN CENTRE en millimètres. |
|---|---|---|
| 1 | 4.5 | 20 |
| 2 | 6.5 | 22.5 |
| 3 | 8.0 | 25 |
| 4 | 10.0 | 27 |
| 5 | 12.0 | 30 |
| 6 | 14.0 | 35 |
| 7 | 16.0 | 40 |
| 8 | 18.0 | 45 |
| 9 | 19.0 | 50 |
| 10 | 20.0 | 52.5 |
| 11 | 21.0 | 55 |
| 12 | 22.0 | 57.5 |
| 13 | 23.0 | 60 |
| 14 | 24.0 | 62.5 |
| 15 | 25.0 | 65 |
| 16 | 26.0 | 67.5 |
| 17 | 27.0 | 70 |
| 18 | 28.0 | 72.5 |
| 19 | 29.0 | 75 |
| 20 | 30.0 | 77.5 |

Figure 5-1: French boilermaker Lemaître broke new ground in 1856 with his design table providing the shank diameter $d$ (centre) and rivet pitch $p$ (right) based on the plate thickness $e$ (left) (Lemaître 1856, 7)

The widespread use of Lemaître's rules of thumb was possible thanks to the mathematical translation made by A. Armengaud the following year in 1857 (Armengaud 1857, 8:178). Based on Lemaître's table, Armengaud suggested an empirical formula for the shank diameter that was valid for any plate thickness (Eqn. 5-2) (Armengaud 1857, 8:182):

$$d = 1{,}5e + 4\ [mm] \qquad (5\text{-}2)$$

The above relationship better known as *Lemaître's empirical formula* predominantly influenced French and Belgian educator-engineers and theoreticians of the decades that followed. Actually, the formula was referred to until the 1930s by both French authors – e.g., Desarces (1913), Champly (1929) – and Belgian authors – e.g., Dechamps (1888), Aerts (1911), Nachtergal (1937).

Figure 5-2 confronts the values of the $d/e$ ratio derived from Lemaître's design table and Armengaud's approximation for plate thicknesses ranging from 5 to 20 mm. Contrary to the constant ratio provided by equation 5-1, the relationship between $d$ and $e$ of Lemaître and Armengaud decreases for increasing plate thicknesses. This is evidenced by the smaller $d/e$ ratios of Lemaître's table observed for plate thicknesses exceeding 10 mm (Fig. 5-2). Armengaud's formulation smooths out the original ratios of Lemaître. It follows from equation 5-2 that the $d/e$ ratio is underestimated for plate thicknesses below 12 mm, and overestimated above that value. In the main, *Lemaître's empirical formula* suggested by Armengaud matches quite well the original recommendations of Lemaître.

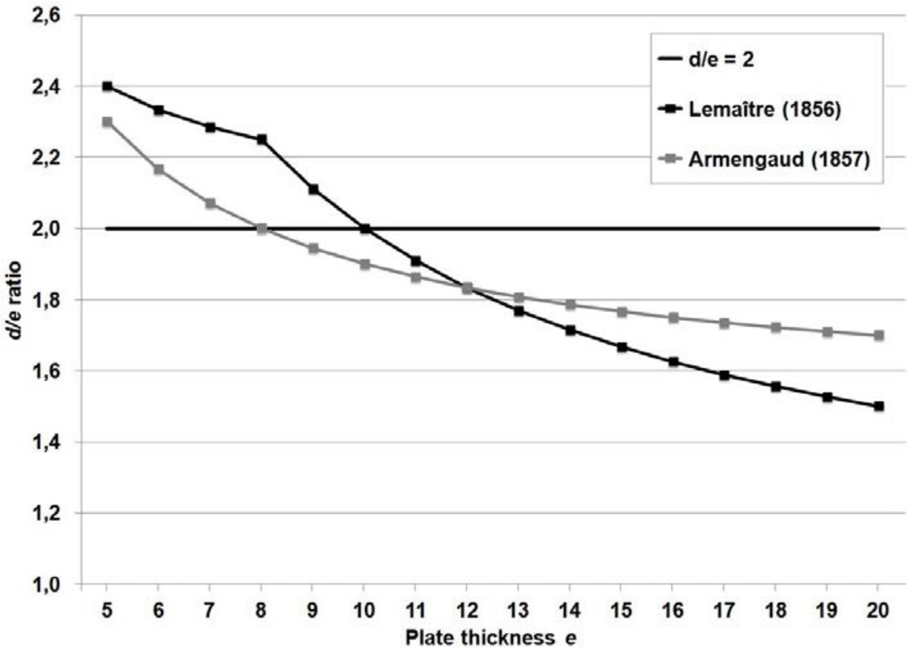



Figure 5-2: The approximation made by Armengaud (1857) matches Lemaître's design table (1856)

From the end of the 19th century onwards, other empirical formulae stating the shank diameter $d$ in function of the plate thickness $e$ were developed. They followed the same trend as the above mentioned ones and further reduced the shank diameter for a given plate thickness. (Jacomy 1983, 73)

## 2.3 RIVETS PATTERN AND SPACING

The geometrical parameters defining the overall layout of riveted connections were all stated as a function of the shank diameter $d$, as evidenced by equation 3-3 (see CH3). Table 5-2 provides the empirical formulae of the rivet pitch $p$, the rivet lap $l$ and

the edge distance $v$ commonly admitted at the time[5]. The rivet pitch $p$ conditioned the pattern of the rivets. It was the key parameter to define to ensure fluid tightness, among others (Armengaud 1857, 8:176). According to Lemaître and Armengaud, the rivet pitch had to average the value of $2{,}5d$ for plate thicknesses ranging from 5 mm to 20 mm (Lemaître 1856, 7; Armengaud 1857, 8:182). So far, no clear distinction has seemed to be made between the rivet lap $l$ and the edge distance $v$. These parameters depended rather on practical matters linked to rivet driving, namely the plate perforation and the driving operation itself (Tab. 5-2) (Jacomy 1983, 74).

Table 5-2: The arrangement of rivets depended solely on the shank diameter

| RIVET PITCH $p$ | RIVET LAP $l$ | EDGE DISTANCE $v$ |
|---|---|---|
| $2{,}5d$ | $1{,}5d$ | $1{,}5d$ |

The empirical methods developed before the 1870s to design riveted connections were thus mathematical translations of riveting practices and experience of boilermakers. The design was based on geometrical parameters, and consequently not mathematically deduced.

## 3 SEMI-ANALYTICAL METHODS

The year 1867 constitutes another milestone in the evolution of the design methods. That year, the German engineer JW. Schwedler was one of the first who developed design principles based on a mathematical model (de Jonge 1945, 14). In addition, the introduction of steel as a structural material led to numerous debates within the engineering world. Its higher mechanical properties impacted on both the $d/e$ ratio and the arrangement of rivets. The end of the 1860s corresponds to the launch of more thorough investigations that were made possible thanks to the development of new testing equipment. Experiments were carried out on wrought-iron and steel materials on an international scale, for instance: D. Kirkaldy (UK), J. Bauschinger (Germany), AH. Emery (Watertown Arsenal, US), etc. (Timoshenko 1953, 123, 276, 279).

The design methods used in France and Belgium in the 1870s and 1880s reflect a transitional period standing at the crossroads between the first empirical formulae derived from boilerwork and the fully analytical approaches introduced at the end of the 19th century. From that moment on, the design was based on the strength of riveted connections, the loads applied to them and their failure modes (Tab. 5-1). Educator-engineers eventually referred to the main findings linked to the extensive test campaigns that had been performed in the 1830-40-50s. For instance, they discussed the recommendations made by W. Fairbairn either directly or indirectly.

[5] See CH3, Fig. 3-7, for a reminder of the geometrical parameters $p$, $l$ and $v$.

For the latter case, they referred to the review made by national scientists and theoreticians on Fairbairn's investigations such as the French physicist A. Morin (Morin 1862, 70–80)[6]. Unfortunately, the presence of erroneous theoretical assumptions detrimentally affected the design philosophy. These assumptions cancelled the contribution of the strength and applied loads within the design methodology that was based solely on geometrical considerations eventually (Tab. 5-1). These design methods are therefore considered as semi-analytical for the above reasons.

## 3.1 PHILOSOPHY AND ASSUMPTIONS

Semi-analytical design methods relied on some of the main failure modes of riveted connections revealed by mid-19th-century investigators[7]. To avoid the crushing of the grip by the bottom surface of the rivet heads, the choice of the shank diameter $d$ had to ensure a $d/e$ ratio that was at the most equalled to 3 (De Vos 1879, 1:96). The failure mechanisms of plate tension – net section – and rivet shear – shank – determined the overall design philosophy. Plate bearing and the notion of ultimate plate bearing strength $f_b$ did not directly impact the design yet (Tab. 5-1). However, the $d/e$ ratio dealt indirectly with the topic to some extent.

In the main, the design philosophy of semi-analytical methods belonged to the allowable stress design model. The design of iron and steel riveted connections rested primarily on this model from then on. This design approach conditioned the majority of the methods and – later – standards that were contemporary to the heyday of structural riveted connections, i.e., until the 1940s. The wide variety of notations hampers, however, a clear understanding of the terms used by French and Belgian authors. In a design, they emphasized the need to consider – what we would call today – allowable stresses to avoid large deformations of the materials in service. Basically, the allowable stresses $R$ commonly called *coefficient de résistance*, *coefficient des charges permanentes* or *charge de sécurité* were stated as a fraction of the ultimate strengths $f$ derived from experiments (Eqn. 5-3) (De Vos 1879, 1:95–96; Aerts 1886, 2). The ultimate strength of the plate in tension $f_t$ and the rivet in shear $f_s$ were involved in the design approach (Tab. 5-1).

$$R = \frac{f}{s} \qquad (5\text{-}3)$$

*Where: $R$ is the allowable stress, $f$, the ultimate strength and $s$, the safety factor.*

[6] Paradoxically, French engineers did not seem to have developed major analytical design methods, despite their superior mathematical background compared to British engineers known to be experimenters (Timoshenko 1953, 123).

[7] See CH4, section 2.2, Tab. 4-1, for more information.

The safety factor $s$ took into account potential calculation errors, variations in material properties and risks of deterioration of the connections in service. The notion of safety addressed by semi-analytical methods differs from the one adopted by current limit state design approaches. Similar safety factors were applied on ultimate strengths but not on the tensile/compressive loads acting on the plates of the connections. Between the 1870s and 1880s, the allowable stresses reported by educator-engineers proved to provide more than sufficient margin of safety. Actually, the level of safety – four to six – was practically twice higher as the one deduced from the test results of British experiments (De Vos 1879, 1:99; Aerts 1886, 23; Twelvetrees 1900, 124). Hence, the main findings of past experiments were not yet fully valorized[8].

Formulae characterizing the allowable load-bearing capacity of rivets in shear and plates in tension were deduced from the two corresponding failure modes considered, that is, plate tension and rivet shear. Basic expressions of the allowable tensile load of one plate $P_t$ and shear load of one rivet $P_s$ are given by equations 5-4 & 5-5 for the standard joining typology of single riveted single lap joint (i.e., $a = 1$). Expectably, the formulae of allowable load involved the geometry and the allowable stresses $R$ of the rivets and plates, similarly to the equations describing their ultimate behaviour (see CH4, Tab. 4-2). Both parameters $P_t$ and $P_s$ had to be at least equal to the tensile/compressive loads applied on the plates.

$$P_t = (G - d)eR_t \qquad (5\text{-}4)$$

$$P_s = a\pi \frac{d^2}{4} R_s \qquad (5\text{-}5)$$

*Where: $G$ is the gage, $R_t$, the allowable plate tensile stress, $a$, the number of shear planes per rivet and $R_s$, the allowable rivet shear stress (see CH3, Fig. 3-7, for a reminder of the geometrical parameters).*

The fundamental calculation assumption of semi-analytical design methods leant on the uniform distribution of stresses between the rivets and the plates constituting a given riveted connection. As a result, the allowable rivet shear load $P_s$ was equalled to the allowable plate tensile load $P_t$ per unit gage (Eqn. 5-6).

$$P_s = P_t \leftrightarrow a\pi \frac{d^2}{4} R_s = (G - d)eR_t \qquad (5\text{-}6)$$

According to the allowable stress design model, the allowable rivet shear stress $R_s$ was expressed as a fraction of its ultimate shear strength $f_s$. From a mechanical viewpoint, the parameter $f_s$ embodying the shear stength of driven rivets was

[8] The allowable stresses peculiar to semi-analytical design methods are discussed together with the ones of analytical design methods in section 4.

assimilated to the USS of rivet irons. Consequently, this assumption disregarded the effect of both rivet manufacture and driving discussed in the previous chapter. An inaccurate USS/UTS ratio of one was assumed within the calculations, as emphasized by De Vos (1879) for instance:

> "D'après les expériences faites, l'effort de cisaillement peut se mesurer par un effort de traction, c'est à dire qu'il faut la même force pour rompre un boulon ou un rivet au cisaillement que pour rompre par traction une tige de fer de même diamètre." (De Vos 1879, 1:95)

This assumption was deduced from the publications to which educator-engineers referred (Aerts 1886, 23). According to Considère (1885), the above reasoning led to an overestimation of the USS of rivet irons of about 20% (Considère 1885, 607).

The number of unknowns had to be reduced in order to solve equation 5-6. At that time, equalling the allowable rivet shear stress $R_s$ to the allowable plate tensile stress $R_t$ proved to be a convenient way to reach this goal (Eqn. 5-7 with $\propto = 1$) (De Vos 1879, 1:97; Aerts 1886, 25). This overestimation of the parameter $R_s$ underlines the fact that the notion of shear was not clearly understood at that time[9]. Authors may have strongly concurred with the findings of 19th-century British investigators who found similar values for the UTS plate net section $f_t$ and USS rivet shank $f_s$ of wrought-iron riveted connections tested in shear up to failure[10]. Therefore, the identification of $R_s$ via $f_s$ was not needed anymore since it could be substituted with the allowable plate tensile stress $R_t$ (Eqn. 5-3, Eqn. 5-7 with $\propto = 1$).

$$R_s = \propto R_t \qquad (5\text{-}7)$$

To sum up, the design philosophy of semi-analytical methods led to two major simplifications. On the one hand, the loads applied on the plates of the connections were not taken into account eventually since the allowable shear load of the rivet $P_s$ was equalled to the allowable tensile load of the plate $P_t$ (Eqn. 5-6). On the other hand, the contribution of allowable stresses in equation 5-6 was neglected as the allowable rivet shear stress $R_s$ was approximated by the allowable plate tensile stress $R_t$ (Eqn. 5-7 with $\propto = 1$). As a result, the design was based only on geometrical parameters, similarly to the fully empirical methods described in section 2 (Tab. 5-1). Basically, semi-analytical design approaches can be seen as a method of equivalent bearing areas for which the total shear planes area corresponds to the plate net section. This is underlined by Aerts (1886) who presumably referred to Rankine's manual published two decades earlier in 1867:

[9] Developed in the 1910s, the von Mises criterion suggested a more accurate shear/tensile yield stress ratio of $1/\sqrt{3}$ (i.e., ca. 0,6) (Timoshenko 1953, 369–70).

[10] The comparison of the figures between table 4-3 and table 4-4 makes it clear (see CH4, sections 2.2.1 and 2.2.2).

> "En admettant que la résistance au cisaillement est la même que celle à la traction, il faut, pour que les rivets soient proportionnés à la force des tôles, que la somme des sections de tous les rivets d'un même côté du joint soit au moins égale à la section la plus affaiblie de la tôle." (Aerts 1886, 25)

> "Inasmuch as the resistance of rivets to shearing is nearly the same with the tenacity of goof iron plates [...], the joint sectional area of the rivets shall be equal to the sectional area of the plate left after punching the rivet holes." (Rankine 1867, 515)

## 3.2 METHODOLOGY

The design methodology involved the three same steps presented in section 2.2. Firstly, the joining typology as well as the plate thickness were again chosen and known parameters. In particular, authors referred to the main findings of renowned engineers such as Fairbairn who promoted the use of efficient joining configurations such as double butt splices (Aerts 1886, 24). Second, the shank diameter $d$ was deduced from the plate thickness $e$ thanks to the $d/e$ ratio retrieved from *Lemaître's empirical formula*. Practicing engineers made sure that the $d/e$ ratio did not exceed the maximal value of three, which was aimed to avoid the crushing of the grip. Third, the arrangement of rivets was determined. Although the number of needed rivets was not really calculated, the design philosophy of equation 5-6 involves this consideration to some extent since it relies on equivalent bearing areas. Especially for splice joints having more than one rivet in a row, the rivet pitch $p$ could be mathematically deduced from equation 5-6.

## 3.3 RIVETS PATTERN AND SPACING

Between the 1870s and 1880s, the arrangement of rivets was likely to be still empirical in most cases. This is stressed by Considère (1886), on the determination of the rivets spacing, who completed Gerber's recommendations linked to maximal values of the $d/e$ ratio:

> "Toutefois la règle de M. Gerber ne fixe que des maxima [the $d/e$ ratio]. Nous la compléterons en rappelant les usages [arrangement of rivets] que l'expérience a fait admettre aux praticiens." (Considère 1886, 142)

Despite the semi-analytical approach embodied by equation 5-6, the rivets pattern and spacing resulted generally from empirical ratios in the end. Actually, French and Belgian authors primarily used the empirical rule formulated by Armengaud in 1857 based on Lemaître's design table, as given in table 5-2. However, they did not always explicitly mention Lemaître's contribution within their publications (De Vos 1879, 1:98; Aerts 1886, 26; Considère 1886, 142). For instance, Considère (1886) referred to the book of the German mechanical engineer and professor F. Reuleaux (1873) who had

referred himself to Armengaud's formulation of *Lemaître's empirical formula* (Eqn. 5-2) (Considère 1886, 142). Ultimately, the overall layout of riveted connections depended on the chosen joining typology, the rivet pitch $p$, the rivet lap $l$ and the edge distance $v$ (Tab. 5-2).

To conclude, the design philosophy of the semi-analytical methods of the 1870-80s was rather obscure by virtue of ambiguities and uncertainties. Originally, their fundaments were analytical since they dealt with allowable stresses and applied loads. Calculation assumptions then cancelled the contribution of the allowable stress design model, which also fortunately ousted some of its inaccurate considerations naturally (i.e., USS/UTS ratio of rivet irons too high). Hence, the actual design philosophy of semi-analytical methods can be seen as a method of equivalent bearing areas. Ultimately, the design of riveted connections was dictated by geometrical considerations established by the empirical methods. French and Belgian authors seemed to make reference, to some extent though, to the findings of rather past than contemporary investigators. They broached the recommendations made in the 1850s – e.g., Fairbairn (1850), Lemaître (1856) – but might not have been fully aware of the more recent theories developed at the end of the 1860s.

## 4 ANALYTICAL METHODS

The end of the 19th century was characterized by the gradual reconciliation between the protagonists of the friction and shear theory. At the design stage, splice joints were eventually considered as shear-type connections, as noticed in the previous chapter. Simultaneously, the introduction of steel as a structural material required to refine existing design methods (Jacomy 1983, 72). From the 1880s onwards, French and Belgian educator-engineers referred gradually to the main theoretical developments peculiar of the 1860s. In particular, two main contributions influenced the evolution of the design methods. On the one hand, the topic of the bearing strength notably broached by H. Gerber (1865) was introduced. However, it was not yet effectively taken into account in a design (Tab. 5-1). On the other hand, the innovative design approach of JW. Schwedler (1867) had a noticeable impact on those authors (Dechamps 1888; Leman 1895; Novat 1900; Aerts 1911).

The design methods used between the 1880s and 1920s can be considered as analytical for two reasons. First, the calculation of the number or rivets $n$ needed to withstand the loads applied on the connection was a major novelty. So far, it was conditioned by the joining typology, the plates' width, and the rivets pattern and spacing. The design philosophy did not rely anymore on the uniform distribution of stresses between the rivets and the plates (Eqn. 5-6). The allowable stress design model could be really implemented and the allowable stresses and applied loads

were taken into account (Tab. 5-1). In addition, the USS/UTS ratio of rivet irons was more adequately expressed. Second, the arrangement of rivets resulted from a semi-analytical approach, unlike the design methods that so far involved fully empirical considerations inherited from the field of boilerwork. From that moment on, the method of equivalent bearing areas peculiar of semi-analytical design methods was effectively implemented to define the rivets pattern and spacing.

## 4.1 PHILOSOPHY AND ASSUMPTIONS

Analytical design methods implied the geometry, the strength and the applied loads (Tab. 5-1). Since the load-bearing capacity of the rivets was eventually related to the magnitude of the applied loads, the contribution of the strength of the connections was not cancelled anymore. The ultimate plate tensile strength $f_t$, rivet shear strength $f_s$ and plate bearing strength $f_b$ influenced each the design but at different steps. Deduced from the parameter $f_s$, the allowable rivet shear stress $R_s$ was the prevalent design criterion. The tensile strength of the plate net section was taken into account for the arrangement of the rivets. From the 1880s onwards, the explicit discussion of the notion of bearing strength was a novelty. Similarly to the behaviour at ultimate (see CH4, Tab. 4-2), the allowable bearing load of the plate $P_b$ was stated as a function of the bearing area $de$ and allowable plate bearing stress $R_b$ (Eqn. 5-8). The theory of Gerber (1865) was notably addressed by educator-engineers (Dechamps 1888, 131). Based on failure modes, Gerber stated that the ultimate plate bearing strength $f_b$ was at least equal to 2,5 times its tensile strength $f_t$. In the same idea as equation 5-6, a uniform distribution of the stresses between the rivets and plates was assumed. Therefore, by equalling $P_t$, $P_s$, and $P_b$, the calculation led solely to a geometrical ratio between the shank diameter $d$ and the plate thickness $e$ (Eqn. 5-9), considering a $R_s/R_t$ ratio equalled to one (Eqn. 5-7 with $\propto = 1$) (Dechamps 1888, 131–32).

$$P_b = deR_b \tag{5-8}$$

$$P_s = P_b \xrightarrow{\begin{cases} R_b = 2{,}5R_t \\ R_s = R_t \end{cases}} \pi\frac{d^2}{4}R_t = 2{,}5deR_t$$

$$\Rightarrow e \cong 0{,}314d \leftrightarrow \frac{\boldsymbol{d}}{\boldsymbol{e}} \cong \mathbf{3} \tag{5-9}$$

*Where: $P_b$ is the allowable plate bearing load and $R_b$, the allowable plate bearing stress.*

The resulting $d/e$ ratio equalled to three was the maximal value recommended to avoid the plate bearing failure mode of single splice joints (Eqn. 5-9). In addition, it prevented the grip to be crushed, as noticed in the previous section. As a

consequence, the notion of bearing strength was hidden by the $d/e$ ratio and did not actually affect the calculations (Tab. 5-1) (Combaz 1897, 2(3):114; Flamant 1897, 289–90)[11].

The fundaments of the design linked to analytical methods relied on two main assumptions (Leman 1895, 187; Flamant 1897, 290; Novat 1900, 195). These assumptions laid the foundation of present considerations on riveted connections as described in current standards[12]. First, riveted connections were assumed to behave in pure shear and the contribution of the frictional strength was neglected. Second, the applied loads were supposed to be uniformly distributed within the rivets of a given connection. Although as early as in 1867, Schwedler was one of the first investigators who pointed out that all the rivets of a connection did not bear an equal share of the applied loads (de Jonge 1945, 14), his findings might not have influenced analytical design methods yet given the complexity of that phenomenon[13]. This is evidenced by Flamant, for instance, in 1897:

> "On ignore, en effet, comment se répartit, entre ces diverses lignes [rivet rows], l'effort total à transmettre par les tôles. On trouve, sur ce sujet, dans les aide-mémoire, des règles empiriques consacrées par la pratique et qu'il convient d'adopter jusqu'à ce qu'une analyse plus détaillée et plus complète de cette question ait pu être faite et donner des indications théoriques plus certaines." (Flamant 1897, 291)

The number of rivets per force transmission $n$ was identified by equalling the total allowable shear load provided by rivets $P_{s,tot}$ to the tensile/compressive load $L$ applied on the plates of the connection (Eqn. 5-10). The number of shear planes per rivet $a$ markedly influenced the parameter $n$ according to whether the splice joint was subjected to single or double shear. In total, double butt splices required the same number of rivets as single lap splices and had a major advantage over the latter given their symmetric configuration (see CH3, Tab. 3-3).

$$L = P_{s,tot} \equiv na\pi \frac{d^2}{4} R_s \leftrightarrow n = \frac{4L}{a\pi d^2 R_s} \qquad (5\text{-}10)$$

*Where: $L$ is the tensile/compressive load applied on the plates and $a$, the number of shear planes per rivet.*

[11] Some authors such as Dechamps (1888) emphasized the need to consider the bearing strength for splice joints subjected to double shear (Dechamps 1888, 135–36). This consideration will be effectively taken into account from the 1920s onwards with the introduction of standards, see section 5.

[12] See CH4, section 1, for more information.

[13] Nowadays, present standards still consider the same assumption provided that the joint does not exceed a given length – i.e., $15d$ between the rivets of the end rows (EC 2005, 29).

As noticed in section 3.1, the allowable rivet shear stress $R_s$ was originally linked to the USS/UTS ratio of rivet irons/steels through the parameter $f_s$. In opposition to the semi-analytical methods that approximated the USS with the UTS, a more accurate USS/UTS ratio of 80% was now asserted (Combaz 1897, 2(3):107). However, in practice, this ratio was not taken into consideration for the determination of $R_s$. Actually, analytical methods described by French and Belgian authors still expressed the parameter $R_s$ as a function of the allowable plate tensile stress $R_t$, similarly to the semi-analytical methods. Again, they may have deduced allowable stress values from the ultimate strengths $f_t$ and $f_s$ revealed by experiments, since the safety factors were independent of the type of failure modes. This time, however, the value of $\propto$, that is, the $R_s/R_t$ ratio, was set at 0,8 instead of 1, without any explanations or precisions provided by educator-engineers (Eqn. 5-7) (Leman 1895, 172; Combaz 1897, 2(3):107–8; Flamant 1897, 289; Novat 1900, 196). At the end of the 19th century, the progressive substitution of wrought-iron splices with steel splices might explain this observation. It is supported by the comparison between the figures of table 4-3 and table 4-4. As a consequence, the decrease of the $R_s/R_t$ ratio may underline the actual impact of the results of 19th-century experiments regarding wrought-iron and steel splice joints subjected to shear loading on the determination of allowable stresses. Ultimately, safety factors $s$ conditioned the values of allowable stresses (Eqn. 5-3). According to the analytical design methods based on allowable stresses, safety factors did not experience any major evolution over time. Historical literature commonly alluded to non-negligible values ranging from 4 to 6, regardless of the material type (Flamant 1897, 287).

Table 5-3 provides the mean values of allowable rivet shear stresses $R_s$ mentioned by French and Belgian authors between the 1870s and 1890s.

Table 5-3: Increase in allowable rivet shear stress $R_s$ – mean values – by the end of the 19th century (De Vos 1879, 1:98–99; Aerts 1886, 23; Combaz 1897, 2(3):92–102, 108; Flamant 1897, 287)

| MATERIAL | ALLOWABLE RIVET SHEAR STRESS $R_s$ (MPA) | | |
|---|---|---|---|
| | 1870s | 1880s | 1890s |
| Wrought-iron splices | 40 | 60 | 70 |
| Steel splices | / | / | 90 |

The figures give evidence of the increase in $R_s$ of wrought-iron splices over time (Tab. 5-3). Though they did not affect the design, the values of $R_s$ mentioned by 1870-80s authors linked to the semi-analytical methods were lower than the ones recommended at the end of the 19th century. It highlights the progressive increase of the mechanical properties of manufactured materials. From the 1890s onwards, the allowable rivet shear stress of steel splices was also mentioned by authors who formulated analytical design methods – e.g., Flamant (1897) in France, Combaz

(1897) in Belgium. The parameter $R_s$ was expectably higher for steel splices compared to wrought-iron splices given their higher strength provided by the material steel (Tab. 5-3). From then on and until the introduction of standards (ca. 1920s), the values of $R_s$ have remained rather constant and averaged 75 MPa and 100 MPa for wrought-iron and steel splices, respectively.

To sum up, the design methods of the end of the 19th century introduced an overall philosophy that was analytical. Though still based on failure modes, the allowable stress design model was actually implemented, and the design resulted consequently from the geometry, the strength and the applied loads (Tab. 5-1). Safety factors determined the value of the allowable stress $R_s$, which in turn primarily conditioned the number of rivets per force transmission $n$ (Eqn. 5-10).

## 4.2 METHODOLOGY

As for the semi-analytical methods, the geometry of the plates constituting a riveted connection was known since it issued from the loads applied to them. The shank diameter $d$ was still deduced from the empirical methods of the 1850s. It resulted from *Lemaître's empirical formula* in most cases[14]. In particular, the $d/e$ ratio equalled to two was used as a convenient pre-design criterion provided that the plate thickness $e$ did not exceed 15 mm (Dechamps 1888, 132; Leman 1895, 186; Combaz 1897, 2(3):115). For plate thicknesses above 15 mm, Lemaître's derivation was not used anymore due to practical constraints. Actually, it would follow from Equation 5-2 that the parameter $d$ would be larger than the maximal standard diameter commonly used for structural applications[15], namely 26 mm. Once the shank diameter was defined, the relationship of Gerber was checked in order to avoid the crushing of the grip as well as too high plate bearing stresses (Eqn. 5-9). Then, the number of rivets per force transmission $n$ was calculated via equation 5-10. The arrangement of rivets could be eventually defined for a given joining typology chosen by the practicing engineer.

## 4.3 RIVETS PATTERN AND SPACING

While the determination of the number of rivets needed to take up the applied loads was based on the analytical expression given by equation 5-10, the arrangement of rivets was, however, still governed by semi-analytical considerations. This is explained by the fact that French and Belgian authors of the 1880s–1920s referred to

[14] Novat (1900) referred to the design table of Morandière to define the shank diameter $d$. The values of Morandière's table were approximately similar to the $d/e$ ratio of Lemaître (Novat 1900, 193). Other more refined formulae that decreased the shank diameter for a given plate thickness were used as well – e.g., Breuil's formula, Hambourg's formula.

[15] See CH3, Tab. 3-1.

the theories of investigators and theoreticians of the 1860s. Hence, the rivets pattern and spacing issued from the assumption of the uniform distribution of stresses between the rivets and the plates in shear and in tension, respectively. The allowable shear load of the rivet $P_s$ was equalled to the allowable tensile load of the plate $P_t$ (Eqn. 5-6), considering a $R_s/R_t$ ratio of one (Eqn. 5-7 with $\propto = 1$). As a consequence, the method of equivalent bearing areas conditioned the rivet pitch $p$, rivet lap $l$ and edge distance $v$. As noticed in sections 3.1 and 4.1, this approach rested on the main findings linked to the ultimate plate tensile and rivet shear strengths $f_t$ and $f_s$ of wrought-iron and steel splices revealed by experiments. In any case, the above method was a main novelty since the rivets pattern and spacing were merely based on empirical methods so far – i.e., *Lemaître's empirical formula*. The influence of empirical considerations was, however, far from being ousted, as evidenced by the definition of the shank diameter $d$.

Table 5-4 gives the mean values of the rivet pitch $p$, rivet lap $l$ and edge distance $v$ of splice joints in single and double shear found in French and Belgian literature (1880s–1920s) (Dechamps 1888, 132–36; Leman 1895, 188–89; Novat 1900, 193; Scharroo and Bertholet 1911, 75; Aerts 1911, 36–49). While the edge distance $v$ did not markedly vary compared to the empirical formulae, the values of the rivet pitch $p$ and lap $l$ increased (Tabs. 5-2 & 5-4). Since at the end of the 19th century the introduction of steel splices went together with the optimization of the $d/e$ ratio for a given plate thickness (Jacomy 1983, 72–73), the expressions of $p$ and $l$ may have led to approximately similar figures in absolute value (Tab. 5-4). The rivet pitch $p$ depended notably on the joining typology and the shear state of the rivets. Rivets subjected to double shear and/or belonging to splices joints of higher stiffness – e.g., multiple riveted connections, double butt splices – could be arranged with larger pitches for instance (Combaz 1897, 2(3):117–19).

Table 5-4: Rivets pattern and spacing provided by analytical design methods remained rather constant between the 1880s and 1920s

| **RIVET PITCH $p$** | **RIVET LAP $l$** | **EDGE DISTANCE $v$** |
|---|---|---|
| $2{,}5d$ to $5d$ | $1{,}5d$ to $2{,}5d$ | $1{,}285d$ to $1{,}5d$ |

In actual fact, the formulae of the above geometrical parameters $p$, $l$ and $v$ were round up values of the ones deduced from the semi-analytical methods of the 1860s. Practical matters linked to rivet driving for example required larger ratios to satisfactorily form the field head (Dechamps 1888, 134; Aerts 1911, 37). One semi-analytical method was particularly adopted by many authors to define the arrangement of rivets, which is the one formulated by JW. Schwedler.

### THE CONVENIENT THEORY OF JW. SCHWEDLER

The German engineer JW. Schwedler broke new ground with his semi-analytical approach dedicated to design riveted connections (de Jonge 1945, 14). 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 behaviour of riveted connections – friction and shear, the joining typologies as well as the arrangement of rivets (de Jonge 1945, 62). 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, 14).

Until the beginning of the 20th century, numerous educator-engineers 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. 5-3). Schwedler assumed a uniform distribution of the loads within the strips and that the joint behaved in pure shear.

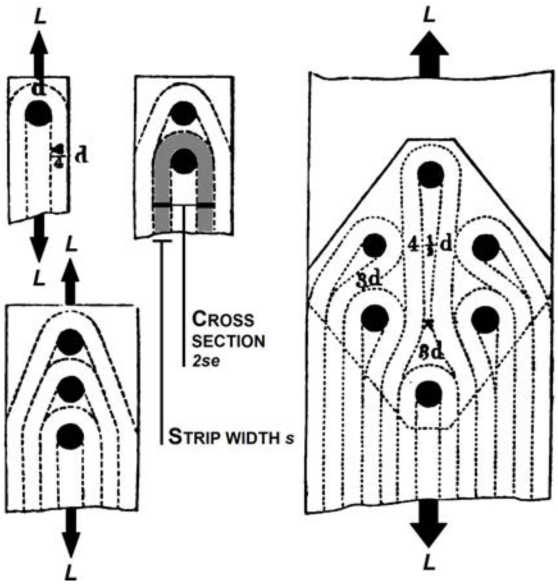



Figure 5-3: Schwedler simplified the shear behaviour of riveted connections by conceptually subdividing their plates into several strips surrounding each a rivet (adapted from Schwedler 1867b, 463–64)

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 $P_{t,strip}$ was equalled to the allowable shear load of the rivet $P_s$ it surrounded (Eqn. 5-11). Considering a $R_s/R_{t,strip}$ ratio equalled to one (Eqn. 5-7 with $\propto = 1$), both allowable stresses were cancelled and the strip width $s$ depended solely on geometrical parameters, that is, the $d/e$ ratio. Equation 5-12 states the width strip $s$ as a function of the shank diameter $d$ for the general rule of $d/e$ equals two. Being very convenient to use in a design, this value of the $d/e$ ratio allowed to simplify the expression of the parameter $s$ towards practicing engineers. (Dechamps 1888, 132, 136)

$$P_{t,strip} = P_s \qquad (5\text{-}11)$$

$$2seR_{t,strip} = \beta\pi\frac{d^2}{4}R_s \xrightarrow{\begin{cases} d/e=2 \\ R_S=R_{t,strip}\end{cases}} \boldsymbol{s = \beta\pi\frac{d}{4}} \qquad (5\text{-}12)$$

*Where: $2se$ is the strip cross-section (see Fig. 5-3), $R_{t,strip}$ the allowable tensile stress of the strip. $\beta$ is a coefficient equalled to one for the plates of splices in single shear and the outer plates of splices in double shear, and equalled to two for the inner plates of splices in double shear.*

Once the width of the strips $s$ was calculated, the rivet pitch $p$, rivet lap $l$ and edge distance $v$ could be easily identified graphically (Fig. 5-3). For single riveted single and double lap and butt splices, equations 5-13 followed from the method of Schwedler (Dechamps 1888, 132–36). By considering equation 5-12, the formulation of the parameters $p$, $l$ and $v$ stated as a function of the shank diameter $d$ corresponds to the minimal values given in table 5-4 [16].

$$p = d + 2s; \qquad l = \frac{d}{2} + s; \qquad v = \frac{d}{2} + s \qquad (5\text{-}13)$$

To conclude, the philosophy of the design methods of the 1880s–1920s was primarily analytical since the allowable stress design model was effectively implemented and the number of rivets needed per force transmission $n$ was calculated. The parameter $n$ was derived from the applied loads $L$, the allowable shear stress $R_s$, the shear state of the rivets as well as their shank diameter $d$ (Eqn. 5-10). The shank diameter was, however, still empirically deduced. Paradoxically, this analytical method was combined with simple derivations related to the arrangement of rivets. Those derivations such as the theory of Schwedler were rather semi-analytical approaches based on the method of equivalent bearing areas. Accordingly, they also reintroduced the main design assumption that consisted of equalling the allowable

[16] The minimal rivet lap $l$ mentioned in table 5-4 – i.e., $1{,}5d$ – was already a rounded up value of $1{,}285d$, in accordance with the recommendations of educator-engineers (Dechamps 1888, 133; Aerts 1911, 36–37).

rivet shear load $P_s$ to the allowable plate tensile load $P_t$ per unit gage (Eqn. 5-6). As a result, analytical methods improved the design philosophy but revived at the same time inappropriate reasoning by referring to the past theories of the end of the 1860s. The introduction of the notion of bearing strength announced the progressive transition towards the model of bearing-type connections – riveted splices treated as pure shear/bearing joints – embodied by the next category of design methods.

# 5 TOWARDS STANDARDS

The progressive set-up of standards institutes at the turn of the 20th century provided an impetus for the rationalization of the dimensions of rivets and head shapes (ABS 1941, 1). Standards institutes were established from the end of the 1910s onwards in France and Belgium. The *Association Belge de Standardisation* (ABS) – present *Belgian Bureau for Standardization* (NBN) – was founded in April 1919, and its French equivalent, the *Association Française de Normalisation* (AFNOR), five years later in June 1926 (NBN 2007; AFNOR 2014). From then on, French and Belgian educator-engineers referred gradually to the design principles formulated by these institutes – explicitly and implicitly, without necessarily disregarding, however, the general rules derived from the previous methods.

Expectably, the design methods developed between the 1920s and 1940s were still governed by an analytical approach, as for the turn-of-the-20th-century methods. The design philosophy followed the allowable stress design model and depended on the geometry, the strength and the loads applied on the riveted connections. Nevertheless, the role of the bearing strength as an actual design criterion was a major novelty in the evolution of the design methods (Tab. 5-1). Similarly to the content of present standards based on the limit state design model, riveted connections belonged to the bearing type. Therefore, the allowable load-carrying capacity of splice joints subjected to shear loading was conditioned by the rivet shear and plate bearing strength. The arrangement of rivets still relied on semi-analytical principles, which themselves were rather derivations of the symbiosis between experimentation and experience.

## 5.1 PHILOSOPHY AND ASSUMPTIONS

The design philosophy of the methods developed by French and Belgian standards leant on the allowable stress design model. Similarly to the analytical methods peculiar to the decades around the turn of the 20th century, the geometry as well as the applied loads were taken into consideration. With regard to the allowable stresses, an additional parameter influenced the design next to the allowable rivet shear stress $R_s$. While it had been introduced by the analytical methods but not yet

effectively implemented, the allowable plate bearing stress $R_b$ acted as the second prevalent design criterion from then on. Both stresses $R_s$ and $R_b$ depended on the allowable plate tensile stress $R_t$. Since the values of the parameter $R_t$ recommended by standards institutes gradually increased over time, $R_s$ and $R_b$ followed that same trend. As stressed by Nachtergal (1937), this observation applied to allowable stresses prescribed on an international scale:

> "La tension admissible pour le métal [allowable plate tensile stress $R_t$] augmente d'un règlement à l'autre, tant en Belgique qu'à l'étranger." (Nachtergal 1937, 30)

The safety factors used to define the allowable stresses were similar to the ones of the analytical methods – i.e., ca. $s = 4$. Expectably, the design methods formulated in the 1920-40s exclusively dealt with the material steel, since it gradually supplanted wrought iron by the end of the 19th century. The allowable rivet shear stress $R_s$ mentioned in literature averaged the value of 120 MPa, considering the same $R_s/R_t$ ratio as for analytical methods (Eqn. 5-7 with $\propto = 0{,}8$). Hence, this value is in line with the discussions of section 4.1 having revealed that French and Belgian authors recommended to equal $R_s$ to 100 MPa for steel splice joints. The allowable plate bearing stress $R_b$ approximated 300 MPa. This figure resulting from a $R_b/R_s$ ratio equalled to 2,5 was based on failure modes, in line with the theory developed by Gerber in 1865[17]. (Nachtergal 1937, 251, 256)

The fundaments of the design methods of steel splice joints developed from the 1920s onwards relied on the determination of the allowable load per rivet $P_{allow}$. The parameter $P_{allow}$ corresponded to the minimal value derived from the calculations between the allowable rivet shear load $P_s$ and allowable plate bearing load $P_b$ (Eqns. 5-5, 5-8 & 5-14).

$$P_{allow} = min(P_s; P_b) \qquad (5\text{-}14)$$

Both parameters $P_s$ and $P_b$ were still expressed as a function of the shank diameter $d$, similarly to the empirical, semi-analytical and analytical methods. For a given $R_b/R_s$ ratio, the stress state of the rivets – single vs. double shear – and the $d/e$ ratio defined whether the parameter $P_s$ or $P_b$ ultimately conditioned the design of the connections. In single shear, the rivet shear strength was typically the prevalent design criterion since the allowable rivet shear load $P_s$ (Eqn. 5-5 with $a = 1$) was generally lower than the plate bearing load $P_b$ (Eqn. 5-8). In double shear, the

[17] As a reminder, Gerber stated that the ultimate plate bearing strength $f_b$ was at least equal to 2,5 times its tensile strength $f_t$. Since safety factors were indenpent of the type of allowable stress, it followed that $R_b/R_t$ was equalled to 2,5 (see section 4.1). Here the methods assumed $R_b/R_s = 2{,}5$, that is, a $R_b/R_t$ ratio equalled to 2 since $R_s/R_t = 0{,}8$.

bearing calculation could lead to a smaller allowable load than the shear calculation, especially for large $d/e$ ratios (Eqns. 5-5 & 5-8 with $a = 2$).

The number of rivets per force transmission $n$ characterized the relationship between the tensile/compressive loads applied on the plates $L$ and the allowable load per rivet $P_{allow}$ (Eqn. 5-15).

$$L = nP_{allow} \leftrightarrow n = \frac{L}{P_{allow}} \tag{5-15}$$

*Where: L are the tensile/compressive loads applied on the plates and n, the number of rivets per force transmission.*

## 5.2 METHODOLOGY

Fundamentally, the design methodology suggested by standards institutes of the beginning of the 20th century was in line with the previous methods. Opting for a symmetric joining typology of splice joint was still recommended to avoid any bias tension and bending of the rivets (Nachtergal 1937, 248). In the main, the methodology involved four main steps. First, the empirical methods of the 1850s allowed to reduce the number of unknowns by means of the $d/e$ ratio. Authors such as Champly (1929) in France or Nachtergal (1937) in Belgium still referred to Armengaud's derivation of Lemaître's design table to define the shank diameter $d$ based on the plate thickness $e$ (Champly 1929, 15:95; Nachtergal 1937, 252). Again, educator-engineers emphasized on the careful choice of $d$ to avoid the crushing of the grip and important bearing stresses by ensuring that the $d/e$ ratio did not exceed the maximal value of three (Jacquemain 1946, 49). Second, the allowable load per rivet $P_{allow}$ could be calculated with the geometry of the connection and allowable stresses $R_s$ and $R_b$ (Eqn. 5-14). Once the parameter $P_{allow}$ was calculated, the number of rivets per force transmission $n$ followed from equation 5-15. Finally, the rivets pattern and spacing could be arranged.

## 5.3 RIVETS PATTERN AND SPACING

From the 1920s onwards, the arrangement of rivets was in accordance with the approach embodied by the analytical design methods of the turn of the 20th century. Empirical rules of thumb derived from experience still competed with semi-analytical principles developed at the end of the 1860s. Both formulations of the rivets pattern and spacing depended yet on the shank diameter $d$. Semi-analytical methods assumed that the allowable rivet shear load $P_s$ equalled the allowable plate tensile load $P_t$ per unit gage (Eqn. 5-6), but here however with $R_s/R_t = 0{,}8$ (Eqn. 5-7, $\propto = 0{,}8$). Finally, the rivet pitch $p$, rivet lap $l$ and edge distance $v$ issued from the empirical and semi-analytical formulae provided similar expressions. This observation

might explain why most of the French and Belgian authors directly provided the relationship between $p$, $l$ , $v$ and $d$ without any detailed mathematical development, as empirical ratios had been tried, tested and approved so far (Champly 1929, 15:93; Nachtergal 1937, 258–59).

The mean values of the rivet pitch $p$, rivet lap $l$ and edge distance $v$ found in French and Belgian literature published between the 1920s and 1940s are given in table 5-5 (Bottieau 1926, 37, 41; Nachtergal 1937, 258–59; Jacquemain 1946, 49, 50, 58–61; Kienert 1949, 81–82). It follows from table 5-5 that the expressions of the geometrical parameters $p$, $l$ and $v$ are in line with the ones of the analytical methods (Tab. 5-4). The rivet pitch ranged from $2{,}5d$ to $5d$ but the value of $4d$ was often mentioned by the authors (Champly 1929, 15:93; Nachtergal 1937, 258–59; Jacquemain 1946, 49–50). The edge distance $v$ slightly increased and matched the formulation of the rivet lap $l$ (Tab. 5-5).

Table 5-5: The rivets pattern and spacing suggested from the 1920s onwards are in line with the formulae provided by analytical design methods (1880s–1920s)

| RIVET PITCH $p$ | RIVET LAP $l$ | EDGE DISTANCE $v$ |
|---|---|---|
| $2{,}5d$ to $5d$ | $1{,}5d$ to $2{,}5d$ | $1{,}5d$ to $2{,}5d$ |

The above ratios have remained rather constant until now. After the 1940s, authors gave similar formulae for the rivets pattern and spacing since they may have referred to their predecessors (Labarraque 1953; Lorin 1968). In the same idea, the minimal values of the parameters $p$, $l$ and $v$ prescribed by present standards approximate the ratios provided by table 5-5. The current minimal ratios are slightly lower – ca. $2{,}3d_{hole}$, $1{,}2d_{hole}$ and $1{,}2d_{hole}$, respectively – but depend this time on the hole diameter $d_{hole}$ (EC 2005, 23–24). Since the hole diameter $d_{hole}$ is by definition larger than the rivet shank diameter $d$, the content of present standards roughly matches the formulae of the first half of the 20th century.

As a consequence, the philosophy of the design methods of the 1920s–1940s based on allowable stresses laid the foundation of the overall design approach prescribed by present standards. It involved the notion of bearing strength that was previously introduced by turn-of-the-20th-century analytical methods. With regard to the arrangement of rivets, it followed the empirical and semi-analytical recommendations of the 19th century on which the content of present standards are likely to be based.

# 6 CONCLUSIONS – PREDOMINANT EMPIRICAL RULES

The present chapter focused on the methods that conditioned the design of historical riveted connections. Through a review of French and Belgian literature (1840s–1940s), the philosophy and theoretical assumptions of the design methods were assessed. Unravelling the fundaments of the design principles allowed to highlight their strengths and weaknesses, despite the – often – confusing, paradoxical and/or less persuasive explanations made by past authors.

Between the 1840s and 1940s, the philosophy of historical design methods evolved markedly. The first rules of thumb derived from the technique and experience of boilermakers were progressively supplanted by analytical approaches complying with the allowable stress design model. The investigations evidenced the recurring presence of a non-negligible time lag between the development of new design models and their actual influence on educator-engineers. Typically, French and Belgian authors referred to the prevalent theories of renowned investigators and theoreticians such as W. Fairbairn, H. Gerber or JW. Schwedler about two – even three – decades after their publication date. 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.

Prior to the 1880s, the design of riveted connections resulted merely from geometrical considerations. The shank diameter $d$, the number of rivets per force transmission $n$ as well as the rivets pattern and spacing were empirically deduced. Inherited from the field of boilerwork, empirical rules of thumb – *Lemaître's empirical formula* in particular (1857) – played a major role within the development of the design methods. Despite the fact that their influence gradually decreased over the decades, they have at least impacted on the identification of the shank diameter $d$ between the 1840s and 1940s. The first analytical principle used in a design was the uniform distribution of stresses between the rivets and plates of a given connection. By equalling the allowable rivet shear load $P_s$ to the allowable plate tensile load $P_t$ per unit gage, this theoretical assumption determined the design philosophy of the methods in the 1870–80s and the arrangement of rivets in the 1880s–1940s. A major change in design philosophy occurred from the 1880s onwards. The design involved the geometry, the strength and the applied loads from then on. Hence, the allowable stress design model had been actually implemented and allowed to define the number of rivets $n$ analytically. Riveted connections were assumed to behave in pure shear. The notion of bearing strength was implicitly taken into consideration by fixing a maximal $d/e$ ratio but it did not affect the calculations yet. The plate bearing strength acted as a design criterion together with the rivet shear strength from the

1920s onwards, contemporary to the set-up of standards institutes. Steel riveted splice joints have belonged to the category of bearing-type connections from that moment on.

Three main parameters influenced the design of riveted connections: the $d/e$ ratio, safety factors, and experience and practical constraints. The shank diameter $d$ had always been issued from the $d/e$ ratio between the 1840s and 1940s. In turn, the shank diameter impacted on the calculations of allowable loads – $P_t$, $P_s$, $P_b$ – and the arrangement of rivets – i.e., the rivet pitch $p$, rivet lap $l$ and edge distance $v$. Since they disregarded the hole diameter $d_{hole}$, the former design methods overestimated the allowable plate tensile load $P_t$. Accordingly, they under-estimated the allowable plate bearing load $P_b$ and even more the allowable rivet shear load $P_s$ (i.e., square diameter $d$, Eqn. 5-5). However, the magnitude of this under-estimation is strongly linked to the quality of the shank upset, as noticed in the previous chapter[18]. Hence, Frémont's breakthroughs (1906) on the quality of riveting did not seem to have affected contemporary design methods. Allowable stresses were defined by high safety factors averaging the value of four/five. The allowable rivet shear stress $R_s$ was stated as a function of the allowable plate tensile stress $R_t$. Originally equalled to one, the $R_s/R_t$ ratio was reduced to 0,8 when analytical methods were introduced from the 1880s onwards. This decrease in $R_s/R_t$ may reflect the progressive switch from wrought-iron to steel splices that occurred at the end of the 19th century. In any case, both ratios confirm the figures related to the ultimate behaviour of wrought-iron and steel splice joints subjected to shear revealed by experiments. The allowable plate bearing stress $R_b$ was also (in)directly deduced from the parameter $R_t$. Riveted connections were thus designed according to a conservative approach. They were generally oversized given the high safety factors combined with the overestimation of the number of needed rivets $n$ induced by the disregard for the difference in shank/hole diameter. Regarding the arrangement of rivets, the rivets pattern and spacing were primarily based on empirical formulae and semi-analytical methods that can be seen as mathematical translations of the know-how and experience in shop and field riveting. Both methods provided similar values of $p$, $l$ and $v$, which were all expressed as a function of the shank diameter $d$. Actually, practical considerations linked to rivet driving tended to round up the values found semi-analytically. Ultimately, the rules of thumb that conditioned the arrangement of rivets proved to be safe over time. This may explain their lasting quality, that is, up to the present time with current standards.

[18] The shank upset depends on the grip length, the driving temperature and the driving technique (see CH4, section 3.2).

So far, the two first parts of the study have valorized the content of historical literature to analyze the technology and design of riveted connections. The next part of the study broaches these two topics by means of experimental investigations. Focused on the material wrought iron and the period of the end of the 19th century, the analyses conducted in Part III aim to qualitatively and quantitatively appraise the structural behaviour of historical wrought-iron riveted connections. The next chapter aims to reveal their original design, manufacturing and installation techniques. This research philosophy contributes to answer some of the issues raised by the discussions of this chapter, for example: the actual implementation of historical design methods, the difference in shank/hole diameters, etc.

# PART III
# EXPERIMENTS

*A riveted joint is a statically highly indeterminate structure, the behavior of which has baffled the investigators up to the present time, i.e., for more than one century.*

(de Jonge, 1945, 13)

# PART III
# EXPERIMENTS

## CHAPTER 6

## GEOMETRY AND METALLOGRAPHY OF HISTORICAL HOT-DRIVEN RIVETS

**Chapter 6 reports on the original design, manufacturing and installation of historical hot-driven rivets. It aims to confront the content of historical literature analyzed so far with the as-built configuration of riveted connections. Through experimental work, the geometry and metallography of rivets dismantled from four wrought-iron structures are studied (1880s–1890s). Geometrical analyses deal with the proportions of the rivets and the prevalent design criterion of the $d/e$ ratio. Metallographic investigations relate to the manufacturing and driving techniques of the rivets. The results are relevant for the structural assessment and rehabilitation of historical riveted structures.**

**Chapter 6 aims to answer the following questions:**

*Did architects and engineers use standard shank diameters?*

*What can we learn from the distinction between the shop head and the field head?*

*Were wrought-iron rivets hand driven and/or machine driven at the end of the 19th century?*

When appraising historical riveted structures, practicing engineers, architects and heritage care specialists often lack information on the technology and design of riveted connections. The understanding of the construction details of riveted structures is often difficult. Some structural appraisal and renovation guidelines however exist but they barely broach the subject (SB 2007a; SB 2007b; SB 2007c; Tilly et al. 2008; Kühn et al. 2008). Recent literature does not go into detail about a variety of topics such as the geometry of rivets, the driving technique used, the quality of riveting and the presence of potential visible and invisible defects. Nevertheless, the knowledge of these topics can support the appraisal procedure of riveted connections. Starting from the as-built geometry of existing connections, reverse engineering approaches allow to reveal valuable information by tracing back their design and fabrication. As stressed by the analyses of Part I and Part II, historical literature can add to our knowledge on the technology and design of riveted connections, provided that the content of literature corresponds to the actual configuration of the built structures.

This chapter aims to reveal the original design, geometry, and manufacturing and driving techniques of existing riveted connections. It allows to check whether the information provided by historical literature matches the actual technology and design of built riveted connections. The research is conducted in two steps to reach this goal. First, the geometry and metallography of hot-driven rivets and riveted connections are studied through experimental investigations with samples dismantled from four load-bearing structures. These investigations are in line with the research approach of the exhaustive studies performed during the first half of the 20th century such as Frémont (1906). Second, the experimental results are analyzed and confronted with the content of historical literature analyzed so far[1]. The provided information deduced from this confrontation is relevant for the structural assessment and rehabilitation of historical riveted structures and contribute to the preservation of their historical significance.

[1] A given scope of historical literature was used for the confrontation, depending on the parameter discussed. Rivet manufacture and driving are studied by means of international literature (Part I). Parameters that are tied to the assessed structures – geometry of the riveted connections – are analyzed through the content of French and Belgian literature (Part II).

# 1 EXPERIMENTAL PROGRAMME

To reveal the original design, manufacturing and driving techniques of hot-driven rivets, the experimental programme was divided into two parts:

GEOMETRY

Geometrical investigations aim to validate the content of historical literature dealing with two main aspects. First, the geometry of hot-driven rivets is assessed to identify their nominal shank diameter $d$. The measured value of shank diameters is then put into perspective with the prevalent $d/e$ ratio. Second, the geometrical affinity of rivets is investigated together with the rivet head shape (Fig. 6-1). The results are compared with historical literature. The geometrical investigations also pinpoint the presence of defects broaching the topic of the quality of riveting.

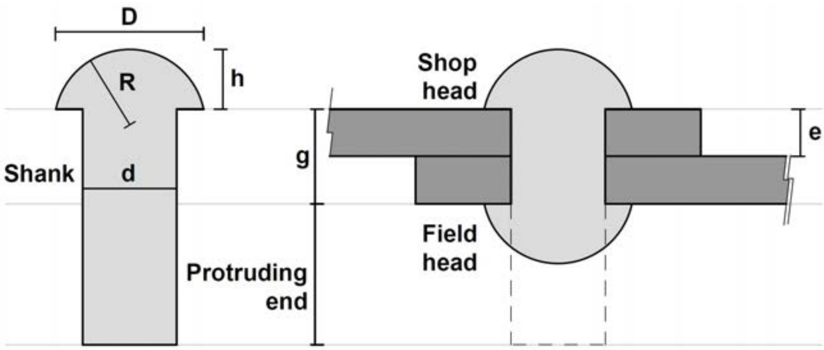



Figure 6-1: Geometrical parameters defining a riveted connection: rivet shank diameter $d$, plate thickness $e$, head diameter $D$, head depth $h$, head radius of curvature $R$ and grip length $g$

METALLOGRAPHY

Metallographic investigations are carried out to reveal the original manufacturing and driving techniques of hot-driven rivets. The metallography of the rivets is studied to differentiate the shop head from the field head with the help of the results derived from geometrical investigations. To distinguish hand-driven from machine-driven rivets, the grain flow and slag orientation within the rivet head and at the interface with the rivet shank are assessed (Fig. 6-2). In addition, the microstructural inhomogeneities are studied to discuss the material quality of the rivets.

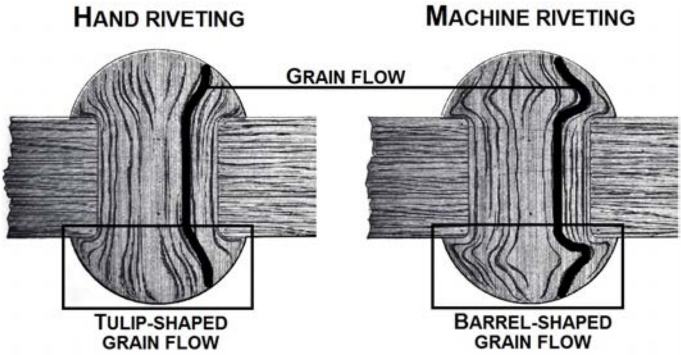



Figure 6-2: 1847 Edwin Clark's engraving of the longitudinal cross-section of hot-driven rivets showing the tulip-shaped grain flow of hand-driven rivets (left) and barrel-shaped grain flow of machine-driven rivets (right) (adapted from Clark 1850, 2:632)[2]

## 1.1 DESCRIPTION OF THE RIVET SAMPLES

In order to investigate the geometry and metallography of hot-driven rivets, samples were collected from four wrought-iron structures that were selected based on their building date, typology and material availability. These structures cover a narrow time period and geographical zone. They were built between the 1880s and 1890s, that is, the period corresponding to the gradual substitution of hand riveting with machine riveting. They are located in France – north-western France (Brittany) and eastern France (Bourgogne) – and Belgium, to link the literature study with the samples. These structures cover different typologies: bridge, pier and hall (Tab. 6-1). The rivet samples were taken from structural members dismantled during either a renovation or demolition project. The structural application of the rivets was either to fabricate built-up sections[3] or assemble structural members together.

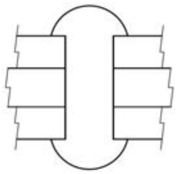
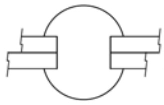
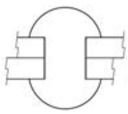
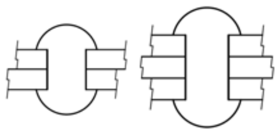
The rivet samples of the Louhans bridge, built in France in 1883, were taken from the bottom-chord member of the primary trusses. From now on we will refer to these samples as FR-1883 indicating the country – FR/BE – and the building date. The samples of the former railway bridge in Brest, built in France in 1893 (FR-1893), were extracted from the bearing pillars. They assembled stiffening angles to the chord members of the triangular legs of the pillars. With regard to the samples of the pier in Cancale, built in France in 1897 (FR-1897), the structural function of the rivets was to fabricate the cross-shaped built-up sections by connecting angles to a central plate. The samples of the north hall of the Brussels Cinquantenaire Park, constructed in 1888 in Belgium (BE-1888), were taken from horizontal trusses stiffening the main

[2] The shop head of the hand-driven rivet was made by hand (Fig. 6-2, left) while the shop head of the machine-driven rivet was formed by a rivet-making machine (Fig. 6-2, right). E. Clark did not discuss the distinction between the shop head and the field head (Clark 1850, 2:632–33).

[3] E.g., vertical post, girder, column, etc.

façade. They assembled diagonals or vertical posts to the chord members of the trusses through gusset plates (Tab. 6-1).

Table 6-1: Presentation and description of the structures and samples

| **STRUCTURE TAG** | **FR-1883** | **FR-1893** |
|---|---|---|
| |  |  |
| Geometry of collected sample |  |  |
| Typology | Bridge | Bridge |
| City, Country | Louhans, France | Brest, France |
| Building date | 1883 | 1893 |
| Structural application[4] | Built-up type | Assembly type |
| Status | Demolished | Existing, renovated |
| | **FR-1897** | **BE-1888** |
| |  |  |
| Geometry of collected sample |  |  |
| Typology | Pier | Hall |
| City, Country | Cancale, France | Brussels, Belgium |
| Building date | 1897 | 1888 |
| Structural application | Built-up type | Assembly type |
| Status | Existing, renovated | Existing, renovated |

[4] See CH1, section 3, for a reminder on the built-up and assembly-type applications of structural rivets.

The rivets required for the experimental work were extracted from these structural members in two ways, namely with or without the plies they clamp[5]. When the connections were intact, the entire rivets together with their plies were removed with a cooled bandsaw to reduce the volume surrounding them. To every entire rivet belong a rivet shank, a shop head and a field head that clamp several plies. When one rivet head had already been removed during the restoration procedure, only half-rivets – without the plies – were extracted from the structural member to which they belonged. A half-rivet consists of one head and – a part of – the rivet shank.

## 1.2 EXPERIMENTAL SET-UP AND INVESTIGATED PARAMETERS

The geometrical and metallographic investigations were performed at the *Laboratoire Brestois de Mécanique et des Systèmes* (LBMS) of the University of Brest (UBO).

For each structure, six rivet heads were assessed to provide a sufficient statistical representation and take potential manufacturing or driving irregularities into account. This value meets the requirement mentioned in the guidelines of Sustainable Bridges: minimum five rivet heads per inspected structure (SB 2007b, 35). As explained in the previous section, entire rivets as well as half-rivets were examined. Only one of the two heads of entire rivets was taken into account if the other one was too distorted or corroded. While for entire rivets the presence and identification of both shop and field heads is obvious, the analysis of half-rivets is more delicate. Every rivet sample was precisely machined along the longitudinal axis of its shank. Then, the rivet samples were polished with silicon carbide paper from grit 120 to grit 2400 to be ready for the experimental investigations and microscopic observations.

### GEOMETRY

For each rivet sample, seven geometrical parameters were investigated. The plate thickness $e$, shank diameter $d$, head diameter $D$, head depth $h$ and head eccentricity $\varepsilon$ were measured with a digital caliper (tolerance of $\pm$0,02 mm) (Fig. 6-1). The head radius of curvature $R$ and circularity tolerance $\Delta R$ were assessed with a coordinate measuring instrument (Mitutoyo Euro-C 544). For each sample, 6 points were measured along the head curvature and $\Delta R$ was estimated with the least square method. The level of accuracy considered was a tenth of a millimetre, as any higher level would be irrelevant with regard to the actual state of the rivets[6].

[5] Unfortunately, the construction detail from which the rivet samples originate could not be accurately localized on the FR-1883, FR-1893, FR-1897 and BE-1888 structures.

[6] Surface irregularities – e.g., multiple paint layers – and defects, approached with the parameter $\Delta R$ for $R$, might have been detrimental to the accuracy of the measurements.

### METALLOGRAPHY

Two microstructural parameters were analyzed during the metallographic investigations: the grain flow and the slag area percentage. First, the polished longitudinal cross section of each rivet sample was photographed using a camera having a resolution of 3504 x 2336 pixels. Then, each optical micrograph was treated by the free image analysis software *ImageJ* that compares grey-scale values, which allowed to measure the slag area percentages present within the ferrite matrix. To reveal the grain flow, the polished surface of the rivet samples were chemically etched both with Nital (2%) and Oberhoffer's etch. The etching time needed to reveal the microstructure was variable[7]. The grain flows reveal by Nital and Oberhoffer's etch were compared with each other. No difference in the grain flow was expected between the two reagents. The most suitable reagent was selected for the pictures. It appears that Nital is a softer and an easier reagent to use on wrought irons. We observed that Nital's etching was particularly inappropriate on certain rivet samples as the grain flow was difficult to reveal. Finally, micrographs of the samples were taken with the same camera to discuss the rivet driving process.

[7] Approximately 10 s for Oberhoffer's etch and one minute for Nital at room temperature. Oberhoffer's etch is usually used on wrought irons to show the distribution of phosphorus around slag inclusions – ghost structures (Sire et al. 2012, 2233).

# 2 GEOMETRY

Analyzing the geometry of the rivet head can directly and indirectly reveal the original design choices and driving process. As discussed in chapter 4, the issue of the uniform contact of the rivet shank with the rivet hole along the grip leads to the distinction between the shop and the field head[8]. The contact between the rivet shank and hole is better near the field head end (Frémont 1906, 58, 66; Landon 1927, 16). In case of a long grip and/or driving errors, the non-uniform contact may induce an asymmetric behaviour of the riveted connection such as bearing stress concentration or deformation.

The geometrical investigations aim to answer the following questions:

- Did architects and engineers use standard shank diameters?
- Are the plate thickness $e$ and the $d/e$ ratio reliable parameters to reveal the nominal shank diameter $d$?
- Are the rivet heads effectively geometrically affine? Can the geometrical affinity help us identify the nominal shank diameter $d$ by a non-destructive way?

## 2.1 RESULTS

Table 6-2 summarizes the results of the geometrical measurements regarding two main aspects, that is, the identification of the nominal shank diameter and the (in)validation of the geometrical affinity of rivets. In addition, it addresses the quality of riveting of the studied rivet samples through their head eccentricity. Samples were labelled as CO-DATE-RC-N, where:

- CO is the country where the structure is located (FR: France; BE: Belgium);
- DATE is the building date of the structure;
- RC is the rivet configuration (i.e., ER: entire rivet; HR: half-rivet);
- N is the sample number (e.g., for ER: NA and NB rivet heads belong to the sample N).

For each structure, the mean value (Mean) and standard deviation (SD) of the shank diameter $d$, head diameter $D$, head depth $h$ and head radius of curvature $R$ are calculated to quantify the scatter of the results.

[8] See CH4, section 3.2 (shank upset).

Table 6-2: Measurements of the rivet head(s) and shank of the samples, mean values and standard deviation per structure

| SAMPLE TAG | RIVET HEAD AND SHANK | | | HEAD CURVATURE | | HEAD ECCENTRICITY | S/F HEAD[9] |
|---|---|---|---|---|---|---|---|
| | $d_{ave}$ (mm) | $D$ (mm) | $h$ (mm) | $R$ (mm) | $\Delta R$ (mm) | $\varepsilon/d_{ave}$ (%) | |
| FR-1883-ER-1A | 22,9 | 37,0 | 14,3 | 19,9 | 0,6 | 5 | S |
| FR-1883-ER-1B | 23,4 | 35,2 | 13,3 | 19,0 | 0,1 | 7 | F |
| FR-1883-ER-2A | 23,5 | 36,3 | 14,1 | 18,7 | 0,1 | 4 | S* |
| FR-1883-ER-2B | 23,4 | 35,0 | 13,5 | 19,8 | 0,6 | 1 | F* |
| FR-1883-ER-3A | 22,8 | 37,0 | 14,5 | 20,2 | 0,4 | 3 | S |
| FR-1883-ER-4A | 23,0 | 36,8 | 14,9 | 19,6 | 0,5 | 4 | S* |
| Mean | 23,2 | 36,2 | 14,1 | 19,5 | / | / | / |
| SD | 0,3 | 0,9 | 0,6 | 0,6 | / | / | / |
| FR-1893-HR-1 | 21,4 | 29,4 | 11,0 | 15,1 | 0,3 | 3 | F* |
| FR-1893-HR-2 | 21,3 | 31,3 | 12,0 | 17,0 | 0,1 | 3 | F* |
| FR-1893-HR-3 | 21,5 | 31,3 | 11,9 | 16,5 | 0,2 | 1 | F* |
| FR-1893-HR-4 | 21,5 | 31,9 | 12,8 | 16,9 | 0,3 | 12 | F |
| FR-1893-HR-5 | 20,7 | 30,0 | 12,3 | 15,0 | 0,2 | 16 | F |
| FR-1893-HR-6 | 21,6 | 29,2 | 11,0 | 15,7 | 0,2 | 5 | F* |
| Mean | 21,3 | 30,5 | 11,8 | 16,0 | / | / | / |
| SD | 0,3 | 1,1 | 0,7 | 0,9 | / | / | / |
| FR-1897-ER-1A | 21,7 | 35,4 | 14,4 | 19,2 | 0,4 | 0 | S* |
| FR-1897-ER-1B | 21,7 | 35,5 | 15,0 | 18,0 | 0,5 | 0 | F* |
| FR-1897-ER-2A | 21,6 | 35,6 | 14,0 | 17,3 | 0,8 | 0 | S* |
| FR-1897-ER-2B | 21,6 | 35,3 | 15,1 | 18,1 | 0,8 | 0 | F* |
| FR-1897-ER-3A | 21,7 | 35,7 | 14,3 | 17,4 | 0,6 | 0 | S* |
| FR-1897-ER-4A | 21,6 | 35,5 | 14,9 | 18,6 | 0,1 | 2 | S* |
| Mean | 21,7 | 35,5 | 14,6 | 18,1 | / | / | / |
| SD | 0,1 | 0,1 | 0,4 | 0,7 | / | / | / |
| BE-1888-HR-1 | 21,2 | 35,3 | 14,8 | 18,2 | 0,6 | 6 | F |
| BE-1888-HR-2 | 21,6 | 35,0 | 12,5 | 18,7 | 0,4 | 6 | F |
| BE-1888-HR-3 | 21,9 | 37,0 | 15,6 | 17,7 | 0,5 | 8 | F |
| BE-1888-HR-4 | 21,0 | 34,7 | 13,0 | 18,4 | 0,4 | 1 | S |
| BE-1888-HR-5 | 20,7 | 34,9 | 13,5 | 17,6 | 0,4 | 1 | S |
| BE-1888-HR-6 | 21,1 | 35,0 | 14,5 | 18,5 | 0,4 | 1 | S |
| Mean | 21,3 | 35,3 | 14,0 | 18,2 | / | / | / |
| SD | 0,4 | 0,8 | 1,2 | 0,4 | / | / | / |

[9] "S" and "F" are the abbreviations of shop and field, respectively. The identification of the shop and field heads results from the analyses conducted in section 3.2.1. The samples for which the result is partially unsure are marked with an asterisk (*).

For every sample, the average value of the shank diameter $d$ was calculated based on the measurements made along the shank (parameter $d_{ave}$, Tab. 6-2). The parameter $d_{ave}$ varies between 20,7 and 23,5 mm, which is a narrow range. The FR-1897 case shows results that have the lowest variation within the sample data.

The measurements of the parameters characterizing the geometrically affinity of rivets – head diameter $D$, head depth $h$, and head radius of curvature $R$ – underline higher spreads of the results compared to the parameter $d_{ave}$ (Tab. 6-2). The FR-1893 case presents the largest variations in $D$ and $R$ (SD) in comparison with FR-1883, FR-1897 and BE-1888. With regard to the head circularity tolerance $\Delta R$, the measured value is relatively small, in general, for every sample within the whole sample data.

The quality of riveting of existing riveted connections can be assessed through an analysis of their potential defects[10]. The following defects were observed on some samples: distorted rivet shank, rivet head degradation due to corrosion, unsymmetrical head, lip around the rivet head, and head eccentricity. The head eccentricity $\varepsilon/d_{ave}$ of the rivet samples is given in table 6-2. While the rivet heads of FR-1897 have almost no eccentricity, FR-1893 shows the largest values within the whole sample data, up to 16% with FR-1893-HR-5 for instance (Tab. 6-2). The head eccentricity of the FR-1883's samples falls within a relatively uniform range comprised between 1% and 7%. Concerning the BE-1888 structure, a clear trend can be observed between the three first and last rivet samples, the latter group of samples having negligible head eccentricities compared to the ones of the former group.

## 2.2 ANALYSIS AND DISCUSSION

### 2.2.1 NOMINAL SHANK DIAMETER

The nominal diameter $d$ in millimetres has to be identified in an attempt to reveal the original design choices and analyze the geometrical ratios. However, the parameter $d_{ave}$ does not reflect the nominal shank diameter since it represents the shank configuration after driving.

[10] The quality of riveting depends also on other parameters such as the applied crushing pressure, the driving time, the geometry of the rivet snap, etc. When assessing the state of a riveted connection in a built structure, the identification of visible and invisible defects allows to retrace original installation errors that affect the quality of riveting (see CH8, Tabs. 8-1 & 8-2).

Reversing the original driving process and referring to the standard diameters of the time allows to find the nominal shank diameter. Therefore, the following effects are taken into account to trace back the original driving process:

1. **The tolerance of fabrication of the rivet shank**. The value of ca. 0,25 mm has to be considered for shank diameters between 16 mm and 25 mm (Van der Veen 1919, 69).
2. **The radial upset of the shank in the rivet hole while being driven**. As discussed in chapter 2, section 2.1, the hole-shank diameter difference ranges from 1 mm to 2 mm, on average (see Eqn. 2-1).
3. **The diametric shrinkage of the shank due to cooling**. As its influence is very limited, the diametric shrinkage of the shank was not taken into account within the calculation.

It follows from the above that the nominal shank diameter $d$ is given by equation 6-1:

$$d = d_{ave} - 1{,}5 \pm 0{,}25\ [mm] \qquad (6\text{-}1)$$

Doing so, the nominal shank diameters found are the following: 22 mm for FR-1883, and 20 mm for FR-1893, FR-1897 and BE-1888 (Tab. 6-3, column header ‘Calc.’).

Next, the determination of the nominal shank diameter was validated by referring to standard values recommended by educator-engineers and theoreticians contemporary with the structures. As noticed in chapter 3, section 1, the even diameters of 16 mm, 18 mm, 20 mm, 22 mm and 24 mm were the most usual ones in countries using SI units, considering practical and economic concerns. Hence, the nominal values of 20 mm and 22 mm meet the standard shank diameters found in historical French and Belgian literature (Tab. 6-3).

Table 6-3: The mean calculated values of $d/e$ do not systematically match the content of historical French and Belgian literature

| STRUCTURE TAG | $e$ (mm)[11] | | $d$ (mm) | | | | $d/e$ (/) | |
|---|---|---|---|---|---|---|---|---|
| | | | CALC. | THEORY | | | MEAS. | THEORY |
| | | | | LEMAÎTRE | LITERATURE | | | LEMAÎTRE |
| FR-1883 | 15 | | **22** | 26 | 21 - 24 | | 1,47 | 1,83 |
| FR-1893 | 6 | | **20** | 13 | 12 - 16 | | 3,33 | 1,88 |
| FR-1897 | 10 | | **20** | 19 | 18 - 22 | | 2,00 | 1,88 |
| BE-1888 | 11 | | **20** | 20 | 18 - 22 | | 1,82 | 1,88 |

[11] For a rivet in double shear, $e$ is the thickness of the outer plies, that is, the thinnest ply.

The $d/e$ ratio was then calculated for each structure based on the nominal shank diameter $d$ and the plate thickness $e$ (Tab. 6-3, column header 'Meas.'). Except for FR-1893, these ratios are not higher than two. As noticed in the previous chapter, the $d/e$ ratio played a predominant role within the morphogenenis of the design principles of riveted connections. The French boilermaker Lemaître broke new ground in 1856 with his design table translated one year later by Armengaud into a formula, known as *Lemaître's empirical formula*. Historical French and Belgian literature provided theoretical values of $d$ based on the plate thickness $e$ (Tab. 6-3, column headers 'Lemaître' and 'Literature')[12]. While for FR-1883, FR-1897, and BE-1888, experimental and theoretical values match quite well, the $d$ values of FR-1893 are largely oversized compared with the theory. This observation is highlighted by its high $d/e$ ratio of 3,33, exceeding the commonly recommended maximal value of three to avoid the crippling of the plies[13]. The design of the FR-1893 bridge was supervised by the acknowledged French engineer Armand Considère (1841-1914). Original correspondence reveals that the overall strength calculations were not based on the 1891 new French regulation for the construction of iron and steel bridges (Sire 2010, 269). In a sense, the high $d$ values of FR-1893's rivets, which do not match the published recommendations of the time, are in line with Considère's *freedom in design* approach.

Hence practicing engineers and architects of the time did not systematically follow the recommendations provided by the theory. Nevertheless, no major damage or failure of the connections was observed. This can be explained by the level of safety of the geometrical rules of thumb, the actual stress state of the structural members, and again on-site practical and economic concerns. As a result, the plate thickness $e$ cannot be considered as a reliable non-destructive assessment criterion – on its own – to define the nominal shank diameter $d$.

### 2.2.2 RIVET HEAD SHAPE AND GEOMETRICAL AFFINITY

Together with a visual inspection, the rivet head shape can be assessed through the measurement of the $h/D$ ratio and the head radius(es) of curvature $R$. The presence of a single $R$ per head – i.e., small circularity tolerance $\Delta R$, Tab. 6-2 – and a $h/D$ ratio approaching the value of 0,37 give evidence for the round head for all the studied structures (Tab. 6-4). Historical French and Belgian sources published at the end of the 19th century provided a mean value of 0,37 for the $h/D$ ratio of round heads[14].

[12] See CH5.

[13] See CH5, section 4.1, Eqn. 5-9.

[14] See CH3, section 2.1. The term of "round head" used in the present chapter is a simplified derivative of the "round snap head" described in chapter 3.

Also, the button head assumption could be dismissed as it has two radiuses of curvature.

Table 6-4: The proportions of the rivet heads deduced from measurements are in line with the content of historical French and Belgian literature

| STRUCTURE TAG | HEAD SHAPE | | HEAD - SHANK | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $h/D$ (/) | | $D/d$ (/) | | $h/d$ (/) | | $R/d$ (/) | |
| | MEAS. | THEORY | MEAS. | THEORY | MEAS. | THEORY | MEAS. | THEORY |
| FR-1883 | 0,39 | 0,37 | 1,65 | 1,69 | 0,64 | 0,65 | 0,89 | 0,86 |
| FR-1893 | 0,39 | 0,37 | 1,53 | 1,69 | 0,59 | 0,65 | 0,80 | 0,86 |
| FR-1897 | 0,41 | 0,37 | 1,78 | 1,69 | 0,73 | 0,65 | 0,90 | 0,86 |
| BE-1888 | 0,40 | 0,37 | 1,77 | 1,69 | 0,70 | 0,65 | 0,91 | 0,86 |

Derived from measurements, the geometrical ratios $D/d$, $h/d$ and $R/d$ were calculated as the mean value of the six rivet heads per structure. The results are summarized in table 6-4 (column headers 'Meas.'). The geometrical affinity of round heads mentioned in historical sources resulted in the $D/d$ and $h/d$ ratios. 19th-century publications provide the following mean values for $D/d$ and $h/d$: 1,69 and 0,65, respectively[15]. Knowing $D$ and $h$, the radius of curvature $R$ was then easily calculated and also expressed as a function of $d$ ($R/d$ = 0,86). The calculated geometrical ratios derived from measurements ('Meas.') show results that satisfactorily match the theoretical ratios for $D/d$, $h/d$ and $R/d$ (Tab. 6-4). This validates the geometrical affinity on the one hand, and the presence of round rivet heads on the other hand. The observed slight differentials might have been caused by surface irregularities or defects. In particular, the smaller $D/d$ ratio of FR-1893 could be explained by the exclusive presence of field heads[16].

As noticed in chapter 4, section 3.1, a minimal value of the $h/d$ ratio had to be satisfied to avoid any rivet head failure under excessive axial tensile stress. Based on Frémont's experiments, the rough ratio of $h/d$ equals $2/3$ proved to be safe, providing a safety margin of ca. 12-15%, that is, $h/d \geq 0{,}56$ (Frémont 1906, 131–33). For $h/d < 0{,}56$, the failure of a rivet under tensile stress would occur at the level of the head instead of the shank. The calculated $h/d$ ratios of the rivet samples all meet Frémont's requirement (Tab. 6-4).

From these observations, it can be concluded that $D$, $h$ and $R$ are relevant parameters to approximate the nominal shank diameter $d$ in a non-destructive way.

15 See CH3, Fig. 3-4.

16 This assumption will be confirmed in section 3.2.1.

## 3 METALLOGRAPHY

Analyzing and characterizing the microstructure of wrought-iron rivets provides information on the structural behaviour of the connections – especially by investigating the rivet driving process, and highlights material inhomogeneities – even within a given structure.

According to Frémont (1906) who refers to the study of Clark (1850), the grain flow and slag orientation reveal the original driving technique and show evidence of rather hand-driven or machine-driven rivets (Frémont 1906, 39). Actually, the forming technique of the head – shop or field head – of a wrought-iron rivet induces an identifiable reorientation of the grain flow and slag within the head as well as at the head-shank interface (Fig. 6-2). The machine driving process creates a reorientation in a "barrel" shape (Fig. 6-2, right) while hand driving generates a "tulip-shaped" grain flow and slag orientation (Fig. 6-2, left). Especially for short grips, machine-driven rivets might benefit from a more efficient upset and contact between the shank and the rim of the hole. This can induce a positive influence on frictional and bearing strengths together with an improved durability, against pack rust, for example (Leman 1895, 181–82). More fundamentally, as observed by Hooper et al. (2003) on the wrought-iron rivets of the RMS *Titanic*, the slag reorientation at the head-shank interface caused by the driving process induces a localized decrease in strength that detrimentally affects the behaviour of the connections (Hooper et al. 2003, 1562).

Reflecting the manufacturing process, slag is, among others, a good indicator to assess the quality of wrought iron and its material properties (Gordon 1997, 15). The quality of wrought iron was increased thanks to repeated hot workings that refined the slag and thus improved the mechanical properties (Tilly et al. 2008, 48; O'Sullivan and Swailes 2009, 261–62).

The metallographic investigations aim to answer the following questions:

- Supported by the results of the geometrical analyses, do metallographic investigations allow to distinguish the shop head from the field head?
- Do the grain flow and slag orientation allow to visually identify the original forming technique of the rivet heads?
- How (in)homogeneous is the microstructure of rivet samples belonging to a given structure?

## 3.1 RESULTS

The results of the metallographic investigations are given below for the two parameters analyzed, namely the grain flow and the slag area percentage.

### 3.1.1 GRAIN FLOW

The grain flow within the rivet shank and heads is clearly visible on the etched samples (Fig. 6-3). In the shank, the orientation of the grain flow is always parallel to the shank axis. Regarding the rivet heads, two main types of grain flows were identified: tulip shape and barrel shape.

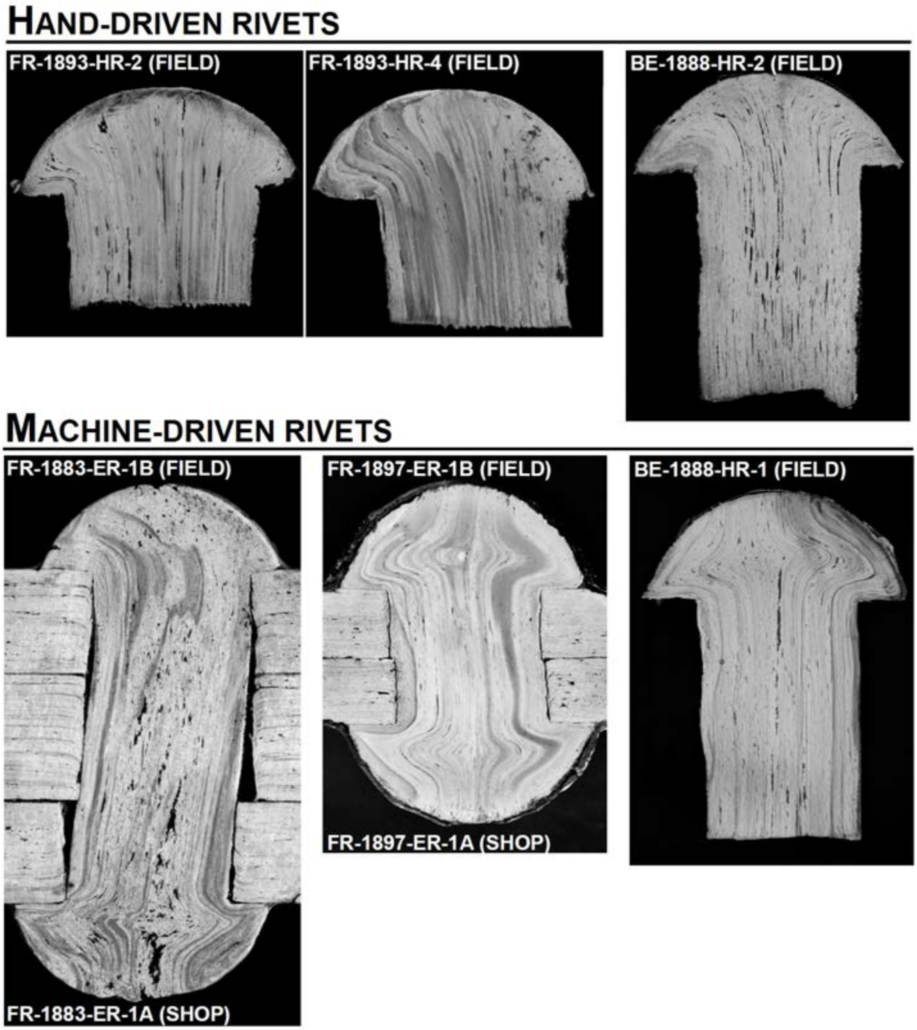



Figure 6-3: The grain flow and slag orientation within the field heads give evidence of the original driving technique (hand riveting vs. machine riveting)

#### 3.1.2 SLAG AREA PERCENTAGE

Slag area percentages measured on the rivets' cross section are provided below in table 6-5:

Table 6-5: Scatter of slag area percentages of the rivet samples of the structures

| STRUCTURE TAG | MIN (%) | MAX (%) | MEAN (%) | SD (%) |
|---|---|---|---|---|
| FR-1883 | 1,1 | 1,9 | 1,6 | 0,4 |
| FR-1893 | 1,0 | 4,5 | 1,8 | 1,3 |
| FR-1897 | 0,05 | 0,4 | 0,2 | 0,2 |
| BE-1888 | 0,5 | 2,5 | 1,5 | 0,8 |

For each structure, the mean slag area percentage of the rivet samples is always inferior to 2% (Tab. 6-5). A noticeable observation is the very low amount of slag of the FR-1897 case. On the contrary, the analysis of the slag area percentages of FR-1893's rivets' cross section reveals high values together with an important scatter of the results. This is especially due to one peculiar rivet sample: the FR-1893-HR-3 head having 4,5% of slag area percentage, that is, FR-1893's maximal value (Tab. 6-5). The visual comparison – almost to the naked eye – between FR-1893-HR-3 and FR-1893-HR-2 samples makes it clear (Fig. 6-4).

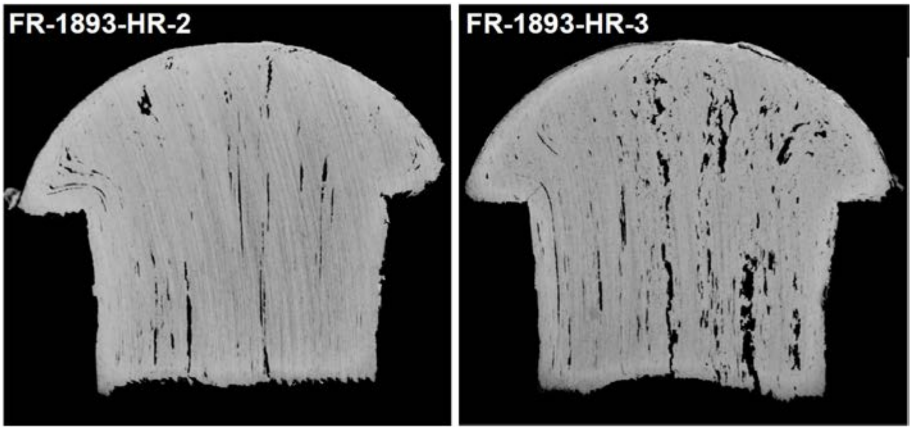



Figure 6-4: Higher slag area percentage and longer slag inclusions of FR-1893-HR-3 (right) compared to FR-1893-HR-2 (left)

### 3.2 ANALYSIS AND DISCUSSION

#### 3.2.1 SHOP HEAD VS. FIELD HEAD

Though difficult to assess, the distinction between the shop and the field head can reveal the localized asymmetric behaviour of some riveted connections within a given structural element. This phenomenon is mainly linked to the variation in contact

conditions between the shank and the rim of the hole along the grip. It results from the upset of the shank during the driving process. Alone, results derived from geometrical analyses are not sufficient to discuss the distinction between the shop and the field head. In particular, the identification of the shop or field head end is even more difficult for half-rivets than for entire ones. Metallographic analyses were thus valorized in an attempt to draw reliable conclusions with the help of the results of the geometrical investigations discussed in section 2.2.

The FR-1883-ER-1 riveted connection reveals major clearances between the shank and the hole (heads FR-1883-ER-1A & 1B, Fig. 6-3). Moreover, the shank diameter $d$ just under the head is 0,5 mm smaller for the FR-1883-ER-1A head compared to the FR-1883-ER-1B head. This would indicate that FR-1883-ER-1A is the shop head. The symmetric grain flow of FR-1883-ER-1A together with the absence of upset of the shank under the head confirm the shop head assumption. The presence of these clearances and non-uniform shank-plies contact give evidence of important bearing and shear stress concentrations within the plies and the shank, respectively. As no fatigue damage was observed, the frictional strength may have been cancelled by the slip of the plies under the influence of the loads. Regarding the FR-1893 structure, while FR-1893-HR-4 could be easily identified as a field head given its asymmetry and the variation of $d$, the better driving quality of FR-1893-HR-2 makes the assessment more difficult (Fig. 6-3). However, shop heads being practically always machine-formed in a shop during the period 1880s-1890s, the exclusive presence of hand-driven rivets tends toward the field head assumption for each FR-1893 sample. The discussion of the FR-1897 rivets, though being entire, was difficult. Nevertheless, combining multiple assessment criteria allowed to elucidate the problem. For example, the slight asymmetry of the grain flow near the head edge – deviation – together with the shape of the FR-1897-ER-1B head at the head-shank interface are strong signs of field head (Fig. 6-3). Indirectly, this interpretational difficulty is synonymous with a high quality of riveting, and thus a full bearing capacity of the FR-1897 connections. For the BE-1888 case, both BE-1888-HR-1 and BE-1888-HR-2 samples are field heads. This observation is based on the decreasing values of the shank diameter $d$ starting from the shank-head interface, the head eccentricity and the head shape (Tab. 6-2, Fig. 6-3).

Provided that a large number of parameters and assessment methods are considered (e.g., measurements, etching), the distinction between the shop and the field head appeared to be possible but comes with uncertainties, regardless of whether the studied rivets are half or entire. Next to the three main geometrical clues – head eccentricity $\varepsilon/d$, variation of the shank diameter $d$, shape of the head, the (a)symmetry of the grain flow and slag orientation within the head and in the shank near the head is a reliable assessment parameter. Paradoxically, a difficult distinction

between the two heads of an entire rivet is a strong sign of high quality of riveting and efficient structural behaviour. More fundamentally, the relevance of discussing the head type depends on the total grip length of the connection. In general, a short grip will benefit from a better quality of riveting, as it was emphasized by the contrast between FR-1897 – i.e., short grip, symmetric behaviour – and FR-1883 – i.e., long grip, asymmetric behaviour.

### 3.2.2 MANUFACTURING TECHNIQUE

Assuming that the shop head can be identified, both geometrical and metallographic investigations can provide information on rivet manufacture. The quality of rivet manufacture can be derived from the analysis of the geometry of the shop head. The uniformity of its shape and alignment with the shank underline a satisfactory quality of manufacture. The orientation of the grain flow and slag within the shop head permits to reveal the original manufacturing technique. For instance, the barrel-shaped grain flow of the FR-1883-ER-1A and FR-1897-ER-1A samples is likely to result from the use of a rivet-making machine (Fig. 6-3). Rivet-making machines were commonly used at the end of the 19th century to manufacture rivets, as noticed in chapter 2.

### 3.2.3 DRIVING TECHNIQUE

The performed metallographic investigations allow to distinguish hand-driven from machine-driven rivets. As for the manufacturing technique, the original driving technique is evidenced by the reorientation of the grain flow and slag within the field heads and at the head-shank interfaces.

#### GRAIN FLOW

The analyses presented in section 3.1.1 revealing the grain flow on the etched rivet samples validate the distinction reported by Frémont in 1906 between hand-driven rivets – tulip-shaped grain flow – and machine-driven rivets – barrel-shaped grain flow (Figs. 6-2 & 6-3) (Frémont 1906, 39). All the field heads of a given structure were formed according to one same technique: hand riveting for FR-1893 and machine riveting for FR-1883, FR-1897, and BE-1888 (Fig. 6-3). However, the rivet sample BE-1888-HR-2 was hand driven. An on-site repair, replacement, or omission might explain this observation. The visual comparison between the BE-1888-HR-1 grain flow – barrel shape – and BE-1888-HR-2 grain flow – tulip shape – makes this clear (Fig. 6-3). Actually, for BE-1888-HR-2, the orientation of slag reveals the original driving process on its own. The use of both forming techniques within the BE-1888 case strengthens the need to assess a sufficient number of rivet samples before drawing any general conclusion applying to the whole structure being appraised.

Hence the experimental results that show a combined use of both driving techniques bring to light the *actual* transition of the period 1880s-1890s, the first riveting machine having been developed by Garforth (UK) in as early as 1847 (Frémont 1906, 22–23).

SLAG ORIENTATION

Next to the grain flow, results show a reorientation of slag within the rivet heads induced by the driving process (Fig. 6-3). The reorientation phenomenon[17] is even more pronounced for machine-driven rivets, especially in the core of the rivet head – e.g., samples FR-1897-ER-1A & 1B, Fig. 6-3. The microstructure of hand-driven rivets seems to be less affected by the driving process, especially as the main reorientation takes place in the edges of the heads – e.g., samples FR-1893-HR-2 & 4, Fig. 6-3. Nevertheless, the FR-1893-HR-4 sample highlights the detrimental effect of a badly driven field head – important head eccentricity, see Tab. 6-2 – on the reorientation of its slag (Fig. 6-3). This can lead to an even more asymmetric behaviour of the riveted connection in service, namely a non-uniform clamping force of the head on the ply. On the other hand, since FR-1893's rivets were hand driven, the overall strength and stiffness of its riveted connections are by definition qualitatively lower than if they were machine driven. Accentuated by the short grip length, the high quality of riveting of the machine-driven FR-1897 rivets is a nice example (Fig. 6-3).

As a result, the investigations corroborate Hooper's findings on the slag reorientation phenomenon observed within the rivet heads (Hooper et al. 2003, 1559). The presence of regions within the rivet – the heads – having lower mechanical properties is thus observed as well. As a reminder, since both yield and ultimate tensile strengths of wrought iron perpendicular to grain are ca. 15% lower than parallel to grain, these regions can be considered as weaker within the rivet (Hooper et al. 2003, 1562; O'Sullivan and Swailes 2009, 269). Stress concentrations or even failure would thus be likely to occur in the rivet heads first.

### 3.2.4 MICROSTRUCTURAL INHOMOGENEITIES

Analyzing the microstructure of wrought iron is, among others, a valuable proxy to assess its mechanical properties and material quality. In particular, excessive and non-uniformly distributed slag within the ferrite matrix has a negative impact on the mechanical properties. (Gordon 1997; O'Sullivan and Swailes 2009)

The results of slag area percentages presented in section 3.1.2 pinpoint the variations observed between the different structures but also within a given structure. Regarding the FR-1893 case, the high percentage, concentration and presence of long slag inclusions in FR-1893-HR-3 might detrimentally affect the ductility of the

[17] Orientation angle from the direction parallel to the shank.

rivet (Tab. 6-5) (Gordon 1997, 15). This could be explained by an insufficient working of the used rivet iron during its manufacturing; repeated working caused the slag inclusions to be refined (O'Sullivan and Swailes 2009, 261).

As a consequence, measurements of the slag area percentage revealed large variations between rivet samples belonging to a given structure, although they were generally formed through one same driving technique, that is, hand riveting or machine riveting. This observation stresses the difficulty to appraise the mechanical properties of existing wrought-iron rivets, and the need to consider a sufficient number of rivet samples for the preliminary analyses.

# 4 CONCLUSIONS – A POOL OF KEY PARAMETERS

The structural behaviour of hot-driven rivets removed from four French and Belgian wrought-iron structures (1880s–1890s) was qualitatively assessed by means of geometrical and metallographic investigations. The measurements and results were discussed and confronted with historical literature to reveal the original design, geometry, manufacturing and driving techniques of the rivets. The relevance and usefulness of the observations relied primarily upon the complementarity of geometrical and metallographic investigations, each being insufficient on their own. With very few exceptions[18], the fact that the test results validate the content of historical literature – riveting practice and theory – establishes the status of this literature as a body of knowledge.

The geometrical analyses underlined the presence of standard shank diameters, as mentioned in historical literature. Though the common values of the $d/e$ ratio were not systematically validated, it confirms the actual use of these diameters by 19th-century architects and engineers. As a consequence, we recommend to trace the nominal shank diameter when remedial works involving the hot-riveting technique are required, with the idea of keeping to the original design principles of a given structure. To identify the nominal shank diameter $d$, either the geometrically affinity – head diameter $D$, head depth $h$, and/or radius of curvature $R$ – or the measurements of $d$ along the shank can be used.

The identification of the shop and field head ends is not systematically relevant or feasible. However, it allows to qualitatively appraise the structural behaviour of existing riveted connections. A difficult or almost impossible shop-field head distinction can indirectly be the sign of a high quality of riveting. Additionally, the presence of large clearances between the shank and the rivet hole together with plies having slipped may reveal both shear and bearing stress concentrations, that is, a decrease in the overall strength of the joint. For grip lengths exceeding 35-40 mm

[18] E.g., the $d/e$ ratio via the plate thickness $e$.

and regardless of the used driving technique, the identification of the shop and field head might testify of asymmetric bearing strength and clamping forces applied by the head on the plies. To facilitate any rivet removal operation, when needed, it is advised to shear off the shop head, since the upset of the shank and its contact with the rim of the rivet hole is better near the field head end. Here the head eccentricity $\varepsilon/d$, variation of the shank diameter $d$, shape of the head, and the (a)symmetry of the grain flow and slag orientation are valuable parameters to assess.

Regarding the driving technique, the use of both hand and machine riveting highlights the actual mutation of rivet driving at the end of the 19th century. To identify the original driving technique of a wrought-iron rivet, a destructive assessment appeared to be the only way to draw reliable conclusions. Here the grain flow and slag orientation within the rivet heads give evidence of the original forming process. In particular, a hand-driven rivet of a 1880s–1890s structure is a strong clue of field head.

Finally, the high scatter of slag area percentages of the rivet samples of a given structure stresses the need to inspect a sufficient number of rivets.

To complete those qualitative analyses, the next chapter suggests to assess the structural behaviour of wrought-iron riveted connections. The shear behaviour of wrought-iron single lap joints and the influence of remedial works are addressed in chapter 7.

# PART III
# EXPERIMENTS

## CHAPTER 7

## SHEAR TESTS ON SINGLE RIVETED SINGLE LAP JOINTS

**The structural behaviour of wrought-iron riveted connections is investigated in chapter 7. It aims to assess the shear behaviour of the connections as well as the influence of remedial works. First, riveted specimens were designed and fabricated in accordance with the technology and design of the 19th century. Then, the quality of riveting of the fabricated specimens was appraised. Finally, a lap shear test campaign was performed on original and repaired wrought-iron single riveted single lap joints. The discussion of the results is put into perspective with both historical and recent literature.**

**Chapter 7 aims to answer the following questions:**

*How do wrought-iron single riveted single lap joints behave in shear?*

*Does the quality of riveting influence the shear behaviour of the riveted specimens?*

*In which proportions do remedial works affect their behaviour?*

The appraisal procedure of existing wrought-iron riveted connections is generally hampered by numerous issues, especially at the level of the preliminary analyses and intervention strategies (see the introduction, Fig. 0-3).

The identification of the material properties of the plates and the rivets constituting the connections is one of the tasks belonging to the preliminary analyses. The anisotropic and inhomogeneous features of the material wrought iron make the results of mechanical tests difficult to interpret (Hooper et al. 2003; McCowan et al. 2011; de Jesus et al. 2011; Sire et al. 2012). Concerning the overall structural behaviour, static analyses implemented on wrought-iron riveted connections are undeservedly under-represented in available literature (e.g., O'Sullivan 2013). Expectably, exhaustive static evaluations of wrought-iron connections are almost exclusively contemporary to the period during which wrought iron was used as a structural material, that is, the second half of the 19th century (Fairbairn 1850; Flint 1892; Twelvetrees 1900). The results of these experiments may not have been fully accurate given the testing equipment used. Past experiments aimed to provide practicing engineers with allowable stresses. Conversely, we are today interested in the influence of remedial works on riveted structures. Recently, other few studies involving static analyses were predominantly performed on riveted connections made of steel, and generally as background studies for fatigue assessment, e.g., Pipinato et al. (2009). In addition, some full static evaluations of steel riveted connections were carried out during the past years (D'Aniello et al. 2011; Jost 2012).

With regard to the intervention strategies, wrought-iron rivets are typically replaced – if applicable – by high strength or injection steel bolts for economic and practical reasons. When the hot-riveting technique is revived, today's standard materials and available techniques are used. When remedial works involve a repair or a strengthening of an existing wrought-iron connection, steel section(s) are connected to the existing wrought-iron section(s) with steel rivets driven by an air hammer in most cases (for field riveting)[1]. Hence, once renovated, the resulting connection combines materials of different strength and ductility. Such interventions modifying the original structural behaviour of the connections and load-bearing structure to which they belong raise various questions that do not seem to have been investigated yet.

## 1 AIMS, METHODOLOGY AND SCOPE

Within the framework of the above-mentioned issues, the investigations conducted in this chapter address the behaviour of both original and repaired wrought-iron riveted connections subjected to shear. The research aim is twofold. First, it aims to assess

[1] For detailed information on actual renovation practices, see CH8, section 2.

the shear behaviour of original wrought-iron riveted connections and the scatter of the test results. The influence of the theoretical inadequaties of historical design methods – highlighted in chapter 5 – on the behaviour at ultimate is analyzed. In addition, the shear tests performed by acknowledged engineers of the 19th century who predominantly marked the history of civil engineering, its design methods and construction practices, can be reviewed. Second, the shear test campaign aims to assess the influence of remedial works involving actual renovation practices. In particular, we investigate the impact of replacing one of the wrought-iron plates of a riveted connection by a modern steel plate. The variations in strength and ductility of repaired riveted connections combining wrought-iron and steel materials are analyzed.

Instead of using riveted connections dismantled from an existing structure, the wrought-iron connections required for the experimental programme were rather fabricated. The amount of unmanageable parameters – e.g., non-uniform geometry, corrosion, hidden defects, etc. – had to be limited so as to improve the relevance of the test results and their discussion. Fabricated specimens allow to master a set of parameters that are known, namely rivet manufacture and driving, which is generally not the case of genuine specimens. Pragmatic considerations also conditioned the type of specimens used. Unfortunately, it was not possible to find a sufficient amount of almost identical standard[2] joining typologies of wrought-iron connections ensuring a good statistical representativeness for the tests. Hence, the use of fabricated specimens is in line with the aims of the study.

The methodology of the research follows three main steps. First, the wrought-iron riveted specimens were designed in accordance with the methods described in historical literature. The specimens were then fabricated in compliance with the materials and techniques of the end of the 19th century. Actual renovation practices were used to fabricate the repaired specimens. Second, investigations on the quality of riveting were conducted prior to the shear test campaign, since it could not be assessed on collapsed riveted specimens. The analyses of the previous chapter are valorized to discuss the quality of riveting. Third, the lap shear tests were performed on the original and repaired specimens fabricated. Supported by the investigations on the quality of riveting, the results are discussed and confronted with literature.

The joining typology chosen for the shear tests is a standard configuration, namely the single riveted single lap joint. This typology does not correspond to the majority of the connections of existing load-bearing structures, which are generally more complex. However, it is essential to understand the shear behaviour of connections fastened with a single rivet before studying more sophisticated joining typologies.

[2] Simple joining typologies involve a limited amount of rivets and plates.

## 2 EXPERIMENTAL PROGRAMME

The results found in Part I and Part II were used to draw up the experimental programme. They permitted to define the geometry of the riveted specimens and to underline key parameters to which peculiar attention had to be paid during both fabrication and testing.

SPECIMENS FOR THE SHEAR TEST CAMPAIGN

Two sets of *single riveted* single lap joints were fabricated (Fig. 7-1):

1. **Joint type O** represents the "original" wrought-iron connections. They were fabricated based on genuine wrought-iron materials that were re-used. Former techniques were revived to fabricate wrought-iron plates and rivets, and connect them together, in an attempt to replicate the riveted connections of the end of the 19th century.
2. **Joint type R** embodies the configuration of a joint type O that underwent remedial works. It consists of one wrought-iron plate that is riveted by a new steel rivet to one steel plate, according to current riveting practices involving available materials and techniques.

Lap shear tests are performed on the above-mentioned sets of single riveted single lap joint types O and R.

SPECIMENS FOR THE QUALITY OF RIVETING

A third set of samples was fabricated to assess how the driving technique influences the quality of riveting. To do so, joints with three adjoining rivets were fabricated, that is, *triple riveted* single lap joints. The plates and rivets of the triple riveted specimens are identical in material to the joint types O and R (Fig. 7-2).

Visual inspections and geometrical investigations are carried out to study this set, similarly to the analyses of chapter 6, section 2.

### 2.1 DESIGN OF THE RIVETED SPECIMENS

The single riveted specimens type O are designed according to the analytical methods characteristic of the decades around the turn of the 20th century (see CH5, section 4). The nominal shank diameter $d$ is empirically deduced from a given plate thickness $e$ through the $d/e$ ratio. The arrangement of rivets can be then defined since their number is a known parameter. The geometrical parameters are expressed as a function of the shank diameter $d$, and validated by the convenient method developed by the German engineer JW. Schwedler.

The layout of the single riveted specimens type R corresponds to the design of the specimens type O. The design of the triple riveted specimens is derived from the one of the single riveted specimens.

### 2.1.1 NOMINAL SHANK DIAMETER $d$

The plate thickness chosen for every riveted specimen was 1/4 in, that is, approximately 6,3 mm. Practical and technical considerations – tension capacity of the testing machine – motivated this relatively thin plate thickness[3].

Once the plate thickness was defined, the nominal shank diameter $d$ could be calculated by referring to the corresponding $d/e$ ratio. The average $d/e$ ratio equals 2,25 for such a thickness[4]. The resulting shank diameter is then given by equation 7-1:

$$\mathrm{e} \cong 6\,\mathrm{mm} \xrightarrow{d/e \,\cong\, 2{,}25} d = 14\,mm \qquad (7\text{-}1)$$

Since a rivet of 14 mm in diameter was not a standard value for structural work, the diameter of 16 mm was chosen for the rivets of both joint types O and R. In practice, it corresponds to rivets having a theoretical shank diameter of 5/8 in (ca. 15,875 mm). The actual $d/e$ ratio equalling now 2,5 complies with the relationship of Gerber – $d/e$ at the most equalled to three – that aimed to avoid the crushing of the grip as well as too high plate bearing stresses (Eqn. 5-9).

### 2.1.2 LAYOUT OF THE RIVETED SPECIMENS

The geometrical parameters defining the layout of the single riveted specimens are all stated as a function of the shank diameter $d$. Since each specimen comprises one rivet, the rivet pitch $p$ has not to be defined and the layout depends only on the edge distance $v$ and rivet lap $l$.

Between the 1880s and 1920s, the value of the edge distance $v$ ranged from 1,285 $d$ to 1,5 $d$ according to French and Belgian literature[5]. The edge distance of the specimens was set to 22 mm. This corresponds to a $v/d$ ratio of 1,375 (Tab. 7-1). The value of 22 mm is close to the result derived from the theory of Schwedler, that is, 21 mm (CH5, Eqns. 5-12 & 5-13). The total width of the single riveted specimens is thus 44 mm.

[3] The reason why the wrought-iron plates used for the fabrication of the riveted specimens are expressed in BI units is explained in section 2.2. The figures given in both BI and SI units are theoretical values that do not take tolerances of fabrication into account.

[4] The $d/e$ ratio was deduced from Fig. 5-2 (see CH5, section 2.2).

[5] See Tab. 5-4 (CH5, section 4.3).

A rivet lap $l$ ranging from 1,5 $d$ to 2,5 $d$ was usually advised by French and Belgian educator-engineers (Tab. 5-4). In accordance with the content of historical literature, the rivet lap of the single riveted specimens was set to 28 mm with the formula 1,75 $d$ (Tab. 7-1). This value validates the minimal rivet lap found with the calculations of Schwedler (i.e., 21 mm, Eqn. 5-13).

Table 7-1: Formulae and values of the geometrical parameters defining the layout of the single and triple riveted specimens

| PARAMETER | SINGLE RIVETED SPECIMENS | | TRIPLE RIVETED SPECIMENS | |
|---|---|---|---|---|
| | FORMULA (/) | VALUE (mm) | FORMULA (/) | VALUE (mm) |
| Rivet pitch $p$ | / | / | 4,375 $d$ | 70 |
| Rivet lap $l$ | 1,75 $d$ | 28 | / | 50 |
| Edge distance $v$ | 1,375 $d$ | 22 | 1,375 $d$ | 22 |

The layout of the single riveted specimens is depicted on Figure 7-1. Joint types O and R follow the same layout. The plate length, set at 200 mm, was verified experimentally (see section 4.1).

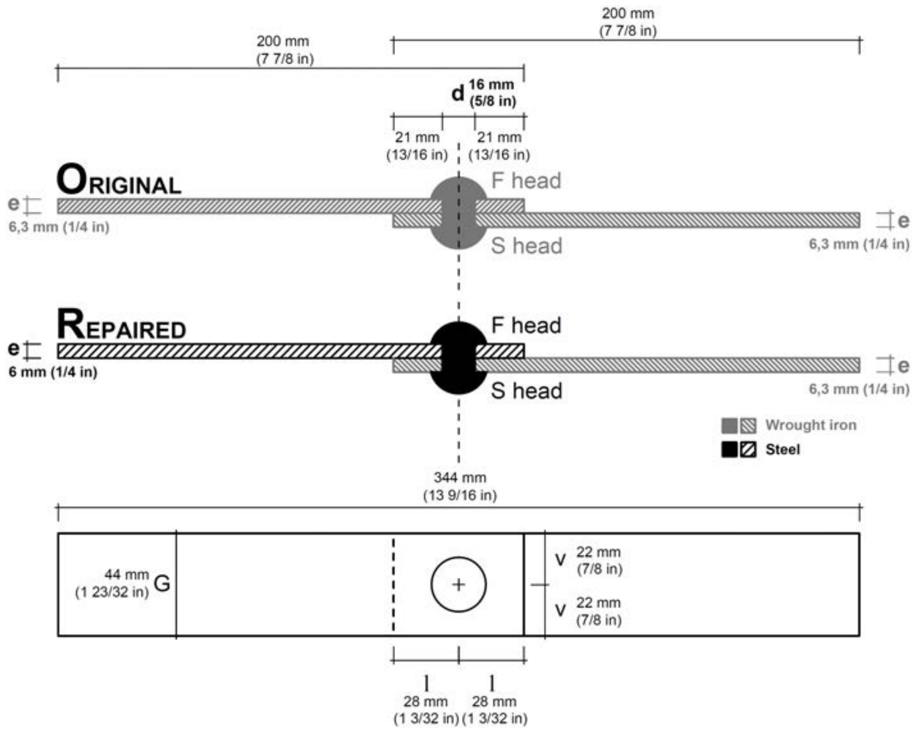



Figure 7-1: Elevation and plan views of the single riveted specimens belonging to the types O and R[6]

[6] "S" and "F" stand for shop and field, respectively.

The geometry of the triple riveted specimens involving three adjoining rivets introduces a third parameter that is the rivet pitch $p$. The value of the parameter $p$ was set at 70 mm by using the formula 4,375 $d$ (Tab. 7-1). This proportion is in line with the content of turn-of-the-20th-century literature that recommended to define the rivet pitch between 2,5 $d$ and 5 $d$ (Tab. 5-4). The edge distance $v$ is the same as for the single riveted specimens. Since the rivet lap $l$ is not an important parameter for the triple riveted specimens that will not undergo any loading, it was set at a value that facilitates rivet driving and ensures a secure fit of the plies (Tab. 7-1).

Figure 7-2 gives the layout of the triple riveted specimens.

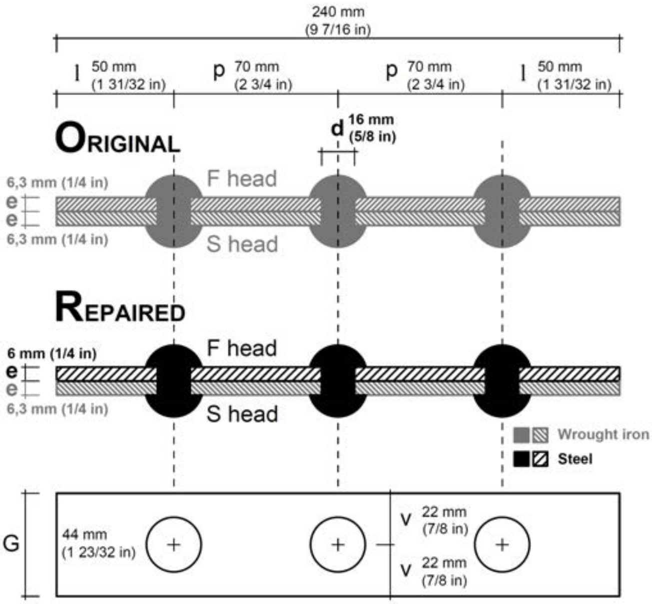



Figure 7-2: Elevation and plan views of the triple riveted specimens belonging to the types O and R

## 2.2 MATERIAL PROPERTIES

Joint types O and R require both wrought-iron and modern steel materials for their fabrication. O specimens consist of two wrought-iron plates connected by wrought-iron rivet(s). R specimens fasten one wrought-iron plate to one steel plate by steel rivet(s) (Figs. 7-1 & 7-2).

### 2.2.1 WROUGHT-IRON COMPONENTS

Wrought iron as a building material is neither used nor available anymore, as it has been progressively substituted with steel at the end of the 19th century. For the experimental programme, the wrought-iron components were supplied by the *Real Wrought Iron Company* located in the UK. This company recycles puddled wrought

iron salvaged from the dismantling of 19th-century roof structures, admiralty anchor chains, railway bridges, gas holders, etc. They re-roll scrap wrought iron into various sections such as plates, round bars, square bars, etc., available in imperial sizes[7]. ("The Real Wrought Iron Company" 2014)

Tensile tests were carried out to assess the mechanical properties of the plate and rivet irons used for the manufacturing of the wrought-iron plates and rivets. The test results support the analyses of the lap shear test campaign developed in section 4.

### PLATES

One plate iron was used for the fabrication of all the riveted specimens. The plate iron results from the re-rolling of wrought-iron sections dismantled from a 19th-century small-span bridge[8]. The recycled wrought-iron material was a part of the web of a built-up I-section of the primary bearing structure of the bridge. The re-rolled plate produced by the *Real Wrought Iron Company* is 1/4 in thick (ca. 6,3 mm).

The plate iron was tested at the LBMS lab of the University of Brest. The results of the tensile tests performed on three specimens machined from the plate iron – PI-A, PI-B and PI-C – are depicted on figure 7-3[9].

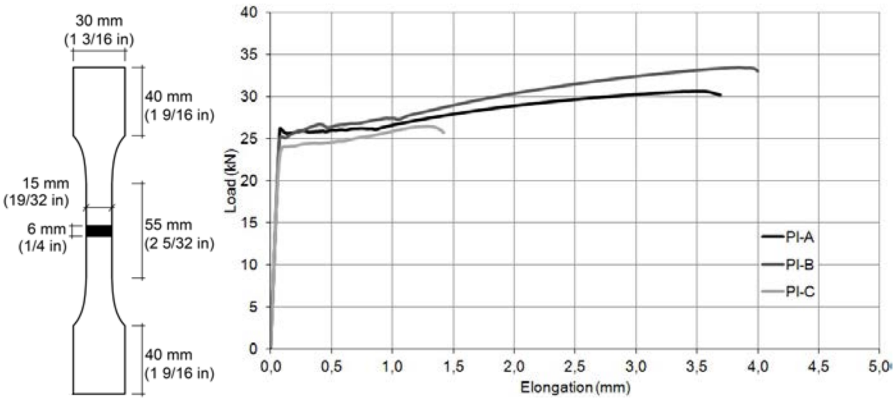



Figure 7-3: Geometry (left) and load-elongation curves (right) of the PI-A, PI-B and PI-C specimens machined from the plate iron

[7] Based in Thirsk, North Yorkshire, the *Real Wrought Iron Company* may be the sole remaining world supplier of genuine wrought iron. They supply wrought-iron sections to blacksmiths involved in the restoration of heritage ironwork ("The Real Wrought Iron Company" 2014).

[8] Unfortunately, accurate information on the bridge was not available (e.g., bridge name, building date, location).

[9] The test specimens were machined from a part of the plate iron cut along the rolling direction.

Table 7-2 confronts the yield strength, ultimate tensile strength and elongation at failure of the specimens[10] with 19th-century British test data since the re-rolled plate iron originate from the UK.

Table 7-2: Yield strength, ultimate tensile strength and elongation at failure of the tested plate iron (bottom) versus historical literature (top)

| TENSILE TESTS | DATE | YIELD STRENGTH (MPa) | ULTIMATE TENSILE STRENGTH (MPa) | ELONGATION AT FAILURE (%) |
|---|---|---|---|---|
| Fairbairn W.[11] | 1838 | / | 311 (22,52 t/in$^2$) | / |
| Kirkaldy D.[12] | 1862 | / | 320 (23,21 t/in$^2$) | 13 |
| Twelvetrees WN.[13] | 1900 | / | 248 - 303 (18,00 - 22,00 t/in$^2$) | / |
| Specimen PI-A | 2014 | 270 | 323 | 7 |
| Specimen PI-B | 2014 | 266 | 354 | 8 |
| Specimen PI-C | 2014 | 247 | 273 | 3 |
| **Mean** | / | **261** | **317** | **6** |
| SD | / | 12 | 41 | 3 |

On average, a yield strength of 261 MPa and UTS of 317 MPa were reached. The mean Young's modulus equals 189 MPa. The ranges of recorded yield strength and UTS all fall within the values mentioned by O'Sullivan (2013)[14]. The mean elongation at failure of 6% shows, however, a limited ductility. The mean UTS of the tested plate iron matches the results of 19th-century experiments very closely (Tab. 7-2).

[10] The yield/ultimate strength was calculated by dividing the yield/ultimate load by the cross section of the specimens. The elongation at failure (%) was measured with an extensometer.

[11] Mean value of Yorkshire, Derbyshire, Shropshire and Staffordshire plates (Fairbairn 1850, 683).

[12] The plate irons tested by Kirkaldy originated from Lowmoor, Yorkshire (data retrieved from: (Fidler 1879, 304)).

[13] Mean mechanical properties of wrought-iron plates based on records of experiments contemporary to the author (Twelvetrees 1900, 60).

[14] The large volume of test data – more than 500 tests – collected by O'Sullivan for plate irons tested along the grain direction can be summarized: mean yield strength of 240 MPa (range: 154 - 363 MPa), mean UTS of 345 MPa (range: 232 - 470 MPa), and mean elongation at failure of 15 % (range: 1 - 36 %). (O'Sullivan 2013, 160)

RIVETS

Provided again by the *Real Wrought Iron Company*, the rivet iron used for rivet manufacture is a round bar with a diameter of 5/8 in (ca. 15,875 mm). This diameter was obtained by re-rolling one half of a chain link – ca. 15 cm in diameter – cut from a salvaged admiralty anchor chain of the 19th century. As for rivet irons, the wrought iron used for the fabrication of admiralty anchor chains was of the very best quality, that is, the "best best best" category (Fidler 1879, 284). Similarly to the production of the wrought-iron plate, tolerances of fabrication generated by the re-rolling technique led to an actual diameter of the rivet iron of 16 mm.

Based in Tholthorpe (North Yorkshire, UK), the ironworkers of the company *Topp & Co* allowed to manufacture the wrought-iron rivets. Since the manufactured rivets were too small to make satisfactory tensile specimens, only the mechanical properties of the rivet iron were assessed. Figure 7-4 shows the load-elongation curves resulting from the tensile tests performed on three specimens machined from the rivet iron (RI-A, RI-B and RI-C).

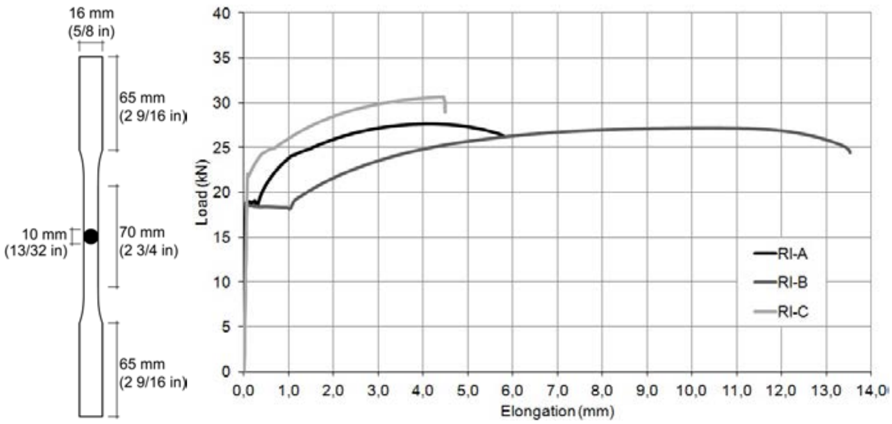



Figure 7-4: Geometry (left) and load-elongation curves (right) of the RI-A, RI-B and RI-C specimens machined from the rivet iron

The yield strength, ultimate tensile strength and elongation at failure of the specimens[15] are again confronted with 19th-century British test data (Tab. 7-3).

Table 7-3: Yield strength, ultimate tensile strength and elongation at failure of the tested rivet iron (bottom) versus historical literature (top)

| TENSILE TESTS | DATE | YIELD STRENGTH (MPa) | ULTIMATE TENSILE STRENGTH (MPa) | ELONGATION AT FAILURE (%) |
|---|---|---|---|---|
| Fairbairn W.[16] | 1838 | / | 345 - 403 (25,00 - 29,25 t/in$^2$) | / |
| Kirkaldy D.[17] | 1862 | / | 370 (26,82 t/in$^2$) | 21 |
| Twelvetrees WN.[18] | 1900 | / | 317 - 345 (23,00 - 25,00 t/in$^2$) | / |
| Specimen RI-A | 2014 | 240 | 355 | 12 |
| Specimen RI-B | 2014 | 238 | 350 | 27 |
| Specimen RI-C | 2014 | 280 | 395 | 9 |
| **Mean** | / | **253** | **367** | **16** |
| SD | / | 24 | 25 | 10 |

On average, a yield strength of 253 MPa and UTS of 367 MPa were noticed, together with a mean elongation at failure of 16%. The mean Young's modulus equals 200 MPa. The test results validate the values mentioned in table 2-1 (CH2) regarding the UTS of rivet irons. However, the elongation at failure is somewhat lower than the one of genuine rivet irons, since the latter ranges between 17% and 36% (Tab. 2-1). As for the plate iron, the mean UTS of the rivet iron matches the test results of 19th-century experiments (Tab. 7-3).

The higher UTS and elongation at failure of the rivet iron compared to the plate iron confirm the superior quality of rivet irons discussed in chapter 2, section 1.1 (Tabs. 7-2 & 7-3). The mean UTS of the tested rivet iron is 16% higher than the mean UTS of the tested plate iron. This value corroborates the findings of 19th-century engineers who reported a difference in UTS of 20% (Fairbairn 1850, 684; Fidler 1879, 303).

The tensile tests performed on the plate and rivet irons reveal close similarities with the mechanical properties of 19th-century wrought irons. Therefore, it validates the relative genuine character of the fabricated riveted specimens type O.

[15] The yield/ultimate strength was calculated by dividing the yield/ultimate load by the cross section of the specimens. The elongation at failure (%) was measured with an extensometer.

[16] Mean values of Staffordshire, Swedish, Welsh and Russian bar irons (Fairbairn 1850, 683).

[17] The rivet irons tested by Kirkaldy originated from Lowmoor, Yorkshire (data retrieved from: (Fidler 1879, 304)).

[18] Mean mechanical properties of rivet irons based on records of experiments contemporary to the author (Twelvetrees 1900, 60).

### 2.2.2 STEEL COMPONENTS

We chose slightly different steel grades for the plate and rivet materials: S275 and S235, respectively[19]. As noticed in chapter 2, section 1.1, it was internationally advised to use rivet steels of the same or somewhat lower strength than the plate steels. The difference in steel grades takes into account the positive influence of rivet driving on the mechanical properties of the driven rivets.

PLATES

Originating from the UK, a steel grade S275 was ordered for the plates needed for the fabrication of the joints type R. However, the steel plates proved to have high mechanical properties. Actually, tensile tests revealed a mean yield strength of 426 MPa and mean UTS of 538 MPa[20]. To match the dimensions of the wrought-iron plates, the thickness chosen for the steel plates was 6 mm.

RIVETS

The steel rivets were manufactured from cut segments of rivet steels corresponding to the grade S235. The Belgian company *Dick bvba* manufactured the steel rivets[21]. The nominal diameter of the steel rivets is 16 mm. This value meets the actual nominal diameter of the wrought-iron rivets manufactured by *Topp & Co*.

Hence, the plate and rivet materials needed for the experimental programme originate from two different countries, namely the UK and Belgium. Such trans-national approach is not unusual for remedial works involving the hot-riveting technique. It highlights the actual issues encountered by today's historic preservationists, architects and engineers with regard to material availability.

*The fabrication of the riveted specimens is detailed in the enclosed notice (next two pages).*

[19] Contrary to their wrought-iron equivalents having imperial sizes, the steel plates and rivets are available in SI units.

[20] Mean Young's modulus of 195 MPa and elongation at failure of 28%.

[21] The steel rivets were manufactured within the framework of the 2010-11 renovation project of the heritage-listed north hall of the Brussels Cinquantenaire Park (Brussels, Belgium).

# 3 QUALITY OF RIVETING

Analyses conducted on the quality of riveting relate to two main fields of investigation: the geometry of the rivet heads and the upset of the rivet shank in the rivet hole.

## 3.1 EXPERIMENTAL SET-UP AND INVESTIGATED PARAMETERS

The triple riveted specimens were precisely machined along the longitudinal axis at mid-width of their gage $G$ (Fig. 7-2). Then, the geometrical investigations and visual inspections were performed on each of the three rivets belonging to a given specimen.

Five parameters were measured to analyze the geometry of each rivet. The head diameter $D$, head depth $h$, and head eccentricity $\varepsilon$ were measured with a digital caliper (tolerance of $\pm$0,02 mm). The head radius of curvature $R$ and the circularity tolerance $\Delta R$ were assessed with a coordinate measuring instrument (Mitutoyo Euro-C 544).

With regard to the upset of the rivet shank, two parameters were investigated by visual inspections. Potential influences of the driving operation on the layout of the specimens were identified. The presence of clearances between the rivet shank and the rim of the rivet hole as well as the surface condition at the head/ply interface were assessed to the naked eye for all rivets of the specimens. The specimens were polished with silicon carbide paper – up to grit 1000.

## 3.2 RESULTS

### GEOMETRY OF THE RIVET HEAD

The experimental results of the geometrical analyses are summarized in table 7-4. Samples were labelled as T-SN-R-HT, where:

- T is the joint type (O: original; R: repaired);
- SN stands for the specimen number;
- R is the number referring to a given rivet within the specimen (rivet 1, 2 or 3);
- HT is the head type (i.e., S: shop head; F: field head).

## FABRICATION OF THE RIVETED SPECIMENS

*The fabrication of the riveted specimens is a delicate step as it has an impact on their structural behaviour. In addition to the expertise and know-how of the riveting gangs who fabricated the specimens, the discussions of chapter 4, section 3.1, were taken into account in an attempt to improve the quality of riveting. In particular, special attention was paid to the heating and driving temperatures.*

- ### JOINT TYPE O

*Joint type O specimens were designed with the idea of replicating historical wrought-iron riveted connections of the end of the 19th century, including the fabrication stage. In addition to the manufacture of the wrought-iron rivets, the company* Topp & Co*, notably its* compagnons du devoir[1]*, made the fabrication of the single and triple riveted joints type O possible.*

*As a reminder, rivet driving consists of three main steps: the plate perforation, rivet heating and the driving operation. The wrought-iron plates were first sized and cut along the grain direction with a hydraulic guillotine[2]. The centre of the rivet holes was precisely localized by slightly chiselling the plates. The hole diameter was defined based on eqn. 2-1 (see CH2, section 2.1). It was set at 11/16 in (ca. 17,5 mm), that is, 1/16 in larger than the 5/8 in shank diameter (16 mm). The plates were perforated in two steps to avoid any damage to the plate material near the edge of the hole on the one hand, and to increase the accuracy of the perforation stage on the other hand. The holes were pre-drilled and the final diameter was obtained by re-drilling the plates with a drill bit of 11/16 in.*

*Second, the wrought-iron rivets could be heated for the driving stage. A traditional forge fed by coke was used to heat the rivets (Fig. 7-5, left). The burning coke was supplied by air through a water-cooled horizontal pipe. Each rivet was heated one by one during a few minutes. As rivet stokers did in the 19th century, the heating temperature and the soaking time were not quantitatively assessed. Rather, the hot rivets were removed from the forge when they had reached a white-hot colour and a glossy/sweaty appearance. The shank end was vertically inserted in the burning coke with the shop head on the top. Consequently, the rivets might not have been perfectly uniformly heated along their length. The calamine was removed from the outer surface of the rivets to be ready for rivet driving.*

---

*[1] One-year secondments of highly skilled metalworkers from the French craftsman's guild.*

*[2] The surface condition of the wrought-iron plates used for the fabrication of the joints type O was "as manufactured" (i.e., no machining or paint layer).*

*Figure 7-5: Traditional forge heating the wrought-iron rivets (left) and fly press used for rivet manufacture and driving (right)*

*Third, the hot rivets were driven to fabricate the riveted specimens. The protruding shank length needed to properly form the field head was pretested on the first single riveted specimen fabricated (O-1). Being slightly too long, it was reduced to ca. 17,5 mm for all other single and triple riveted specimens. The field head was formed with the help of a fly press, as for rivet manufacture (Fig. 7-5, right)*[3]*. After having inserted the hot rivet in the rivet hole, the shop head was bucked up by a holder-up at the bottom side. The rivet was then driven according to a vertical axis and the field head was formed on the top side. The driving operation consisted of a series of blows – five blows on average – applied by the rivet snap end of the fly press on the protruding shank end of the rivet.*

*The triple riveted specimens were fabricated in the same way as the single riveted specimens. An important heating of the wrought-iron plies of the triple riveted specimens was observed due to heat conductivity induced by the three adjoining rivets that were successively driven. In total, eight single and two triple riveted joints type O were fabricated (Figs. 7-1 & 7-2).*

- ***JOINT TYPE R***

*Techniques used by today's riveting gangs were implemented to fabricate the joint type R specimens. The experienced riveting gang of the Belgian company* Anders Construct bvba *allowed to fabricate these specimens*[4]*.*

[3] *A fly press is a machine press that consists of a screw shaft driven by a bar equipped with a weight at its end. The fly press used by the ironworker of* Topp & Co *was operated by hand.*

[4] *Based in Deinze, Belgium, the company* Anders Construct bvba *is specialized in the construction and renovation of iron and steel structures ("Anders Construct Bvba" 2009).*

*First, the wrought-iron and steel plates were precisely sized and cut*[5]*. Since plate perforation could potentially affect the structural behaviour of the connections, the wrought-iron and steel plates were perforated by* Topp & Co *in the UK according to the same geometry and technique as for the fabrication of the joints type O. The two other steps – rivet heating and driving – were performed in Belgium by* Anders Construct bvba*.*

*Second, the steel rivets were heated in an electric chamber furnace (Küppersbusch – TMH 25/19/40) that enables an accurate setting of the heating temperature (Fig. 7-6, left). The adequate heating temperature was defined based on a trial-and-error approach. Eventually, the heating temperature was set to 1100 °C (2000 °F) for all the specimens. This value arose out of a compromise between avoiding to damage the specimens – plate distortion, overheated rivets – and facilitating the driving operation (satisfactory shape of the field head). Several steel rivets could be simultaneously heated in the electric chamber furnace. Though the device allowed to accurately check the heating temperature, the rivet stoker assessed the heating of the rivets based on their colour and external appearance, as for the joints type O. On average, each rivet was heated during a few minutes.*


*Figure 7-6: Electric chamber furnace heating the steel rivets (left) and riveting set used for rivet driving (right)*

[5] *As for the joints type O, the surface condition of the wrought-iron and steel plates used for the fabrication of the R specimens was "as manufactured".*

*Third, the riveting gang proceeded with rivet driving to fabricate the specimens. The driving operations were conducted in the shop of* Anders Construct bvba*, next to the electric chamber furnace*[6]*. The relatively small proportions of the specimens made their fabrication delicate. While a secure fit of the plies of the triple riveted specimens could be ensured with installation bolts, the layout of the single riveted specimens required another approach (Fig. 7-1). To counteract the vibrations induced by the heavy blows of the riveting machine, the plies of the single riveted specimens were tightened with the help of two vise grips (Fig. 7-6, right). In addition to the heating temperature, the adequate protruding shank length was also pretested. Since the head proportions of the steel rivets were slightly larger than the ones of the wrought-iron rivets, the protruding shank length defined for all the riveted specimens was also larger, that is, an average value of 30,5 mm. The steel rivets were machine-driven with the help of a portable air hammer NISSIN B-90*[7]*. Once the steel rivet was white-hot, it was inserted in the rivet hole and its shop head was bucked up in a rivet snap acting as a holder-up on the bottom side. As for the joints type O, the rivet was driven according to a vertical axis by crushing the top end of the rivet with the air hammer to form the field head (Fig. 7-6, right). For each specimen, the field head has been formed against the steel plate to prevent the wrought-iron plate from any major damages.*

*Given their small proportions, a significant heating of the plies of both the single and triple riveted specimens was observed during – and after – the driving stage, especially in the vicinity of the rivets. In total, eight single riveted and two triple riveted joints type R were fabricated (Figs. 7-1 & 7-2).*

*[6] Shop riveting can be considered as the most optimal and easiest working environment to carry out rivet driving, since neither the weather nor accessibility matters can detrimentally affect the quality of riveting. Hence it may provide better results compared to field riveting.*

*[7] Working at 920 blows per minute, the NISSIN B-90 air hammer (N° A1669) was fed by compressed air at ca. 7 bars.*

Table 7-4: Measurements of the rivet heads of the triple riveted joint types O and R, mean values and standard deviation per specimen[22]

| SPECIMEN | HEAD PROPORTIONS | | HEAD CURVATURE | | HEAD ECCENTRICITY |
|---|---|---|---|---|---|
| | $D$ (mm) | $h$ (mm) | $R$ (mm) | $\Delta R$ (mm) | $\varepsilon/d$ (%) |
| O-1-1-S | 25,9 | 10,8 | 13,3 | 0,3 | / |
| O-1-1-F | 23,7 | 11,3 | 12,4 | 0,3 | 0 |
| O-1-2-S | 25,9 | 10,8 | 13,4 | 0,5 | / |
| O-1-2-F | 25,2 | 11,4 | 13,2 | 0,3 | 3 |
| O-1-3-S | 25,1 | 10,8 | 13,4 | 0,3 | / |
| O-1-3-F | 24,4 | 11,9 | 12,6 | 0,2 | 2 |
| Mean | 25,0 | 11,2 | 13,1 | / | / |
| SD | 0,9 | 0,5 | 0,4 | / | / |
| O-2-1-S | 25,9 | 10,7 | 13,5 | 0,4 | / |
| O-2-1-F | 24,4 | 10,8 | 12,9 | 0,1 | 1 |
| O-2-2-S | 25,8 | 11,1 | 13,7 | 0,2 | / |
| O-2-2-F | 24,4 | 11,2 | 13,0 | 0,5 | 1 |
| O-2-3-S* | 24,8 | 9,8 | 13,5 | 0,5 | / |
| O-2-3-F* | 24,4 | 10,7 | 12,6 | 0,5 | 12 |
| Mean | 25,0 | 10,7 | 13,2 | / | / |
| SD | 0,7 | 0,5 | 0,4 | / | / |
| R-1-1-S | 28,8 | 11,9 | 14,6 | 0,2 | / |
| R-1-1-F | 28,0 | 13,2 | 14,4 | 0,6 | 2 |
| R-1-2-S | 28,2 | 12,0 | 14,6 | 0,3 | / |
| R-1-2-F | 27,6 | 13,3 | 14,5 | 0,3 | 11 |
| R-1-3-S | 28,4 | 12,5 | 14,5 | 0,5 | / |
| R-1-3-F | 27,3 | 12,6 | 14,5 | 0,2 | 5 |
| Mean | 28,1 | 12,6 | 14,5 | / | / |
| SD | 0,5 | 0,6 | 0,1 | / | / |
| R-2-1-S | 28,6 | 11,9 | 14,6 | 0,2 | / |
| R-2-1-F | 26,6 | 13,0 | 13,7 | 0,2 | 17 |
| R-2-2-S | 27,9 | 11,2 | 14,7 | 0,3 | / |
| R-2-2-F | 27,1 | 13,8 | 13,9 | 0,1 | 9 |
| R-2-3-S | 27,8 | 11,6 | 14,3 | 0,2 | / |
| R-2-3-F | 26,9 | 12,4 | 13,7 | 0,2 | 8 |
| Mean | 27,5 | 12,3 | 14,2 | / | / |
| SD | 0,7 | 1,0 | 0,4 | / | / |

[22] Loose rivets are marked with an asterisk (*).

The rivet head proportions of the O-1 and O-2 specimens do not indicate any noticeable difference between the shop head and the field head. For R-1 and R-2, however, a trend can be observed. In the main, the field heads of the R specimens are characterized by a more hemispheric shape compared to the proportions of the shop heads[23], i.e., slightly smaller head diameters $D$ together with higher head depths $h$. Overall, every rivet head has a small circularity tolerance $\Delta R$ (Tab. 7-4).

To analyze and discuss the eccentricity of the field head, the eccentricity measured on the cross section of the machined specimens was expressed as a percentage of the nominal shank diameter $d$. The small $\varepsilon/d$ ratio of the field heads belonging to O-1 and O-2 underlines the almost complete absence of any eccentricity. The high eccentricity of the O-2-3-F rivet head is explained by the presence of defects (badly-driven and loose rivet). The eccentricity of the field heads of R-1 and R-2 is not negligible, especially for R-2-1-F and R-1-2-F (Tab. 7-4).

For both O and R specimens, the field heads are partially unfilled at the interface with the outer ply. In addition, pitting on the shop heads of the R specimens was observed.

#### UPSET OF THE RIVET SHANK

The driving operation can affect the integrity of the riveted connection in fabrication because of the upset of the rivet shank in the rivet hole. After their fabrication, an angular distortion was observed on the R specimens along the longitudinal axis of the plates. This phenomenon was amplified by the heating of the plates induced by the hot rivets. As it was not noticed on the O specimens, this observation may be explained by the driving technique – air hammer – and the riveting set used for the fabrication of the R specimens. The layout of the longitudinal cross section of one O and one R specimen shown on figure 7-7 makes this clear. In addition, some rivet holes were misaligned, regardless of the joint type. Holes misalignment noticed on one – or more – rivet(s) of a given O or R specimen may be attributed to allowable slight inaccuracies in the perforation of the plates.

[23] The slightly larger head proportions of the R specimens in comparison with the O specimens result from different manufacturing processes, namely steel rivets vs. wrought-iron rivets, respectively.

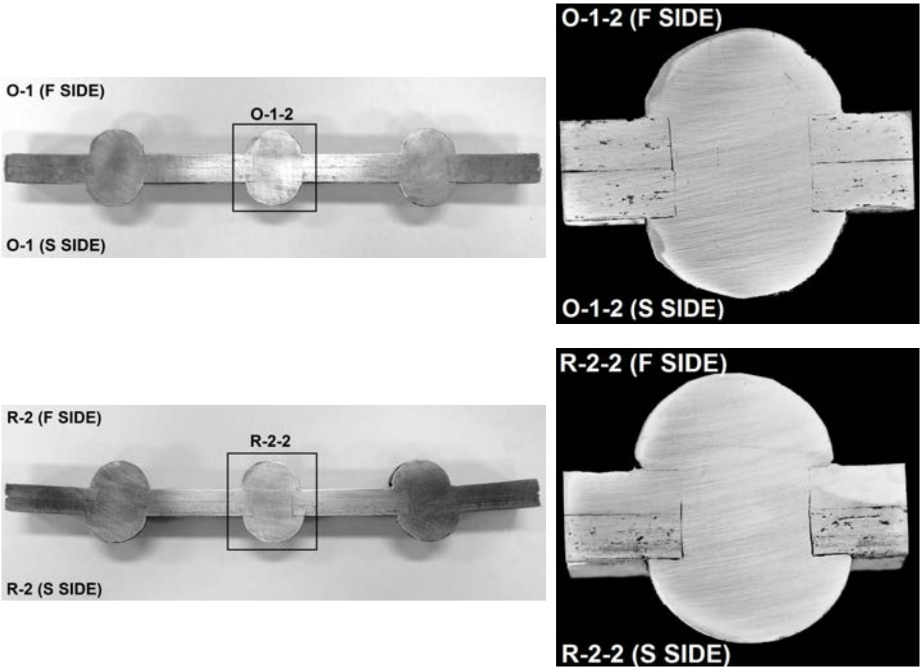



Figure 7-7: Longitudinal cross section of the O-1 specimen (top-left) and R-2 specimen (bottom-left), zoom showing the upset of the O-1-2 rivet shank (top-right) and R-2-2 rivet shank (bottom-right)

Slight non-uniform contact conditions between the rivet and the plies were identified on some rivets of the O and R specimens. Small clearances occurred at two distinctive places within the riveted specimens (Fig. 7-7, right). First, the contact at the interface between the bottom of the shop head and the external surface of the ply showed slight clearances on every rivet of the O and R specimens. Second, clearances were observed between the rivet shank and the rim of the rivet hole along the grip. Though it concerned both O and R specimens, the former were more moderately affected than the latter (Fig. 7-7, right). Clearances were more likely to occur at the level of the ply being against the shop head, particularly for the R specimens (Fig. 7-7, bottom-right). Rivet shanks upset in misaligned rivet holes presented the highest clearances.

## 3.3 ANALYSIS AND DISCUSSION

The partially unfilled field heads of both O and R specimens underline the technical difficulty of rivet driving. Despite the high level of accuracy used to adjust the protruding shank length – the tenth of a millimetre, a uniform and perfect shape of the field head could not be achieved. Slight tolerances in fabrication of the plates combined with unavoidable driving inaccuracies of the riveters might have caused this defect. All in all, the results showed an average lower quality of riveting for the R

specimens (Tab. 7-4). For instance, the eccentricity of their field heads is markedly higher. The proportions of the field heads of the R specimens differ from the ones of the shop heads as the geometry of the rivet snaps used for rivet manufacture and driving was not exactly the same.

The difference in quality of riveting between the O and R specimens may be attributed to the riveting technology on the one hand, and the intervention of the riveting gang on the other hand. Paradoxically, defining the adequate heating temperature of the rivets turned out to be more difficult with the electric chamber furnace (R specimens) in comparison with the traditional forge (O specimens)[24]. The presence of pitting on the shop heads of the R specimens testifies to the delicate compromise that arose between the improvement of the field head shape and the limitation of the heating temperature of the rivets[25]. With regard to the driving operation, the working of the machine tools handled by the riveters introduced differentiated conditions in execution. The heavy blows generated by the percussions of the air hammer driving the steel rivets of R specimens was more delicate to handle than the fly press used for the O specimens. Though the mechanization of the riveting technology allowed to reduce the labour cost and speed up the job, it did not, however, necessarily ease the implementation of rivet driving.

The visual inspections of the upset of the rivet shank revealed the presence of clearances on one – or more – rivet(s) of the specimens. All in all, the magnitude of the clearances was limited, as it could be expected given the small grip length. The fact that the clearances between the rivet shank and the rim of the rivet hole were larger near the shop head side validates the analyses conducted in chapter 6 [26]. Though slightly more pronounced on some rivets of the R specimens, clearances were noticed on both joint types O and R. As a consequence, no relationship can be established between the uniformity of the upset of the shank in the rivet hole along the grip and the type of riveting machine used to drive rivets. This observation confirms the findings derived from the experimental investigations conducted by Frémont (1906) or Cox and Munse (1952) for instance (Frémont 1906, 58,66; Cox and Munse 1952, 7). More fundamentally, it indicates that other parameters – next to the grip length – more predominantly affect the shank upset during the driving operation, for example: the secure bucking up of the shop head against the ply, the driving temperature of the rivet, the ability of the riveter, etc.

[24] See enclosed notice on the fabrication of the specimens.

[25] The defective characteristic of overheated or burned rivets is not new, as it was sometimes common practice at the time (see CH2, section 2.2).

[26] Actually, the values of the diameter $d$ measured along the shank progressively decreased away from the field head side, as a result of the shank upset induced by rivet driving. See CH6, section 3.2.1.

Results showed that holes misalignment is a contributing factor towards the presence and magnitude of clearances.

# 4 LAP SHEAR TEST CAMPAIGN

Lap shear tests are performed on the fabricated single riveted specimens. The test results of the joint types O and R are first assessed separately. The shear behaviour of the joints type O is discussed and compared with historical test data. Then, the influence of remedial works is investigated by confronting the results of joint types O and R with each other.

The shear behaviour of each specimen is assessed by means of three parameters. The two first ones are the ultimate shear load $F_{s,u}$ and elongation at failure $u_u$. The failure mode – type and location of the failure – is the third parameter analyzed.

The lap shear test campaign aims to answer the following questions:

- How do wrought-iron single riveted single lap joints behave in shear and what is the scatter of the results?
- Do the results (in)validate the findings of the test campaigns conducted in the 19th century?
- Does the quality of riveting affect the structural behaviour of the connections?
- How do remedial works affect the shear behaviour of wrought-iron riveted connections?

## 4.1 EXPERIMENTAL SET-UP AND INVESTIGATED PARAMETERS

The lap shear test campaign involves the same experimental set-up for both joint types O and R (Fig. 7-8, left). The experiments were performed with an electromechanical universal testing machine Instron® 5585 having a load cell of 200 kN (Fig. 7-8, right).

The test fixtures consisted of hydraulic grips located on both the movable cross head and the stationary cross head (Fig. 7-8, right). Scraps salvaged from wrought-iron and steel plates acted as calibration blocks to ensure the alignment of the specimen inside the testing machine (Fig. 7-9). A clamping pressure of ca. 300 bar was applied on the hydraulic grips to fix both ends of each specimen. The displacement speed of the movable cross head was set at 0,5 mm/min. An acquisition frequency of 2 Hz was assumed.


Figure 7-8: Joints type O (top-left) and joints type R (bottom-left), and set-up into the Instron® 5585 testing machine (right)

The tensile load $F$ applied on each specimen as well as the displacement $u$ of the movable cross head were recorded every 0,5 s. The failure modes were assessed by visual inspections.

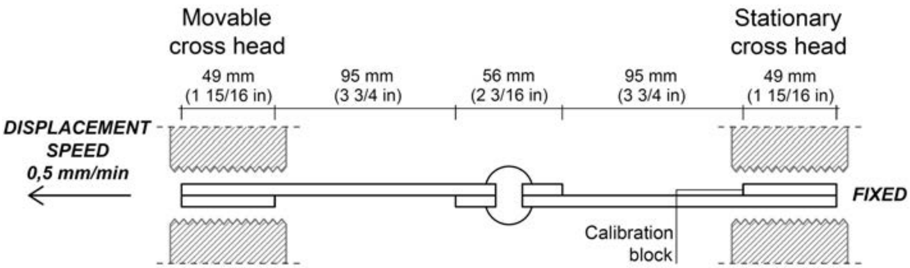



Figure 7-9: Set-up and boundary conditions of the tested specimens

Each lap shear test was launched after having first tared the initial load and displacement resulting from the fixtures stage. The Bluehill® software by Instron® suited for static testing was used for data collection. The displacement of the movable cross head could be verified by means of images acquisition of the specimens during the tests (one image every 5 s). The out-of-plane displacements measured near the grips were considered as negligible compared to the elongation of the tested specimens (Fig. 7-1).

## 4.2 RESULTS

Table 7-5 provides the ultimate shear load $F_{s,u}$ and elongation $u_u$ of each specimen at failure[27], together with the mean values and scatter of the results per joint type. The corresponding primary failure mode and location of the failure are also given. Two kinds of failure modes were observed: plate tension (T) and plate bearing (B). The column header "Failure location" provides the location where the failure occurred, that is, the plate either on the shop head or field head side (Tab. 7-5).

Table 7-5: Ultimate shear behaviour and primary failure mode of the O and R specimens

| **SPECIMEN** | **ULTIMATE SHEAR BEHAVIOUR** | | **PRIMARY FAILURE MODE** | | |
|---|---|---|---|---|---|
| | $F_{s,u}$ (kN) | $u_u$ (mm) | **TYPE** (/) | **FAILURE LOCATION** | |
| | | | | **SHOP HEAD SIDE** (/) | **FIELD HEAD SIDE** (/) |
| O-1 | 50,50 | 4,46 | T | **x** | |
| O-2 | 45,24 | 3,28 | T | **x** | |
| O-3 | 33,80 | 2,13 | T | | **x** |
| O-4 | 44,67 | 3,73 | T | **x** | |
| O-5 | 45,02 | 3,62 | T | **x** | |
| O-6 | 47,32 | 3,89 | T | | **x** |
| O-7 | 51,78 | 4,88 | T | **x** | |
| O-8 | 51,78 | 5,43 | T | | **x** |
| Range | 33,80 - 51,78 | 2,13 - 5,43 | / | / | / |
| **Mean** | **46,26** | **3,93** | / | / | / |
| SD | 5,86 | 1,02 | / | / | / |
| R-1 | 66,10 | 3,53 | T | **x** | |
| R-2 | 64,91 | 3,21 | T | **x** | |
| R-3 | 67,62 | 5,19 | T | **x** | |
| R-4 | 59,20 | 2,59 | T | **x** | |
| R-5 | 67,60 | 3,93 | T | **x** | |
| R-6 | 67,15 | 4,14 | T | **x** | |
| R-7 | 65,81 | 3,79 | T | **x** | |
| R-8 | 68,18 | 3,59 | B | **x** | |
| Range | 59,20 - 68,18 | 2,59 - 5,19 | / | / | / |
| **Mean** | **65,82** | **3,75** | / | / | / |
| SD | 2,89 | 0,75 | / | / | / |

[27] Since the point of view of the analyses concerns the riveted specimens themselves, the two parameters initially recorded by the testing machine – the tensile load $F$ applied on the specimen and the displacement $u$ of the movable machine's cross head – are substituted with the shear load $F_s$ and elongation $u$ of the specimen from now on, respectively.

The load-elongation curves of the O and R specimens are plotted on figure 7-10.

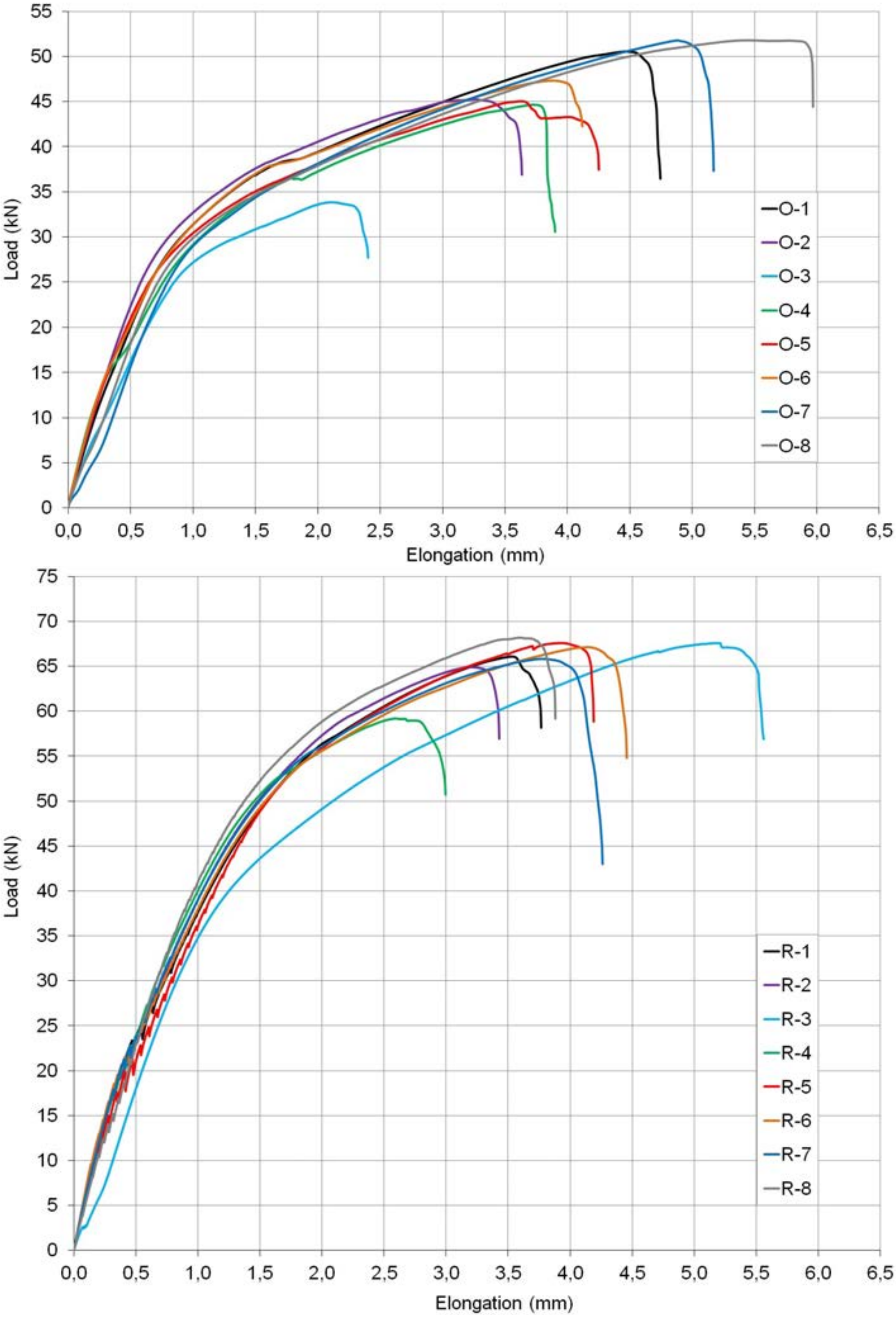



Figure 7-10: Set of load-elongation curves of the O specimens (top) and R specimens (bottom)

#### 4.2.1 O SPECIMENS

At ultimate, the O specimens failed at a mean shear load $F_{s,u}$ of 46,26 kN and elongation $u_u$ of 3,93 mm (Tab. 7-5).

Each O specimen collapsed according to the same primary failure mode, which is plate tension (failure mode T) (Fig. 7-11, left). Despite the almost instantaneous crack propagation, a visual inspection of the fracture surface seems to reveal that the crack initiated at the level of the rim of the rivet hole. For all O specimens, the crack developed only along one edge distance, towards the inner part of the plate rather than in the rivet lap side (Fig. 7-11, left). The failure was located in the wrought-iron plate on the shop head side for five of the eight specimens while the three other specimens consequently failed on the field head side (Tab. 7-5).

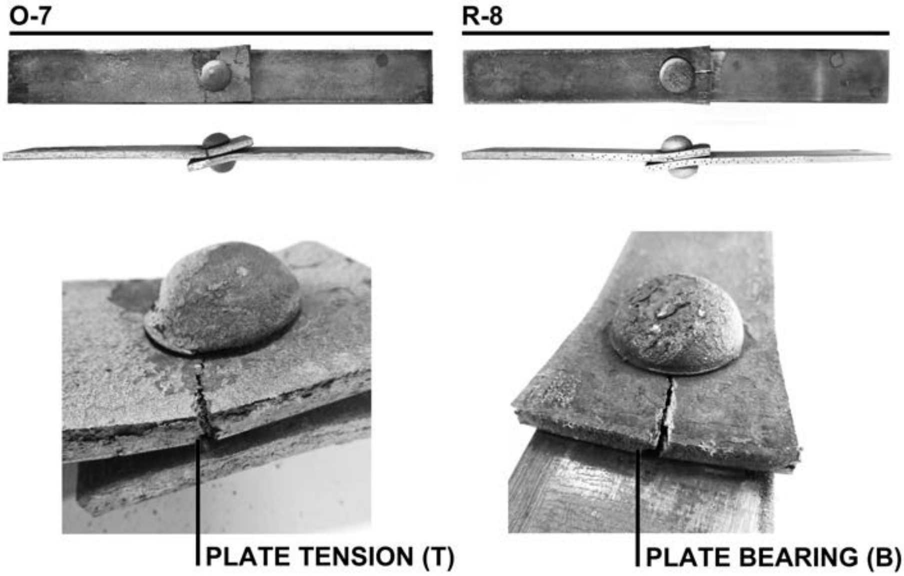



Figure 7-11: The primary failure mode of all the O and R specimens was plate tension (T) (e.g., specimen O-7, left) except the specimen R-8 that failed in bearing (right)

#### 4.2.2 R SPECIMENS

The R specimens failed at a mean shear load $F_{s,u}$ of 65,82 kN and elongation $u_u$ of 3,75 mm (Tab. 7-5). Unlike the O specimens, the behaviour underlines the presence of a stage having "sawtooth discontinuities", in the vicinity of the shear load and elongation values of ca. 22,5 kN and 0,5 mm, respectively (Fig. 7-10, bottom). The length of this stage as well as the average height of the discontinuities vary considerably from one specimen to another.

A tensile failure of one plate net cross section (T) conditioned the ultimate shear behaviour of all the R specimens, except one, which is R-8 (Tab. 7-5). For all specimens, the plate on the shop head side made of wrought iron expectably failed, regardless of the failure mode[28]. With regard to the seven specimens that collapsed in tension (T), the crack developed along one edge distance towards the inner part of the wrought-iron plate, similarly to the O specimens (Fig. 7-11, left). The bearing strength of the wrought-iron plate was responsible for the collapse of R-8 (failure mode B, Tab. 7-5). A crack developed towards the rivet lap of the wrought-iron plate before any major hole distortion could be noticed to the naked eye (Fig. 7-11, right).

## 4.3 ANALYSIS AND DISCUSSION

To answer the questions formulated at the beginning of the chapter, the results of the lap shear test campaign are discussed through three distinctive sections. The shear behaviour of the O and R specimens is separately addressed in the two first sections (4.3.1 and 4.3.2), to be then confronted with each other in the third section (4.3.3).

### 4.3.1 O SPECIMENS

#### SHEAR BEHAVIOUR AND FAILURE MODE

The shear behaviour of the O specimens follows the same trend, except for O-3 that is the weakest specimen (Fig. 7-10, top). The specimens were slip-resistant until their frictional strength was overcome. Since no visible slipping was observed for increasing shear loads, a smooth transition occurred from the friction-type to the bearing-type behaviour of the specimens. The small magnitude of the clearances between the shanks and the rivet holes discussed in section 3.3 corroborates this observation. Actually, the wrought-iron plates were almost brought – physically – into direct bearing against the rivet shank after the fabrication stage of the specimens (Fig. 7-7).

By visual inspection, the geometry of the wrought-iron rivet shank seems to have been moderately affected by the shear test. Hence, the UTS of the wrought-iron plate net section that failed may have been significantly lower than the USS of the driven wrought-iron rivet. This brings us back to the design of the riveted specimens made in accordance with the analytical methods of the turn of the 20th century (section 2.1). According to these methods, the rivets pattern and spacing issued from the assumption of the uniform distribution of stresses between the rivets in shear and the plates in tension, considering a $R_s/R_t$ ratio of one[29]. Similar ultimate strengths were

[28] The field head was formed against the steel plate for each R specimen (see enclosed notice on the fabrication of the specimens).

[29] See CH5, section 4.3.

clearly not experimentally verified, given the recurring failure mode (T). As noticed in chapter 5, the fact that the nominal shank diameter $d$ characterized the theoretical rivet's shear capacity caused significant errors within the calculations. Actually, since the rivet hole diameter $d_{hole}$ conditioned the actual geometry of the connection, it led to an overestimation of the plate net section – 6% in the present case – together with an major under-estimation of the rivet shear plane area – 19% in the present case. Hence, the conducted experiments confirm the lower load-carrying capacity of the connected plates compared to the rivets, as a result of the design philosophy of turn-of-the-20th-century analytical methods.

The tensile failure mechanism T was the primary failure mode of the O specimens (Tab. 7-5). In addition, a secondary failure mode of moderate influence could be identified, which is plate bearing (B). Mixed failure modes had to be expected given the asymmetric joining typology of the fabricated specimens. The machined longitudinal cross section of the failed O-1 and O-6 specimens is shown on figure 7-12. Plate bearing is evidenced by the deformation of the rivet hole showing major clearances between the rim of the hole and the rivet shank (Fig. 7-12).

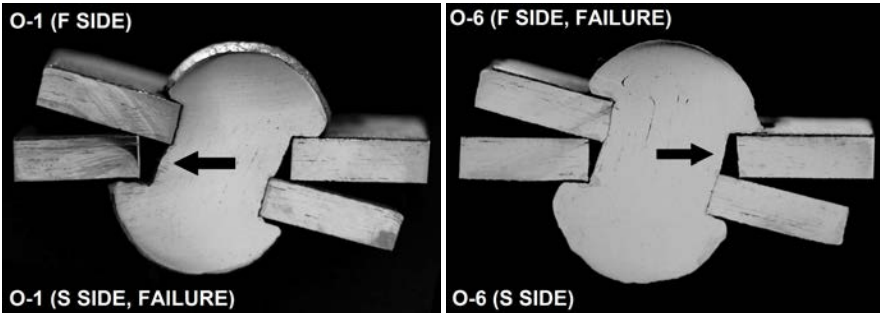



Figure 7-12: The plate responsible for the failure of the O specimens shows larger deformations

For every O specimen, the crack developed along one edge distance towards the inner part of the plate, as noticed in section 4.2.1. This location concurs with the part of the wrought-iron plate that was subjected to the most important deformations. Expectably, the plate showing the largest hole deformation is the one that failed in tension. This corresponds to the plate on the shop head side for O-1 and on the field head side for O-6 (Fig. 7-12, Tab. 7-5). Therefore, differences in the wrought-iron plates material properties – in particular their ductility – may account for the fact that the tensile failure took place either on the shop or field head side.

### INFLUENTIAL PARAMETERS

The effect of the materials and quality of riveting on the ultimate shear behaviour of the O specimens is analyzed below:

- **Effect of material inhomogeneities**. The material properties of both plate and rivet irons are characterized by a non-negligible scatter of the results, especially in elongation at failure (section 2.2). Such variations thus account for the scatter of the results of the shear tests summarized in table 7-5.
- **Effect of quality of riveting**. The quality of riveting of the single riveted specimens could not be destructively appraised as their integrity had to be preserved for the shear tests. However, some aspects could be assessed prior to the tests without damaging the specimens. For instance, the fabrication stage slightly distorted the specimens. These distortions do not impact the shear behaviour, provided that they remain limited. In addition, visible defects could be identified. No trend can be established between any – or a combination – of these visible defects and the ultimate shear behaviour. Neither the field head eccentricity $\varepsilon/d$, nor its unsymmetrical shape, nor the camming effect has any noticeable influence on the shear behaviour of the O specimens.

To sum up, the strength and ductility of the wrought-iron rivets and plates expectably determined the ultimate shear behaviour of the specimens. In particular, the weaker mechanical properties of the plates conditioned the failure of the specimens. The quality of riveting might not affect the ultimate behaviour for defects of limited magnitude.

### HISTORICAL LITERATURE

Table 7-6 summarizes the results of shear tests performed by Greig & Eyth and Stoney on wrought-iron single lap joints[30] that failed in tension (T). The wrought-iron plates were perforated according to the drilling technique. The values of UTS plate net section $f_t$ were expressed in tons per square inch. In addition, Twelvetrees recommended to safely consider the mean value of 19,00 t/in$^2$ (ca. 262 MPa) (Tab. 7-6). (Twelvetrees 1900, 109–11)

[30] The results relate to the overall typology of single lap joints. However, the comparison of the results may involve single lap joints that can be either single riveted or multiple riveted. In addition, it is obvious that their geometry vary as well (plate thickness, shank diameter). Since all the tested specimens failed in tension, we assume that those differences in joining typology and geometry can be neglected for the discussions.

Table 7-6: The UTS plate net section and joint efficiency of the O specimens closely match the results of end-of-the-19th-century experiments

| LAP SHEAR TESTS | DATE | ULTIMATE TENSILE STRENGTH | | JOINT |
|---|---|---|---|---|
| | | PLATE NET SECTION $f_t$ (MPa) | PLATE MATERIAL (MPa) | EFFICIENCY (%) |
| Greig D. & Eyth M. | 1879 | 272 (19,75 t/in$^2$) | 306 (22,20 t/in$^2$) | 89 |
| Stoney BB. | 1885 | 267 (19,39 t/in$^2$) | 302 (21,90 t/in$^2$) | 89 |
| Twelvetrees WN. | 1900 | 262 (19,00 t/in$^2$) | / | / |
| O specimens | 2014 | 263 | 317 | 83 |

The close match between 19th-century experiments and the ones of the O specimens is striking (Tab. 7-6)[31]. Both the genuine wrought-iron connections and the fabricated riveted specimens have a similar UTS plate net section $f_t$, despite the different testing equipment.

The joint efficiency of the O specimens averages the value of 83% (Tab. 7-6)[32]. This value is very close to the 89% joint efficiencies calculated by Greig & Eyth and Stoney in 1879 and 1885, respectively.

As a result, the lap shear test campaign performed on the O specimens allows to validate, to some extent though, the accuracy and representativeness of the data output reported by acknowledged 19th-century engineers on the shear behaviour of wrought-iron single lap joints.

### 4.3.2 R SPECIMENS

SHEAR BEHAVIOUR AND FAILURE MODE

In the main, the overall shear behaviour of the R specimens follows a similar trend (Fig. 7-10, bottom). Unlike the O specimens, the shear behaviour presents "sawtooth discontinuities". This stage seems to reflect the stepwise loss of frictional strength of the specimens for increasing shear loads. These discontinuities give evidence of successive micro-slips of the connected plates. This observation can be explained by the higher inner clamping force induced by the air hammer and the somewhat larger magnitude of the clearances observed in section 3.2 between the shanks and the rivet holes. R-3 stands out of the pool of specimens. It has the highest elongation at failure and its behaviour does not present any "sawtooth discontinuities".

[31] The parameter $f_t$ was calculated based on the mean value of $F_{s,u}$ (46,26 kN, Tab. 7-5) and the plate gross section reduced by the rivet hole area (176 mm$^2$). Here the nominal shank diameter was taken into account (16 mm) in order to keep to the historical design methods. The UTS plate material corresponds to the mean UTS of the plate iron tested (Tab. 7-2).

[32] See CH4, section 3.2, $G/d$ ratio, for a reminder of the notion of joint efficiency.

The wrought-iron plate conditioned the ultimate state of every R specimen, regardless of the failure mode that occurred (Tab. 7-5). Apart from R-8, the specimens failed according to the same mechanism as for the O specimens: primary failure mode of plate tension (T) combined with plate bearing (B). The lower UBS of the wrought-iron plate is evidenced by the major clearances observed between the steel rivet shank and the rim of the wrought-iron rivet hole (Fig. 7-13). The higher stiffness of the R specimens provided by the use of modern steel materials and the air hammer permitted to positively limit the magnitude of the out-of-plane displacements of the specimens (Fig. 7-13).

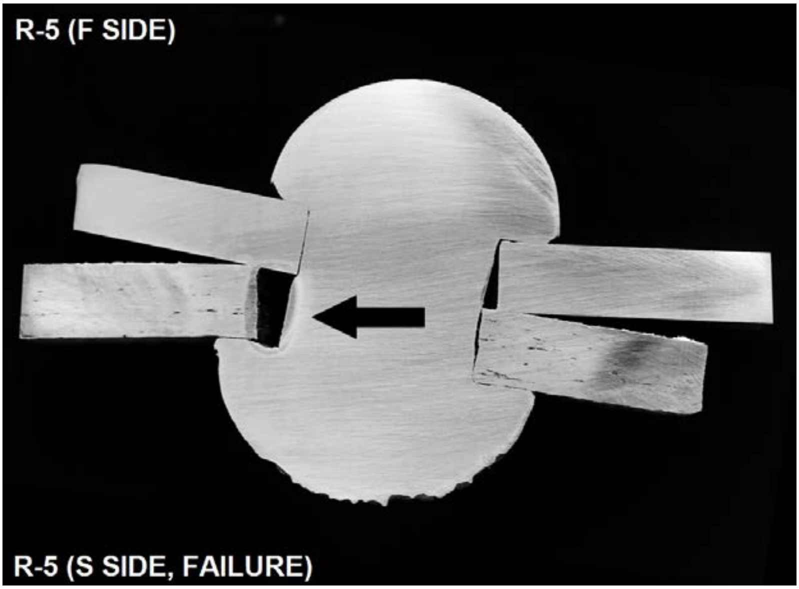



Figure 7-13: The modern steel materials and the air hammer limited the magnitude of the out-of-plane displacements of the R specimens

The UBS of the wrought-iron plate lap $f_b$ conditioned the failure of the R-8 specimen (failure mode B, Tab. 7-5). The parameter $f_b$ was thus exceeded as a result of the bearing pressure exerted by the steel rivet shank on the rim of the wrought-iron rivet hole. Hence, the UBS of the wrought-iron plate lap $f_b$ was lower than its UTS plate net section $f_t$. This observation may reveal the higher UTS of the plate iron from which it originate compared to the other R specimens, since R-8 is the strongest specimen within the pool of R specimens (Tab. 7-5, Fig. 7-10, bottom).

INFLUENTIAL PARAMETERS

The effect of the materials and quality of riveting on the ultimate shear behaviour of the R specimens is analyzed below:

- **Effect of material inhomogeneities**. The scatter of the results regarding both the ultimate shear load $F_{s,u}$ and elongation at failure $u_u$ issue from the material inhomogeneities of the wrought-iron plate. The steel materials, combined with the effect of the air hammer, positively influence the net efficiency of the R specimens that is equalled to 118% (Tabs. 7-5 & 7-6). This observation confirms the discussions of chapter 4, section 2.2.1. In addition, it corroborates the findings of Schenker et al. (1954) on steel riveted connections having small $G/d$ ratios, recently confirmed by D'Aniello et al. (2011), but here however for repaired riveted connections combining wrought-iron and steel materials.
- **Effect of quality of riveting**. No relationship can be established between the quality of riveting and the ultimate shear behaviour of the R specimens. Neither the distortions resulting from the fabrication stage nor the defects identified affect the shear behaviour of the R specimens. Actually, some R specimens showing a very pronounced field head eccentricity $\varepsilon/d$ behaved quite well in shear[33].

To sum up, the steel materials contributed to smooth the shear behaviour of wrought-iron riveted specimens. In particular, the scatter of the results linked to the ultimate shear load was significantly reduced. The ductility of the remaining wrought-iron plate proved to be a key parameter. While the quality of riveting might not influence the shear behaviour, the subject is of concern as it conditions the sustainability of repaired riveted connections (e.g., head corrosion, pack rust).

### 4.3.3 FROM O TO R, INFLUENCE OF REMEDIAL WORKS

The ranges of load-elongation curves of the O and R specimens are depicted on the area chart of Figure 7-14[34]. The remedial works virtually conducted on the O specimens and embodied by the R specimens improved the shear behaviour markedly. The repair intervention involving one steel plate and rivet increased the ultimate shear load $F_{s,u}$ by ca. 40% (Fig. 7-14).

The significant positive influence of the repair may result from the use of modern steel materials combined with a higher frictional strength of the R specimens. The higher mechanical properties of the steel plate and rivet permitted to limit the deformation of the specimens (i.e., plate bending, out-of-plane displacements). The

[33] E.g., field head eccentricity of 22% for R-5 and 20% for R-8.

[34] The rough area between the upper- and lower-bound plotted lines of the original and repaired specimens represents the range in which all the load-elongation curves are included. The last figures of each lines plotted onto the chart correspond to the behaviour at ultimate ($F_{s,u}$; $u_u$).

frictional strength depends mainly on the amount of clamping force applied by the rivets heads on the plates tightened to one another. The magnitude of the longitudinal shrinkage of the rivet shank while cooling is restrained by the fit of the plates it connects. Driving a rivet with an air hammer ensures a tighter fit given the important pressure and heavy blows exerted by the air hammer. The stage with "sawtooth discontinuities" observed for the R specimens gave evidence of a higher shear load required to fully cancel their frictional strength (Fig. 7-10, bottom). Hence, the use of modern steel materials combined with the higher prestress state provided by the repair intervention relieved, in a sense, the specimens and postponed their yielding.

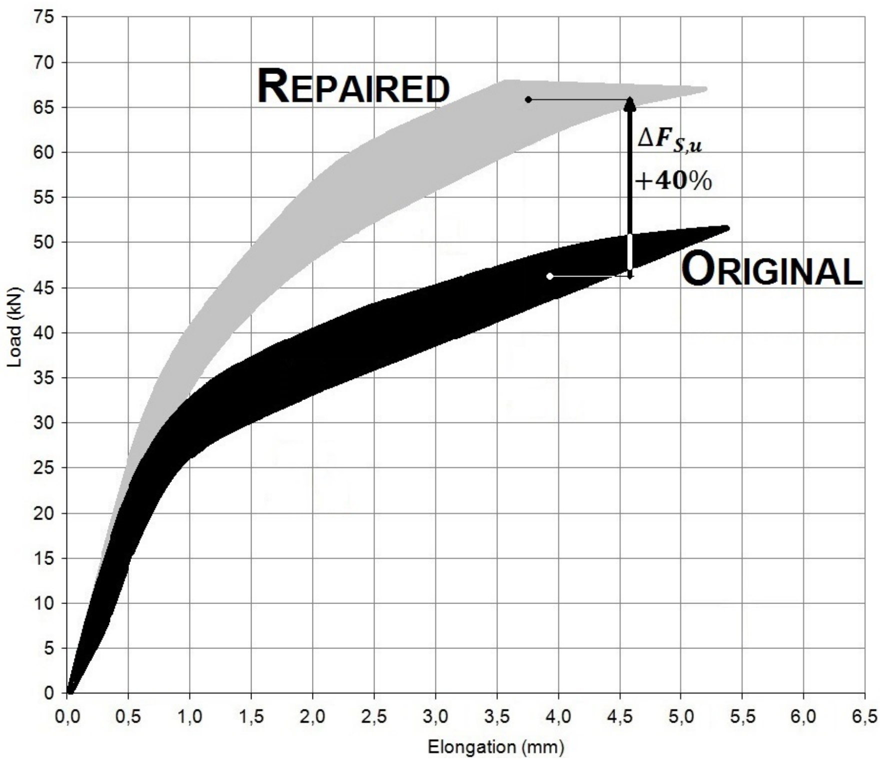



Figure 7-14: The repair intervention significantly increased the ultimate shear load ($\Delta F_{s,u}$ of ca. 40%)

## 5 CONCLUSIONS – STRENGTHENED SHEAR CAPACITY

The shear behaviour of single riveted single lap joints was assessed by means of experiments. It aimed to provide insights into the shear behaviour of wrought-iron riveted connections and to analyze the influence of remedial works. The riveted specimens were designed and fabricated in accordance with the historical design methods and techniques of the end of the 19th century.

The shear tests performed on the original specimens fabricated revealed an important scatter of the results in ultimate shear load and even more in elongation at failure. The UTS plate net section was the predominant criterion as every specimen failed in tension. The UTS plate net section and joint efficiency of the tested specimens closely match the results of 19th-century shear tests. This may underline the accuracy of the shear tests conducted by 19th-century engineers who markedly influenced the theory and design of riveted connections. In addition, the recurrent failure mode of plate tension confirmed the theoretical inconsistencies inherent to the analytical design methods of the turn of the 20th century. An under-estimation of the actual shank diameter and USS of the rivet shank might explain the recurrent tensile failure of the wrought-iron plate net section.

For both original and repaired specimens, the quality of riveting did not seem to affect their shear behaviour. In any case, remedial works involving the hot-riveting technique must ensure a sufficient quality of riveting since it can have a negative influence on the sustainability of the connections. Regarding the upset of the rivet shank, the investigations revealed that actual renovation techniques may not – even for short grips – systematically provide better results, despite the higher pressure applied by the riveting machine. In particular, the clearances noticed between the shank and the rim of the rivet hole were amplified by holes misalignment. Though holes misalignment may not negatively impact the static shear behaviour of the connections, it is a sensitive factor for load-bearing structures subjected to cyclical loadings.

The virtually conducted remedial works significantly improved the shear behaviour of the original specimens at ultimate, especially in terms of shear load. The repair intervention involving one steel plate and rivet increased the ultimate shear load by ca. 40%. The phenomenon may issue from the steel materials and driving technique used (i.e., portable air hammer). As a consequence, local repair interventions of the connections of wrought-iron riveted structures may modify their overall structural behaviour. Unpredictable stress redistribution phenomena would be likely to occur within the structure in question.

The research approach developed in this chapter took advantage of the analyses conducted in the six previous chapters by covering all the main topics to which this study is dedicated. Indirectly, the experience gained in the field of the riveting technology allowed to emphasize on parameters and phenomena on which peculiar attention should be paid when renovating historical riveted connections. In this context, the next chapter – CH8 – valorizes the key findings revealed by the study so far to suggest assessment tools and intervention recommendations.

# CHAPTER 8

# ASSESSMENT TOOLS AND INTERVENTION RECOMMENDATIONS

**Based on the results gathered from Part I, Part II and Part III, chapter 8 provides a selective list of assessment tools and intervention recommendations. The tools and recommendations aim to support practicing engineers, architects and historic preservationists for the structural assessment and intervention strategy of riveted connections. The discussions emphasize on parameters and phenomena on which more attention should be paid.**

**Chapter 8 aims to answer the following questions:**

*How to assess the structural integrity of historical riveted connections?*

*Which parameters are helpful?*

*Which renovation practices and techniques are used today? Which recommendations can be made?*

The technology and design of historical riveted connections between the 1840s and 1940s were revealed by the analyses described in previous chapters. The investigations were conducted within the framework of a multidisciplinary approach belonging to the fields of structural engineering and heritage preservation. They allowed to pinpoint parameters that can impact on the structural behaviour of riveted connections. Some of them also relate to the intervention strategies applied on these connections – repair, replacement, strengthening. These considerations bring us back to the overall appraisal procedure addressed in the introduction of the study and reminded below (Fig. 8-1):

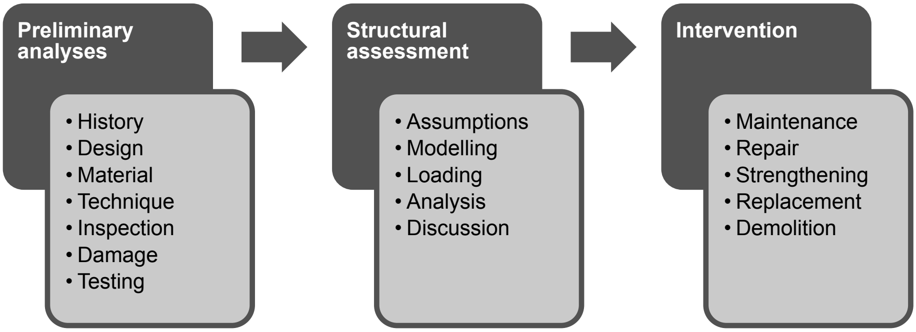



Figure 8-1: Typical appraisal procedures of historical riveted structures primarily follow three steps

From preliminary analyses of existing structures to the intervention itself, numerous steps have to be taken when assessing the structural integrity of riveted connections. In addition to available literature (SB 2007a; SB 2007b; SB 2007c; Kühn et al. 2008; Tilly et al. 2008), this chapter support the appraisal procedures of historical riveted connections. It suggests a non-exhaustive list of assessment tools and intervention recommendations. These tools and recommendations are devoted to advise practicing engineers, architects and historic preservationists on both theoretical and practical issues inherent to the topic. This approach contributes to the preservation of our built heritage by stimulating adequate and less intrusive remedial works.

The recommendations deal with the preliminary analyses conducted prior to any structural assessment as well as the intervention strategy itself (Fig. 8-1). The tools related to the preliminary analyses take advantage of a selection of parameters that are relevant for a structural assessment. Among others, they provide qualitative and quantitative information on the geometry, the load-bearing capacity, the stiffness and the sustainability of riveted connections. Concerning the intervention, the recommendations review a selection of actual renovations practices and propose potential ways to improve them.

The discussions rely on the results gathered from the analyses, literature reviews and experiments performed so far, complemented with conversations with experienced

riveters and steel construction companies. The tools and recommendations are presented in the form of tables, timelines and guidelines depending on the topic broached. The way to use them is explained too. The reader can also cross information from multiple tools to hone his/her judgment. Their limitation(s) are mentioned when applicable. The discussions relate to the hot-riveting technique and scope out the subjects addressed throughout the study so far.

# 1 PRELIMINARY ANALYSES

The structural assessment of historical riveted connections is supported by the results derived from preliminary analyses (Fig. 8-1). The state of the connection, its potential damage(s), can be revealed by on-site inspections. A careful appraisal is required since different materials and techniques – e.g., wrought iron and steel, hand and machine riveting – could be combined within a given riveted connection. In addition, it is important to determine whether the connection was made in the shop or on the job site. The geometry and strength of the connection have to be investigated. In particular, the hole diameter and UTS of the *driven* rivet are two parameters needed when assessing the structural safety of existing riveted connections (EC 2005, 27).

## 1.1 DAMAGES

On-site inspections belong to the pool of the preliminary analyses that are conducted within the appraisal procedure (Fig. 8-1). They permit to identify potential or presumed damages that condition the intervention strategy and its scope – i.e., maintenance, repair, strengthening, replacement. This allows to appraise the structural integrity of the connections that is linked to their quality of riveting. The quality of riveting is influenced by a large number of parameters, for example: rivet manufacture and driving, the ability and commitment of the riveting gang, working conditions (shop vs. job site), service life, environmental effects, etc.

Damages can affect the plates and the rivets of a connection. Defective plate and rivet characteristics can be either visible or invisible to the naked eye. Visible defects such as missing rivets, sheared off rivet heads and irregular head forms can be easily revealed. Conversely, invisible defects are more difficult to assess and generally require destructive testing methods. The understanding of the origin(s) of these damages and their potential influence on the structural behaviour of the connections can be a delicate task. Is a defect caused by fabrication errors or service life – e.g., corrosion? What does the presence of a lip around a rivet head mean? A number of questions arise but their answers are not systematically found. In the same idea, the identification of structural rivets is not always straightforward when inspecting riveted

connections on site. For instance, while some rivets are ornamental, others can be camouflaged bolts called ***faux rivets***[1].

The two assessment tools given below provide non-exhaustive lists of visible and invisible defective plate and rivet characteristics (Tabs. 8-1 & 8-2). These illustrated tools can help practicing engineers link a given visible defect to its origin(s) and influence(s) on the structural behaviour, but also strengthen their awareness of invisible defects. The defects mentioned in bolt are briefly described in footnote and further discussed in the translation dictionary and glossary closing the study.

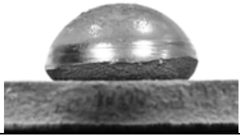
### 1.1.1 VISIBLE DEFECTS

Table 8-1 suggests a non-exhaustive list of rivet defects that are visible to the naked eye.

Table 8-1: Visible defective plate and rivet characteristics

| DEFECT | ORIGIN(S) | INFLUENCE(S) / POTENTIAL FAILURE |
|---|---|---|
| EXCESSIVE $d/e$ RATIO  (SB 2007b, 72, defect 11) | Inappropriate design choice; Rationalization of the different used shank diameters | Crushing of the grip |
| BADLY SHAPED RIVET HEAD  | Manufacturing or driving imperfections | Decrease in UTS of the head / Rivet head popped off |
| PITTING ON THE RIVET HEAD  | Overheated/burned rivet | Rivet brittleness |

[1] A *faux rivet* is a bolt where the head has the form of a round rivet head. See the translation dictionary and glossary for more information.

| | | |
|---|---|---|
| UNFILLED RIVET HEAD[2]<br> | Driving temperature too low;<br>Protruding shank length too short | Reduced clamping force & frictional strength<br><br>/ Rivet head popped off |
| UNSYMMETRICAL HEAD<br><br>(Vermes 2007, fig. A–1) | Driving error of the riveter;<br>Holder-up diameter too small | / |
| LIP AROUND THE RIVET HEAD (BURR)<br> | Excessive shank length;<br>Snap diameter too small | Insufficient upset of the shank (for lips too large) |
| LOOSE RIVETS<br> | Improperly tightened plates before riveting | Movement of the rivet;<br>No frictional strength |
| RIVET HEAD DEGRADATION<br>(SB 2007b, 72) | Rivet corrosion | Reduced clamping force & frictional strength<br><br>/ Rivet head popped off |
| **PACK RUST**[3]<br>(Heinemeyer and Feldmann 2011, fig. 5) | Insufficient tight connection;<br>Inadequate maintenance;<br>Exposure to water/moisture | Shank failure (bursting pressure)<br><br>/ Rivet head popped off |

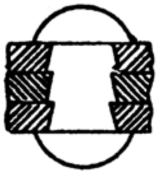
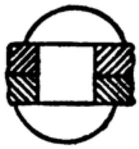
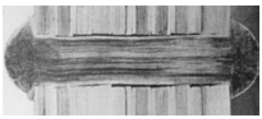
[2] Field head generally.

[3] Interfacial corrosion between the plies.

### 1.1.2 Invisible defects

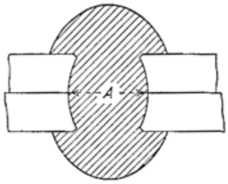
A non-exhaustive list of invisible plate and rivet defects is given in table 8-2.

Table 8-2: Invisible defective plate and rivet characteristics

| Defect | Origin(s) | Influence(s) / potential failure |
|---|---|---|
| Strain hardened edge of the plate (rivet hole)<br><br>(Twelvetrees 1900, fig. 41) | Punched rivet hole (without reaming/re-drilling) | Plate brittleness<br><br>/ Microcracks in plate (fatigue crack initiation) |
| Head eccentricity[4]<br><br>(Twelvetrees 1900, fig. 45) | Driving error of the riveter | Asymmetric transverse compressive stresses on the plies;<br>Difficult removal (if applicable) |
| **Camming effect**[5]<br><br>(Twelvetrees 1900, fig. 42) | Holes misalignment before driving | Reduced shear plane(s) area;<br>Non-uniform bearing contact;<br>Difficult removal (if applicable) |
| Hand-driven field head | Building date;<br>Field riveting;<br>Available space for driving | Reduced frictional strength |
| Insufficient shank upset<br><br>(Frémont 1906, fig. 93) | Long grips;<br>Hand riveting;<br>Driving temperature too low;<br>Holes misalignment before driving | Reduced shear and bearing strength |
| Variations in microstructural properties (shank/head interface) | Slag reorientation during the driving operation | Decrease in UTS ductility of the head<br>/ Rivet head popped off |

[4] Field head generally. This defect may be visible in some cases, depending on the joining configuration.

[5] Non-straight rivet shank (once driven).

| | | |
|---|---|---|
| RIVET HOLE DEFORMATION   (Vermes 2007, fig. 5) | Excessive driving pressure | (Deep) grooves on the rivet shank |

## 1.2 RIVET SHANK DIAMETER

When assessing the structural safety of historical riveted connections, present standards involve the hole diameter $d_{hole}$ into the calculations of the design resistances per rivet (EC 2005, 13, 14, 27)[6]. The hole diameter $d_{hole}$ can be identified by means of destructive and non-destructive techniques. On the one hand, the nominal shank diameter $d$ permits to approximate the hole diameter by a non-destructive way. On the other hand, machining the longitudinal cross section of rivets gives evidence of the hole diameter. It reveals the shank diameter of the rivet in its driven configuration $d_{driven}$. The parameter $d_{driven}$ corresponds to the diameter of the rivet shank resulting from the driving operation. Both the geometry of the connection and the quality of riveting affect the upset of the shank in the rivet hole and thus $d_{driven}$. In any case, the value of $d_{driven}$ lies somewhere between the nominal shank diameter $d$ and the hole diameter $d_{hole}$ (Eqn. 8-1).

$$d \leq d_{driven} \leq d_{hole} \qquad (8\text{-}1)$$

*Where: $d_{driven}$ is the diameter of the rivet shank in its driven configuration.*

### 1.2.1 NON-DESTRUCTIVE TECHNIQUE

The nominal shank diameter $d$ was a key parameter since it influenced the formulation of the rivet head proportions, the philosophy of the design methods and the arrangement of rivets. Three methods can be used to identify the parameter $d$. Firstly, the thickness of the connected plates $e$ can reveal $d$ through the $d/e$ ratio[7]. Secondly, the geometrical affinity of rivets permits to deduce the parameter $d$ from the measurement of the dimensions of the rivet heads, that is, the head diameter $D$, head depth $h$ and head radius of curvature $R$. Analyzing the rivets pattern and spacing can be the third way to identify $d$ – i.e., rivet pitch $p$, rivet lap $l$ and edge

[6] The hole diameter is represented by the symbol $d_0$ in the Eurocodes. The terminology of "design resistance per rivet" used by current standards is comparable to the notion of allowable load per unit gage mentioned by former design methods.

[7] The parameter $e$ refers only to the thickness of the plates but by no means to the cover plates' thickness. The thickness of the thinnest plate may be considered for connections having plates of different thicknesses.

distance $v$. Nevertheless, taking advantage of the geometrically affinity of rivets seems to be the most reliable method. In particular, the measurement of the head diameter $D$ is a convenient assessment method on site.

Table 8-3 links the diameter $D$ of a round rivet head to the expectable value of its nominal shank diameter $d$. Though less accurate, the right part of table 8-3 allows to retrace the parameter $d$ based on the plate thickness $e$ and the rivets pattern and spacing ($p$, $l$ and $v$)[8]. The primary assessment relies on the identification of $d$ based on $D$. Then, the found value of $d$ can be validated or adjusted by the confrontation of the results provided by the derivations from $e$ and $p$, $l$, $v$ (Tab. 8-3).

Table 8-3: The head diameter $D$ is a valuable proxy for the identification of the nominal shank diameter $d$

| HEAD DIAMETER $D$ (mm) | ➔ | SHANK DIAMETER $d$ (mm) | 🡐 | PLATE THICKNESS $e$ (mm) | RIVET PITCH $p$ (mm) | RIVET LAP $l$ (mm) | EDGE DISTANCE $v$ (mm) |
|---|---|---|---|---|---|---|---|
| 26 - 28 | | 16 | | 6 - 8 | 40 - 80 | 24 - 40 | 24 - 40 |
| 28 - 32 | | 18 | | 8 - 10 | 45 - 90 | 27 - 45 | 27 - 45 |
| 32 - 36 | | 20 | | 10 - 12 | 50 - 100 | 30 - 50 | 30 - 50 |
| 36 - 40 | | 22 | | 12 - 14 | 55 - 110 | 33 - 55 | 33 - 55 |
| 40 - 44 | | 24 | | 14 - 16 | 60 - 120 | 36 - 60 | 36 - 60 |

Once a value of the nominal shank diameter $d$ is identified, the hole diameter $d_{hole}$ can be deduced from the following relationship (Eqn. 8-2):

$$d_{hole} = d + \begin{cases} 1 \text{ to } 2\ mm, & SI\ units \\ 1/16\ in, & BI\ units \end{cases} \quad (8\text{-}2)$$

The above non-destructive method applies to rivet shanks that are cylindrical in their driven configuration. It is not fitted for punched rivet holes that were neither reamed nor re-drilled. Obviously, the original perforation technique cannot be revealed non-destructively. Therefore, this assessment tool is rather suitable for riveted structures built from the 1880s onwards, that is, when rivet holes were likely to be more properly made. Table 8-3 is a convenient on-site assessment tool to quickly estimate the hole diameter through the nominal shank diameter.

In any case, this tool allows to trace back to the original design of historical riveted connections. When an intervention requires to drive new rivets, it would be preferable to use the same nominal shank diameter as the original one, insofar as possible. This approach ensures a visual uniformity between the heads of historical and new rivets. In a sense, re-using the original dimensions of rivets contributes to preserve the

[8] The figures related to $p$, $l$ and $v$ are mean values for the period 1840s-1940s. The figures of table 8-3 apply for standard joining configurations of splice joints, in accordance with the scope of the study.

genuine character and historical significance of the riveted structures to which they belong.

### 1.2.2 DESTRUCTIVE TECHNIQUE

A destructive assessment of the hole diameter $d_{hole}$ proves to provide a higher level of confidence compared to the method described in the previous section. The parameter $d_{hole}$ can be deduced from machined cross section of riveted connections.

Present standards take the hole diameter $d_{hole}$ into account to define the shear and tension resistance per rivet $F_{s,Rd}$ and $F_{t,Rd}$, respectively, whereas the design bearing resistance per rivet $F_{b,Rd}$ depends on the nominal shank diameter $d$ (EC 2005, 14, 27). While these assumptions are accurate and conservative for the parameters $F_{t,Rd}$ and $F_{b,Rd}$, respectively, the same is not systematically true for $F_{s,Rd}$. Nowadays, the load-bearing capacity of a rivet in shear is expressed as a function of the hole diameter since it is assumed that the shank completely fills the rivet hole when driven. However, we must keep in mind that this theoretical assumption is not always in line with real configurations of riveted connections. It is the driven shank diameter $d_{driven}$ that determines the actual shearing capacity of rivets in service.

Provided that a satisfactory quality of riveting is ensured – driving temperature and technique, the approximation of $d_{driven}$ with $d_{hole}$ can be considered as adequate for short grip lengths that do not exceed 30 mm to 40 mm (Frémont 1906, 57–68; Van der Veen 1919, 71–72). For long grips involving multiple plies[9], the rivet shank does not completely fill the rivet hole, regardless of the driving technique – i.e., portable air hammer, hydraulic jaw riveter. As a result, present standards may lead to an overestimation of $F_{s,Rd}$ for long grips by referring to the hole diameter $d_{hole}$.

Assessing the driven shank diameter $d_{driven}$ is difficult given its variability and the large amount of parameters on which it depends. Practicing engineers should be aware of the potential overestimation of the shearing capacity of rivets – especially for long grips – when implementing the calculations through present standards.

## 1.3 ULTIMATE TENSILE STRENGTH OF DRIVEN RIVETS

In addition to the hole diameter $d_{hole}$, the UTS of rivets in their driven configuration $f_{ur}$ is needed for the calculation of design resistances, in accordance with current standards (EC 2005, 27). The standard EN 1993-1-8 dealing with the design of the joints of steel structures refers the reader to the National Annex that may provide information on the parameter $f_{ur}$ (EC 2005, 10). In turn, the National Annex advises to consult the German standard DIN 124:1993-05 entitled *Halbrundniete* –

[9] A larger number of plies increase the probability of holes misalignment. The misalignment of rivet holes detrimentally affects the quality of the shank upset.

*nenndurchmesser 10 bis 36 mm*[10], which has been actually superseded by DIN 124:2011-03 in 2011 (DIN 2011a, 3). The latter refers the reader to another German standard, DIN 101:2011-02, which briefly emphasizes on the following rather factual requirement:

> "The rivet material shall be as specified in the relevant product standards." (DIN 2011b, 9)

Ultimately, information on the UTS of driven rivets is not explicitly provided by present standards. Therefore, today's practicing engineers may be likely to base their structural assessment on the only value of $f_{ur}$ given by the standard EN 1993-1-8:

> "For grade S 235 steel the "as driven" value of $f_{ur}$ **may** be taken as 400 N/mm$^2$." (EC 2005, 25)

Both the appraisal of the structural safety of historical wrought-iron and steel riveted connections and the establishment of an intervention strategy – if applicable – rely on the parameter $f_{ur}$. The ultimate tensile strength of a driven rivet depends primarily on the material properties of the rivet iron/steel from which it originates. More fundamentally, the hot-riveting technique improves the ultimate tensile strength of rivets in their driven configuration. On average, the parameter $f_{ur}$ of a driven rivet is ca. 15% higher than the UTS of its original rivet iron/steel.

Table 8-4 gives the value of $f_{ur}$ for machine-driven rivets made of wrought iron, steel and high-strength steel. This table is provided in order to compensate the lack of information of present standards. The figures of table 8-4 are mean values deduced from the results of tensile tests conducted on *driven* rivets in France, the UK, Canada and the US between the 1900s and 1950s (Frémont 1906, 107; Wilson and Oliver 1930, 8, 23, 24; Schenker, Salmon, and Johnston 1954, I–6).

Table 8-4: The following UTS values of **machine-driven** rivets $f_{ur}$ are relevant to consider for the structural assessment of riveted connections

| **WROUGHT-IRON RIVETS** (MPa) | **STEEL RIVETS** (MPa) | **HIGH-STRENGTH STEEL RIVETS** (MPa) |
|---|---|---|
| 400 | 480 | 670 |

The values of $f_{ur}$ are expectably larger than the mean UTS of rivet irons, steels and high-strength steels mentioned in table 2-1 (CH2)[11]. It follows from table 8-4 that the value of 400 MPa advised by the Eurocodes for the $f_{ur}$ of steel rivets – S235 – does not match experimental results. Actually, the suggestion made by the Eurocodes seems to be quite conservative. More fundamentally, the Eurocodes do not address

[10] Translation by the author: steel round rivet heads with nominal diameters ranging from 10 mm to 36 mm.

[11] As a reminder, the UTS of a driven rivet is higher than the UTS of the rivet bar from which it originate because of the thermo-mechanical treatments induced by hot riveting (see CH4, section 3.1, for more information).

the UTS of driven wrought-iron and high-strength steel rivets. As a result, the information given by table 8-4 may be considered as relevant within the framework of appraisal procedures related to riveted connections (Fig. 8-1). These values can apply on an international scale since there was much similarity between the mechanical properties of rivets bars used in different countries, especially for driven steel and high-strength steel rivets (Schenker, Salmon, and Johnston 1954, I–2). With regard to wrought-iron rivets, the information of table 8-4 can be considered regardless of the building date of the structure since the mechanical properties of rivet irons did not evolve significantly over time (Fairbairn 1850, 681; Fidler 1879, 304; Twelvetrees 1900, 60; O'Sullivan and Swailes 2009, 267).

The following methodology may guide practicing engineers to identify which value of the parameter $f_{ur}$ should be used in the assessment of a riveted structure. Ideally, both tensile tests and metallographic analyses should be conducted on dismantled rivet samples to reveal $f_{ur}$ and the original driving technique, respectively. Carrying out tensile tests on driven rivets is a delicate task given their small dimensions. When they cannot be conducted, metallographic investigations should be still performed to assess the material type and original driving technique. After having machined and etched their longitudinal cross section, the material type of the rivets – wrought iron or steel/ high-strength steel – can be notably evidenced by their microstructure. At first sight, the presence of slag inclusions gives evidence of wrought-iron rivets. If the field head of the rivet can be identifiable (see chapter 6), the orientation of the grain flow reveals its original driving technique: hand-driven rivets show a tulip-shaped orientation and machine-driven rivets, a barrel-shape orientation. By default, the parameter $f_{ur}$ may be taken as 380 MPa for wrought-iron rivets. The value of 400 MPa can be considered when it is evidenced that they were machine-driven (Tab. 8-4). For steel rivets, the determination of the original driving technique is not essential as they were machine-driven in common practice. Here $f_{ur}$ can be fixed at 480 MPa (Tab. 8-4). If neither tensile tests nor metallographic analyses can be carried out, it may be advised to consider the following assumptions and values of $f_{ur}$: the wrought-iron rivets were hand-driven ($f_{ur} = 380\ MPa$) and the steel rivets were machine-driven ($f_{ur} = 480\ MPa$).

When the overall appraisal procedure requires the installation of new steel rivets for replacement or strengthening purposes, the parameter $f_{ur}$ can be expressed as a function of the mean UTS of the rivet steels used for rivet manufacture. Based on the investigations of chapter 4, the author developed two easy-to-use formulae that can be used to define $f_{ur}$ (Eqns. 8-3 & 8-4).

$$f_{ur} = \begin{cases} 1{,}1\ UTS_{rivet\ bar} & air\ hammer \\ 1{,}2\ UTS_{rivet\ bar} & hydraulic\ riveter \end{cases} \qquad (8\text{-}3)$$

$$f_{ur} = 1{,}15\ UTS_{rivet\ bar} \quad (8\text{-}4)$$

If the practicing engineer is aware of the driving technique that will be employed in the shop and/or on the job site, the value of $f_{ur}$ can be obtained by equation 8-3. Otherwise, the general rule given by equation 8-4 may apply by default.

## 1.4 DRIVING TECHNIQUE

In addition to the use of destructive methods, the evolution of the driving techniques can support practicing engineers into their assessment of the parameter $f_{ur}$ and the overall appraisal of riveted connections in general – i.e., qualitative information on their stiffness, their frictional strength, etc. The driving technique has a more predominant influence on the structural behaviour than rivet manufacture. Nevertheless, rivet manufacture can affect the sustainability of the connections if not properly carried out.

A timeline dealing with the evolution of the driving techniques used between the 1840s and 1940s in Europe is shown in figure 8-2. Hand and machine riveting were the two main driving techniques. Machine riveting is subdivided into three main categories: steam riveter, hydraulic riveter and air hammer (i.e., pneumatic energy). The timeline provides the reader with the technique(s) that were contemporary to the investigated riveted structure provided that its rough building date is known within a decade. The wide central rectangle-shaped area on which the driving technique is written corresponds to the period of its common application. The starting or end group of adjoining thin rectangle-shaped areas relates to the gradual use or disuse of a given technique, respectively (Fig. 8-2).

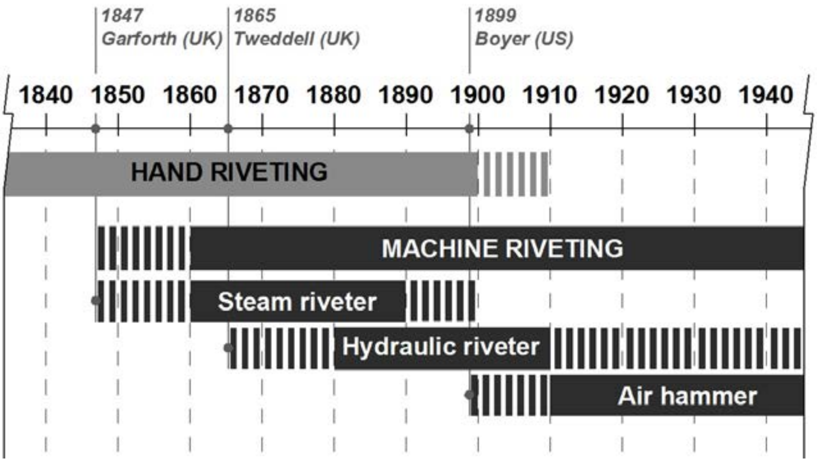



Figure 8-2: Hand riveting had been progressively supplanted by machine riveting at the turn of the 20th century

It follows from the above timeline that both hand and machine riveting were used prior to ca. 1910. Hand riveting was eventually ousted by machine riveting at the beginning of the 20th century. Hence, the rivets of a 20th-century riveted structure are likely to be machine-driven as a general rule. Accordingly, steel and high-strength steel rivets were generally machine driven while wrought-iron rivets could be driven either by hand or with a riveting machine.

The turn of the 20th century (1880s–1910s) may be the most delicate period to deal with because of its transitional feature. On the one hand, both hand and machine riveting techniques coexisted with each other. On the other hand, hydraulic riveters could be used together with portable air hammers (Fig. 8-2). As noticed in the previous section, hydraulic riveting machines further improved the UTS of driven rivets in comparison with air hammers (Eqn. 8-3). Unfortunately, the riveted connections themselves do not permit to straightforwardly reveal whether their rivets were driven with the help of a hydraulic riveter or air hammer. Additional information would be needed to assert the actual implementation of one of those two driving techniques. When available, such information might be provided by building specifications, building site pictures, private archives of iron and steel construction companies, etc.

The working of air hammers was based on a pneumatic transmission. Air hammers embodied the widespread use of pneumatic machines developed as early as in the 1870s in the US[12]. Portable pneumatic machine tools underwent a fast development in the US from 1900 onwards. In Europe, air hammers came into general use from 1910 onwards eventually (Fig. 8-2). They progressively replaced hydraulic riveters, particularly for field riveting. However, hydraulic riveting machines were still used in the shop under certain conditions[13] since it was – and still is – considered as the best driving technique.

[12] See CH2, section 2.3.1.

[13] A hydraulic riveter is more difficult to handle than an air hammer. The jaw opening of the hydraulic riveting machine also limits its range of applications to some extent.

## 2 INTERVENTIONS

Preliminary analyses and structural assessments of riveted structures are used by practicing engineers and architects as the basis for decision-making for potential intervention (Fig. 8-1). Intervention strategies primarily include maintenance, repair, replacement, strengthening and demolition. In accordance with the scope of this study, the focus lies here on the types of intervention involving the hot-riveting technique, that is, repair, replacement, and strengthening.

Damages arising from original defects or service life can require repair and replacement interventions on the plates and/or the rivets. For buildings under static loading as for bridges under cyclic loadings, the connected plates are likely to be often problematical, rather than the rivet itself (DiBattista, Adamson, and Kulak 1998b, 792; Vermes 2007, 6; Aelterman 2013). Common interventions may consist of replacing plates and/or sections that are distorted, corroded, or cracked, but also strengthening existing built-up sections such as adding stiffening angles on a web. In addition, the strengthening of existing riveted structures can result from rehabilitation projects that aim to increase their load-bearing capacity for instance. Missing or defective rivets might also be an issue in some cases.

The above interventions require decision-makers to make choices and involve various renovation techniques. The present section attempts to offer us new insights into the intervention strategies related to the hot-riveting technique. It reviews actual renovation techniques and suggests ways to improve them. In addition, this section provides guidelines to both decision-makers and riveting gangs.

## 2.1 PACK RUST REMOVAL

As introduced in section 1.1.1**, pack rust** is generally observed on built-up sections where interfacial corrosion or rust had developed between the plies connected by rivets and generating a buckle.

Pack rust removal consists of two main steps. First, the buckled outer ply is locally heated to a temperature of ca. 400–500 °C with an oxygen fuel torch between two consecutive rivets (Fig. 8-3, left)[14]. Second, the rust is driven out from the buckle by shaking the plies with a pneumatic riveting hammer equipped with a modified snap at its end (Fig. 8-3, right). The plies retrieve their flattened configuration eventually. Special care must be taken in order to avoid any damage to the rivets, as well as to the sequence of the operations to prevent the distortion of the section. (Mesler 2007)

Figure 8-3: The buckled ply between two adjoining rivets is heated with a torch (left) prior to the removal of the pack rust with a pneumatic riveting hammer (right) (LCC-WT shop, 2013)

When pack rust popped off the head or induced the failure of the shank of rivets, their removal is needed.

[14] I.e., 800–900 °F.

## 2.2 RIVET REMOVAL

Most of the interventions require the removal of some rivets. Two typical applications of rivet removal are failures in rivet shanks or rivet heads and the replacement of damaged plates and/or built-up sections.

Rivet removal is a delicate and expensive operation for which no clear standard procedure seems to exist. Shearing off one rivet head with a hand-held chisel bit to then firmly push the rivet out with a blunt bit is practically not done anymore, as these operations are too tough for the human body. Techniques such as directly using a **rivet buster**[15] or burning the rivet out with a torch are applied in practice. The rivet buster shears off one rivet head and then drives the rivet out. However, theses techniques can damage the base metal of the plies or upsize the original hole diameter of the connection. Procedures that may minimize the chance of damaging the plies and the rivet hole are briefly discussed below (Vermes 2007, 7–8; Mesler 2013):

- Preheat one rivet head with an oxygen fuel torch and then wash off the head. The rivet shank is cut out to remove material as much as possible. The rivet is then removed by driving it out. This method was carried out in 2009 for the restoration of the 1881/1910 Hays Street bridge in San Antonio (TX, USA)[16].
- Directly pierce the rivet with a cutting torch having a concentrated acetylene flame. One rivet head is then sheared off with a rivet buster. Finally, the rivet is removed by driving it out. Implemented on the rehabilitation of the Main Avenue bridge in Cleveland (OH, USA) in the 2000s, the method seemed to be satisfactory provided that the piercing was carefully done.
- The seismic retrofit of the Golden Gate bridge in San Francisco (CA, USA) performed in the 2000s incorporated an efficient method. After having first removed one rivet head, this method consisted of drilling inside the shank to remove material by reducing the diameter (Fig. 8-4). It allows to relieve stresses in the area at the interface between the rim of the rivet hole and the rivet shank. The remaining shank is then driven out. This method does not damage the base metal and eases the remedial works performed by the riveting gang.

[15] A rivet buster is a kind of pneumatic riveting hammer. See the translation dictionary and glossary for more information.

[16] This method of rivet removal is illustrated by a video related to the Hays Street bridge filmed by S. Patrick Sparks. The standard technique that involves the sole use of a rivet buster – less adequate – is also shown at the end of the video. https://www.youtube.com/watch?v=qD9eWgcAtLg&list=UUff_NjTsF3uskS-O9BXd7kg.

Figure 8-4: Samples of rivets drilled out within the framework of the seismic retrofit of the Golden Gate bridge carried out in the 2000s (Vermes 2007, fig. 16)

When the damage relates only to the rivets – failed heads for instance, the inspector-engineer may allow a defective rivet to remain if its removal could loosen adjacent rivets. Accordingly, a difficult rivet removal might testify to an original driving operation of bad quality – e.g., holes misalignment, head eccentricity, etc. (Tab. 8-2). The rim of the rivet holes should be carefully examined after each removal operation as it may damage the plies, especially for wrought-iron structures (SB 2007c, 197; Vermes 2007, 11).

## 2.3 PLATE AND RIVET MATERIAL

Theoretically, wrought-iron or steel materials – plates and rivets – can be used for repair, replacement and strengthening interventions.

When a rehabilitation project does not require to increase the load-carrying capacity of an existing wrought-iron structure, the use of wrought-iron plates and rivets may be sufficient from a structural viewpoint, as riveted connections were generally oversized. Moreover, the application of wrought-iron materials might not significantly modify the original structural behaviour of the connections – e.g., stiffness, redistribution phenomena, stress raisers. The use of wrought iron is however hampered by the material availability.

Nowadays, common renovations techniques involve the material steel given financial, structural and pragmatic considerations – e.g., material availability, fundaments of present standards. When applying steel, it is recommended to choose a steel grade of the rivet bars that is lower than or at the most equal to the one of the plates, regardless of the type of intervention and original material of the connections. As a reminder, the UTS of driven steel rivets $f_{ur}$ is higher than the UTS of the rivet steels due to the hot-driving technique. In particular, a careful attention should be paid to strengthening interventions applied to wrought-iron riveted structures. In accordance with the results of the structural assessment, the needed steel grade

should be limited to a minimum to avoid major differences in strength and ductility between the genuine wrought-iron parts and the new steel ones. Practicing engineers should avoid unnecessary upgrades of the used steel.

## 2.4 PLATE PERFORATION

The drilling technique should be used for plate perforation. Each plate can be drilled separately to be then ready for rivet driving. However, it is recommended – when possible – to perforate the plates of a given connection all together to avoid any holes misalignment before driving (Aelterman 2013).

For round rivet heads, a difference in diameter of ca. 1 mm between the nominal shank diameter $d$ and the hole diameter $d_{hole}$ may be considered. This recommendation complies with the standard DIN 124:2011-03 (DIN 2011a, 11).

The alignment of the rivet holes and the smooth surface condition of their rim must be checked prior to the driving operation. Both have to be ensured to improve the quality of the upset of the shank. A satisfactory shank upset is essential as it conditions the actual shear and bearing strength of riveted connections (Tab. 8-2). Rivet holes must be systematically reamed/re-drilled if any misalignment is noticed.

## 2.5 SECURE FIT OF THE PLIES

Prior to rivet driving, the plates have to be adequately tightened with temporary installation bolts; one bolt every three to five rivet hole on average. If the distance between two bolts is too large, their tightening can be insufficient and the driven rivets can be loosened (Tab. 8-1). Loose rivets can result in a lack of clamping force and thus a decrease in frictional strength of the connection. Moreover, it can detrimentally impact on the sustainability of the connection – e.g., risk of pack rust.

## 2.6 RIVET HEATING

Heating rivets in a forge is now largely obsolete. Portable furnaces are fitted for both shop and field riveting. These appliances can be electric furnaces but can also be fired by propane gas, the latter leading to very compact types (Fig. 8-5). A qualified rivet stoker is required to ensure an adequate and homogeneous heating temperature of the rivets. The rivet stoker's assessment is based on the colour and appearance of the rivets being heated. Standard soaking times range from 5 to 15 minutes depending on the appliance used. It is recommended to not simultaneously heat a large amount of rivets to ensure that their actual temperature matches the preset one.

Figure 8-5: Electric chamber furnace (left) and small portable furnace using propane as a fuel source (right)

Another preferred appliance that is more fitted for shop riveting uses an intense electric current as heating method. Each rivet is pinched at its ends by clamps and an electric current goes through the rivet to heat it from its core. Although highly energy-consuming, this technique does not need any preheating and uniformly heats the rivet in the shank and in the shop head. It quickly heats rivets – ca. 30 seconds – and minimizes the loss of heat by radiation (Weiss 1926, 2:260) (Fig. 8-6). Finally, rivets can be flash-heated through an induction process; here only a few seconds are needed. The induction technique requires heavy equipment, e.g., water-cooling system, and can merely be done in the shop.

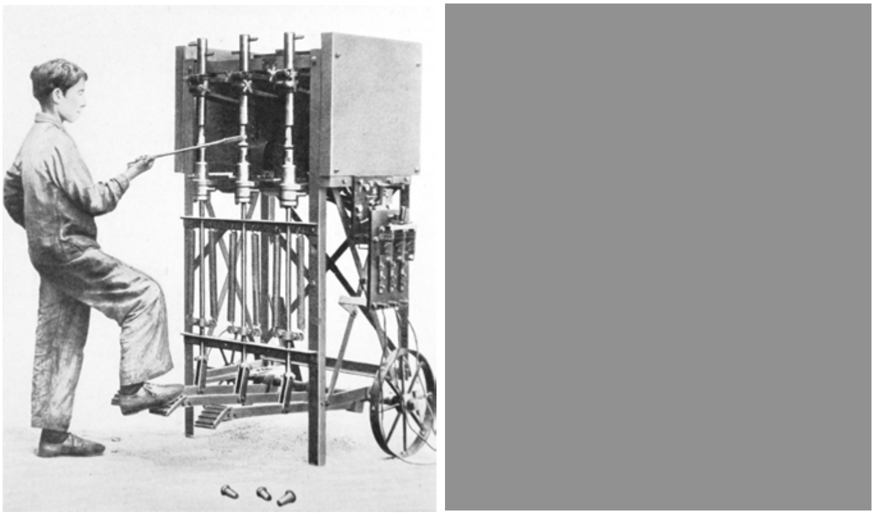


Figure 8-6: Appliance heating rivets through electric current, (left) former illustration (Weiss 1926, 2:260) and (right) actual practice (Baeck & Jansen shop, 2010)

Steel rivets should not be overheated and the soaking time has to be followed up as well – i.e., not too long. As soon as a rivet is removed from the furnace, the driving operation should follow quickly – insofar as possible – to ensure a sufficiently high driving temperature.

The presence of scale, glowing particles or any other dirt must be removed from the rivet prior the driving operation by quickly shaking or hitting it against a hard surface for instance. Failure to do so may result in an inefficient upset of the shank in the rivet hole (Twelvetrees 1900, 89).

## 2.7 DRIVING OPERATION

The driving operation is a difficult technique to implement. Although it had been a well-mastered technique in the 19th and 20th century, the same cannot be said today. Only few qualified riveting crews able to carry out hot riveting remain today. Riveting practice is a know-how that is taught at some technical colleges but, more commonly, know-how transfer occurs through training steel constructors in the shop. In addition, on-the-job training arises out of insufficient experience of the riveting gang. Testifying to a lack of know-how, typical issues and inappropriate practices can be as follows: inadequate protruding shank length, irregular head form, driving temperature too low or too high. It is always preferable to involve experienced riveting gangs when possible. All in all, the hot-riveting technique goes, by definition, hand in hand with a trial-and-error process. Therefore, trial riveting must be performed on benchmark connections to adjust key parameters – e.g., shank length, heating temperature – and check the quality of riveting beforehand (DIN 2011a, 10).

Not only the action of riveting is difficult, rivet material and equipment are also hard to find. Rivet manufacture is not a standard production anymore and it is not unusual to be forced – especially in small countries – to order steel rivets abroad. To benefit from economies of scale, one shank length can be ordered per shank diameter, that is, long enough to match various grip lengths. Similar difficulties are encountered regarding the riveting equipment such as the furnace, riveting machine or holder-up tool. Some steel constructors specialized in renovation have their own machines and tools, and will carefully maintain them. Others rent them or also adapt existing tools according to a do-it-yourself approach in order to match various riveting conditions (e.g., shop vs. field riveting, portable machines)[17].

Rivets are typically machine-driven for structural applications. This can be done in the shop and/or on the job site. The majority of the driving operations should be performed in the shop as it provides better results. In the shop, portable air hammers

[17] These tools are generally not patented and act as strategic assets towards competitors.

and powerful hydraulic riveting machines can be used[18]. A rivet driven by a hydraulic riveter is considered as the best technique since it positively influences the structural behaviour of the connections. However, it comes up with some restrictions. Actually, the jaw opening of the hydraulic riveter must be compatible with the geometry of the structural section to be repaired (Fig. 8-7, right). The advantage that hydraulic riveting machines have over air hammers is the higher compressive force applied on the protruding shank end to form the field head. This allows to compensate or visually conceals some installation errors such as the unsecure fit of the plies, the misalignment of rivet holes or inferior driving temperature. On the job site, air hammers may be the only feasible alternative today (Fig. 8-7, left). Unfortunately, portable derivatives of hydraulic riveters used in the shop do not seem to be available anymore. On average, a riveting gang can drive ca. 40 rivets per hour – even up to 80 rivets per hour under perfect circumstances – with an air hammer on the job site (Aelterman 2013)[19].

Figure 8-7: (Left) Air hammer handled by the author (LCC-WT shop, 2013) and (right) hydraulic riveting machine (Steve Howell shop, 2013)

Driving rivets in grips that are too long should be avoided as it can detrimentally affect the shear behaviour of riveted connections. Hence, the grip length $g$ should be limited in order to guarantee an efficient shank upset and uniform structural behaviour.

[18] Examples of shop riveting performed with an air hammer and hydraulic riveter at Steve Howell's shop – *Ballard Forge*, Seattle, WA, USA – can be watched on https://www.youtube.com/watch?v=P3ohhK15SCs.

[19] Strengthening interventions related to the Hays Street bridge in San Antonio – TX, USA – carried out on the job site with an air hammer can be viewed on https://www.youtube.com/watch?v=Xi_LRrsv8QA.

The following relationships may be considered as a general rule for the grip length $g$ of steel rivets driven either with an air hammer (Eqn. 8-5) or hydraulic riveter (Eqn. 8-6)[20]:

$$g \leq min(4d; 100\ mm) \qquad with \qquad d \in [16, 18, 20, 22, 24] \qquad (8\text{-}5)$$

$$g \leq min(5d; 150\ mm) \qquad with \qquad d \in [16, 18, 20, 22, 24] \qquad (8\text{-}6)$$

A careful inspection of the quality of riveting should be implemented after each driving operation. The identification of critical defects such as loose rivets or pitting on the heads should result in the removal of the newly-driven rivet (Tab. 8-1). Other visible defects could be allowed to remain from a structural viewpoint – e.g., unfilled field head, lip around the field head. Nevertheless, the removal of these rivets might be advised since the unsatisfactory shape of their field head can initiate corrosion at the head/ply interface (Aelterman 2013). Therefore, such configurations should be avoided as they affect the sustainability of the remedial works performed.

## 3 CONCLUSIONS – TOWARDS A REVIVAL

Assessment tools and intervention recommendations were suggested to support practicing engineers, architects and historic preservationists faced with the appraisal of historical riveted connections. The findings deduced from the analyses conducted in Part I, Part II and Part III of the study were used to provide the reader with these tools and recommendations. Such approach contributes towards the revival of the riveting practice that is a real challenge to deal with in a foreseeable future.

On-site inspections of the condition of riveted connections are the first preliminary analyses that can be conducted within any overall appraisal procedure. The identification of damages help decision-makers assess the structural integrity of the plates and rivets of the connections from a qualitative viewpoint. Damage analyses are essential since they inform on the present state of riveted structures and allow also to trace back to their original design and technology. The determination of the plates and rivets material type(s) can be then identified. Thorough investigations are needed since different materials may be combined within a given structure or even structural member – e.g., built-up sections made of steel angles and wrought-iron flat bars connected with steel rivets. The characterization of the mechanical properties of driven rivets may not be systematically carried out by experiments as a result of pragmatic difficulties. However, alternative methods permit to roughly approximate

[20] The formulation of eqns. 8-5 & 8-6 leans on the recommendations of both historical literature – see CH3, section 1 – and present standards (DIN 2011a, 13–14; EC 2005, 25). In any case, the value of 150 mm should act as an upper-bound value, regardless of the nominal shank diameter $d$.

these parameters. The suggested tools can be used to reach this goal. Preliminary analyses support the implementation of the structural assessment of riveted connections.

Structural assessments complying with present standards rely primarily on two parameters: the hole diameter $d_{hole}$ and the UTS of rivets in their driven configuration $f_{ur}$. The geometrically affinity of rivets is a valuable proxy for the estimation of the hole diameter $d_{hole}$. As a consequence, the amount of destructive tests that enable to identify this diameter can now be reduced during remedial works. Regarding the parameter $f_{ur}$, the results of past experiments can be valorized to estimate the UTS of driven rivets when tensile tests are not performed. Moreover, the building date of the appraised riveted structure can support the determination of $f_{ur}$ with regard to the type of driving technique used. When replacement or strengthening interventions require the hot-riveting technique, the value of $f_{ur}$ can be extrapolated from the UTS of the rivet bars.

When the actual state and/or structural assessment require(s) remedial works, they generally involve multiple renovation techniques. Rivet removal and rivet driving techniques are both typically implemented within any repair, replacement or strengthening intervention. The scope of the intervention depends primarily on its purpose – i.e., maintenance vs. rehabilitation, the state of the connections, their structural safety, the historical significance of the structure, etc. In a nutshell, the following recommendations on intervention strategies should be considered when applicable/possible:

- Remedial works should not damage the adjoining parts of the riveted structure in question.
- Wrought-iron rivets comply with the actual standards.
- The steel grade of new plates and rivets does not have to be unnecessarily upgraded in accordance with the requirements linked to the structural assessment.
- A sufficient driving temperature must be ensured prior to the driving operation.
- Shop riveting is preferable to field riveting.
- It is better to use hydraulic riveters than air hammers.
- The members of the riveting gang should have enough experience and skills to carry out the hot-riveting technique.
- Quality control inspections must be conducted before – e.g., rivet holes – and after the driving operation – e.g., visible defects.

In any case, decision-makers and riveting gangs should strive to implement less intrusive remedial works to preserve the historical significance of riveted structures.

# CONCLUSIONS AND PERSPECTIVES

The interventions carried out today on historical metal structures arise out of the need to rehabilitate them or preserve their service life. Intervention strategies generally involve the riveted connections of iron and steel structures. Preliminary analyses report on their design, identify potential damages and characterize the material type(s) and their properties. In compliance with current standards and calculations, the structural assessment of riveted connections takes, primarily, the geometry and strength into consideration. Ultimately, the decision-makers can define the scope of the intervention. Those three steps – preliminary analyses, structural assessment, and intervention – all raise several issues with which engineers, architects, historic preservationists as well as riveting gangs are faced in their renovation practice. This brings us back to the main research questions formulated in the introduction of the study, section 2, reminded below:

- Which materials and techniques were used to fabricate riveted connections?
- What can be learned from the original design of riveted connections?
- Which parameters affect the structural behaviour of riveted connections?

Answering the above questions proved to not be so straightforward because of the theoretical and practical inadequacies of available resources – specialized literature and know-how. To partially fill this gap, this study unravelled the technology and design of historical iron and steel riveted connections, investigating a wide range of parameters that may qualitatively or quantitatively affect their structural behaviour. The findings of the research constitute an input for the structural assessment and intervention strategy of existing riveted connections. The study scoped out the static behaviour of standard splice joints fabricated with the hot-riveting technique between the 1840s and 1940s in France and Belgium. A multidisciplinary research in the field of construction history brought historical, technological, analytical and experimental approaches together through a tripartite methodology. First, the riveting technology – rivet manufacture and driving – was assessed on an international scale by referring to literature and Belgian patents (1830–1940). Second, French and Belgian literature was reviewed to understand the fundaments of the design of riveted connections – i.e., geometry, theory, and design methods. And third, experimental investigations were performed on dismantled and fabricated riveted connections to appraise the research conducted so far and analyze the influence of remedial works. The end of the study offers assessment tools and intervention recommendations.

# 1 CONTRIBUTION OF THE THESIS

This section provides answers to the main research questions, with the findings revealed by the conducted investigations. The discussions are enriched by pragmatic recommendations for the decision-makers involved in the appraisal of historical riveted connections. These recommendations are linked to a selection of figures, tables and equations, presented throughout the study.

**Which materials and techniques were used to fabricate riveted connections?**

Prior to the 1880s, riveted connections were typically made of wrought iron and their rivets were hand driven. Riveted structures erected around the turn of the 20th century may be the most delicate ones to assess given the transitional characteristic of that period. Both wrought-iron and steel materials were used – even within a given structural member – and the rivets were hand or machine driven. From the 1910s onwards, riveted connections were usually made of steel and their rivets were all machine driven.

On an international scale, it was commonly advised to use a rivet material having somewhat lesser or at the most the same mechanical properties as the plate material. In practice, this consideration was often met for steel riveted connections. For wrought-iron riveted connections, however, it was contradicted by the actual difference in mechanical properties between rivet and plate irons[1]. In any case, rivet irons and steels had to be sufficiently ductile to be driven.

Wrought-iron rivets were usually handmade before the 1850s. The mechanization of rivet manufacture occurred between the 1850s and 1880s. Rivet-making machines were systematically used for the manufacturing of steel rivets. Technological mutations accompanied an improved quality of manufacture. Typical defects such as the asymmetry or presence of a lip around the shop head were gradually eliminated. These imperfections do not seem to impact on the structural behaviour of the connections but they do affect their sustainability.

A riveted structure built before the 1880s could show punched rivet holes that were neither reamed nor re-drilled (Tab. 8-4). This would evidence that the strain-hardened area may not have been removed prior to the driving operation. The assessment of the rivet hole shape informs us on the perforation technique and, more fundamentally, the actual hole diameter $d_{hole}$. From the end of the 19th century onwards, rivet holes were generally subpunched, later pre-drilled, and then upsized – 2-3 mm – to the wished hole diameter by reaming.

[1] The ultimate tensile strength of rivet irons was ca. 20% higher than that of plate irons.

Regardless the numerous heating devices available, it is rather the heating temperature that is a source of concern. Unscrupulous rivet stokers could overheat or even burn rivets for practical convenience. When inspecting riveted connections on site, the presence of pitting on the rivet heads gives evidence of heating temperatures that were too high (Tab. 8-3). Such rivets benefit from a higher ultimate tensile strength than average (driven configuration) but have a lower ductility.

Wrought-iron and steel rivets could have been either hand driven or machine driven before the 1910s. The orientation of the grain flow and slag inclusions within the field heads is a valuable proxy for the identification of their original driving technique (Fig. 6-2). From the 1910s onwards, steel rivets were usually driven by an air hammer both in the shop and on the job site (Fig. 8-2). In addition, hydraulic riveters were used in the shop under certain conditions.

**What can be learned from the design of riveted connections?**

The design of historical riveted connections has to be analyzed to support the structural assessment and potential interventions. By means of a reverse engineering approach, useful information can be revealed by a non-destructive way, in addition to the findings deduced from destructive assessments. Such an approach notably requires the knowledge of the core philosophy of the design methods contemporary to the period 1840s-1940s.

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. Splice joints have belonged to the category of – what we call today – bearing-type connections. Nevertheless, the notion of bearing strength effectively affected the design from the 1920s onwards (Tab. 5-1). Riveted connections were designed according to a rather conservative approach. High safety factors defining allowable stresses, combined with theoretical inaccuracies made them usually oversized.

The joining configuration can help us decipher which rivet(s) is/are likely to be the weak chain of a connection. The rivets of end rows should require special attention as they take up a larger part of the loads. In particular, the configuration of convergent zigzag connections – lap and butt splices – acts as a stress-raiser towards the rivets of end rows (Fig. 3-5). Hence, the state of these rivets should be thoroughly inspected on site.

The hole diameter $d_{hole}$ needed for the structural assessment can be approximated by the nominal shank diameter $d$ (Eqn. 2-1). The shank diameter $d$ is a key parameter as it conditions both the shop head's proportions and the arrangement of rivets (Eqns. 3-2 & 3-3). The shop head diameter $D$ and depth $h$ can be measured

on site to estimate the parameter $d$, provided that the shop head is distinguishable (see CH6). Then, the plate thickness $e$ and arrangement of rivets – rivet pitch $p$, rivet lap $l$, and edge distance $v$ – allow us to cross-check the identified value of $d$ (Tab. 8-3). Note that $d/e$, $p/d$, $l/d$ and $v/d$ are theoretical ratios that were rounded up/down by practical and economical constraints (Eqns. 5-1 & 5-2, Tab. 5-5).

In addition, a reverse engineering approach revives valuable – often forgotten – information provided by historical literature. Though developed more than 150 years ago, the convenient empirical rules of thumb can still help us limit the value of the nominal shank diameter $d$ (Eqn. 5-9) and grip length $g$ (Eqns. 8-5 & 8-6) or pre-set the protruding shank length (Eqn. 3-1) for instance.

**Which parameters affect the structural behaviour of riveted connections?**

The current structural behaviour of historical riveted connections results from their original design and fabrication as well as from external effects occurring during service life. Taking into account the high number of parameters induced by hot riveting, it is still difficult to assess the structural behavior of standard splice joints. Therefore, the mechanical response of – original and repaired – splice joints subjected to shear loading is anything but uniform and predictable, as evidenced by the shear tests discussed in chapter 7 (Fig. 7-10). In any case, this should not prevent us from being aware of the known parameters that affect the structural behaviour. These parameters scoped out by the study can be merged into three categories as follows: design, materials and techniques, and riveting practices.

The joining typology, geometry and dimensions of riveted connections are determined at the design stage. The definition of the joining configuration, symmetry of the joint, use of cover plates, number of rivet rows, rivets pattern, etc., originally conditions the stiffness of the joint and inner stress state of its rivet(s) and plates. Then, the hole diameter $d_{hole}$ and grip length $g$ primarily influence the structural behaviour, together with geometrical ratios such as $d/e$ or $G/d$.

Expectably, the plate and rivet materials predominantly account for the structural behaviour of the connection to which they belong. The perforation stage of the plates could affect their tensile strength. Next, the thermo-mechanical treatments induced by the hot-riveting technique improve the ultimate tensile strength of rivets but, however, decrease their ductility. This decrease is even more accentuated by heating temperatures too high and/or soaking times too long. The quality of the shank upset in the rivet hole is a key parameter that influences both the rivet shear and plate bearing strengths. A sufficiently high driving temperature and an efficient driving technique can ensure a satisfactory shank upset, within an acceptable range of grip lengths though (Fig. 4-5). Hydraulic riveters further improve the load-bearing capacity compared to portable air hammers.

To a great extent, riveting practices embody the unquantifiable contribution affecting the structural behaviour. Presumably, the experience of riveting gangs favourably influenced the behaviour by optimizing, in a sense, all the different stages of rivet driving, that is, the synchronization of all the operations. Conversely, unfavourable practices and neglects regarding the secure fit of the plies, the heating temperature, or quality controls for instance, could result from a lack of commitment. However, we must keep in mind that the hot-riveting technique was a very difficult and tough work, particularly on site.

## 2 RESEARCH PERSPECTIVES REVEALED BY THE THESIS

The analyses carried out throughout the study underlined key parameters of influence and periods of investigation that would be worth further examinating. In addition, the scope of the conducted analyses inherent to the multidisciplinary feature of the study could be widened. This section suggests possible avenues of research regarding the technology and design of historical riveted connections that may help us apprehend their structural appraisal with more confidence.

In Part I, the evolution of the riveting technology was investigated by confronting the content of international literature with historical patents. Uncertainties on the innovativeness of patented rivet-making and riveting machines are the main drawback of such research methodology. Based on the drawn up patent database, the effective commercialization and use of these machines could be more systematically revealed by referring to literature dealing with exhibitions and world fairs, archives of machine manufacturers (i.e., trade catalogs), advertisements, etc.

Next to the technology, the development of the theory behind riveted connections should be further analyzed. On that topic, the book published in 1945 by the American engineer R. de Jonge provides the reader with an extensive critical literature review of international interest (de Jonge 1945). Revealing the effective impact of pioneering theoretical developments on educator-engineers of countries other than France and Belgium would allow to complete this study. Moreover, the fundaments of the design methods may differ from one country to another. This includes the design philosophy and calculation assumptions, the methodology, and the arrangement of rivets. Also, the content of historical design methods could be further confronted with the as-built configuration of existing riveted connections. Here, a global approach that takes both the proportions of rivets and the overall layout of the connections into consideration would be recommended.

Experimental investigations are essential as they allow to effectively assess the influence of the technology and design on the structural behaviour. Riveted structures built between the 1880s and 1920s require a careful assessment. This

period proved to be the most challenging one, given the transition in materials, design methods and driving techniques. Additional experimental investigations could be conducted in four steps. First, microstructural analyses should be carried out on rivet samples dismantled from iron and steel riveted structures. Second, static evaluations should be performed on fabricated iron and steel splice joints to ease the discussion of the results. The investigations could focus on the effect of the following key parameters: the perforation technique[2], the heating temperature, the driving temperature, the driving technique[3], the working conditions[4], and the synchronization of the stages of rivet driving. Shear tests may be preferably performed on asymmetric configurations of single riveted splice joints after symmetric ones. The number of rivet rows per force transmission could be then increased to assess the non-uniform distribution of the loads among the rivets. Third, the findings of the previous experiments would contribute towards the better understanding of the shear behaviour of – this time – genuine iron and steel riveted connections, which are more complex. And finally, the influence of remedial works on existing riveted connections could then be appraised. Test results from static experiments may support the definition of the experimental programme of fatigue assessment.

Besides experimental investigations, numerical modelling analyses are also of interest to assess the structural behaviour of riveted connections. The findings of both experimental and numerical analyses should improve the content of present standards.

Further research on historical riveted connections could also include the cost-efficiency of remedial works involving the hot-riveting technique, as well as the effect of other renovation techniques using bolted or welded connections for instance.

[2] Punching vs. drilling.

[3] Hand vs. machine riveting, air hammers vs. hydraulic riveters.

[4] Shop vs. field riveting.

## 3 FINAL CONCLUSIONS

The ultimate challenge of all the above avenues of research might be the valorization of their respective findings. Appraisal and intervention guidelines should be developed and disseminated amongst engineering offices, heritage care authorities, governmental agencies, road and railway authorities, and, last but not least, riveting gangs. This issue is strongly linked to educational considerations. Both decision-makers and riveting gangs may not always have the adequate knowledge to appraise historical riveted structures, and specialists in their preservation barely exist. Next to the structural safety, the appraisal approach should also take into account the technology and design of the connections since they are an integral part of the heritage value of these structures. Although substitute fasteners such as high strength or injection bolts are convenient, satisfactory and cost-effective alternatives, they affect however the historical significance of the riveted structures. Despite being unpredictable, difficult and expensive, the hot-riveting technique has also some advantages over bolts. When properly driven, rivets can guarantee a sustainable secure fit for the connected plates, which is essential for structures under cyclical loadings for instance, unlike the self-loosening of bolts. More fundamentally, the preservation of the original technology and design of the riveted connections is not necessarily an additional cost driver – e.g., nominal shank diameter, arrangement of rivets.

Inevitably, no universal appraisal procedure exists and each riveted structure has to be treated on a case-by-case basis. In any case, intervention strategies should follow a respectful approach towards the built heritage when extending the service life. Comparably to the hot-riveting technique, it is a tough work to preserve both the service life and the heritage value of historical riveted structures. However, the reward makes the effort worthwhile for the millions of people who will live, work and commute using these structures belonging to the city's landscape – and their millions of rivets – for the decades and hopefully centuries to come.

# TRANSLATION DICTIONARY AND GLOSSARY

## 1 TRANSLATION DICTIONARY

The translation dictionary given in table A provides the French and Dutch translations of the most important technical English words used throughout the thesis. In some cases, synonyms are added to the most common word found in literature (in bold).

Table A: Translation dictionary (EN-FR-NL) of technical vocabulary

| ENGLISH | FRENCH | DUTCH |
|---|---|---|
| anneal, to | recuire | uitgloeien |
| buck up, to | bloquer/maintenir en place | vasthouden |
| butt joint, single/double | assemblage bout-à-bout à un/deux couvre-joint(s) | stompe verbinding met één stuikplaat/twee stuikplaten |
| **button head**, knobbled head | tête *en goutte de suif* | klinknagelkop met twee kromtestralen (talkdruppels) |
| camming effect | déformation de la tige | vervorming van de schacht |
| caulking | matage | breeuwen, het |
| chain riveting | disposition alignée (rivets) | uitgelijnde klinknagels |
| cherry-red | rouge cerise | kersrood |
| clamping force | force de serrage | klemkracht |
| clearance (hole) | jeu | spelling |
| countersunk head | tête fraisée | verzonken kop |
| cover plate | couvre-joint | stuikplaat |
| crippling | écrasement | verbrijzeling |
| drive, to (a rivet) | installer (un rivet) | klinken |
| driven diameter | diamètre final (rivet installé) | einddiameter (geklonken klinknagel) |
| driven strength | résistance (rivet installé) | weerstand (geklonken klinknagel) |
| edge distance | pince transversale | randafstand |
| fastener | organe d'assemblage | verbindingsmiddel |
| **field head**, second head | tête fermante, deuxième tête | sluitkop |
| field rivet | rivet installé sur chantier | klinknagel op de bouwplaats geklonken |
| **field riveting**, site riveting | rivetage sur chantier | klinknagelen op de bouwplaats |
| fixed-shop riveter | machine à river d'atelier | vaststaande klinkmachine (werkplaats) |
| **forge**, **furnace**, rivet hearth | four, forge | smidsvuur |
| gage | largeur unitaire | eenheidsbreedte |
| grip length | épaisseur (assemblage) | verbindingsdikte |
| gusset plate | gousset | koppelplaat |
| hand riveting | rivetage manuel | handmatig klinknagelen, het |
| hand-driven (rivet) | installé à la main (rivet) | handmatig geklonken (klinknagel) |
| head depth (of a rivet) | hauteur de tête (de rivet) | hoogte van de (klinknagel)kop |
| holder-on | personne bloquant la 1ère tête de rivet | tegenhouder |

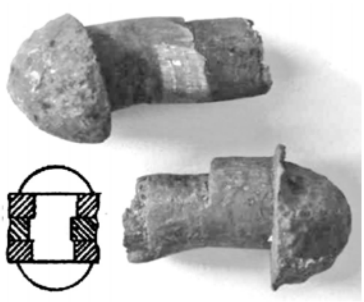
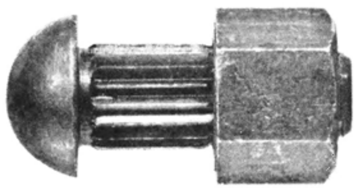
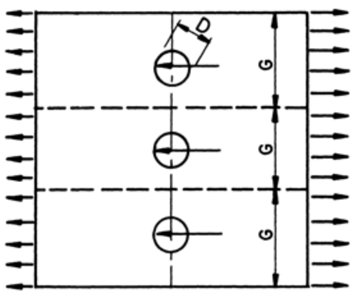
| | | |
|---|---|---|
| **holder-up**, dolly bar | tas, contre-bouterolle (outil bloquant la 1ère tête de rivet) | zethamer (werktuig om de zetkop tegen te houden) |
| lap joint, single/double | assemblage à simple/double recouvrement | lapnaad met enkelvoudige/tweevoudige overlapping |
| lopsided (rivet head) | asymétrique (tête de rivet) | asymmetrische (klinknagelkop) |
| machine riveting | rivetage à la machine | machinaal klinknagelen, het |
| machine-driven (rivet) | installé à la machine (rivet) | machinaal geklonken (klinknagel) |
| pack rust | *pack rust* | *pack rust* |
| ply | tôle (couche) | plaat (laag) |
| protruding (shank) | dépassant du trou (tige de rivet) | uitspringend deel (klinknagelschacht) |
| punch | poinçon | stempel |
| punch, to | poinçonner | ponsen |
| ream, to | aléser | uitboren |
| reamer | alésoir | poleerboor, ruimer |
| rim (rivet hole) | paroi (trou de rivet) | gatwand (klinknagelgat) |
| rivet | rivet | klinknagel |
| rivet buster | outil pneumatique (enlever la tête de rivet) | pneumatisch werktuig (klinknaglekop verwijderen) |
| rivet catcher | personne réceptionnant le rivet | persoon die de klinknagel ontvangt |
| rivet head | tête de rivet | klinknagelkop |
| rivet lap | pince longitudinale | eindafstand |
| rivet over, to | bouteroller | / |
| **rivet passer**, carrier | "passeur" de rivet | klinknagel "doorgever" |
| rivet pitch | entre-axe (rivets) | asafstand (klinknagels) |
| **rivet shank**, rivet shaft | tige de rivet | klinknagelschacht |
| **rivet snap**, driving die, riveting die | bouterolle | **snapper**, dopbeitel |
| rivet stoker, forge boy | chauffeur de rivet | klinknagel stoker |
| rivet-bolt, ribbed bolt | faux rivet | *faux rivet* |
| rivet, to | riveter, river | klinknagelen |
| riveter | (1) riveur (personne), (2) machine à river | (1) klinker (persoon), (2) klinkmachine |
| riveting | rivetage | klinknagelen, het |
| **riveting gang**, riveting crew | équipe de rivetage | klinknagelploeg |
| riveting hammer | **rivoir**, marteau à river | klinkhamer |
| riveting machine | machine à river | klinkmachine |
| round head | tête ronde (bombée) | bolronde kop |
| **shop head, manufactured head**, first head | tête de pose, première tête | zetkop |
| shop rivet | rivet installé en atelier | klinknagel op de werkplaats geklonken |
| shop riveting | rivetage en atelier | klinknagelen op de werkplaats |
| soaking time | durée de chauffage | verwarmingsduur |
| splice | raboutage | stuik |
| strike, to (manual riveting) | frapper (rivetage manuel) | slaan (handmatig) |

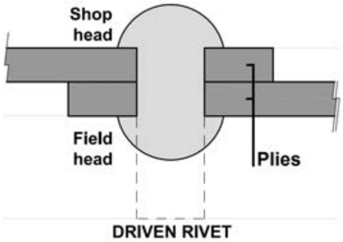
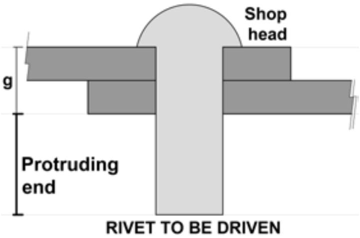
| | | |
|---|---|---|
| strip | lanière | riem |
| tearing (off) | arrachement | uittrekken, het |
| **tongs**, clip | tenailles, pince à rivet | nageltangen |
| **undrive**, unrivet, to | (1) pas encore riveté, (2) dériveter, dériver | (1) nog niet geklonken, (2) klinknagels verwijderen |
| upset, to (rivet shank) | refouler (tige de rivet) | opstuiken |
| white-hot | chauffé à blanc | witgloeiend |
| **zigzag riveting**, **staggered riveting**, cross riveting | disposition en quinconce (rivets) | zigzag schikking (groepering bij vijven) |

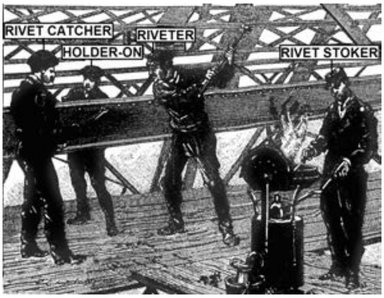
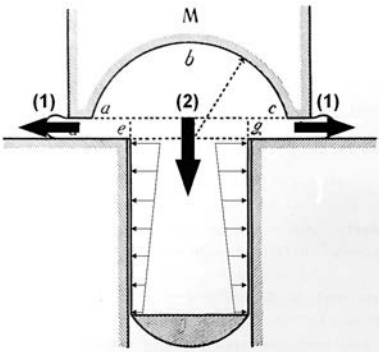
## 2 GLOSSARY

A brief definition of some of the above technical terms is given below (Tab. B):

Table B: Definition of technical terms and illustrations

| TERM (AND ILLUSTRATION) | DEFINITION |
|---|---|
| CAMMING EFFECT  (adapted from Vermes 2007, fig. 6; Twelvetrees 1900, fig. 42) | Prior to the driving operation, the rivet hole is not perfectly straight because of a misalignment of the plates that are tightened to one another. The riveting gang might have then carried out rivet driving without any hole adjustment. Actually, white-hot rivets were flexible enough to be placed in an imperfectly aligned hole. Hence, in its driven configuration, the irregularly-shaped rivet shank is not straight and has a variable cross section along the grip. (Vermes 2007, 3–4) |
| DRIVING TIME | The driving time represents the total duration of the driving operation – hand or machine riveting – that consists of forming the field head of the rivet by crushing its protruding shank end to fabricate the riveted connection. |
| FAUX RIVET  (DTC 1933, 135) | A *faux rivet* is a bolt where the bolt head has the form of a round rivet head. Another variation is the Dardelet "rivet-bolt" (Dardelet Threadlock Corporation, New York) used from the mid-1930s onwards in the US: "It consists of a standard rivet head, an axially ribbed neck or grip section, and a Dardelet-threaded end to which a nut is applied" (DTC 1933, 135). Rivet-bolts were used when high strengths were required and/or when not enough space was available to drive a rivet properly. |
| GAGE $G$   (Schenker, Salmon, and Johnston 1954, fig. 2–10) | It is assumed that one plate of a riveted connection can be virtually divided into a number of strips of equal width, each having a rivet hole in its center. The gage is the width of the strips. |

<table>
<tr><td>SOAKING TIME</td><td>The soaking time refers to the duration of rivet heating. It corresponds to the period during which the manufactured rivet is heated in the forge/furnace.</td></tr>
<tr><td>PACK RUST<br><br>(NACE 2014, ©Termarust - Wayne A. Senick)</td><td>In particular for riveted structures, pack rust is a localized corrosion that generally affects built-up members. It develops at the level of the faying surfaces between two plies. The deformation of the riveted connection can shear off the rivet head because of the increase in tensile stress that has to be taken up by the shank. Hence it cancels the frictional strength but might not affect the bearing strength of the connection. (Vermes 2007, 6)</td></tr>
<tr><td>PLY<br>
</td><td>A ply is the part of a plate or section effectively tightened to another ply/other plies by the two rivet heads. For instance, a rivet connecting three plates/sections clamps three adjoining plies. Throughout the study, the terms "ply" and "plate" can be considered synonymous for the sake of clarity.</td></tr>
<tr><td>PROTRUDING SHANK<br>
</td><td>Part of the shank that sticks out of the outer ply on the side on which the field head will be formed by the driving operation. Prior to rivet driving, the protruding shank length has to be accurately defined to satisfactorily form the field head and avoid the presence of defective characteristic(s).</td></tr>
<tr><td>RIVET BUSTER<br></td><td>Kind of pneumatic riveting hammer equipped with a chisel bit at its end. A rivet buster is used today to shear off the head of a rivet that has to be removed.</td></tr>
</table>

| | |
|---|---|
| RIVETING GANG   Manual riveting: rivet stoker, rivet catcher, holder-on and riveter (adapted from Tissandier 1889) | Members of the team in charge of the installation of rivets. Typically, manual riveting required the contribution of four to five persons: the rivet stoker heating the rivet, the rivet passer tossing the rivet to the rivet catcher who put it in the rivet hole, the holder-on holding in place the shop head and the riveter hammering on the protruding shank to form the field head eventually. Riveting gangs using machines to install rivets generally involve three persons: the rivet stoker, the holder-on and the riveter. |
| UPSET   (adapted from Frémont 1906, fig. 111) | The upset also called upsetting results from the driving operation aimed at the fabrication of the riveted connection itself. The protruding end of the heated rivet is deformed by the pressure applied by the hand-held hammer or riveting machine. It partially/completely fills the rivet hole and forms the field head. According to Frémont (1906), the upset develops in two stages. The field head is formed first and a lip around its bottom can be generated by the further crushing (1), provided that a sufficient protruding shank length was defined. Then, the material being compressed under the head fills the hole by lateral expansion until the crushing strength against the shank upset exceeds the development of the lip (2). (Frémont 1906, 69–70) |

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# APPENDIX

## PATENT DATABASE

A copy of the patent database dealing with the riveting technology that supports the quantitative and qualitative patent analyses of chapter 2 (PART I) is enclosed on the CD-ROM below[1].

180 patents registered in Belgium between 1830 and 1940 are listed in the patent database. The use of filters eases search queries within the database. To each filter corresponds a parameter that characterizes the patent. These parameters are concisely presented below:

PATENT NUMBER

Different numbering systems characterized the period 1830-1940. Until 1858, patent inventories[2] were handwritten and there was no table of contents. In most cases, the

[1] A digital copy of the thesis in PDF format is also enclosed on the CD-ROM.

patent number was a four-digit number (column header "Patent numbering B"). For some patents, however, the numbering was confusing as it combined two four-digit numbers, generally linked by a hyphen (combined "Patent numbering A" and "Patent numbering B"). Between 1859 and 1940, the patent number comprised four to six digits ("Patent numbering C").

#### PATENTEE

The patentee(s) was/were either a – group of – person(s) or a company. The family name and first letter of the first name(s) of the patentee(s) are provided.

#### PATENT TITLE

The patent title is the full title mentioned in the inventories. Note that this title could slightly differ from the one written on the patent application. Patent titles are provided in their original language (French).

#### PATENT TYPE

The abbreviations "Inv", "Imp" and "Perf" stand for *invention*, *importation* and *perfectionnement*[3].

#### FILLING YEAR

In the inventories, the filling year of patents registered before 1858 was not accurate since each inventory covered several years of registration. The specific year when the patent was registered was clearly provided from 1859 onwards.

#### INVENTORY

As a general rule, the title of the patent inventory was *Catalogue des brevets d'invention* between 1830 and 1854 (Dujeux 1842), and *Recueil spécial des brevets d'invention* from then on (RSBI). A volume number corresponds to most of the inventories. When applicable, the category to which the patent belongs is given. The category – a letter and/or a number – refers to a given field of industry such as (mining and) metallurgy, machines and mechanics or civil engineering.

[2] See the introduction of the study, section 4.1, for further information.

[3] *Perfectionnement* means improvement in French.

PATENT TOPIC (AND SUBTOPIC)

Each patent is described by one or two keyword(s) – a topic (and a subtopic) – to further ease search queries. The six topics used are as follows:

- rivets;
- rivets and bolts;
- rivets and nails;
- rivets and screws;
- rivets, bolts and screws;
- rivets, nails and bolts.

The above topics overlap with each other since most of the inventions concerned multiple types of fasteners.

The subtopics deal with manufacturing, heating and driving techniques. When available, the type of riveting machine is mentioned in the subtopic name – i.e., pneumatic or hydraulic riveting machine.

# RIVETED CONNECTIONS IN HISTORICAL METAL STRUCTURES (1840-1940)

## HOT-DRIVEN RIVETS: TECHNOLOGY, DESIGN AND EXPERIMENTS

QUENTIN COLLETTE

Waiting for a train at London St Pancras railway station or reading a book on the Berlin underground are simple everyday actions. Conversely, preserving the service life of such historical metal structures enabling those routine actions is a challenge. The overall safety and stability of historical iron and steel structures and, more in particular, the state of their connections, are of concern to engineers, architects and heritage care specialists. Rivets were the primary fastener used to fabricate these connections through a technique called *hot riveting*. Although well developed in the nineteenth century, hot riveting fell into disuse when the welding technique was invented. Nowadays, the appraisal of riveted connections raises numerous theoretical and practical issues that remain to be solved. Therefore, we reviewed international historical literature and carried out experiments. This study unravels the technology and design of historical riveted connections built in France and Belgium (1840s-1940s).

Major evolutions occurred at the turn of the 20th century. The material iron was replaced by steel, rivets were not installed by hand anymore but with machines, and the design of riveted connections relied on a scientific approach. The appraisal of riveted structures of that period thus calls for additional care. The knowledge of past techniques and design methods can help engineers apprehend the assessment of riveted connections with more confidence. The study supports decisions-makers and workmen for inspection, structural assessment and intervention purposes. We should strive to preserve both the service life and the heritage value of historical metal structures belonging to the city's landscape for the decades and hopefully centuries to come.

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