SAHC

A Study of Test Data for an Informed Assessment of Old Metallic Structures and Early Reinforced Concrete Structures

Mehdi Kord

Portugal | 2013

ADVANCED MASTERS IN STRUCTURAL ANALYSIS
OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

Master's Thesis

Mehdi Kord

A Study of Test Data for an Informed Assessment of Old Metallic Structures and Early Reinforced Concrete Structures

University of Minho

UNIVERSITAT POLITÈCNICA
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I hereby declare that the MSc Consortium responsible for the Advanced Masters in Structural Analysis of Monuments and Historical Constructions is allowed to store and make available electronically the present MSc Dissertation.

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Dedicated to my parents

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ABSTRACT

Over the course of the 19th century, structural framing was dominated first by cast iron, then wrought iron and finally steel. Many steel/iron constructions (buildings and bridges) of the 19th century and early 20th century belong to the cultural heritage of historical monuments. At the end of the 19th century the reinforced concrete was also invented. This composite material was rapidly a success due to its low cost and plastic component, from the architectural point of view.

The strength of existing iron and steel structures, or early reinforced concrete structures needs to be considered in relation to the standards in force at the time of original construction, although with extensive testing it may be possible to justify an increase in the allowable stresses specified at that time.

In metallic structures or reinforced concrete structures that were built between 1800 and 1940, the material parameters are in many cases not available. The knowledge on the material properties of existing structures is essential for the resistance assessment and for the determination of the remaining lifetime of these structures.

In the context of this dissertation, material properties of wrought iron, cast iron and steel used in various structures are investigated. Several experimental tests on wrought iron, cast iron and steel elements used in 19th and 20th century metallic and reinforced concrete structures have been done in different countries in order to analyze their chemical and mechanical properties. Collecting historical test results and recent test data obtained in experimental works gives a better understanding of the average values of properties of metallic materials.

This work is complemented with the experimental testing performed on steel reinforcement collected from an old reinforced concrete Portuguese bridge, built according to the Hennebique technique. Several test specimens are prepared from a steel bar sample collected in the bridge. A tensile test is done on each specimen and mechanical properties such as stiffness and strength, as well as the stress-strain curve are measured.

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RESUMO

No decorrer do Séc. XIX, os elementos estruturais mais usuais foram inicialmente realizados com ferro fundido, mais tarde com ferro forjado e por fim, já perto do final do século e no início do Séc. XX, em aço. Muitas das construções (edifícios e pontes) realizadas nessa altura fazem agora parte da herança cultural comum e algumas delas são monumentos históricos. No final do Séc. XIX, foi também inventado o betão armado. Este material tornou-se rapidamente num sucesso devido ao baixo custo e plasticidade, capaz de proporcinar novos desafios arquitectónicos.

A capacidade resistente de estruturas metálicas ou estruturas de betão armado antigas deve ser avaliada tendo em consideração os regulamentos vigentes à data da sua construção. No entanto, com base em resultados de ensaios experimentais, é possível justificar um aumento nas tensões máximas admissíveis à data de construção.

Nas estruturas metálicas construídas entre 1800 e 1940 ou nas estruturas de betão armado construídas no início do Séc. XX, os parâmetros definidores do comportamento dos materiais são em muitos casos desconhecidos. A caracterização dos materiais utilizados nessas estruturas é essencial para a avaliação do seu estado atual e para a determinação da sua vida útil restante.

No âmbito da presente tese, são analisadas as propriedades dos seguintes materiais metálicos utilizados em diversas estruturas construídas no final do Séc. XIX e início do Séc. XX, em diversos países: ferro fundido, ferro forjado e aço. São recolhidos resultados obtidos em ensaios de caracterização química e mecânica realizados com provetes dos materiais referidos. A recolha deste tipo de resultados, obtidos tanto na época em que as estruturas foram construídas como mais recentemente, permite obter um melhor conhecimento acerca dos valores médios dos parâmetros mais importantes para o comportamento dos materiais em estudo.

O trabalho desenvolvido é complementado com a realização de ensaios de caracterização mecânica realizados sobre provetes executados a partir de varões de aço recolhidos numa ponte portuguesa de betão armado, construída no início do Séc. XX segundo a técnica Hennebique. São testados vários provetes, sendo possível avaliar propriedades do aço como a rigidez e a resistência à tração. Também é medida completamente a curva de tensão-extensão.

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چکیده

در این پایان نامه ویژگی های فولاد چدن و آهن استفاده شده در سازه های مربوط به سده های گذشته مورد بررسی قرار میگیرد. بدلیل استفاده زیاد آهن و فولاد در سازه های ساخته شده بعد از انقلاب صنعتی بسیاری از این سازه ها که در حال حاضر متعلق به میراث فرهنگی میباشن در معرض خطر میباشند.

با پیشرفت روشهای ساخت آهن و فولاد در سده های نوزدهم و بیستم این مواد و مصالح فلزی به میزان زیاد در ساخت سازه ها مرد استفاده قرار گرفتند.در بیشتر سازه های فلزی قرن نوزدهم ویژگی های مکانیکی مصالح فلزی قابل اندازه گیری نبوده و داده های بسیار کمی از ویژگی های این مصالح در دسترس است.بدلیل اینکه بیشتر این سازه های فلزی در زمانی ساخته شده اند که قبل از گردآوری استانداردهای ساخت بوده است و داده های موجود در شرکت ها در دسترس است بنابراین بررسی بیشتر ویژگی های آهن و فولاد استفاده شده در سازه های سده های قبلی ضروری میباشد.

آزمایشهای آزمایشگاهی بسیاری بر روی چدن آهن و فولاد استفاده شده در سازه های فلزی و بتن آرمه سده های نوزدهم و بیستم به منظور ارزیابی ویژگی های فیزیکی شیمیایی و مکانیکی این مصالح صورت گرفته است.نتایج این آزمایش ها به منظور مقایسه با سازه های فولادی و بتنی جدید مورد بررسی قرار گرفته است.

همچنین در این پایا نامه یک بررسی موردی بر روی ویژگی های شیمیایی و مکانیکی میلگردهای فولادی بکاررفته در یک پل بتن آرمه ساخته شده با سیستم هنبیک در پرتغال مورد ارزیابی قرار گرفته است.ویژگی های شیمیایی و ترکیب شیمیایی یک نمونه میلگرد با تکنیک میکروسکوپ الکترونیک بررسی شده است. با انجام آزمایشهای کششی بر روی نمونه های مختلف میگرد ویژگی های مکانیکی از جمله کرنش مقاومت نهایی تنش مدول الاستیسیته تنش تسلیم و نمودار تنش-کرنش مورد ارزیابی قرار قرار گرفته است.نتایج این آزمایشها میتواند در نهایت با نمونه های مشابه ساختمان های ساخته شده در سده نوزدهم و بیستم مورد مقایسه و ارزیابی قرار بگیرد.

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1 INTRODUCTION

1.1 General

Over the course of the nineteenth century, structural framing was dominated first by cast iron, then wrought iron and finally steel. Many steel/iron constructions (buildings and bridges) of the 19th century and early 20th century belong to the cultural heritage of historical monuments. At the end of the 19th century the reinforced concrete was also invented. This composite material was rapidly a success due to their low cost and their plastic component, from the architectural point of view.

Cast iron is an alloy of iron and carbon with carbon content up to 5% (Derucher et al., 1998). As the name indicates, it is heated to molten state then poured and cooled in sand beds, allowing it to be easily casted into any shape. Cast iron has a granular internal structure and is therefore a brittle material that cannot be forged, welded or worked mechanically (Sutherland, 1997).

Wrought iron is almost the pure reduction of iron ore containing only trace amounts of carbon (less than 0.1%). In contrast to cast iron, it is strong in both compression and tension. It is ductile and malleable to be forged and bent. Moreover, it is tough and fatigue resistant. Ductility and tensile strength can be improved by reheating and reworking (Derucher et al., 1998). From the forging process, wrought iron obtains a fibrous internal structure similar to timber. The resulting ductile nature allows advanced warning prior to failure (Sutherland, 1997).

Practically all early structural steel materials were mild steels, or plain carbon steel, particularly before 1930s in the U.K. (Bussell, 1997). Steel is an alloy of iron and carbon like cast iron but with carbon level up to 2%. Modern steel, generally considered as steel produced after 1950, contains considerable amounts of other elements. Carbon content, portions of other elements, heating treatment and mechanical working together determine the strength of steel. Similar to wrought iron, steel is strong in both compression and tension (Derucher et al., 1998). The moderate carbon content gives steel a combination of strength, hardness and ductility. Its malleability allows it to be worked without breaking, but retains its shape even with heavy usage (Thorne, 2000).

The reinforced concrete was invented by Joseph-Louis Lambot e Joseph Monier at the end of the 19th century as an alternative structural system to the steel structures. François Hennebique (1842-1921), French Engineer, considerer as the “Napoleon of the reinforced concrete”, proposed and developed a structural system for beams, characterized by the use of U-shaped steel stirrups with rectangular cross-section, connecting the longitudinal bars from the positive to negative bending moment regions and by the use of longitudinal bars in the negative bending moment regions. For slabs, Hennebique proposed similar system to the one proposed for beams. In 1892 Hennebique patented his system which rapidly succeeds, being used in many countries with more than 40000 structures spread worldwide.

In structures that were built between 1870 and 1940, the material parameters are in many cases not available. The knowledge on the material properties of existing structures is essential for the resistance assessment and the determination of the remaining lifetime of these structures.

The strength of existing iron and steel structures, or early reinforced concrete structures needs to be considered in relation to the standards in force at the time of original construction, although with extensive testing it may be possible to justify an increase in the allowable stresses specified at that time.

This thesis focuses on collecting historical test data and more recent test data that can be useful in establishing average values for metallic materials, both used in 19th century metallic structures and early 20th century reinforced concrete structures. The work is complemented with some experimental testing performed on steel reinforcement collected from old reinforced concrete structures, built according to the Hennebique technique.

1.2 Motivation

After industrial revolution, many manufacturing methods of wrought iron, cast iron and steel invented and these metallic products were used massively in building structures. Dilapidation of the metallic structural elements in 19th century and early 20th century structures is endangering the strength of these structures. Analyzing the physical, chemical and mechanical properties of these elements which used directly as a main structural member or as composite elements with concrete is a good step for refurbishment of the old structures.

A better understanding of properties of elements can be done by collection and analysis of previous experimental test results in order to obtain the properties for further investigation. Also doing new experimental tests on properties of metallic elements of an old reinforced concrete, built in early 20th century in Portugal, is completing the main research of this thesis.

1.3 Objectives

This thesis aims to fulfill the following general objectives:

- To establish the relevant chemical and mechanical characteristics of the analyzed metallic materials
- To describe the methods and ways of production of the analyzed materials; raw materials, technology used, equipments needed.
- To collect historical experimental data and results of experimental tests previously performed by different authors
- To establish average values and a chronology for the characteristics of the materials studied
- To perform experimental tests on steel reinforcement bars collected from an old reinforced concrete structure.

1.4 Thesis organization

The present study is focused on the material characterization of old metallic structures and early reinforced concrete structures built during the 19th century and in the early 20th century. It begins by presenting the historical background on the application of metallic materials in different structures and also on the application of steel bars in the Hennebique construction system. It follows with information on the methods used to produce cast iron, wrought iron and early steel structural elements. The material characteristics of cast iron, wrought iron and early steel are also presented.

The collection of experimental results obtained in experimental tests performed by different authors in the past is investigated and followed with its evaluation. The thesis finishes with some experimental tests performed on samples of reinforcement collected in a bridge constructed according with the Hennebique construction system, located in Terras do Bouro village in Portugal. These tests are done to evaluate the mechanical behavior of these steel bars. The tests are performed in the University of Minho laboratory.

2 METALLIC MATERIALS IN 19TH AND 20TH CENTURY

2.1 General

A major change in the use of metallic materials happened during the industrial revolution period. In the 19th century the traditional building techniques that have been used up to that time were considerably changed owing to the use of cast iron and later wrought iron and steel. In fact, the industrial revolution, initially based in England, would not have been possible without these materials. The advent of more efficient production methods allowed the manufacture of large members; cast iron was used as a material in civil construction more frequently. The use of cast iron for structural purposes began in the late 1770s,when Abraham Darby III built the iron bridge, although short beams had already been used, such as in the blast furnaces at Coalbrookdale. These progressed via the puddling furnace, introduced by Henry Cort in 1784, which made possible the production of wrought iron, the Bessemer converter 1855, and the Siemens-Martin open hearth process and led to continuous improvements in building technology [38].

The rolling process, introduced in 1830s, allowed the shaping of wrought iron members in sufficient quality to make it a reasonable choice for structural material for the fabrication of T-beams and I-beams, which replaced their heavy and brittle cast iron predecessors, by 1845.

Wrought iron was eventually replaced in practically every civil application by structural steel in the late 19th century. As a result, wrought iron production on an industrial level has virtually ceased.

The main difference between cast iron, steel and wrought iron is the carbon content. The broad range of values for this proportion is given in Table2.1 (D.K.Doran, 1992), [5] .

Table 2.1 : Carbon content of cast iron, steel and wrought iron

Material	Carbon content (%)
Cast iron	2.0-4.5 (generally 2.5-4)
Steel	0.2-1.5
Wrought iron	0.025-0.5

By looking at the structural achievements with the iron and steel in the last 250 years, it is convenient to class these in relation to the period, or age, when each of the three ferrous metals was dominant. Inevitabley, these periods overlap and it is significant that in each case it took quite a long time-before what was found to be possible become commercially widespread. The periods are broadly as follows:

Cast Iron:

- Beams and inclined roof rafters, etc-from 1780 to 1870
- Columns-from 1850 to 1900

Wrought Iron:

- I-section beams and fabricated riveted plate girders and trusses-from 1850s until the 1890s
- Wrought iron columns are (cast iron columns were stronger and cheaper)
- Tie-rods and strapping to timber roof trusses-from late medieval times until the 1890s

Steel:

Introduced in 1885, dominant by 1900; had replaced both cast iron and wrought iron by 1914[39].

2.2 Cast Iron in 19th and 20th century

Cast iron, as the name implies, is”cast”or shaped by pouring molten metal into a mould and letting it solidify; a wide variety of often very intricate forms is thus possible. It is very strong in compression, relatively weak in tension. It is, much stiffer than timber, but brittle.

2.2.1 History of the use of cast iron in 19th and 20th century

The use of cast iron as a building material dates back to the second half of 18th century. During the period of 1830 to 1900 cast iron was extensively used as a building material and in many important structures. With the advent of more efficient production methods that allowed the manufacture of large members, cast iron was used more frequently as a material in civil construction material. A good example of its application is the Iron Bridge of Coalbrookdale, England (1779), the first metal bridge that spans 30m and survives to this day, Figure 2.1. The arched shape of the bridge is meant to make the maximum use of the material’s high compressive strength while attempting to avoid tension in all members [4].

The explosive growth of industrial activities in the 19th century was reflected in iron production and in the structural use of iron.

Before the 19th century and before changing the fuel from charcoal to coke, molten or cast iron was hard to produce on a large scale. Abraham Draby is generally credited with the mastery of coke smelting and even though this was in 1709, coke smelting did not dominate the industry until about 1750 in Britain and considerably later in other parts of Europe [4].

Between about 1810 and the early 1840s there was an increasing interest in cast iron floor beams. A Good example of these is the 12 meters span beams used in the British museum, in the early 1820.The first cast iron structures were mainly subjected to Compressive loadings [40].

Figure 2.1: The Iron Bridge of Coalbrookdale [44]

2.2.2 Types of cast iron

The major types of cast iron, used in 19th and 20th century are:

1. Grey cast iron

Grey cast iron is characterized by its graphitic microstructure, which causes a grey appearance in the fractured surface of the material [10].

It is the most commonly used cast iron and the most widely used cast material based on weight. Virtually all cast iron used structurally, has been grey cast iron, now known as flake graphite cast iron. The name comes from the dull grey appearance of a freshly fractured surface. The greyness comes from the flakes of graphite (pure carbon) that are deposited, as the molten iron cools slowly in a mould.

Grey cast iron was made from the best quality pig iron and was therefore the most reliable. It was produced by re-melting pig iron (when iron ore is first smelted, pig iron is the resulting material) in a furnace, skipping off the slag (waste material) which floats on the top, pouring this molten iron into a mould made of sand and then allowing it cool.

Silicon is essential to make grey cast iron. When silicon is alloyed with ferrite and carbon in amounts of about 2 percent, the carbide of iron becomes unstable. Silicon causes the carbon to rapidly come out of the solution as graphite, leaving a matrix of relatively pure, soft iron.

2. White cast iron

It is an iron that displays a white fractured surface due to the presence of cementite. With lower silicon content and faster cooling, the carbon in white cast iron participates out of the melt as the metastable phase cementite Fe_3C, rather than graphite. The cementite which participates from the melt forms as relatively large particles.

These eutectic carbides are much too large to provide precipitation hardening (as in some steels, where cementite precipitates might inhibit plastic deformation by impeding the movement of dislocations through the ferrite matrix).Rather, they increase the bulk hardness of the cast iron simply by virtue of their own very high hardness and substantial volume fraction, such that the bulk hardness can be approximated by a rule of mixtures.

In any case, they offer hardness at the expense of toughness. Since carbide makes up a large fraction of the material, white cast iron could be reasonably classified as cement. White iron is too brittle for use in many structural components, but with good hardness, high abrasion resistance and relatively low cost, it finds for use in such applications as the wear surfaces of slurry pumps, shell liners and lifter bars in ball mills and autogenously grinding mills, balls and rings .

White cast iron can also be made by using a high percentage of chromium in the iron. Cr is a strong carbide-forming element, so at high enough percentages of chrome, the precipitation of the graphite out of the iron is suppressed. High-chrome white iron alloys massive a casting to be sand cast, i.e., a high cooling rate is not required, as well as providing impressive abrasion resistance.

3. Malleable cast iron

Malleable iron starts as a white iron casting that is then heat treated at about 900 °C. Graphite separates out much more slowly in this case, so that surface tension has time to form into spherical particles rather than flakes. Due to their lower aspect ratio, spheroids are relatively short and far from one another, and have a lower cross section via a propagating crack or phonon. They also blunt boundaries, as opposed to flakes, which alleviates the stress concentration problems faced by grey cast iron.

In general, the properties of malleable cast iron are similar to mild steel. There is a limit to how large a part can be cast in malleable iron, since it is made from white cast iron.

4-Ductile cast iron

A more recent development is ductile cast iron. Tiny amounts of magnesium or cerium are added to these alloys. They slow down the growth of graphite precipitates by bonding to the edges of the graphite planes.

Along with careful control of other elements and timing, this allows the carbon to separate as spheroidal particles of the material solidify. The properties are similar to malleable iron, but parts can be cast with larger sections [4].

2.2.3 Application of cast iron

Because of the early manufacture method the casting molten iron into moulds, sections were purpose made of each particular application and therefore it is not possible to give details of actual shapes and sizes. The brittle characteristics of cast iron make it unsuitable for purposes where a sharp edge of flexibility is required.

The two main structural elements in cast iron are beams and columns, which were used either separately or together. For instance, cast iron beams were often supported on brick work or on columns and cast iron columns were used to support timber. In 19th century, cast iron survived in structural use only as an ornamental material on account of its ease of shaping while molten. Very large beams could be cast in sections and joined by bolts or be strengthened by trussing with wrought iron tie-rods.

Column bases were usually relatively simple, with an enlarged plate to spread the load, stabilize the column and sometimes engage a corresponding flange on the column below to which it might be bolted. Figure 2.2 shows a surprisingly common late 18th and early 19th century column head arrangement in mills and factories where power was supplied via belt-driven shafting from a central steam engine house [4].

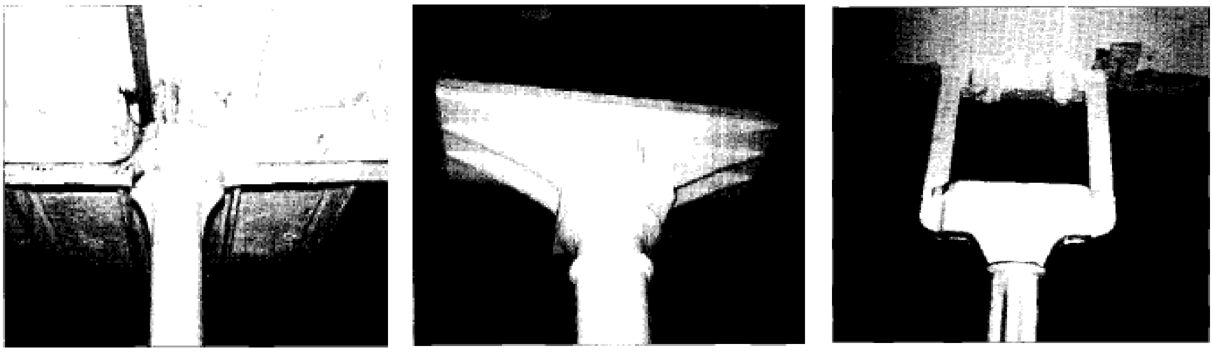


Figure 2.2: Typical cast iron column heads [4]

The solid cast iron arch is seldom found in buildings. The cast iron arch has however been widely used in bridge engineering, from the iron bridge of 1779 until the late 19th century.

Cast iron has been used only in small tie members and where the forces to be resisted are very modest, due to its weakness in tension.

The weakness of cast iron in tension does not make it a likely material for one-piece trusses. Certainly it was widely used for compression members in trusses assembled from individual components, but entirely cast iron trusses might seem unlikely. Cast iron was much used in the 19th century for secondary lattice elements such as cantilever brackets supporting railway station platform roofs.

Complete frames of cast iron are to be found in buildings as diverse as textile mills (beams and columns, with overall stability dependent on load bearing masonry walls) and large conservatories and greenhouses [11].

2.3 Wrought iron in 19th and 20th century

Wrought iron is a commercially pure iron(less than 0.1% carbon). In contrast to steel, it has very low carbon content. It is a fibrous material due to the slag inclusions (a normal constituent).This is also what gives it a "grain" that resembles wood; this appearance is visible when it is etched or bent to the point of failure. Wrought iron is malleable, tough, ductile and easily welded.

Wrought iron is produced by direct reduction of iron ore in the presence of carbon or by heating of cast iron in the presence of oxygen.

2.3.1 History of wrought iron in 19th and 20th century

Wrought iron, probably because it was costly to produce, began to be replaced by steel at about 1850 and very little wrought iron was used after 1890.There is evidence of some use of wrought iron sections as late as 1910 and also mixtures of wrought iron and steel in identical sizes in the same structure.

During the period 1850 to 1900, wrought iron was used to replace cast iron in beams for building construction. Some wrought iron joist shapes of very limited depth were produced; above around 20.32 cm riveted fabricated girders made up of angles and plates or in some instances of angles latticed with small plates, were used. The use of wrought iron in this period coincides with the advent of rationalized, engineered designed of structures, where the forms are dictated by structural requirements rather than architectural rules.

One of the earliest and most innovative uses of wrought iron in construction was as a reinforcing element in the form of clamps and bars, very similar to modern concrete rebar’s in form and function, in the construction of the Paris Pantheon in 1790 [41].

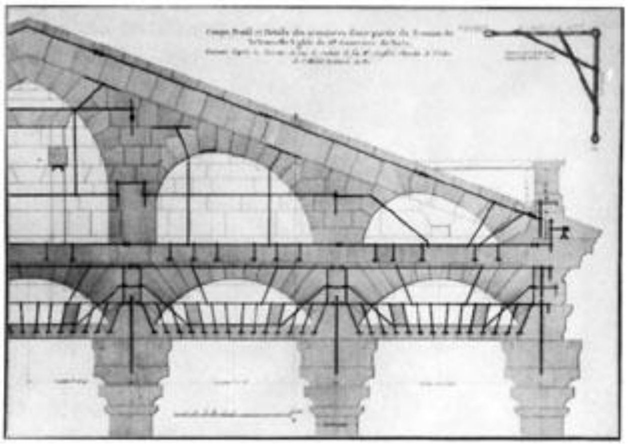


Figure 2.3 :Wrought iron reinforcement in Paris pantheon [41]

In the production of wrought iron from pig iron, Joseph Hall demonstrated in 1816 that the addition of iron waste from the slag expelled in wrought iron working produced a rapid reaction in the puddling furnace. The waste contained iron oxide; its oxygen reacted fiercely with carbon in the molten iron, producing raw iron and flameless carbon monoxide. Wrought iron also was cheaper to produce, more widely available and consequently rapidly displaced cast iron as the preferred metallic material. It was recognized that quality and tensile strength could be improved by re-working and several grades were adopted to identify the different types [38].

2.3.2 Application of wrought iron

In the early 19th century structural wrought iron changed from being essentially a “Craft” material to an industrial material. Certainly straps could still be made by hand on an anvil, but structural components needed stream-powered hammers, slitters and pressers. These could produce the simple basic sections that were available until the I-beam and channel were introduced around 1850.The most common wrought iron sections used in beams were small I-beams, often ‘compounded’ with riveted flange plates and plate girders made up largely from plate, angles, rivets.

The actual sizes of the angles used in girders can be determined by measurement. It can be assumed that many of the mild steel sizes given later were originally produced in wrought iron. It has been reported that the annual production of wrought iron plates and sections in 1870 amounted to around 3 million tones. When evaluating the strength of any structures, built between 1850 and 1890 caution should be adopted and the lower stresses of wrought iron assumed [8].

Wrought iron was not widely used for columns as cast iron was. Wrought iron columns are more common in industrial buildings (warehouse, factories, sheds, etc) where appearance was less important. By the end of the 19th century, various built-up multiple sections were being used. Solid fabricated arched wrought iron elements are sometimes found in roofing or larger buildings.

Wrought iron was the natural 19th century structural material for components in tension. It was exploited as straightforward rod, chain, cable and links. Wrought iron building frames and structures become common in the second half of the 19th century, particularly for industrial and commercial use as in railway stations, archades, factories and sheds [12].

2.4 Steel in 19th and 20th century (designated as early steel)

Steel is an alloy of iron and other elements, including carbon. When carbon is the primary alloying element, its content in the steel is between 0.002% and 2.1% by weight. Generally, carbon is the most important commercial steel alloy. Increasing carbon content increases hardness and strength. But carbon also increases brittleness and reduces weldability because of its tendency to form martensite. This means that carbon content can be both a blessing and a curse when it comes to commercial steel. And while there are steels that have up to 2 % carbon content, they are the exception. Most steel contains less than 0.33% carbon.

2.4.1 History of steel in late 19th and early 20th century

Until the mid 18th century, steel was difficult to manufacture and expensive. Steel was made in small quantities and used mostly for swords, tools and cutlery. Prior to the invention of Bessemer converter steel was made mainly by the so-called cementation process, Bars of wrought iron would be packed in powdered charcoal, layer upon layer, in tightly covered stones boxes and then heated. After several days of heating, the wrought iron bars would absorb carbon. The resulting blister steel would then be heated again and brought under a forge hammer to give it more resistance texture.

In the 1740s, while searching for higher quality steel for making clock springs, the English clockmaker Benjamin Huntsman for making clock springs, discovered that blister steel could be melted in clay crucibles and further refined by the addition of a special flux that removed fine particles of slag that cementation process could not remove. This was called Crucible Steel. It was of high quality but expensive [4].

During the last quarter of the nineteenth century, mild steel became increasingly used on account of its increased strength. It is reputed that by changing from wrought iron to mild steel for the forth railway bridge design stresses were increased from 5.0 to 6.5 tons per square inch.

Steel sections were produced in quantity from about 1883; through some smaller sections were available in mild steel before that date.

Prior to the formation of the British Standard Institute in 1900, shapes and sizes were settled by the individual manufacturer, mainly to meet their customer's requirements.

The beginning of the industrial revolution was severely hampered by the lack of a large-scale process for the production of good steel. The production of large amounts of steel was common, the essential part was blowing large amount of air into the fire with the aid of mechanical bellows powered by steam engines.

The leading British production accounted for 2.5 million tons of iron in 1850, but the production of steel was still a difficult and expensive business, accounting for a few percent of the total production.

The mass production of cheap steel only becomes possible after the introduction of the Bessemer process. In 1856 Bessemer designed a converter, a large, pear shaped receptacle with holes at the bottom to allow the injection of compressed air. Bessemer reasoned that carbon in molten pig iron unites rapidly with oxygen, so a strong blast of air through molten pig iron should convert the pig iron into steel by reducing its carbon content. After the production of steel in an industrial level was possible, structural steel members began to be used in the construction of bridges, skyscrapers, railroads and a multitude of other civil applications. Steel bars allowed the introduction of reinforced and prestressed concrete, which revolutionized civil construction.

This technique would once again change the appearance and structural function of metallic member connections, even though it would take a few more decades for the method to become advantageously useful and, as a consequence, widespread in civil construction.

After 1890, the Bessemer process was gradually supplanted by open hearth steelmaking and by the middle of the 20th century; it was no longer in use. The crucible process also remained important for making high quality alloy steel into the 20th century. By 1900 the electric arc furnace was adapted to steelmaking and by the 1920s, the falling cost of electricity allowed it to largely supplant the crucible process for special steels.

Steel has flourished in 20th century, and today is the natural choice for a structural frame in competition with reinforced concrete [31].

2.4.2 Application of steel in the late 19th and early 20th century

Early steel beams followed the form of wrought iron beams and developed deeper, heavier and wider compound sections. More recent developments include the castellated beam, patented in 1939 and the greater use of high tensile steel in beams, often of welded fabrication with additional flange plates, web stiffness and service openings in the beam web.

The steel truss is a very common structural element, often used in long span roofs but also found in galleries, long-span floors, and similar applications.

A common use of structural steel in early 20th century buildings was in foundation grillages under single or multiple columns and walls Figure 2.4. These grillages comprised one or more layers of steel beams, each acting as a spreader for the load above [4].

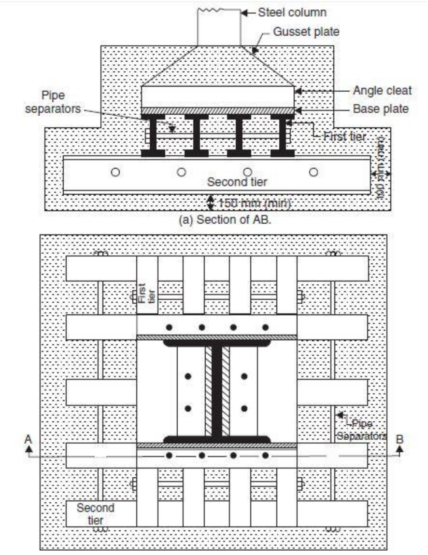


Figure 2.4: Typical foundation grillage in early
20th century building [4]

2.5 Application of metallic materials as composite elements

Cast iron and wrought iron often used as composite materials together or with combination with other materials such as masonry, timber and later with concrete, in order to achieve benefits such as fireproofing properties in construction. Steel also is used as an element in composite structures mostly like steel-concrete composite elements.

Wrought iron rod or bar was used as integral reinforcement in cast iron beams in tension zone. Similar reinforcement with wrought iron is found in ornamental cast iron brackets and cantilevers. Another use of wrought iron and cast iron as composite element is the combination of tensile strength of wrought iron tie-rods or tie-bars with the compressive strength of cast iron element in trussed beams [4].

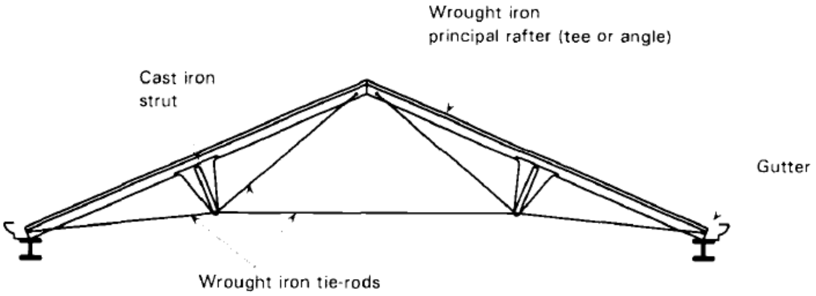


Figure 2.5: Composite cast and wrought iron roof truss [4]

In combination of iron and masonry, the early combination which was called ‘jack-arch’ floor, in which, brick (stone or concrete) barrel-vault was supporting by beams. The beams at the beginning were timber but later replaced by cast iron beams introduced in 1790s. Figure 2.6 shows the use of cast iron beams in jack-arch system.

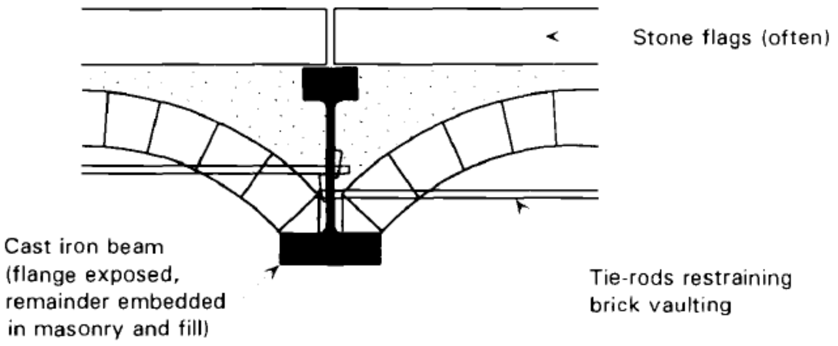


Figure 2.6: Section through a beam in jack-arch floor [4]

Another use of iron-masonry composite elements, is acting as a fireproof structure. This composite element consists of stone slab which were supported by small secondary cast iron beams.

In timber beams, wrought iron and cast iron plates were used as composite elements and also by using two plates bolted together and enclosing with the timber or by a sandwich combination of plate between two timber and bolted together. Timber trussed beams with wrought iron tie-rods have the same structure as trussed cast iron beams, which is using in dock, railways.

Filler -joist or joist-concrete structures were common composite constructions of concrete and iron (later steel) in floors or flat roofs.

Combination of steel and concrete which is known as reinforced concrete is introduced in the late of 19th century and beginning of 20th century. Early reinforcement concrete systems as composite elements were used steel bars and rod profiles as steel reinforcement [4].

2.6 Steel used in Hennebique construction systems (early reinforced concrete structures)

Francois Hennebique (1842-1921) was a French engineer and self-educated builder who patented his pioneering reinforced concrete construction system in 1892.He integrated separate elements of a construction, such as columns and beams, into a single monolithic element. The Hennebique system was the one of the first appearance of the modern reinforced concrete method of construction.

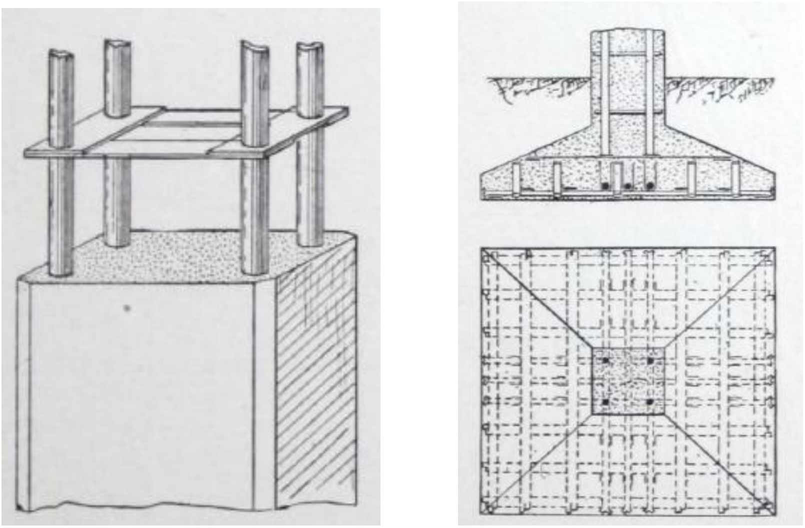
Hennebique had firstly worked as a stone man, later becoming a builder, with a particular interest in restoration of old churches. ‘Hennebique Béton Armé’ system started out by using concrete as a fireproof protection for wrought iron beams [13].

Originally, the Hennebique system was designed to withstand the tensile forces against the weakness of concrete elements. Hennebique’s idea of strengthening concrete consists of steel reinforcing bars that are embedded within the bottom face of the concrete slab. The idea of reinforcing concrete originated on a house project in Belgium in 1879 where Hennebique used concrete as a fireproof protection of wrought iron beams. In this house an iron frame was replaced by steel bars encased in concrete. The first reinforced concrete structure with this system was a bridge built in 1894 in Wiggen, Switzerland. Another example of using reinforced concrete was Imperial Palace Hotel in Nice (1900) which was the first hotel designed by the Hennebique reinforcing system [13].

2.6.1 Application of steel used in Hennebique construction systems in early 20th century

François Hennebique invented a rational kind of reinforcement for beams and columns. After several years of tedious and extensive tests, he patented and put on the market a system of construction of reinforced concrete in which the armature of the beams was formed by steel bars placed at the lower flange, where the tensile stresses occur, and by vertically placed stirrups embracing the steel tension bars, and intended to take the vertical and horizontal shear developed in the beams. Thus a rational reinforced concrete beam was formed, where the concrete taking care of all the compressive stresses and the steel taking care of tensile and shearing stresses.

The columns also was designed in this system according to the same principles and the steel rods were embedded near the corners and tied together at close intervals by means of hoop steel ties or collars, as shown in Figure 2.7.Columns consist of rods embedded in the concrete near the periphery. They are connected by means of ties of hoop iron or wire. Thus the radius of gyration is increased and the rods take care of the tensile stresses which occur from eccentric loading or from bulking of the columns. The horizontal ties prevent the bulking of the rods and increase the strength of the concrete.



(a) (b)

Figure 2.7: Hennebique elements (a) Column (b) Column footing [32]

Footing of columns are with steel rods, placed, from with the concrete a flat plate, which distributes the load equally over the soil, see Figure 2.7. These two elements of construction permitted Hennebique to erect buildings entirely in reinforced concrete. He also invented the bent bar thus designed more economical and stronger beams and girders. For two kinds of Hennebique floor beds, flat and arched, the reinforcement system is shows in Figure 2.8 and Figure 2.9 both types are well suited for longer spans. The small rise of the arched construction gives a very appearance and is adapted to the ceilings of crypts, etc.

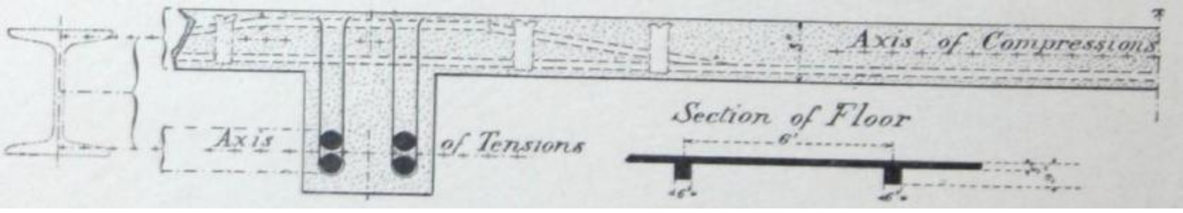


Figure 2.8: Flat floor Hennebique system [32]

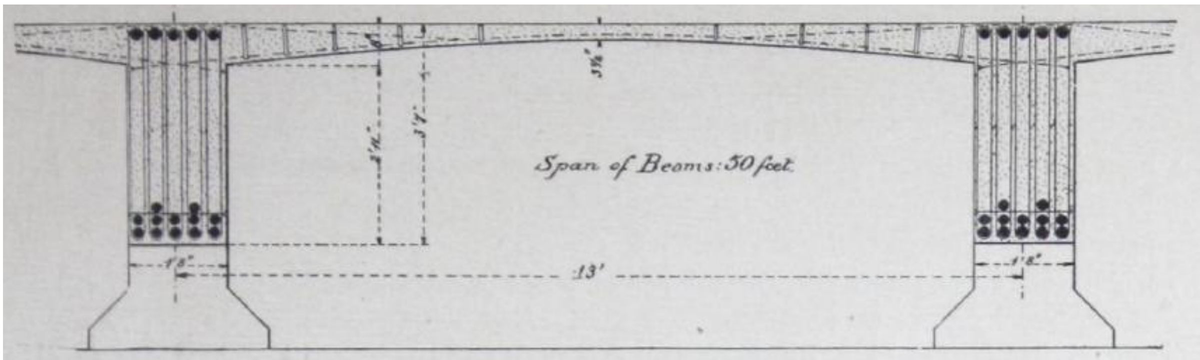


Figure 2.9: Arched floor Hennebique system [32]

In Hennebique beam, the concretes relied upon to resist the compressive stresses in the upper part of the system, while the steel rods resist all tensile stresses in the lower portion. The concrete also forms the connection between two flanges, assisted by the stirrups, generally formed of hoop steel. In beams, stirrups are placed closer together near the supports to take vertical shear stresses.

There are two kinds of rods in Hennebique beam, straight and bent. The bent rods, besides taking their proportions of the direct tension and of the shear, take any tensile stresses in upper part due to a negative bending moment over the support. Figure 2.10 shows the reinforcement system over support.

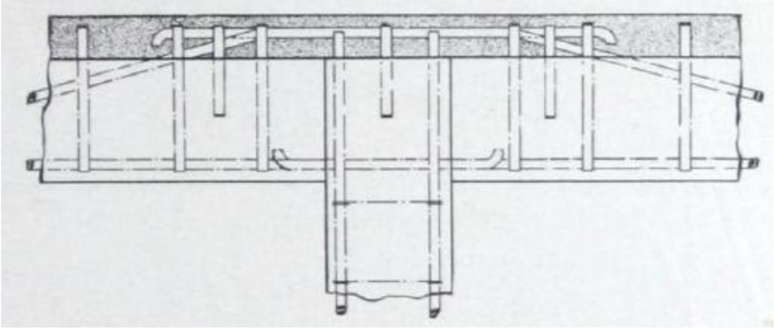
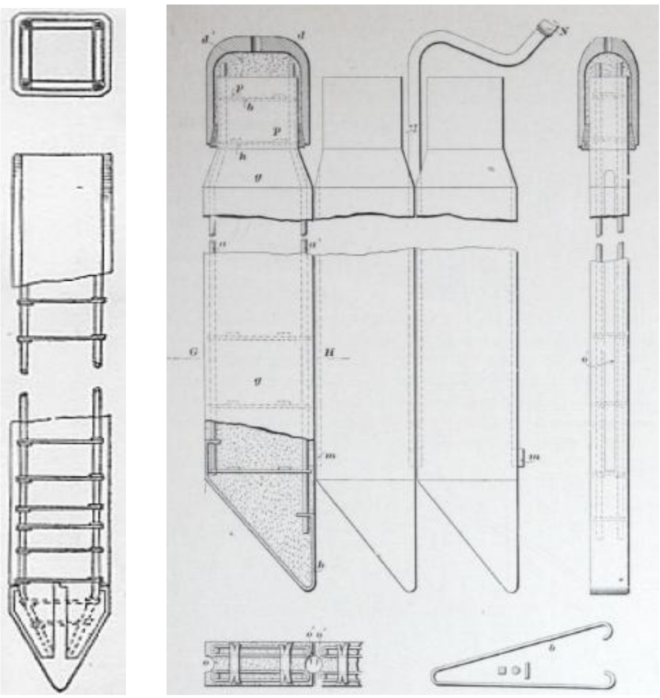


Figure 2.10: Reinforcement of beams over support in Hennebique system [32]

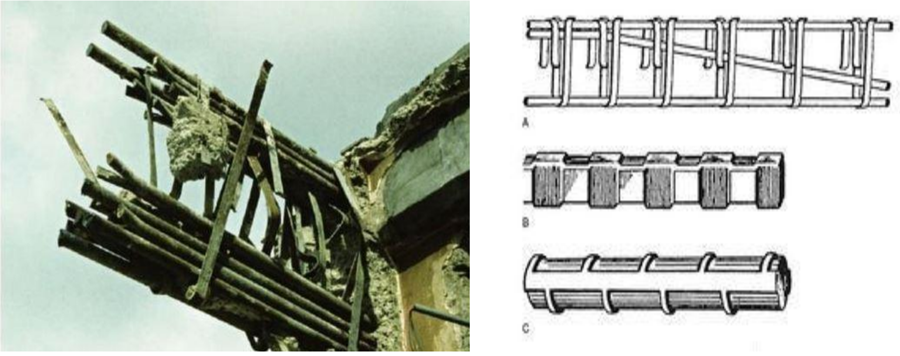
Hennebique pile is similar in construction to the Hennebique columns. It is protected by a cast iron or sheet metal shoe. In the sheet piles the point is formed by beveling one of the narrow faces so as to form a wedge with the opposite face, and the both narrow faces are slotted by a semi-circular groove running from point to butt. Figure 2.11 (a) also shows the use of Hennebique reinforcement pile and Figure 2.11 (b) shows Hennebique sheet pile.



(a) (b)

Figure 2.11: Hennebique elements:(a) Hennebique pile
(b) Hennebique sheet pile [32]

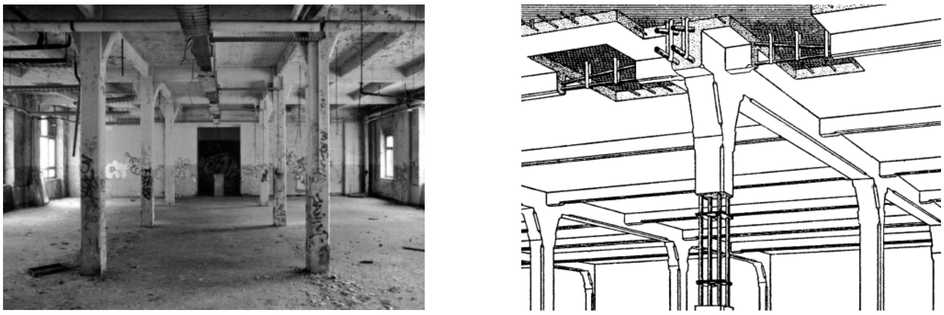
Hennebique reinforcing system was made by using of round mild steel bars in order to provide tensile resistance in bending and compressive strength in columns. In single span beams, only bottom reinforcement was necessary but for multi spans cantilevers and beams, also top reinforcement in order to resist tension forces, was provided. The ends of the bars were slit and spread to form Y-shaped to improve the mechanical anchorage of the bars in concrete and complementing the frictional bond between steel bars and concrete. By using flat steel strips or linked wrapped around the bars, shear resistance of the elements will improve. A Hennebique structure of 1907-10 in London reveals during demolition a beam by using the round bars and flat stirrups in both bottom and top of the beam showed in Figure 2.12 (a) .Some common patent reinforcement bars in Hennebique systems are shown in Figure 2.12 (b).



(a) (b)

Figure 2.12: Hennebique system(a) King Edward street post office, London 1907-10 , (b) Hennebique reinforcement bars (A indented ,B square ,C round) [34]

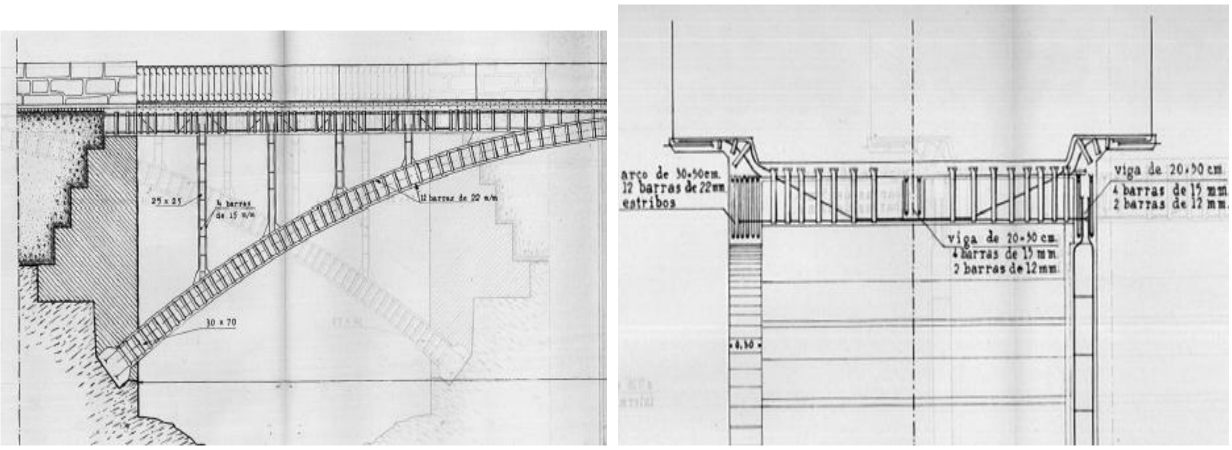
One of the examples of Hennebique construction system is printer shop at Leipzig in Germany which is recognized as the oldest Hennebique construction in Germany. The multi-story structure in reinforced concrete following Hennebique invention in Germany was erected in 1898 which brick walls and brick-vaulting supported by cast iron and steel columns and steel beams. The reinforcement bars used in the columns is affected by perforated strips of sheet-iron and the binding of the reinforcement bars in the trusses was also done with bended strips of sheet-iron [34].



(a) (b)

Figure 2.13: Printer shop at Leipzig, Germany: (a) The interior of the first floor (b) Hennebique's drawing showing the reinforcement with the bars of sheet-iron [34]

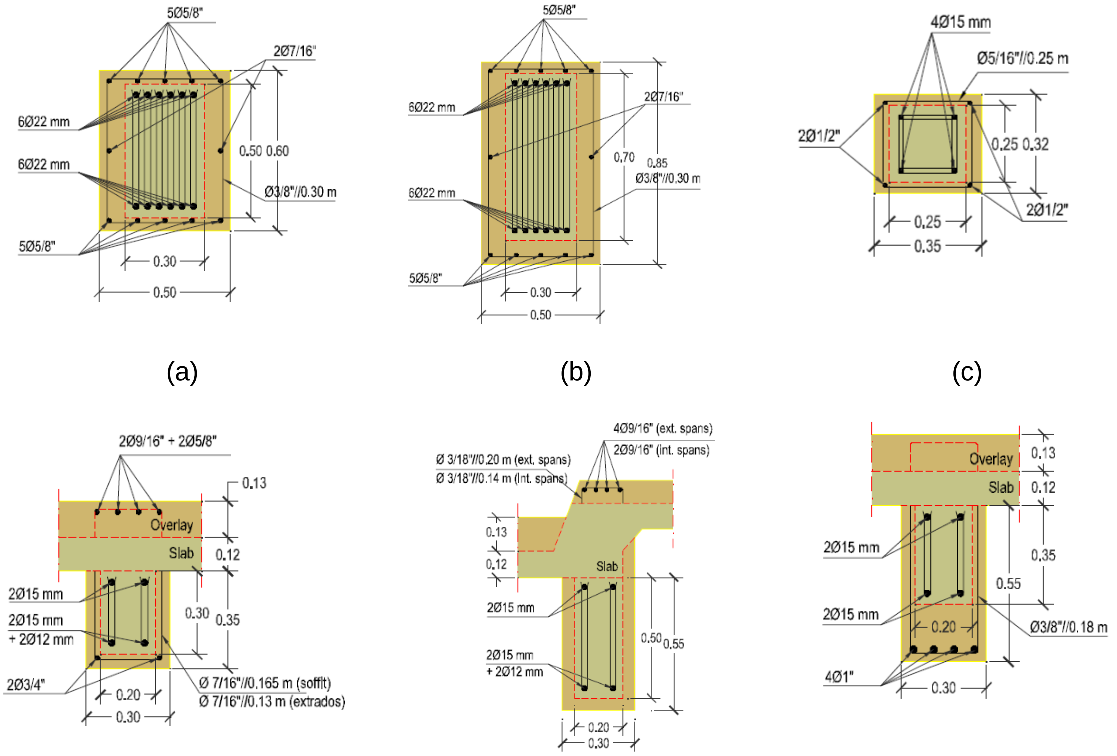
Another example of Hennebique reinforced system is Bôco Bridge in north of Portugal. The bridge was built in between the years of 1909 and 1910 by Moreira de Sá & Malevez Company, dealers of the patented Hennebique system in Portugal. The structure of the Bôco Bridge shows two parallel arches, with a rectangular cross-section of 0.30 m x 0.70 m at the abutments, and 12 longitudinal steel bars of diameter (12Ø22) and stirrups with characteristic U-shape. The deck of the bridge, with 0.12 m thick, is supported by two lateral longitudinal girders with a cross section of 0.20 m x 0.50 m with 2Ø15 at the top and 2Ø12+2Ø15 at the bottom (Sena-Cruz et al., 2012). Figure 2.14 shows the original geometry and steel reinforcement used in the deck of Bôco Bridge [35].



(a) (b)

Figure 2.14: Original geometry and steel reinforcement : (a) downstream elevation (b) cross-section of the deck [35]

Steel bars used in the Hennebique reinforcement structure of Bôco Bridge shows as cross-sections in Figure 2.15.



(a) (b) (c)

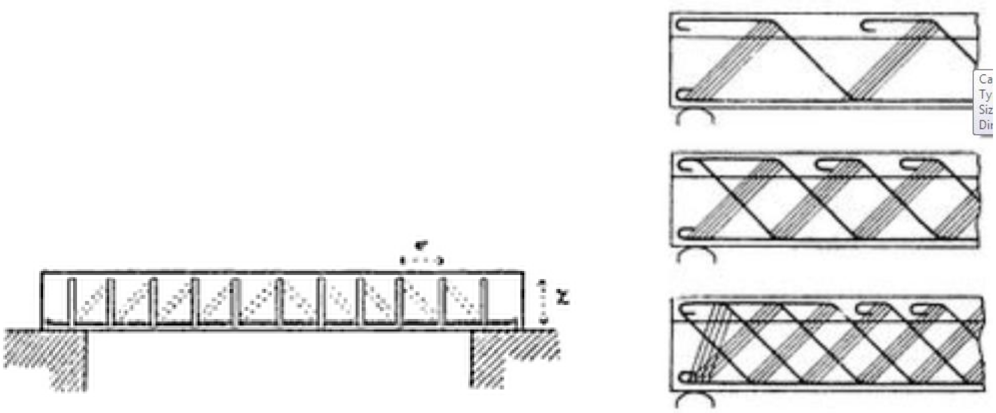
(d) (e) (f)

Figure 2.15: Current cross-section geometry (a) arches at mid span (b) arches at the abutments (c) columns (d) intermediate longitudinal girders (e) lateral longitudinal girders (f) transverse girders [33]

Another type of Hennebique system which is attributed to Francois Hennebique is the first trussed framework model for a reinforced concrete beam. According to Hennebique, the bars of flat steel placed around the longitudinal round steel bars should resist the shear forces. For designing and calculating the allowable shear forces of the trussed framework model, Hennebique assumed that the stirrups together with the longitudinal bars and the concrete form a sort of truss framework, which stirrups presented as tie and concrete acted as struts. Figure 2.16 (a) shows the Hennebique trussed framework.

Another trussed framework in Hennebique system, designed by Emil Morsch in 1903, shows the improvement of shear resistance by using 45^{o} bent up longitudinal bars in bottom of the beam Figure 2.16 (b).

The patents of Hennebique system's were used in large number of structures built in England during the period of 1897 to 1919, including buildings, bridges, viaducts, maritime structures , tanks , water towers and canal works. In these structures, steel reinforcement was placed correctly in the tension zone of the concrete structures. Figure 2.17 shows the use of general arrangement of reinforcement in beams and use of plates in columns in order to tie the vertical reinforcement [32].



(a) (b)

Figure 2.16:Hennebique reinforcing(a) Hennebique trussed framework model,1899 (b) Morsch’s trussed framework model [32]

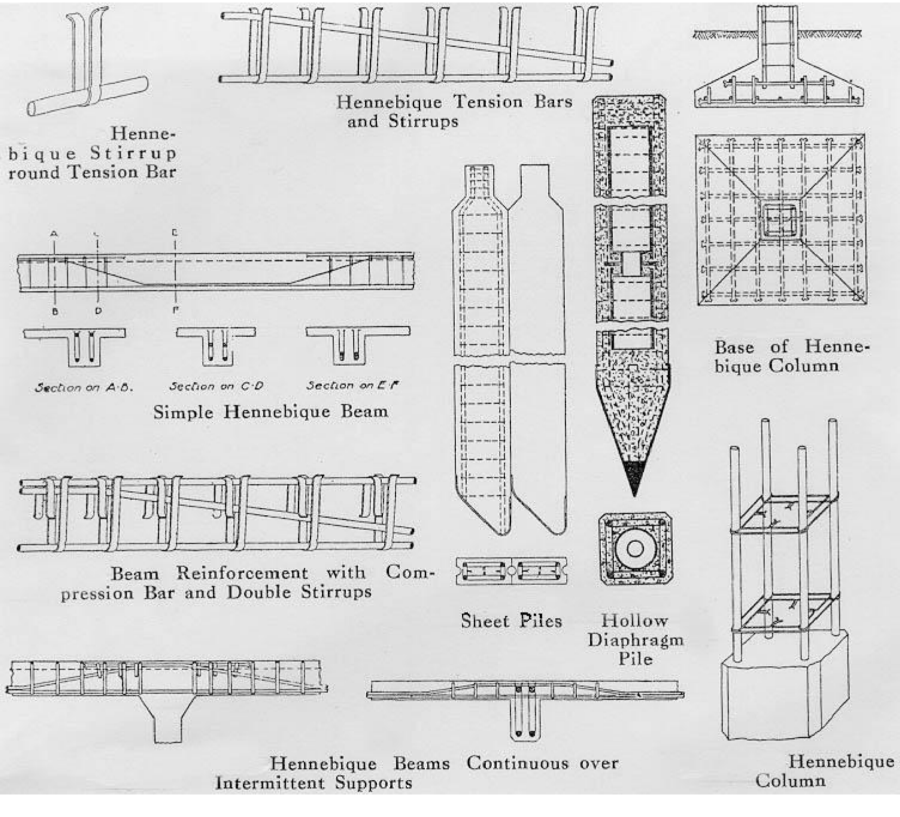


Figure 2.17: general reinforcement in Hennebique system [32]

3 Production methods

3.1 Production of materials

The production of iron by humans began sometimes after 2000 BCE in the Bronze Age in south-west or south-central Asia, in the Caucasus region. Thus began the Iron Age, when iron replaced bronze in implements and weapons. This shift occurred because iron when alloyed with a bit of carbon, is harder, more durable and holds a sharper edge than bronze.

The earliest method of extraction, possibly discovered by chance in the Bronze Age (c.2000 to c.1000 BC), was by heating iron ore in contact with the charcoaled embers of a wood fire. The carbon in the charcoal combined with oxygen in the iron ore at 700°C, resulting in a spongy solid lump of iron knows as a bloom. This was a mixture of pure iron and cementite (iron carbide), with charcoal and other impurities that had not been driven off by modest heat [38].

In Europe, there was no fundamental change in the technology of iron production for many centuries. Iron productions were continued in bloomeries. The medieval period brought two developments, the use of water power in the bloomery process and the first production of cast iron. (A history of metallurgy, R.F.Tylecote)

Before industrial revolution production of iron was restricted to small-scale smelting of iron ore, and the amount that could be produced was limited. Iron was produced by smelting it with charcoal (wood that has been heated in the absence of air to burn off the impurities in the wood leave it enriched in carbon. This partial burning produces an excellent fuel which is much more effective than wood.

Charcoal is more than just a heat source for producing iron from its ores. The key step in smelting iron ore to make raw metal is providing a reducing agent as well as heat: a reducing agent is a chemical that reacts with the iron oxides in the ore to release the iron in metallic form. The simplicity of charcoal is that it acts as both the heat source and the reducing agent.

The development of cast iron as an engineering material is very much the story of the Darby family, who developed large-scale methods of making valuable material.

Abraham Darby had the idea of using not coal, but coke to smelt the iron. Coke is made by controlled heating of coal in same way that charcoal is produced from wood. Coke was the key step in developing a furnace capable of making cast iron on a large scale. The old furnace, parts of which still exist today, was the forerunner of the modern blast furnace. It was used to make the members of the first cast iron bridge, spanning the Severn at coalbrookdale, which also still stands [4].

Figure 3.1: The old furnace of coalbrookdale [38]

In this furnace, coke, together with limestone and iron ore, was fed in at the top and heated by burning in air that was fed in lower down; the molten cast iron was extracted at the base. The air was fed in by pipes leading in about halfway up the furnace, which blasted a draught of hot air to the charge. The mechanical properties of the coke were important because the mixture had a porous enough so that reduction of the ore proceeded smoothly, and it had to resist the weight of material above it. The molten iron could be tapped and run directly into moulds. This furnace was especially important for making the key parts of steam engines. Some of the carbon of the coke dissolved in the iron (about 4%) to give the material a relatively low melting point, but also made the material relatively brittle. The limestone helps in the reduction process, and also mops up some of the impurities to form a slag that floats on top of the liquid iron, and can be removed separately.

A key discovery was that the amount of carbon present in the iron controlled not only its melting point but also its properties. By controlling the additions of carbon through the use of coke, a form of iron was made which could be cast on the industrial scale.

More ductile wrought iron could be made at the start of the industrial revolution, but only by a slow, small-scale and labor intensive process, so wrought iron was an expensive commodity.

The critical step forward was made by Henry Bessemer in 1856, in a series of classic experiments with various designs of furnace of burning off the carbon in the iron.

In Europe, the first traces of the blast furnace with charcoal as a combustion material were found in the Rhine valley in the 15th century and in Belgium in the 16th century. As from that date on, it was possible to produce pig iron [39].

In the 17th century, it was Abraham Darby who in 1709 invented a practical method of producing pig iron with coal.

Iron exists naturally in iron ore. Since iron has a strong affinity for oxygen, iron ore is an oxide of iron. It also contains varying quantities of other elements such as silicon, sulfur, manganese and phosphorous.

Smelting is the process by which iron is extracted from iron ore. When iron ore is heated in a charcoal fire, the iron ore begins to release some of its oxygen, which combines with carbon monoxide to form carbon dioxide. In this way spongy, porous mass of relatively pure iron is formed, intermixed with bits of charcoal and extraneous matter liberated from the ore, known as slag. The formation of this bloom of iron was as far as the primitive blacksmith. This is wrought iron (Wrought means" worked ") and contained generally from 0.2 to 0.8 percent of carbon, just enough to make the metal both tough and malleable. Wrought iron was the most commonly produced metal through most of the Iron Age [10].

At very high temperatures, the iron begins to absorb carbon rapidly and the iron starts to melt, since the carbon content lowers the melting point of the iron. The result is cast iron, which contains from 3 to 4.5 percent carbon. This high proportion of carbon makes cast iron hard and brittle, it is liable to crack or shatter under a heavy blow and it cannot be forged at any temperature.

By the late middle ages, European iron makers had developed blast furnace tall chimney-like structure in which combustion was intensified by a blast of air pumped through alternating layers of charcoal, flux and iron ore.

Until the mid 1800s, steel was difficult to manufacture and expensive. It was made mainly by the so-called cementation process. Bars of wrought iron would be packed in powdered charcoal, layer upon layer, in tightly covered stone boxes and heated. After several days of heating, the wrought iron bars, would absorb carbon; to distribute the carbon more evenly, the metal would be broken up, rebounded with charcoal powder and reheated. The resulting blister steel would then heat again and brought under a forge hammer to give it more consistent texture [17]

Powered Bloomeries

Bloomery is a type of furnace once widely used for smelting iron from its oxides. The bloomery was the earliest form of smelter capable of smelting iron. A bloomer’s product is a porous mass of iron and slag called a bloom. This mix of slag and iron in the bloom is termed sponge iron, which is usually considered shingled and further forged into wrought iron.

A bloomery consists of a pit or chimney with heat-resistant walls made of earth, clay or stone. Near the bottom, one or more pipes (made of clay or metal) enter through the side walls. These pipes, allow air to enter the furnace, either by natural draft, or forced with bellows [39].

An opening at the bottom of the bloomery may be used to remove the bottom, or the bloomery can be tipped over and the bloom removed from the top.

The first step taken before the bloomery can be used in the preparation of the charcoal and the iron ore. The charcoal is produced by heating wood to produce the nearly pure carbon fuel needed for the smelting process. The ore is broken into small pieces and usually roasted in a fire to remove any moisture in the ore.

The small particles of iron produced in this way fall to the bottom of the furnace and become welded together to form the spongy mass to the bottom. The bottom of the furnace also fills with molten slag, often consisting of favalite, a compound of silicon, oxygen and iron mixed with other impurities from the ore. Because the bloom is highly porous, and its open spaces are full of slag, the bottom must later be reheated and beaten with a hammer to drive the molten slag out of it. Iron resulted in this way is wrought and resulting nearly pure iron wrought iron or bar iron. It is also possible to produce blooms coated in steel by manipulating the charge of and air flaw to the bloomery [40].

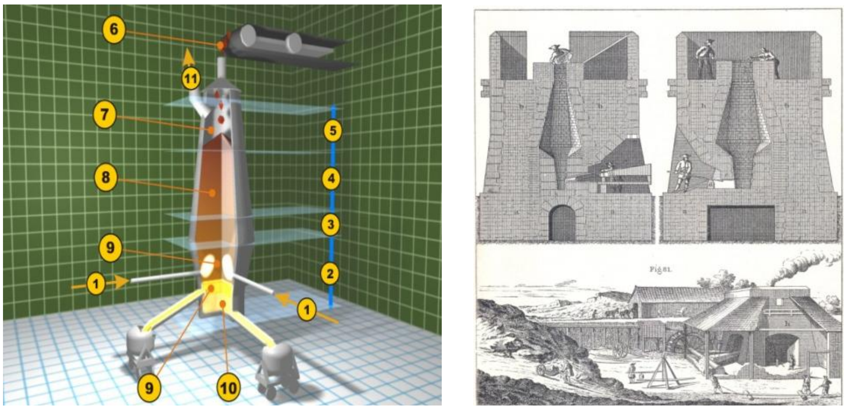
Blast Furnace

A blast furnace is a type of metallurgical furnace used for smelting to produce iron. The raw materials used to produce pig iron in a blast furnace are iron ore, coke, sinter and limestone. Iron ores are mainly iron oxides and include magnetite, hematite and many other rocks. The iron content of these ores ranges from 70% down to 20% or less. Coke is a substance made by heating coal until it becomes almost pure carbon. Sinter is made of lesser grade, finely divided iron ore which, is roasted with coke and lime to remove a large amount of the impurities in the ore. In a blast furnace, fuel, ore and flux (limestone) are continuously supplied through the top of the furnace, while air is blown into the lower section of the furnace, so that the chemical reactions take place throughout the furnace as the material moves downward. The end products are usually molten iron and slag phases tapped from the bottom and flue gases existing from top of the furnace.

Blast furnace is a tower-shaped structure, made of steel, and lined with refractory or heat resistant bricks. The mixture of raw material, or charge, enters at the top of the blast furnace. At the bottom of the furnace, very hot air is blown, or blasted, in through nozzles called tuyeres. The coke burns in the presence of the hot air. The oxygen in the air reacts with the carbon in the coke to form carbon monoxide. The carbon monoxide then reacts with the iron ore to form carbon dioxide and pure iron [38].

The molted iron sinks to the bottom of the furnace. The limestone combines with the rock and other impurities in the ore to form a slag which is lighter than the iron and floats on top. As the volume of the charge is reduced, more is continually added at the top of the furnace. The iron and slag are drawn off separately from the bottom of the furnace. The melted iron might go to further alloying process, or might be cast into ingots called pigs. The slag is carried away from disposal.

The hot gases produced in the chemical reactions are drawn off at the top and routed to a gas cleaning plant where they are cleaned, or scrubbed and sent back into the furnace; the remaining carbon monoxide, in particular, is useful to take chemical reactions going on within the furnace [25].



(a) (b)

Figure 3.2: Blast Furnace Diagram [25]

1. Hot blast from Cowper stoves
2. Melting zone
3. Reduction zone of ferrous oxide
4. Reduction zone of ferric oxide
5. Pre-heating zone
6. Feed of ore, limestone and coke
7. Exhaust Gases
8. Column of ore, coke and limestone
9. Removal of slag
10. tapping of molten pig iron
11. collection of waste gases

The starting of blast furnace in operation is called 'blowing in'. A light fire is started in the hearth and is for a while supplied only with enough fuel to keep it going. Care must be taken to heat up and dry out the furnace very slowly to avoid cracks in the newly built or repaired parts or in the slag coating which acts as a protection to the furnace walls. Limestone occurs naturally and is a source of calcium carbonate.

A blast furnace is used for smelting to produce industrial metals such as iron. In this technique, iron ore and charcoal (or coke) is charged from the top. Air is blown in the bottom. The coal burnt to CO which reacts with the ore and reduces it [38].

In principle: The waste rock in the ore is lighter that iron and floats as slag. The melted iron and the slag are tapped at the bottom.

The raw materials used to produce pig iron in blast furnace are iron ore, coke, sinter and limestone. Iron ores are mainly iron oxides and include magnetite, hematite, limonite and many other rocks. The iron content of these ores ranges from 70% down to 20% or less. Coke is substance made by heating coal until it becomes almost pure carbon. Other metals are sometimes mixed with iron in the production of various forms of steel, such as chromium, nickel, manganese and etc [31].

Finery process

A Finery forge is a hearth used to fine wrought iron, through the decarburization of the pig iron produced by blast furnace. Finery forges were used as early as 3rd century BC, based on archeological evidence found at a site in Tieshengguo, China. The Finery forge process was replaced by puddling process and roller mild, both developed by Henry Cort in 1783-4, but not becoming widespread until after 1800.

In the Finery, a workman known as the finer re-melted pig iron so as to oxidize the carbon(and silicon).This produced a lump of iron(with some slag) known as bloom. This was considerate using a water-powered hammer and returned to the finery.

The next stages were undertaken by a hammer man, who in some iron-making areas was also known as the stringsmith, heating his iron in a string-furnace. Because the bloom is highly porous, and its open spaces are full of slag, The hammer man’s or string smith’s tasks were to beat the heated bloom with a hammer to drive the molten slag out of it, and then draw the bloom out into a bar to produce what was known as bar iron. In order to do this, he had to reheat the iron, for which he used the chafery. The fuel in the finery had to be charcoal because impurities in any mineral fuel would affect the quality of the iron [39].

Cementation Process

The cementation process is an obsolete technique for making steel by carburization of iron. Unlike modern steel making, it increased the amount of carbon in the iron. It was apparently developed before the 17th century. Derwentcote steel furnace built in 1720 is the earliest surviving example of cementation furnace.

The process begins with wrought iron and charcoal. It uses one or more long stone pots inside a furnace. Typically each was 14 feet by 4 feet and 3.5 feet. Iron bars and charcoal are packed in alternating layers, with a top layer of charcoal and then refractory matter to make the pot or coffin airtight. Some manufacturers used a mix of powdered charcoal, soot and mineral salts called cement powder. In large works up to 16 tons of iron was treated in each cycle.

Depending on the thickness of the iron bars, the pots were heated from below for a week or more. Bars were regularly examined and when the correct condition was reached the heat was withdrawn and the pots were left until cool, usually around fourteen days. The iron had gained a little over 1 % in mass from the carbon in the charcoal, and had become heterogeneous bars of blister steel [31].

Crucible steel process

The crucible steel process starts with the manufacture of special clay pots or crucibles. These are about 50 cm tall and about 20 cm wide. Each can hold about 20 kg of steel.

The crucibles are heated in a coke fired furnace set in the floor for the furnace shop. When they are at white heat, they are filled with broken bars of steel and a flux to collect impurities. As lid is then placed over the pot and the furnace is charged with more coke.

The steel is then melted for about three hours. The furnace operator keeps adding more coke and checks the melting steel at the same time. To start with, the steel bubbles as it melts. Eventually the bubbling stops and the surface of the melt become clear. The steel is now ready for teeming.

The pot is lifted out of the furnace using long handled tongs which grip round the outside of the crucible. The pot is then stood on the furnace room floor and picked up using another set of tongs which fit round the middle of the crucible.

The molten steel is then poured from the crucible into the cast iron ingot mould. When the steel has solidified and cooled, the mould is opened so that the steel bar can be removed.

After the steel has been poured, the crucible is replaced in the furnace and another charge of raw steel is added for melting. Most of the crucibles can be re-used for three melts before becoming too weak, when they are thrown away.

Direct Reduce Iron

It is produced from direct reduction of iron ore by a reducing gas produced from natural gas or coal. The reducing gas is a mixture majority of hydrogen and carbon monoxide, which acts as reducing agent.

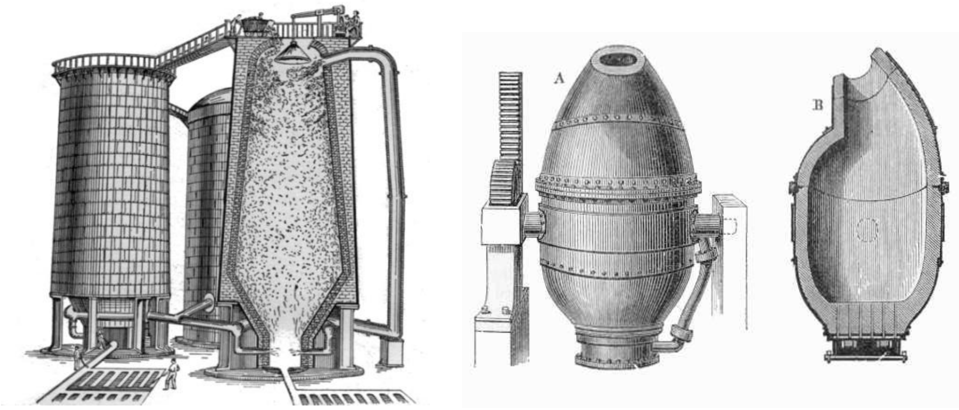
Direct reduction, an alternative route of iron making has been developed to overcome some of these difficulties of conventional blast furnace. DRI is successfully manufactured in various parts of the world through either natural gas or coal based technology.

In this process, iron ore is reduced in solid state at 800 to 1800^{o} C either by reducing gas ($\mathrm{H_2 + CO}$) or coal.

Hot blast

It refers of preheating of air blown into a blast furnace or other metallurgical process. As first developed it worked by alternately shoring heat from the furnace flue gas in a firebrick lined vessel with multiple chambers, then blowing combustion air through the hot chamber. This is known as regenerative heating. This has the result of considerably reducing the fuel consumed in the process. This was invented and patented for iron furnace in 1828 in Scotland, but was latter applied in other contexts, including late bloomeries. Later the carbon monoxide in the flue gas was burned to provide additional heat.

Hot blast was the single most important advance in fuel efficiency of the blast furnace and was one of the most important technologies developed during the industrial revolution.



(a) Hot blast furnace (b) Bessemer Process

Figure 3.3: Iron making process (a) hot blast furnace (b) Bessemer process [40]

Bessemer process

The Bessemer process was the first inexpensive industrial process for the mass production of steel from the molten pig iron prior to the open heath furnace. The process is named after its inventor Henry Bessemer, who took out a patent on the process in 1855.The process, was independently discovered in 1851 by William Kelly. The process had also been used outside of Europe for hundreds of years, but no on an industrial scale. The key principle of is removal impurities from the iron by oxidation with air being blown through the molten iron. The oxidation also raises the temperature of the iron mass and keeps it molten.

When required steel has been formed, it is poured out into ladles and then transferred into moulds while the lighter slag is left behind. The conversion process called the blow is completed in around twenty minutes. During this period the progress of the oxidation of the impurities is judged by the appearance of the flame issuing from the mouth of the converter. The modern use of photoelectric methods of recording the characteristics of the flame has greatly aided to blower in controlling the final quality of the product. After the blow, the liquid metal is recarburized to the desired point and the other alloying materials are added, depending on desired product. Figure 3.3 (b) shows the Bessemer converter [25].

Basic oxygen process

It is a method of primary steel making in which carbon-rich molten pig iron is made into steel. Blowing oxygen through molten pig iron lowers the carbon content of the alloy and changes it into low-carbon steel .The process is known as basic due to the type of refractories-Calcium oxide and magnesium oxide-that line the vessel to withstand the high temperature of molten metal.

In this process, First molten pig iron from a blast furnace is poured into a large refractory-lined container called a ladle. The metal in the ladle is sent directly for basic oxygen steel making or to a pretreatment stage. Pretreatment of the blast furnace is used to reduce the refining load of sulfur, silicon and phosphorus. In desulfurizing pretreatment, a lance is lowered into the molten iron in the ladle and several hundred kilograms of powdered magnesium are added. Sulfur impurities are reduced to magnesium sulfide in a violent exothermic reaction. The sulfide is then raked off.

Filling the furnace with the ingredients is called charging. This process is autogenous: the required thermal energy is produced during the process. Maintaining the proper charge balance, the ratio of got metal to scrap, is therefore very important. The vessel is one-fifth with steel scrap. Molten iron from the ladle is added as required by the charge balance [25].

The vessel is then set upright and a water-cooled lance is lowered down into it. The lance blows 99% pure oxygen onto the steel and iron, igniting the carbon dissolved in the steel and burning it to form carbon monoxide and carbon dioxide, causing the temperature to rise about 1700^{o}C. This melts the scrap, lowers the carbon content of molten iron and helps remove unwanted chemical elements.

Fluxes are fed into the vessel to form slag, which absorbs impurities of the steel making process. During blowing the metal in the vessel forms an emulsion with the slag, facilitating the refining process. Near the end of the blowing cycle, hick takes about 20 minutes, the temperature is measured and samples are taken. The vessel is tilted again and steel is poured into a giant ladle. This process is called tapping the steel. The steel is further refined in the ladle furnace, by adding alloying materials to give the steel special properties required by the customer. After the steel is removed from the vessel, the slag, filled with impurities, is poured off and cooled [38].

Electronic arc furnace

It is a furnace that heats charged material by means of an electric arc. Arc furnace differ from industrial furnace in that the charge material is directly exposed an electric arc, and the current in the furnace terminals passes through the charged material.

The cycle will starts with the charging of the furnace with steel scrap. After the furnace is charged and the roof is in place the operator lower the electrode or electrodes, each of which has its own regular and mechanical drive. Current is initiated and the electrodes bore through the scrap to form a pool of liquid metal. The scrap helps to protect the furnace lining from the high intensity arc during meltdown.

Subsequently, the arc is lengthened by increasing the voltage to maximum power. Most modern furnace equipped with water cooled panels in the upper half of the sidewall, rather than refractories, which allow for longer arcs and higher energy input to the furnace in the final stage, when there is a nearly complete metal pool, the arc is shortened to reduce radiation heat losses and to avoid refractory damage and hot spots. After meltdown oxygen is injected to oxidize the carbon in the steel or charged carbon [25].

3.2 Production of structural elements

Iron has been produced for several thousands of years but it was not until the eighteenth century that it began to be used as a structural material. The first cast iron bridge by Darby was built in 1779 at Coalbrookdale in Shropshire. Fifty years later wrought iron chains were used in Thomas Telford’s Menai straits suspension bridge. However, it was not until 1898 that the first steel frame building was constructed. Nowadays most construction is carried out using steel which combine the best properties of cast and wrought iron. Cast iron is basically remelted pig iron which has been cast into definite useful shapes.

Cast iron Elements

Cast iron components were manufactured by casting the molten metal in sand moulds that allowed fairly complex shapes to be produced. Cast iron was formed into structural elements by pouring the molten and extremely fluid material into moulds formed in damp sand.

The ends of structural elements were shaped during the casting process to facilitate jointing. By the end of 18th century, the craft of sand moulding was highly developed so that intricate and complicated shapes could form quickly and accurately. Much of this skill went into stylistic enterprises like mass producing columns but it means that the problem of connecting one element to another could be tackled in a divers rang of ways.

The manufacturing process of cast iron elements begins with a pattern, typically in wood. This is made slightly larger than the required cast iron element, since cast iron shrinks about 1% as it cools from molten to solid. The design of pattern is important; though must be given to cooling rates, the rapid and unhindered flow of molten iron, and ease of pattern removal from the mould.

An ideal cast iron section would be thin and hollow, and spherical as the former aspects promoter rapid cooling and hence greater tensile strength, while the shape, by symmetry, eliminates the development of shrinkage stresses by minimizing restraint. Reality demands thicker, irregular sections for structural use, but even the skilled pattern-maker can help by careful design [4].

The pattern is placed in a mould. For structural castings it is and was normal to use compacted sand, either green-sand (damp, highly adhesive sand) or dry-sand (sand dried or backed before casting), both of which would hold their shape while the molten iron solidified.

For hollow sections, such as cylindrical columns, an internal core would be required. This might be positioned eccentrically, or distort during casting, resulting in an unsymmetrical cross-section which could affect structural performance.

Once the iron has cooled, the mould is removed and the casting is cleaned of flash metal that has leaked into mould joints or poorly compacted sand-by fettling it follows that every sand or loam mould is made and used once only, being broken up to release the casting, while wooden cores are rapidly charred by the molten iron and do not lost long. Fettling cleans off surplus iron but does not usually remove the characteristic sandy or gritty surface texture of the casting.

Cast iron beams evolved as research, testing and understanding combined to produce structurally more efficient shapes. Figure 3.4 show typical cast iron beams cross-sections [4].

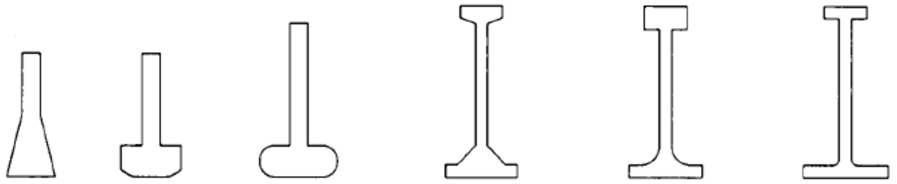


Figure 3.4:Typical cast iron beams cross-section [4]

The profiles generally show an awareness of the relative weakness of cast iron in tension, as reflected by an enlarged bottom flange, and also of the variation of being moment along the beam, resisted efficiently by the fish-belly or humpbacked bowing of the beam elevation and/or by a similar bellying-out on plan of the flanges. The moulding and casting process made such variation very easy to achieve.Very large beams could be cast in sections and joined by bolts, or be strengthened by trussing with wrought iron tie-rods .

As with beams, the nature of cast iron made sectional and elevational variations easily possible. Small sections were usually star-shaped or cruciform (Figure 3.5).these was found to cool more rapidly and with less risk of shrinkage cracking than a solid square. Experience again no doubt showed that solid circular columns (Figure 3.5 (a), Figure 3.5 (b)) cooled faster and were less likely to crack. Columns developed from crude star-shapes section to cruciform with projecting ribs, often moulded with a shape following classical principles for stone pillars.

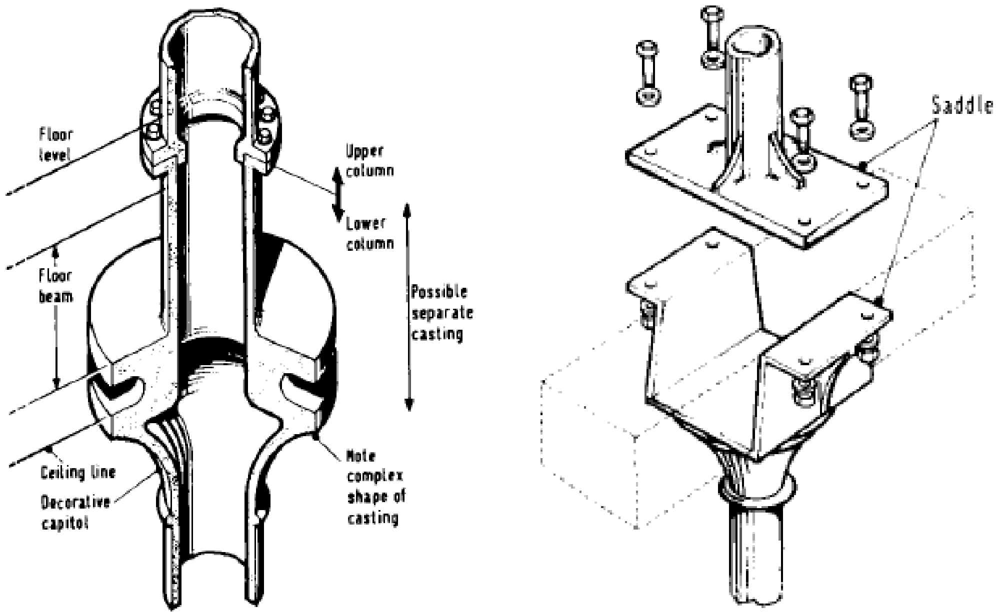


Figure 3.5: Typical cast iron columns and sections [4]

Wrought iron elements

In the early 19th century structural wrought iron changed from being essentially a craft material to an industrial material, although the blacksmith may well have had a hand (literally) in the smaller components of some buildings. Certainly straps could still be made by hand on anvil, but practical structure components needed steam-powered hammers, slitters, rolls and presses. These could produce the simple basic sections: plates, angles and tees, all that were available until the I-beam and channel were introduced towards 1850.Even the I-beams deeper than about 1 foot (305mm) were seldom rolled in wrought iron, although sections 20 inches(508mm) deep or more are known [12].

The rolling process meant that wrought iron sections were essentially of constant cross-section. In this respect, wrought iron structural elements resemble steel members used today, although the former are likely to be made up of more, smaller components riveted together, whereas the latter typically comprise a few larger components connected by welding.

The most common wrought iron sections used in beams were small I-beams, often compounded with riveted flange plate and plate girders made up largely from plate, angles and rivets. Such girders-much used for railway bridge-may have flange plates added towards midspan to increase their bending strength and web stiffer provided it might be assumed to enhance shear resistance to resist concentrated web loads. More practically, it should be recognized that the web plates, of limited size, had to be connected to each other as well as to the flanges and the web stiffer also served for this. Typical cross-section of wrought iron beams and plates shows girders in figure 3.6:

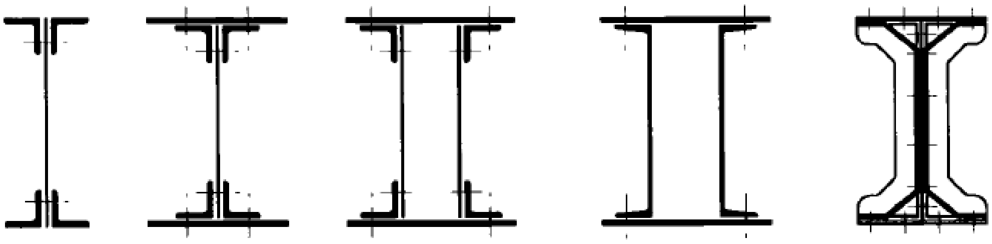


Figure 3.6 :Typical cross-section of wrought iron beams and plates shows girders [4]

Wrought iron columns would generally be either I-beams or built-up plate sections, with or without additional flange plates.

Solid fabricated arched wrought iron elements are sometimes found in the roofing of larger buildings. They would be cheaper than might be expected since they would be fabricated in the same way as a straight girder, with only tapered web plates and kinked flange plates distinguishing them.

Tie rods could be rolled directly from flat bar. The rolling process produced a road with excellent longitudinal strength, and it could be easily worked to form a flattened end which could then be drilled to receive a pin. Alternatively, it could be threaded for attachment of a nut or hammered out to form an enlarged head [4].

Steel

Steel section were produced in quantity from about 1883 through some of the smaller sections were available in mild steel before that date. Early steel beams followed the form of wrought iron beams and developed deeper, heavier and wider compound sections. In normal building use, these sections were based on I-beams with riveted flange plates, which is commonly made with structural steel. Instance of true plate girders were common where long spans and/or heavy loading demanded it. These were riveted until the Second World War, although welding was available at that time.

Rolled steel beams are made by forcing pliable metal through large rollers so as to flatten and mold it into the desired shape. Beams can be either hot-rolled. Hot-rolled beams are made from steel that has been heated above the recrystalization point (over 1000 degrees) and then rolled. Cold-rolled beams are made from steel that has not been heated before rolling. Beams can also be fabricated by extrusion, in which the steel is forced through a die; this can also be done either hot or cold [31].

Beams can also be fabricated by welding. In this process, sheets of steel are cut to the desired specifications and then welded together using industrial welding tools. The beams can be made by riveting as well. For riveting, sheets of steel are cut, holes are cut into the steel pieces and the pieces are held together by rivets to form beams.

More recent developments include the castellated beam, patented in 1939 when it was known as the ‘Boyd beam’ and the greater use of high tensile steel in beams, often of welded fabrication with additional flange plates, web stiffeners and service openings in the beam web. Hollow steel tubes were produced from the turn of the century in round, square, hexagonal, octagonal and other shapes. Beam supports and base plates would be riveted to the tubular profiles [4].

4 Material properties of iron

The element Iron (in Latin: Ferrum) is atomic number 26, relative atomic mass 55.85.It is the most common element (by mass) forming the planet earth. Its abundance makes it most used metal in civil construction or otherwise, constituting 95% of all metal used worldwide. Much of Iron normally occurs of three oxidation states iron (metallic iron), iron (II) (Iron with a charge of 2+) and iron (III) (Iron with a charge of 3+).Iron (II) and iron (III) compounds were formerly called ferrous and ferric respectively. Some of its physical and chemical properties are in Table 4.1:

Table 4.1: Chemical and physical properties of pure iron

Density	g/cm^3	7.874
Melting Point	K	1811
Magnetic order		Ferromagnetic -1043K
Electrical Resistivity	nΩm	96.1
Thermal Conductivity	W$m^{-1}k^{-1}$	80.4
Thermal Expansion	$\mu mm^{-1}k^{-1}$	11.8
Speed of Sound	m/s	5120

Pure metallic iron is characterized by its high strength, relative softness and tendency to revert to its most common form, which is most type of iron oxide or carbonate like magnetite ($\mathrm{Fe_3O_4}$), hematite($\mathrm{Fe_2O_3}$),goethite(feo(oh)),limonite(FeO(OH).n$\mathrm{H_2O}$) or siderite(Fe$\mathrm{CO_3}$).The elastic and strength properties of pure iron are presented in the Table 4.2:

Table 4.2: Elastic and Strength properties of pure iron

Young’s Modulus	GPa	211
Shear Modulus	GPa	82
Bulk Modulus	GPa	170
Poisson’s Ratio		0.29
Mohs Hardness		4.0
Vickers Hardness	MPa	608
Brinell Hardness	MPa	490

The most common contaminants in iron ore are silicon, phosphorus, aluminum and sulphur. To bypass the natural shortcomings of pure iron, it is not used in metallic form but in some type of alloy in which the chief contaminant is carbon. The chemical compositions of some type’s commercially available iron are presented in the Table 4.3: [22]

Table 4.3: Chemical composition of some forms of iron (%)

Material	Fe	C	Mn	S	P	Si
Pig Iron	91-94	3.5-4.5	0.5-2.5	0.018-0.1	0.03-0.1	0.28-3.5
Carbon Steel	98.1-99.5	0.07-1.3	0.3-1.0	0.002-0.06	0.002-0.1	0.005-0.5
Wrought Iron	99-99.8	0.05-0.25	0.01-0.1	0.02-0.1	0.05-0.2	0.02-0.2

Carbon content defines much of the final alloy’s characteristics and, most importantly, the type of the ally. Cast iron, wrought iron and steel each have distinct properties that differ considerably from each other. Figure 4.1 shows the phase diagram of iron carbides. For carbon content values over 2% the material is considered cast iron, below 0.25% wrought iron and steel for intermediate values [40].

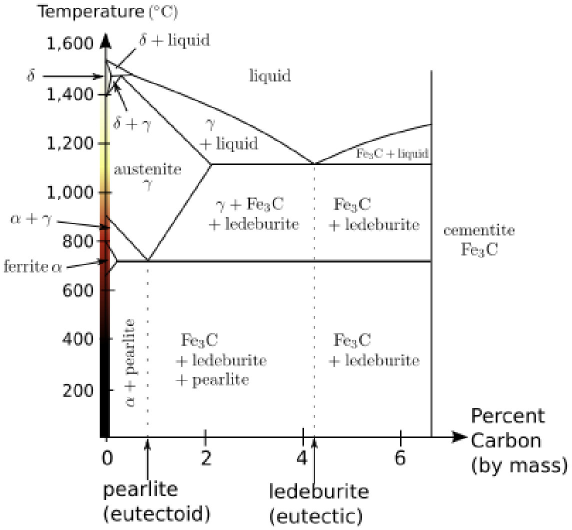


Figure 4.1: Equilibrium diagram of combinations of carbon in a solid solution of iron [42]

Mechanical properties of the metallic material reveal the elastic and inelastic reaction when force is applied or involve the relationship between stress and strain, such as elasticity, tensile strength or fatigue limit. In the metal industry they are typically derived from microstructures of investigated materials. It means that the precise metallographic sample must be cut and analyzed visually.

The mechanical properties of structural iron were also significantly improved in the years following the onset of the industrial revolution, both in terms of strength and ductility, owing to advances in the chemical manipulation and technological aspects of iron production [22].

The capability of decreasing or orienting slag inclusions in more than one direction reduced the inhomogeneity of the final product. The bare wrought iron and slag grains running in one main direction, plate iron, made of cross piling bars, had about the same ultimate tensile strength and ductility along the grain and reduction of less than the typical 15% across the grain for bar iron. The improvements through time can mainly be observed in examining structural and reinforcement steel strength during 20th century.

4.1 Properties of cast iron

Cast iron is one of the oldest ferrous metals used in construction and outdoor ornament. It is primarily composed of iron (Fe), carbon(C) and silicon (Si), but may also contain traces of sulphur (S), manganese (Mn) and phosphorus (P). It has relatively high carbon content of 2% to 5%.It is a complex alloy containing mainly a total of up to 10% carbon, silicon, manganese, sulphur and phosphorus as well as varying amount of nickel, chromium, molybdenum, vanadium and copper. The metallic matrix of common boundary cast iron consists of perlite and ferrite in the structure with the same form of graphite precipitation that improves the mechanical properties.

Virtually all cast iron used structurally has been grey cast iron, now known as flake graphite cast iron. The name comes from the dull grey appearance of a freshly fractured; as compared with the brighter surface of a white chilled cast iron. The greyness comes from flakes of graphite (pure carbon) which are deposited as the molten iron cools slowly in a mould. White iron is either cooled quickly or contains other trace elements, so that carbon in the form of graphite flakes doesn’t occur. Another variant, mottled iron, in intermediate between grey and white cast iron in possessing some flakes of graphite but like the white form, it is not normally found in structural use [11].

The carbon content of commercial cast iron ranges between about 2% and 5%.The lowest melting point of pure iron carbon system is at about 1150^o C, when the carbon content is around 4.25% In 18th and 19th century iron furnaces, liquid iron was produced at the near this lowest melting point once sufficient charcoal or coke had provided some carbon to combine with the iron. Impurities would contribute to this process by reducing the actual carbon requirement, the overall effect-taken with the relatively slow air cooling in a mould-being to produce grey cast iron.

To modify the constitution and properties of a grey cast iron, it must be either re-melted or reduced in carbon content, as in making wrought iron or steel, or cooled very rapidly to produce white or chilled iron which can then be subjected to heat treatment to give malleable cast iron.

The graphite flakes have a profound influence on the properties and on the behavior of grey cast iron. Effectively, having no strength, these flakes acting as voids or cracks within the iron whose behavior therefore is not that of a homogeneous material. Under tensile stress the cracks are stress-raisers, with the consequence that grey cast iron has a low tensile strength, typically one-quarter to one-third of its compressive strength [18].

A more recently developed from of cast iron is the spheroidal or nodular graphite variety, obtained by adding magnesium and sometimes cerium during manufacture. In this, as in the heat-treated malleable irons, there are no graphite flakes: the carbon is present in other forms such as chemically combined cementite (ferrite carbon) or graphite nodules. These results in a higher tensile strength and improved ductility compared with grey cast iron [4].

Table 4.4: Typical properties of structural grey cast iron [4]

Property	Typical Value (N/mm^2)
Ultimate Tensile Strength	
Lowest	65-100
Mean	123
Highest	150-280
Flexural tensile strength(Modulus of Rapture)	
Rectangular bar not exceeding 2.54 cm wide	315
Rectangular bar 7.62 cm wide	208
Round bar 2.54 cm diameter	355
Round bar 5.08 cm diameter	309
I-Beams of various section sizes	116-134
Ultimate compressive Strength	587-772
Ultimate shear Strength	Not less than UTS
Young's Modulus Tension(kN/mm^2)	66-94
Compression(kN/mm^2)	84-91
Poisson Ratio	0.25

Of direct interest to structural engineers is the flexural tensile strength or modulus of rupture of cast iron. For brittle materials, such a grey cast iron, flexural tensile strength can be calculated conventionally by assuming that the section is linear elastic, so that the modulus of rapture can be determined by dividing the bending moment at failure by the elastic section modulus.

For various reasons-including the nonlinear behavior of grey cast iron-the modulus of rapture is not a true stress in the way that the tensile strength of a bar can be called a true stress, but it is useful parameter.

Essentially both tensile strength and modulus of rapture of cast iron diminish with increase of the tested section size.

.It is also resistant to destruction and weakening by oxidation and has good fire resistance, both major factors to be considered in its application. It is very high compressive strength, comparable to that of mild steel. It is easy and cheap to produce, its cost being a fraction that of wrought iron and steel. Cast iron is crystalline in composition. It is strong in compression but weak in tension. Its high carbon content means that it is hard and strong but also brittle. Grey cast iron (the most commonly used type of cast iron for architectural castings) is formed by re-melting pig iron in furnace, skimming off the slag(waste material) which floats on the top, pouring this molten iron into a mould made of sand and allowing it cool.

Its high carbon content gives cast iron a series of characteristics common among most of its varieties. As its name implies, it boasts good fluidity and castability, making it well suited to casting in simple or complex shape alike. [18]

Its carbon content in the form of graphite provides good machinability of the material. It counteracts the normal shrinkage of the metal casting; reduce vibration and aids lubrication on wear surface. Most of the carbon stays combined with the iron in the material, yet the presence of hard iron carbines on the surface provides abrasion resistance. Cast iron has a lower melting point than other metals which makes it ideal for casting. The exact chemical composition of the cast iron used in the casting process is determined by the size and shape of the end product.

It has a low melting point of about $1200^{o}\mathrm{C}$ or about $300^{o}\mathrm{C}$ less than the pure iron. Cast iron tends to be brittle, except for malleable cast irons. Its brittleness (very low tensile strength) is an important characteristic which narrows its use in civil construction mainly to that of massive compressed members.

It is very difficult to weld, necessitating the use of connections made of wrought iron rivets and plates. It is sensitive to fatigue, resulting in the opening of cracks in bridge members under cyclic loading.

Cast iron offers a good strength to weight ratio, as well as a lower cost per unit of strength compared to other materials. The addition of other chemical components can increase the strength capability of the cast iron material as needed for certain engineering designs.

Cast iron is preferred around the world for draining, waste, water distribution and water vent pipe application. Though the material initially corrodes, this layer of corrosion products is dense and adherent, sealing the material against future corrosion [5].

For spheroidal graphite cast irons the size, shape and number of black round nodules of the graphite phase can affect the final applicability significantly. Typical microstructures of basic types of cast irons with different magnifications are in Figure 4.2 and the structure-dependent behavior can be summarized as follows:

- Grey Iron:
  - Low toughness
  - Low tensile strength
  - Cheap
  - Easily castable
- Spheroidal graphite cast iron
  - Generally good mechanical properties
  - Expensive
  - Less castable
  - Less machinable
- Malleable Iron
  - Good mechanical properties
  - Different cast
  - Expensive to heat treat

(a) (b) (c)

Figure 4.2: Microstructure of cast iron (a): Spheroidal graphite cast iron (b): grey cast iron (c): malleable cast iron [37]

The mechanical properties of a metal depend very much on its microstructure. This is especially true for cast iron. The structure depends on the interaction between the effects of the elements present and the cooling rate during and after solidification in the mould. The properties of cast iron are affected by the structure of the austenitic dendrites, graphite flakes and eutectic cells, as well as the formation of different alloying additions to the base metal. The alloying elements added should therefore be selected on the basis of their effect in controlling both nucleation and growth of graphite and primary austenite [37].

It is generally acknowledged that most of the mechanical qualities of cast iron can best be represented by its tensile strength. Since cast iron is very brittle material, its yield strength can in practice be taken to be equal to its ultimate tensile strength (UTS).Optimum tensile strengths can be obtained in cast iron by increasing the amount of graphite-free area(in most cases, primary austenitic dendrites),refining eutectic cell size and establishing the pearlitic matrix structure. By increasing the eutectic cell count, the effective span and stress concentrating effect of the graphite can be reduced, thus improving the tensile strength.

Cast iron is not a linear-elastic material, nor does it have the same stiffness in compression as in tension. This is largely due to the presence of the graphite flakes which reduce the effective sectional area of iron and also react to stress by changing their geometry. Some local plastic deformation occurs under loading, so that there is a very small proportion of the strain which is not recoverable when the loads are removed.

Figure 4.3 illustrates the stress-strain curve for a typical modern grey cast iron. The low tensile strain at failure and the absence of a yield plateau should be noted. Failure in tension is brittle, and lacks the ductility of failure in wrought iron or steel. This is one reason why the factor of safety for cast iron was higher than for wrought iron or steel [4].

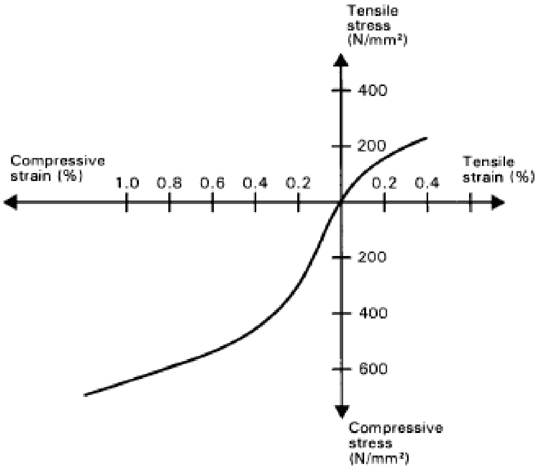


Figure 4.3: Stress-Stain curve for typical cast iron [5]

Cast iron has a relatively poor resistance to impact in view of its brittle nature. The lack of ductility means that it is likely to shatter under substantial dynamic or shock loading. This has not generally produced problems in building structures, where dynamic loads are relatively low compared with road and railway bridges. Also when cast iron is subject to thermal shock-as in fires, such as when cold water from a firehose strikes a hot beam or column. Flows in casting also are points of weakness under impact loads.

Determining the tensile strength of a cast iron member, and more practically its flexural tensile strength, is without doubt a difficult task, not least because cast iron fails in a brittle rather than a ductile manner. Factors influencing its tensile strength are:

- Carbon content-the more carbon that is present in the melt, the more graphite flakes will form (for a given cooling rate) and the lower will be tensile strength.
- Rate of cooling-slow cooling procedure a grey cast iron with graphite flakes: slower cooling tends to produce larger flakes and lower tensile strength. Very rapid cooling as already noted will produce white or mottled iron. Structural cast iron was invariably cast in mould and allowed to air to cool, producing grey cast iron except for a possible thin surface layer of white or mottled cast iron.
- Size and shape of member-these aspects influence rate of cooling and the development of locked-in shrinkage stresses. A thick section will cool more slowly than a thin one, and a squat section will likewise cool more slowly than a slender one. Faster cooling means higher tensile strength and thus small and/or thin sections will be stronger in flexural tension than larger and/or thicker sections [4].

Of direct interest to structural engineers is the flexural tensile strength or modulus of rupture of cast iron. Foe brittle materials, such a grey cast iron, flexural tensile strength can be calculated conventionally by assuming that the section is linear elastic, so that the modulus of rapture can be determined by dividing the bending moment at failure by the elastic section modulus. For various reasons-including the nonlinear behavior of grey cast iron-the modulus of rapture is not a true stress in the way that the tensile strength of a bar can be called a true stress, but it is useful parameter.

Essentially both tensile strength and modulus of rapture of cast iron diminish with increase of the tested section size.

In the 19th century, cast iron was regarded as a treacherous material in fire. Although it did not melt, and its basic strength was not adversely affected by temperature up to at least $400^{\circ}\ C$,it was believed to be liable to crack suddenly, often followed by immediate collapse. This might occur during the fire, but was more likely to happen when the fire brigade arrived and directed cold water onto the hot material. The effect was often to shatter the iron explosively. It was feared that this might result in progressive structural collapse.

Cast iron was also seen as vulnerable to the effects of thermal expansion. Although its coefficient of expansion is slightly lower than that of wrought iron or steel, it is- because of brittleness-vulnerable to distortions of the structure around it [4].

Thus, where a cast iron column is rigidly attached to exposed iron or steel beams, a temperature rise of $600^{\circ}\mathrm{C}$ on a 10m span could induce an imposed sidesway on a column of some 60mm, quite enough unfortunately to produce rapture of the column by tensile bending failure. In contrast, timber would heat up more slowly and expand less, so that the chances of survival of a cast iron column supporting timber beams are better.

Hardness is the resistance of a material to localized deformation. The term can apply to deformation from indentation, scratching, cutting or bending. In cast iron, the deformation considered is plastic deformation of the surface. the lack of a fundamental definition indicates that hardness is not be a basic property of a cast iron, but rather a composite one with contributions from the yield strength, work hardening, true tensile strength, modulus and other factors [21].

The chemical composition of cast iron is one of the most important factors that influence the hardness of the casting. The composition of iron determines the quality and character of the graphite and metallurgical characteristics of the metallic matrix for some specified set of cooling conditions. The cooling rate is also an important factor which effects hardness, especially when the liquid metal enters the mould cavity.

The effects of graphite content and alloy content on the hardness of pearlitic cast iron containing no steadite and less than approximately 3% eutectic carbide have been characterized. Equations have been developed for predicting changes in the Brinell hardness of the pearlitic cast iron with changes in chemical compositions.

The equations correlate the Brinell hardness with the matrix hardness and graphite content. They also correlate the matrix hardness with the concentration of alloying elements producing solid solution strengthening of interlamellar ferrite within the pearlite thereby increasing the hardness.

It is well known to the foundryman that fully sound castings under ordinary circumstances cannot be produced by simple techniques since cast irons are subjected to microporosity and shrinkage porosity during solidification. This defect can be minimized by making solidification directional by setting up steep temperature gradients directed towards the riser, and this can be achieved by employing chills. Typical benefits of employing chills for the solidification of cast iron are the densification of the section and the promotion of directional solidification, resulting in sound castings.

The endurance limit of cast iron is generally at least one-third of its ultimate tensile strength and this, in conjunction with the low fluctuating stress levels in most building structures, indicates that fatigue is not usually a prime factor appraisal [11].

The fatigue performance of a particular cast iron depends on the quantity, size and the shape of the free graphite constituent as well as its interaction with the matrix. Tensile and compressive behavior of cast iron can be different. Compressive strength and modulus are greater than the tensile strength and the modulus [4].

Fatigue analysis of cast iron requires special considerations of this asymmetric stress strain response. Different types of Cast irons have different stress strain behavior.

In Ductile cast iron, fatigue cracks initiate not only from nodules but also from casting imperfections such as inclusions, microshrinkage pores and irregularly shaped graphite clusters. These irregularities initiate cracks at an earlier stage in life than well formed nodules. As a result, the quality of casting will have a large influence on the fatigue life of ductile iron castings. Even at long lives, cracks are observed very early in the lifetime of ductile iron.

Graphite in grey cast iron is highly branched and interconnected within a eutectic cell structure. These cell structures are composed of sharp flakes which provide an easy fracture path as well as areas of high stress concentration.

Cracks start on the first loading cycle at flakes oriented perpendicular to the applied tensile stress. Since grey cast iron already contains cracks, it is not very notch sensitive [21].

4.2 Properties of wrought iron

Wrought iron is a composite material, not in structural sense but in the metallurgical sense. It is composed of two phase, one ferrite-iron with a body centered cubic crystal structure and the other slag. Wrought iron is relatively malleable and ductile due to low carbon content, typically less than 0.05%.Steel has carbon content in the rang 0.2-1.0%.The slag is not well bonded to the ferrite and so does not enhance of the iron. As noted by Walker (2002, 444),”the amount of slag in wrought iron can be up to 3 wt% of the total. It is a glassy substance composed of iron silicate and iron oxide.”The thickness of the slag inclusions can range from microscopic size of 3 mm.

They appear as narrow elongated strands or streaks and are given this shape by rolling the iron in a particular direction while the iron is hot. By dividing the metal into strands of ferrite the iron can be described as having a macroscopic grain due to its fibrous appearance. This texture is the best seen when a nicked bar is bent backwards tearing open the metal Figure 4.3. [8].

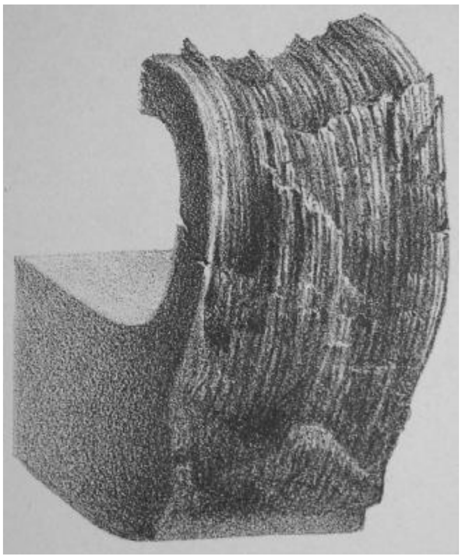


Figure 4.4: Fibrous texture of wrought iron [8]

The size, shape and distribution of the slag inclusions in wrought iron vary greatly. In cases for which the degree of elongation is high, the ferrite matrix is divided into columns (Gordon, 1988).In this condition, low ductility can be observed in test samples even though the ferrite itself is quite ductile.

Long ferrite columns make the metal more prone to internal rupture .Excessively long slag inclusions, from insufficient working of the metal, cause low ductility.

Equally bad are tiny, globular slag inclusions that result from excessive working of wrought iron. An iron with such a microstructure “lacks the fibrous texture typical of good wrought iron, and behaves like dirty low-carbon steel: it tends to be brittle and has poor fatigue properties”(Jeffrey 1959,21).This is why wrought iron exhibits improved mechanical properties up to approximately the sixth working and the mechanical properties deteriorate thereafter with future working. Excessive working of iron may have occurred when rolling complex shapes.

The condition of a lack of cohesion when the wrought iron is red-hot is described by the term red-shortness. The wrought iron cracks or crumbles when being hot worked.

This condition is caused by an excess of sulfur and results from the iron not being sufficiently purified in the puddling furnace (Skelton, 1924).sections rolled between the grains when the iron is heated to red-hot(Johnson,1939).cold short iron is the condition of low ductility at normal temperatures due to an excess of phosphorus or copper .

As noted by (Jeffrey,1959),a good wrought iron would have a maximum sulfur content of 0.05% and a maximum phosphorus content of 0.16%.The manganese content should be less than 0.1% and silicon content less than 0.2%.Of all the impurities elements, phosphorus has the most significant effect on mechanical properties. Elevated phosphorus content causes higher yield strength and ultimate strength but causes a sharp fall in ductility and impact resistance.

Wrought iron contains very little carbon and it’s fibrous in composition due to the presence of long strands of slag contained within the iron. It is malleable (easily shaped by hammering and rolling) and ductile (can be shaped by extrusion through dies to form wires).It is strong in tension and has good corrosion resistance. Wrought iron was formed by melting pig iron in a special furnace and boiling it to reduce the amount of carbon it contained [31].

The resulting material was rolled into a ball known as a bloom, hammered and then rolled into bars. The bars were chopped up, reheated and then hammered and rolled again. The more times this process was repeated, the better quality of wrought iron is obtained.

Wrought iron today is currently an over-used term that is often applied to any type of worked steel. Wrought iron is shaped by hammering, rolling, punching and machining. Wrought ironwork is usually composed of several individual pieces fitted together and because it is shaped by hand, matching elements will rarely be identical [12].

Table 4.5: Typical properties of structural wrought iron [4]

Property		Typical Value
Ultimate Tensile Strength and Flexural tensile strength(Modulus of Rapture)	MPa	278-593
Elastic limit	MPa	154-408
Ultimate compressive Strength	MPa	247-309
Ultimate shear Strength	MPa	At least two-third of UTS
Young’s Modulus Tension	GPa	154-220
Elongation at failure	(%)	7-21
Poisson Ratio		0.25

Wrought iron, like steel, is substantially linear elastic up to the elastic limit or yield point. It has high elongation at failure (>15%). Figure 4.5 show a typical stress-strain curve, based on published test results.

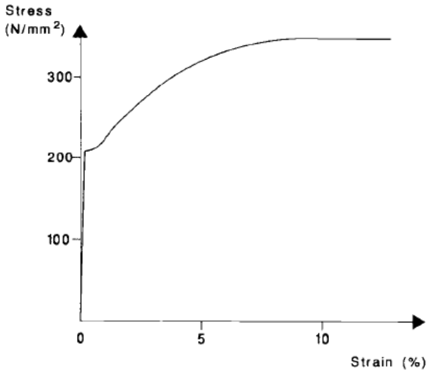


Figure 4.5: Stress-strain curve of typical wrought iron [4]

Wrought iron, being a ductile material, is not particularly vulnerable to impact. Wrought iron shows 18% reduction in ultimate tensile strength and elongation at failure under shock loading.

The tensile properties of wrought iron are largely those of ferrite plus the strengthening effect of any phosphorus content, which adds approximately 608 MPa for each 0.01% above 0.10% of contained phosphorus.

The direct tensile strength and the flexural tensile strength of wrought iron are effectively the same for wrought iron because of the material ductility. The material's yield strength is more relevant but the ultimate tensile strength was usually determined and quoted when structural wrought iron was being used in the second half of the 19th century [4].

The repeated working (up to about 6 times) of wrought iron, when cold or at moderate temperatures increased its strength but reduced its ductility. Further working was likely to be harmful, although annealing by subsequent reheating to white heat would restore properties to the unworked condition. Wrought iron begins to lose strength between 200 to 400 ºC. Heating work-hardened wrought iron will anneal it and hence reduce its strength to that of the source metal [4].

4.3 Properties of steel

Steel is manufactured by mixing iron and carbon in a specific ratio, in which the percentage of carbon may range from 0.2 percent to 2 percent of the total weight. The carbon atoms insert themselves between iron atoms and significantly improve the rigidity of steel. Other than carbon, the alloying materials used in manufacturing steel include chromium, manganese, vanadium and tungsten. Of these materials carbon is most cost effective element. All the alloying elements help in altering the mechanical properties of steel.

Steel differs from wrought iron and cast iron, only in the percentage of carbon content. Steel contains more carbon than wrought iron and lesser carbon than cast iron. It is because of this reason that steel is considered to occupy a position between these two metals.

The physical properties of steel depend on the percentage composition of the constituent elements and the manufacturing process. One of the major properties of steel is the ability to cool down rapidly from an extremely hot temperature after being subjected to water and oil. And a particular amount of carbon can be dissolved in iron at a specific temperature [4].

The physical properties of steel include high strength, low weight, durability and resistance to corrosion. Steel offers great strength though it is light in weight. In fact, the ratio of strength to weight for steel is lower than any other building material.

Unlike the constituent element iron, steel doesn't corrode easily, on being exposed moisture and water. The dimensional stability of steel is a desired property. It is found that the dimension of steel remains unchanged even after many years, or being subjected to extreme environmental conditions. Steel is also a good conductor of electricity.

Steel is characterized mainly by its high strength, high young's modulus, and isotropic behavior, ductility and weldability.

Early steel has a generally good resistance to impact at normal temperatures. It seems clear that in the 19th century there was awareness of impact effects on strength, but lacking the availability of a yardstick for measurement, since little was agreed beyond the fact that shock loading reduced both UTS and elongation at failure.

The ultimate strength of structural steel is effectively the same in tension and compression. There is no separately prescribed value for ultimate compressive strength and ultimate tensile strength of structural steel, past or present, in relatively the interaction of bulking squash load will determine the ultimate compressive capacity of a steel member [22].

The shear strength of structural steel is given as $\left({}^{1}/_{\sqrt{3}}\right)$, i.e.0.577, times the corresponding tensile strength. In real conditions, other than pure shear, behavior will be influenced by combined flexure, bearing and axial forces.

The hardness, strength and ductility of steel depend on the elements (carbon, chromium, manganese) and their percentile participation in the final alloy.

Higher carbon content produces brittle steel with more strength and hardness. Nickel and manganese increase tensile strength while chromium and vanadium increase hardness and melting temperature. Chromium in particular is a key element in the production stainless steel (about 18%).The effect of carbon content in strength and hardness is given in the Figure 4.6.

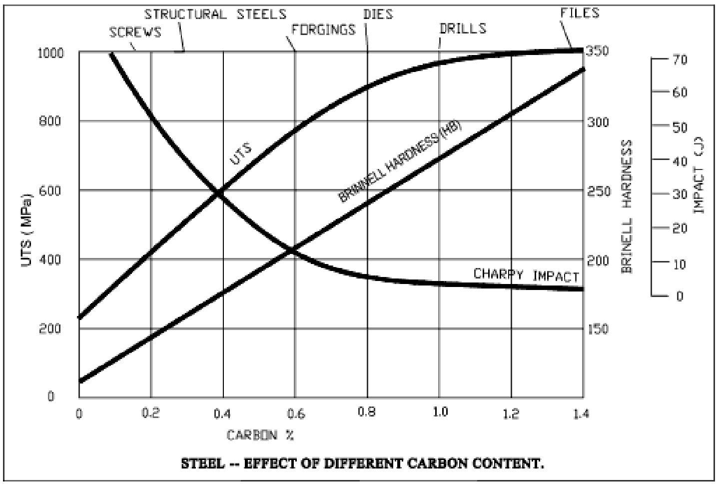


Figure 4.6: effect of carbon content in strength and hardness[44]

5 Experimental tests

5.1 General

This chapter focuses on collecting historical test data and experimental results obtained on wrought iron, cast iron and early steel structural elements. In most historical metallic structures, mechanical properties of the structural elements such as yield stress and modulus of elasticity were not measured at the time they were built. Furthermore, quality of material varied considerably in that period. Because of the shortage of knowledge of mechanical properties and microstructures of elements in historical iron buildings and for better understanding of the mechanical and chemical properties of iron, several experimental tests on different structures has been done.

5.2 Evaluation of properties of wrought iron structures

In the late 19th century, due to the increasing use of steel in structures, the structural use of wrought iron was gradually reduced. As a result, the mechanical properties of wrought iron elements are less documented than the properties of other metallic elements. There an interest in the properties of wrought iron manufactured in the second half of the 19th century, and several studies in this area were conducted (Beardslee 1879; Kirkaldy 1862).However, experimental studies and researches made in 19th century did not have the capacity to measure the exact properties of wrought iron structural elements.

David Kirkaldy, a Scottish researcher, conducted some valuable tests on wrought iron elements in the 19th century. Kirkaldy used standard testing procedures, standard specimens and performed more than 1000 tensile tests on wrought iron elements taken from the bars, plates and angle irons.

More recently, in order to evaluate the historical wrought iron structures, there has been great interest in understanding the mechanical properties of wrought iron. Several experimental tests on wrought iron specimens extracted from historical structures have been done. Gordon and Knopf (2005) examined the mechanical properties of 19th century wrought iron truss bridges in United States. Mechanical properties such as strength, hardness, ductility and chemical composition were investigated. They also evaluated the importance of a balance between wrought iron's ductility and strength for it to continue to safely serve in a load bearing structure.

Other testing on historic bridges wrought iron includes the work of Elleby et al. (1976), Fu and Harwood (2000), and Keller and Kirkpatrick (2006).They tested a small number of specimens in order to obtain the material properties of historical wrought iron structures.

Wrought iron was the dominant structural framing material from 1850 to 1890.With similar properties to early mild steel, wrought iron is more variable, creating uncertainty in the assessment of existing structures for which sampling and testing opportunities are limited. Strength value of wrought iron lies between wide limits. Source of variability include test methods used, the grade or quality of wrought iron, and the type of structural element tested or from which samples have been taken [27].

5.2.1 Mechanical properties of six 19th century wrought iron truss bridges located in Massachusetts (Sean. L. Kleton, 2011)

In order to evaluate the mechanical properties, mechanical testing was conducted on wrought iron specimens taken from six 19th century truss bridges by Department of Civil and Environmental Engineering at the University of Massachusetts. The first bridge was built in 1880 and the last bridge was built in 1895. These bridges are mostly short span lengths, ranging from 12m to 31m, used in rural town roads. Wrought iron was extracted from square and round beam hangers of several bridges to obtain mechanical properties. Mechanical testing included tensile and hardness tests; where parameters like yield strength, percent reduction in area and Rockwell hardness were determined.

Test specimens were extracted from square and round beam hangers of all analyzed bridges and from additional elements of Shattuckville and Chester bridges. Some extra test specimens extracted from Shattuckville Bridge such as eye-bar that was originally from bottom part of the chord of bridge, a looped bar that acted as tension diagonal in one of the panels, and several lacing members. From Chester Bridge, additional members were extracted from lacing that made up the guard rail of the bridge [4].

Four different geometries were adopted for tensile specimens in order to account for the different cross-sectional geometries of the specimens' source material, Figure 5.1. The standard specimen extracted from beam hangers, presented a cylindrical shape with a total length of 12.7 cm, a reduced section length of 5.08 cm and a 1.27 cm diameter reduced cross section. For the thinner lacing elements, a plate specimen with a total length of 17.78 cm with 5.08 cm of reduced section and a thickness of 0.508 cm was used. Designing of both specimens are based on ASTM E8 (2003).

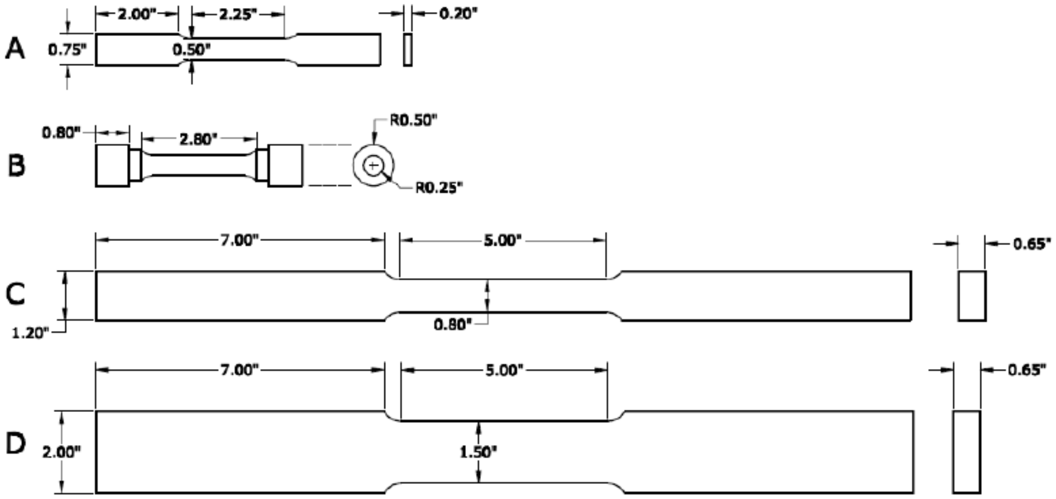


Figure 5.1: Four tensile specimens used: A for lacing bars, B for all beam hanger material, C for looped bars, and D for eye bars material [27].

Figure 5.2 shows the different types of test specimens sampled from the bridges and their locations on the truss bridges. Hardness tests were performed on each tensile specimen according to the

Rockwell B scale, ASTM E18 (2003). For hardness test, a 1.6 mm ball indenter was used, with a minimum load of 10 kgf and maximum load of 100 kgf.

For measuring the ductility of each specimen, percent reduction in cross sectional area was calculated by measuring the final cross sectional dimensions at the fracture of each specimen after testing. Measurements were taken on each piece of the broken test specimen and the average value was used to determine the final area [27].

Test result for each sample from bridges are presented in which shows the evaluated values of hardness test, tensile strength and percent reduction in area of each specimens.

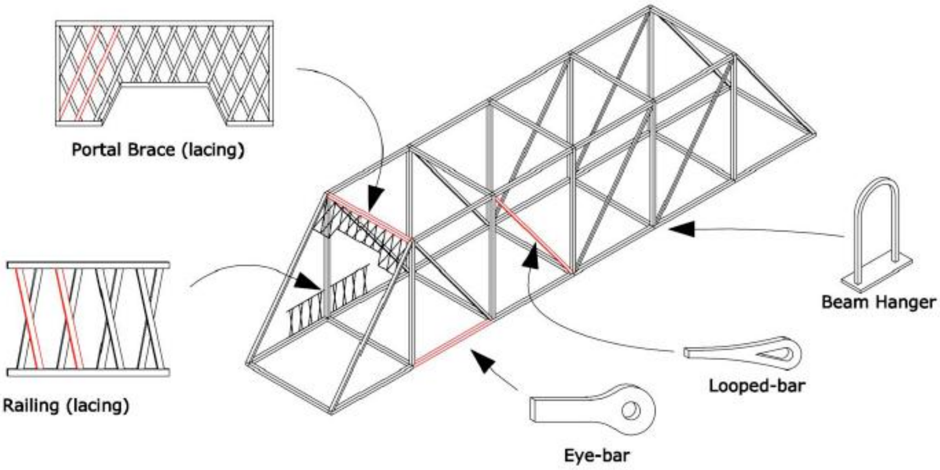


Figure 5.2: Relative locations on a schematic truss bridge of the different members sampled for testing [27]

Table 5.1: Testing results for each specimens [27]
*This table presents the test results of just one sample from each bridge

Specimen	Reduction in area (%)	Hardness	Yield stress (MPa)	Tensile stress (MPa)
Bondsville Bridge	48	52	154	273
Reeds Bridge	22	49	200	316
Golden Hill Bridge	50	56	242	341
Galvin Bridge	53	55	224	347
Chester Bridge	33	62	189	328
Shattuckville Bridge	46	59	234	323

5.2.2 Experimental test data of wrought iron structures collected by (Sullivan and Swailes, 2009)

The experimental tests presented in this part were performed in the laboratory of Massachusetts Institute of Technology to determine the properties of wrought iron structures. The laboratory was established in 1883 by Gaetano Lanza. He was particularly interested in testing full-size structural members (Lanza, 1912).The results of the experimental test show the wide variety of strength values obtained on wrought iron elements. The variety of values results from the test methods used, from the quality of wrought iron elements and from the type of structural test samples

Tensile strength of wrought iron bar

The tensile strength of wrought iron elements in the direction of rolling is greater than across it because, when loaded across the grain, the slag filaments run perpendicular to the load path. In this direction, they act as voids for the propagation of internal cracks across the specimen. If loaded along the grain, the ferrite is more continuous with reduced tendency for the formation of internal rupture surfaces. The tensile strength is greater in narrow bars and thin plates than in thick bars or large forgings. (Sullivan, 2009) [8]

Tensile strength of different bars with the same materials and diameter varying from 10 mm to 50 mm was tested. With increasing diameter of bars, yield strength is reducing. The thinner bars have greater strength because they previously experienced a greater amount of hot rolling, which makes the ferrite grain sizes smaller and also causes greater cohesion between grains (Johnson, 1939). Figure 5.3 shows the stress-strain graphs of tested wrought iron bars.

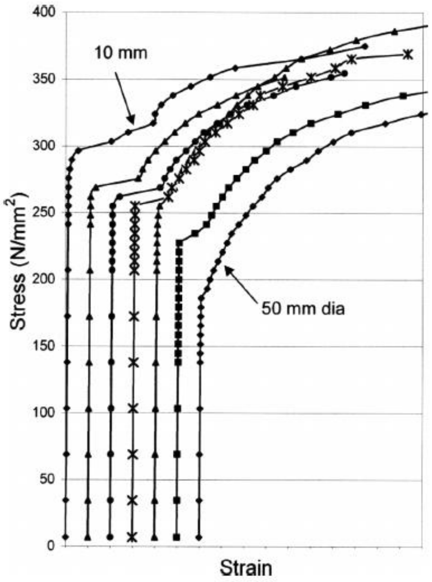
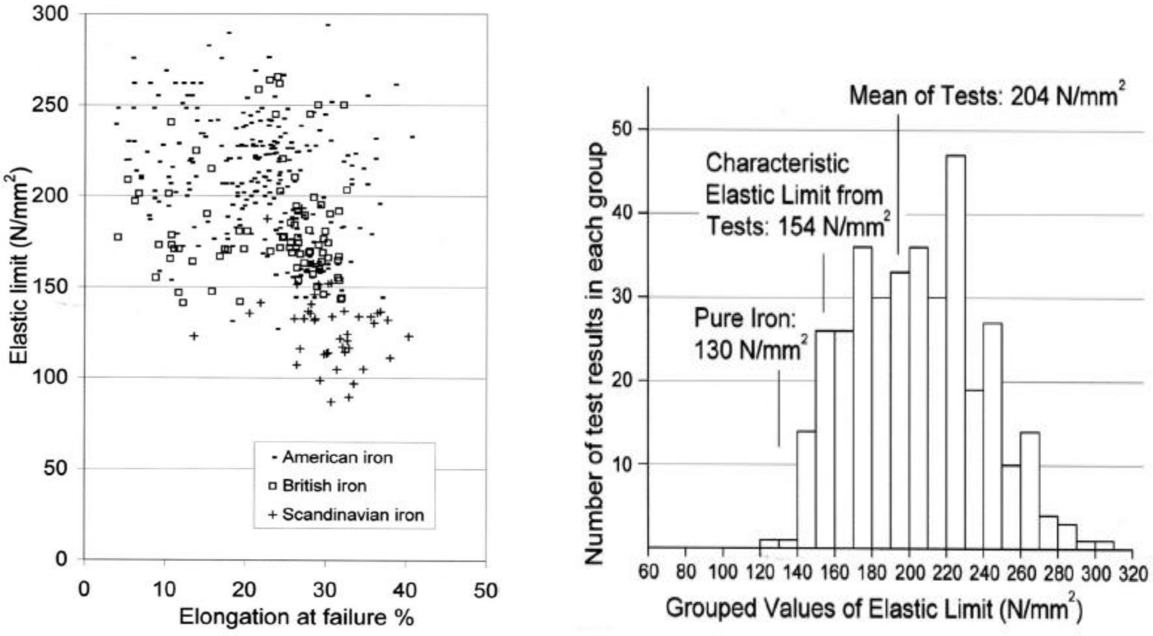


Figure 5.3: Stress-Strain graph of 7 round bars with diameters 10,13,17,23,26,39 and 50 mm [8]

Identifying ranges of different types of wrought iron elements, such as bars, plates, beams and angles is reasonable because different types of structural sections undergo different degrees of working. Figure 5.4 and Table 5.2 give the results obtained on the tensile test performed on wrought iron bars. Because of regional variations on wrought iron elements, the results were divided according to country of manufacture. From this data, the Scandinavian iron has a lower elastic limit but higher ductility than British or American irons. This high ductility was due to the Scandinavian ores being naturally low in phosphorus but also due to the use of charcoal rather than coke in smelting furnace (Fairbairn, 1864).



(a) (b)

Figure 5.4: (a) Scatter graph of the elastic limit and ductility of American, British and Scandinavian bar iron,390 test results(O'Sullivan,2007) (b) Histogram of the elastic limit of American and British iron bar: 355 test results (Sullivan,2007) [8]

For determining the quality of wrought iron elements, toughness is the property that should be used in, which is determined by both strength and ductility. Figure 5.4 (b) shows the measured elastic limits of British and American wrought iron bars [8].

Table 5.2:Summary of tensile test data on British and American bar iron tested parallel to grain:355 test results [8]

	Elastic Limit (MPa)	Ultimate Tensile Stress (MPa)	Elongation at failure (%)
Range	127-304	278-533	3.7-40.5
Mean	204	353	22
Standard deviation	35	26	8

Tensile strength of wrought iron plate

For wrought iron plates, an effective mean of equalizing the strength parallel and perpendicular to the direction of grain was cross-piling, in which the bars were piled in alternating directions as show in Figure 5.3, before being rolled into a thin plate, (Sullivan, 2009).The greater strength is resulting for the plates iron, which were formed with the outer layers in same direction.

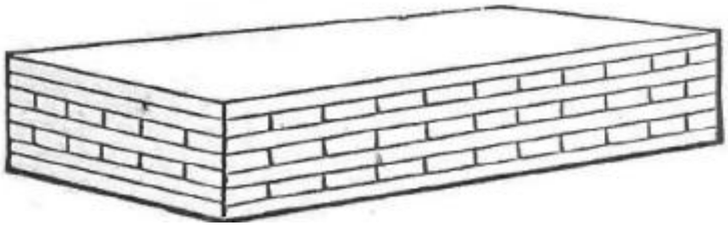


Figure 5.5: Illustration of cross-piling to form plate-iron [8]

Tensile test results from approximately of 550 samples along the grain and 115 samples perpendicular to the grain shows that wrought iron plates is an average 15% stronger in the direction of dominant grain. The test results shows along and perpendicular to the grain shows in Table 5.3 and Table 5.4.

These results are because that plates girders were constructed with the grain of the plate along longitudinal direction of the girder. The resulted data of yield strength shows in Figure 5.5 along the grain is 185 N/mm^{2,} which is lower that the value of 220 N/mm^2 in United Kingdom Highway Standard BD21.

Table 5.3:Summary of test data on plate iron tested parallel to grain:550 test results

	Yield stress (MPa)	Ultimate Tensile Stress (MPa)	Elongation at failure (%)
Range	160-363	232-470	1-35
Mean	240	345	15
Standard deviation	32	35	7

Table 5.4:Summary of test data on plate iron tested perpendicular to grain:550 test results

	Yield stress (MPa)	Ultimate Tensile Stress (MPa)	Elongation at failure (%)
Range	154-298	183-389	0.1-29.2
Mean	208	296	8
Standard deviation	36	39	7

Strength of angle, tee and beam wrought iron

Tensile test data for wrought iron angle and tee is given in Table 5.5. Rolling from pile iron layers of parallel grain of angle and tee iron, causes the greater tensile strength of angle and tee iron plate iron. With regard to the more complex rolled I-section, there is few data to make any generalization on this form. Tests conducted at MIT on samples cut from I-beams gave mean yield strength of 165 N/mm^2, where as tests conducted at the Institute of Science and Technology University of Manchester on samples cut form a Belgian I-beam gave a mean yield strength of 319 N/mm^2 (Kontos, 1996).

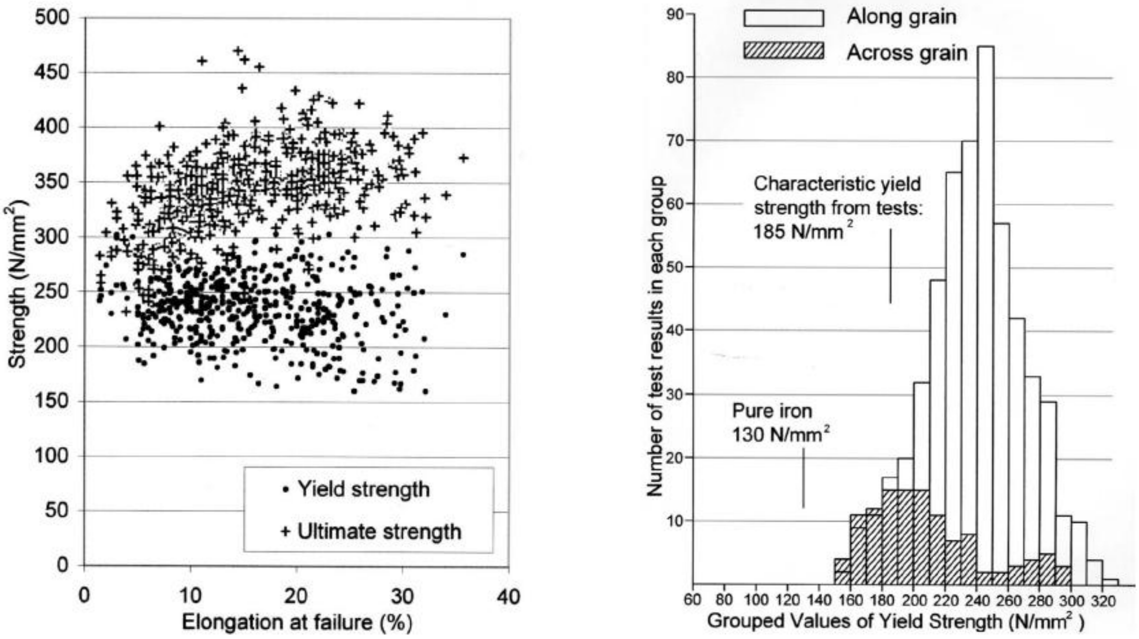


Figure5.6 : (a) Scatter graph of the yield and ultimate strength of plate iron tested along grain direction(Sullivan,2007) (b) Graph of the yield strength of plate iron tested along and across grain direction(Sullivan,2007) [8]

Compressive strength of wrought iron

Tests conducted by Marshall in 1887 and Kirkaldy in 1866 (as reported in Barlow 1867) show that for practical purposes the tensile and compressive strengths of wrought iron can be taken as the same. However, Gordon in 1988 has proposed that, in cases for which the slag inclusion in excessively elongated, test samples can exhibit lower compressive strengths due to the ferrite matrix being divided into columns that can buckle prior to yielding of the ferrite.

Table 5.5 :Summary of tensile test data on angle and tee wrought iron tested parallel to grain: 94 test results

	Yield stress (MPa)	Ultimate Tensile Stress (MPa)	Elongation at failure (%)
Range	193-351	301-448	4-37
Mean	245	370	22
Standard deviation	27	30	7

Brittle failure of wrought iron

Past failure of wrought iron structural elements have included suspension bridge chain links. William Kirkaldy investigated the failure of a tie-bar from Charing Cross Station roof London, United Kingdom) roof in 1905 (Swailes and Marsh 2005).

More recently, a beam failure in a building in Leeks, United Kingdom, was reported (Bland 1984).The consequence of failure are more sever for some structures than others. Different factors of safety may be applied to different types of structures to take this aspect into account. However, for reasons of simplicity and lack of sufficient data, the use of a single factor of safety is prevalent.

Lack of toughness rather than strength has been attributed to various failures of structural elements. Wrought iron from the ship the S.S Great Britain (Morgan, 1996) and Walnut Street Bridge in the United States (Green et al.1999) showed a high ductile to brittle transition temperature indicating that wrought iron is potentially prone to brittle fracture at normal temperatures. Impact test data indicate that the toughness of wrought iron is quite variable. Charpy values for wrought iron from an American truss bridge were in the range 34-144 Joules (Sparks and Badoux 1998), whereas Charpy values for material from another American Bridge were in the range 10-80 Joules (Green et al.1999).For a rolled wrought iron beam tested at UMIST (Institute of Science and Technology at University of Manchester), the Charpy values were quite low, 10 Joules for the flanges and 23 Joules for the web (Steude, 2000)

Modulus of elasticity

Tensile tests on various American, British and Norwegian wrought iron specimens were compiled to produce the histogram of values for modulus of elasticity shown in Figure 5.7. A numerical summary of the data is given in Table 5.6. Outlaying values are a consequence of experimental measurement error.

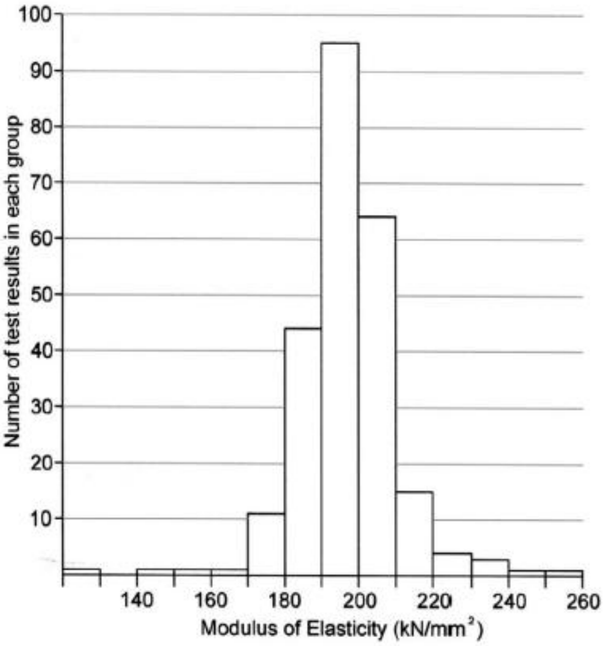


Figure 5.7: Graph of the modulus of elasticity of wrought iron bar [8]

Table 5.6: Numerical summary of the modulus of elasticity data represented in figure 5.5, Sample tested parallel to grain: 242 test results (Sullivan,2007)

	Modulus of Elasticity (GPa)
Range	124-253
Mean	197
Standard deviation	13

5.2.3 Material properties of wrought iron and steel bridges

This experimental test presents the evaluation of wrought iron and steel bridges in 19th and early 20th century bridges. Because the sections and geometry of the main members are relatively simple to model, material characterization becomes a key issue in the structural analysis of historic bridges (Spark, 2008). The materials characterization is based on the data's of microstructures, chemistry, hardness and other properties obtain from tensile test.

In this test, the first thing is to determine are the type of metallic element and the variety of the metals used in historic bridges. This determination can be done with no damage to the structure by the Spark test (Tschorn, 1963) to qualitatively distinguish carbon content. The spark test uses a high-speed grinder to produce a stream of sparks, which exhibits the characteristics of chemical compositions of iron elements. For doing the Spark test, the surface of the test specimens should be polished.

Macro-etching is used for preparing the surface of test specimens and for visual or low magnification. Macro-etching is polishing the metal with a very fine grit and etching for observation with a microstructure. Macro-etching is done with a suitable reagent such as nital or to show phosphorus segregation, Oberhoffer's reagent can be used.

Chemical analysis of specimens extracted from an iron structure can assist the identification of the elements and give an indication of quality and consistency in the structure. Chemical constituents have a strong effect on the strength, ductility and weldability of metals. The main determinants in steel structure are carbon (C), Manganese (Mn), Sulfur (S) and phosphorus (P). In wrought iron structures, same determinants have an important role. Test results on wrought iron show phosphorus content about equally distributed between the ferrite matrix and the slag(Higgins,1934),though Aston & Story(1936) give a representative of 0.10% in ferrite and 0.02% in the slag. Table 5.7 shows the values for wrought iron and steel chemical contents. The amount of manganese content in steels should normally be at least six times the sulfur content. The amount of manganese content in wrought iron is usually less than 0.10% by weight thought it does not seem to have an adverse effect on ductility [29].

Table 5.7: Suggested values for chemical analysis of wrought iron and steel (%)

	C	P	S
Wrought iron	0.1	0.3	0.04
Steel Pins	0.2	0.05	0.04
Steel Eyebars	0.3	0.08	0.05

Several field hardness methods are available for field use on bridges including ultrasonic contact impedance (UCI) method, used in instruments such as the Krautkramer MIC10.Regardless of the instrument used the results should be presented in Brinell Hardness Number (BHN), which is closely correlated with strength in carbon steels. As a rule hardness values should be obtained at the same locations as the chemical and metallographic tests (Spark, 2008)

Table 5.8 shows the evaluated hardness values results and typical and maximum values for wrought iron and steel. Higher values in the table may present the uses of alloy or high strength steels which can be verify by chemical analysis [29].

Table 5.8 : Suggested values of Brinell Hardness Number (BHN) for different materials.

	Typical Range	High Range
Wrought iron	95-120	130
Steel Pins	120-140	145
Steel Eyebars	100-120	140

Experimental tests were done on Parker truss bridge, built in 1896, based on visual observations, a simple spark test and limited field metallography. By using the spark test, the carbon content of the test specimens of eyebars, rolled sections and pins was estimated from lower to higher carbon content. The test results of spark test for eyebars were similar to wrought iron or very low carbon steel specimens (<0.08%C).The pins showed carbon indications similar to medium carbon steel.

The test specimens of the bridge should exhibit ductile to brittle transition, based on their carbon content, as a function of temperature. Chemical analysis of steel specimens showed that the sulfur and phosphorus contents were below the maximum values allowed for mild structural steels [29].

Table 5.9 shows the chemical composition and Hardness test results on eyebars.

Table 5.9: Steel properties of 1896 Parker Truss bridge eyebars

Member	BHN	C (%)	Mn (%)	P (%)	S (%)
Eyebars					
T10W	101	0.11	0.72	0.05	0.02
T4E	121	0.09	0.70	0.02	0.04
T5E	108	0.13	0.74	0.04	0.04
Average	110	0.11	0.72	0.04	0.04

The chemical compositions and Hardness test results of rolled sections are shown in Table 5.10.

Table 5.10 : Steel properties of 1896 Parker Truss bridge rolled sections

Member	BHN	C (%)	Mn (%)	P (%)	S (%)
Rolled sections					
Floor beam	104	0.14	0.44	0.01	0.03
Chord channel	105	0.15	0.48	0.01	0.04
Post channel	94	0.12	0.44	0.01	0.03
Post channel	100	0.14	0.47	0.02	0.02
Average	101	0.14	0.72	0.01	0.03

The chemical compositions and Hardness test results of pins is shown in Table 5.11.

Table 5.11: Steel properties of 1896 Parker Truss bridge pins

Member	BHN	C (%)	Mn (%)	P (%)	S (%)
Pins					
L12W	146	0.19	0.50	0.02	0.03
L1E	143	0.15	0.46	0.02	0.04
L3E	140	0.18	0.45	0.03	0.04
L4E	135	0.18	0.48	0.03	0.04
Average	141	0.18	0.47	0.02	0.04

Estimated yield stress for steel specimens is shown in Table 5.12.

Table 5.12: Estimated values for assessment of 1896 steel truss bridge

	Yield stress (MPa)
Eyebars	220
Loop rods	207
Pins	317
Rolled sections	220

5.3 Evaluation of properties of cast iron structures

5.3.1 Compression & tensile test of Cast Iron Bridge in Germany (Volker Wetzk, 2012)

An experimental test on small scale material samples of a bridge was performed in order to determine essential mechanical properties of bridge bearings made from cast iron. By the end of 19th century, cast iron was the material most widely employed for bearings. The material samples of the test stem from bearings of bridge built during early decades of the 20th century.

The materials for the samples were extracted from the massive base bodies of the dismantled bearings. The base bodies were made from cast iron and steel. Some time before 1900 engineers were equipped with a material for bridge bearing that combined the advantages of the two different metallic materials widely used at that time-cast iron and rolled steel: the possibility of free shaping to create a product with high compression and tensile strength. Beyond that, the material's malleability allowed for machining the surface if required.

Comprehensive examinations performed on the bearings during spring 2011 at the BAM federal institute for materials research and testing in Berlin, established the outstanding quality of the material in the majority of cases. Altogether 10 bearings that were structurally identical were subjected to a variety of procedures. These investigation present tests with small-scale compression specimens to see how the mechanical parameters derived from the compression tests correlate with those from the tensile tests. Table 5.13 shows the average values of the tensile tests which R_{eh} is upper yield point stress, R_{el} is lower yield point stress, $R_{p0,\ 2}$ is 0.2% of the offset yield point stress and R_m is compressive stress. Figure 5.8 represents the position of the specimens inside the bearing [14].

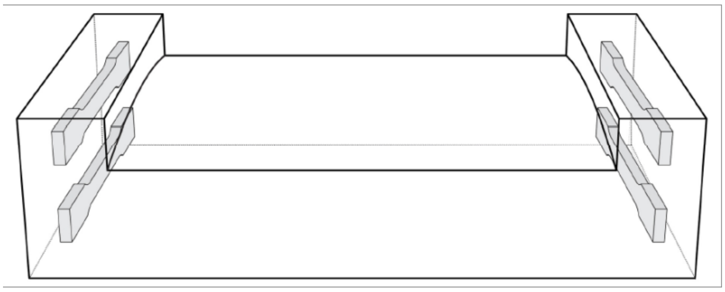


Figure 5.8: Position of tensile specimens within the bearing member [14]

Two series of specimens for the small-scale compression tests were produced based on compliance with DIN 50 106 [14].

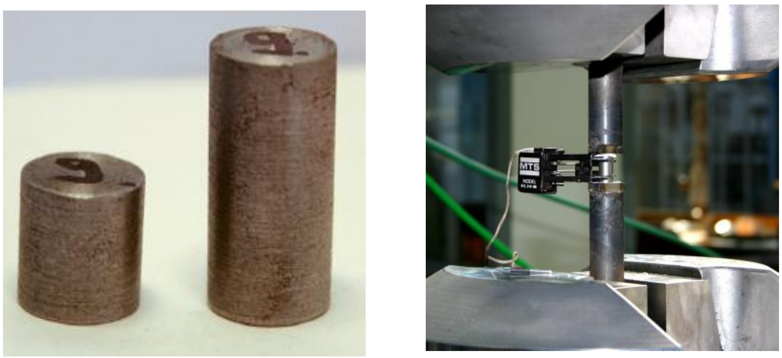
1. Series: d=10 mm with h=10 mm (h/d=1)

2. Series: d=10 mm with h=20 mm (h/d=2)

Figure 5.9 (a) shows the two specimens derived from bearing no.9.The specimens were fixed between transfers made from round steel. Small, well-contoured pieces of high-carbon steel were welded onto their ends allowing for both the best possible positioning of each specimen and a good transmission of the applied load. The strain was recorded with the help of an extensometer directly fixed to the specimen. Figure 5.9 (b) shows the testing equipment.

Table 5.13:Results of the tensile tests (MPa)

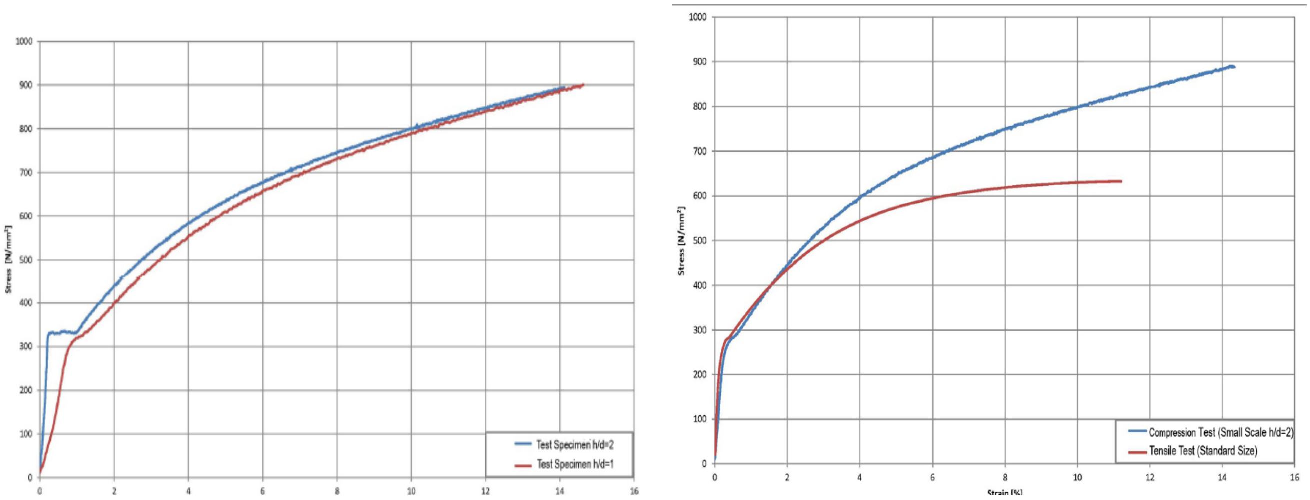
Bearing No.	R_{eh}	R_{el}	$R_{p0,2}$	R_m
0	-	-	282	634
1	-	-	278	633
2	340	336	-	644
3	344	343	-	648
4	346	342	-	656
5	-	-	284	635
6	276	272	-	626
7	309	302	-	686
8	-	-	280	636
9	308	304	-	601



(a) (b)

Figure 5.9 : (a)Test specimen (b) Testing set-up [14]

Results show that the compressive strength of the material could not be described as a point of failure. If the test load was increased beyond the compression yield point, the short sample (h/d=1) was squashed in a progressive fashion: the specimen bulged outward on the sides becoming barrel-shaped because friction between the specimen and the end plates prevented lateral expansion. The longer sample (h/d=2) showed the tendency to escape the load by lateral buckling caused by any imperfections as for instance impurities in the texture of the material.



(a) (b)

Figure 5.10: (a) Pressure stress-strain curve of bearing (b) Pressure and tensile stress-strain curve of bearing [14]

Figure 5.10 (a) shows the results for the samples taken from bearing no.3 and displays the systematic character of the tests in representing the compression yield point depending on the specimens' geometry. In the case of using large specimen (h/d=2), the compressive yielding point is barely distinguishable in the test. Figure 5.10 (b) shows the result of compression and tensile test [14].

Because of the distinctive yielding results of tensile test,the compression yield point in the small-scale compression test was convincingly equivalent to the tension yield point resuting from the tensile test.

The test results demonstrated that small-scale compression specimens allow for a reliable determination of yield point of the material.

5.3.2 Mechanical evaluation of existing cast iron columns

Experimental tests on mechanical properties of cast iron columns have been done by J.Rondal and K.Rasmussen in 2003.Experimental data result and investigations shows that cast iron beams and columns were used for textile mills and warehouses from about 1800, and from about 1820 for other buildings. Many historical buildings currently being refurbished were constructed between 1840 and 1940.In many cases, they therefore feature cast iron columns as part of load-carrying structures. The strength of cast iron columns cannot be estimated on the basis of current design guidance for steel structures, such as Eurocode. The main reason is that the strain-stress curve is nonlinear which leads to a reduced bulking strength when the material gradually loses stiffness [37].

Structural cast iron as produced in the 19th century basically consisted of iron and a carbon content varying between 2% and 5%.As a result of the high carbon content, high compressive strength was achieved. However high carbon content lead to much reduced tensile strength. The cast iron used in 19th century was primary grey cast iron, characterized by a high carbon content and essentially no other alloying elements. Several other types of cast iron exist and today's cast iron types contain several alloying elements, notably silicon and magnesium, to enhance their ductility and tensile properties.

The stress-strain diagram of cast iron as produced in 19th century shows a continuous hardening and a very different response in compression and tension. In fact cast iron can be considered as ductile in compression but brittle in tension. Figure 5.11, gives two examples of the initial parts of the stress-strain curves for cast iron under tension and compression [37].

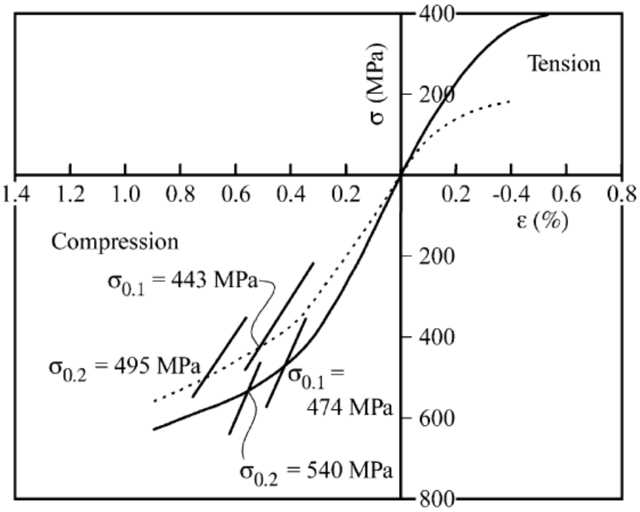


Figure 5.11: Stress-strain curves for typical structural cast iron [37]

The design procedures prevailing between 1840 and 1930 determine the column strength in terms of the ultimate compressive strength of the material (σ_{uc}) and the column slenderness (L/r), where the ultimate strength was obtained as the crushing strength of a small block of material. The concept of yield strength did not exist in the design of cast iron steel columns. Accordingly, values are readily available for the ultimate compressive strength (σ_{uc}) and the initial elastic modulus (E_0), as summarized in Table 5.14.

Table 5.14: Ultimate strength and initial modulus of elasticity of cast iron

Compression test	σ_{uc} (MPa)	E_0 (GPa)
Grey cast iron	750	88
Iron	590-780	85-90
Tension test		
Grey cast iron	75-160	91
Iron	124	66-93

5.3.3 Characterization of cast iron and wrought iron materials in United States Capitol dome

Experimental test results are presented by McCowan et al. (2011), on material properties of cast iron and wrought iron elements used in the structure of Capitol dome, United States. The dome consists of 36 arched ribs that bear on 36 paired pillars that, in turn, bear on 36 pairs of cast iron brackets embedded in the masonry walls of the Great Rotunda. The ribs are tied together at multiple levels by bands or hoops, consisting of either cast iron sections or wrought iron riveted plates (McCowan, 2011). Due to the leaking of moisture into interior areas of the building, restoration of corroded wrought iron and cast iron elements used in the building is needed. Several test specimens from wrought iron and cast iron elements of the capitol dome were extracted in order to examine the microstructures, composition and tensile properties of the samples.

Table 5.15: Compositions of three specimens from different grey cast iron elements of Capitol dome

Element	Specimens		
	A (%)	B (%)	C (%)
C	3.36	3.62	3.86
Mn	0.67	0.82	0.48
Si	3.20	2.18	2.31
P	0.78	0.82	0.60
S	0.11	0.08	0.06
Cr	-	-	0.01
Ni	-	-	0.04
Mo	-	-	0.01
Cu	-	-	0.02
Al	-	-	0.001
Ti	-	-	0.11

The cast iron surface of the dome is a ferrite-pearlite grey iron with carbon and silicon content. The microstructure of the cast iron elements shows good morphology and distribution of different types of graphite flakes that are appropriate for the intended service of casting (McCowan, 2011). For chemical analysis of cast iron elements, three specimens extracted. All specimens were analyzed by X-ray spectrometer for carbon, sulfur, manganese, silicon and phosphorous content. Also one specimen was analyzed for chromium, nickel, molybdenum, copper, aluminum and titanium. Table 5.15 shows the result of chemical analysis of the samples extracted from skin of cast iron elements of the dome [30].

Evaluation of chemical compositions of the samples shows that both carbon and silicon contents of the iron are at high level of expected compositional range in modern grey cast iron.

Evaluation of chemical compositions of wrought iron specimens shows 0.9% of Mn, 0.62% of P, 0.3% of Si and 0.3% of S. In comparison with a wrought iron specimen(0.025 %C) taken from a plate at the Capitol dome, the chemical analysis in 1989 shows 0.13% Mn , 0.13% P , 0.10% Si and 0.01% S , which is an alloy with higher quality.

A piece of gutter from cast iron elements were taken for evaluation of tensile strength. After the relatively low elongation value observed in the first specimen tested, the dual displacement strain measurements were designed. Bending would have relatively large effect on the measurement of small elongations, and the excellent correspondence between the data for the front and back of specimens confirmed that little bending occurred(McCowan, 2011).The results on tensile specimens testing samples show a strength of 120 to 130 MPa [30].

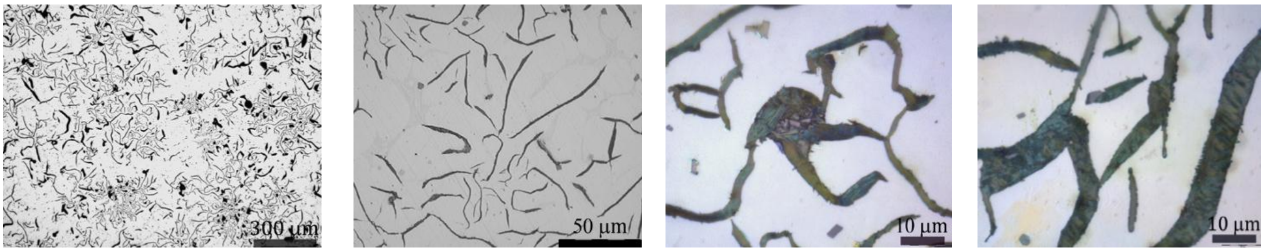
For measurement of yield strength, because all specimens failed before or just after meeting the 0.2% offset plastic criterion of ASTM 8, no result of yield strength was reported. Uniaxial test in compression was performed in order to analyze the compression strength of some elements of the structure of the dome. The ultimate compressive strength of the specimen tested was about 540 MPa at a strain of about 1.6%.Mechanical evaluation shows that grey cast iron strength in compression is twice in compare with tension and it has greater ductility.

Fatigue testing results are shown in Table 5.16. In the maximum tensile stress of 105 MPa, the fatigue specimen is still intact and crack-free up to 180,000 cycles. The tests were terminated after this value because it corresponds to about 500 years of daily thermal cycles. Most of the loads on the dome are expected to be compressive, so these test results would be estimates of compressive fatigue behavior (McCowan, 2011).

Table 5.16: Fatigue data from cast iron specimens taken from the skin on the dome of the dome

Maximum stress (MPa)	Minimum stress (MPa)	Cycles to fatigue
35	17.5	>180,000
70	35	>180,000
105	53	60,000
105	53	>180,000
140	70	>180,000

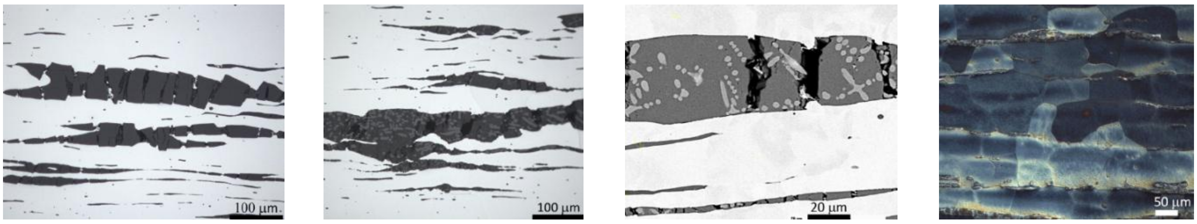
Microstructure of skin of cast iron elements of the dome, contained graphite flake morphologies of both flake (Type A) and rosette (Type B) structures. Chemical analysis shows that the type A flakes are relatively large and are dispersed randomly and type B is formed in near-eutectic compositions with higher cooling rates. Figure 5.12 shows the results of microstructure analysis of cast iron elements used in the Capitol dome [30].



(a) (b) (c) (d)

Figure 5.12: Graphite flake morphologies typical of cast iron skin elements: (a)Typical B rosette graphite structure (b) Type A graphite flakes (c) internal structure of graphite with cross-polarized light (d) internal microstructure of graphite flake under cross-polarized light [30]

The microstructure of wrought iron elements from the capitol dome is illustrated in Figure 5.13.The principal features of the microstructure are ferrite grains and large inclusions that is composite-like. The ferrite grain structure is separated by a multitude of dark horizontal lines, which are slag in inclusions.



(a) (b) (c) (d)

Figure 5.13: Inclusions and ferrite grain morphology in a wrought iron steel of Capitol dome: (a)large single phase inclusion (b) large dual phase inclusion (c) multi-phase inclusion (d) ferrite grains and inclusions [30]

5.4 Evaluation of properties of steel structures

5.4.1 Material analysis of St.Stefan church in Istanbul

Experimental tests were performed, in order to analyze the material properties of steel used in the St.Stefan Bulgarian metal church built at the end of 19th century in Istanbul (Blagovesta Ivanova, 2013).The church was produced and assembled by the Rudolph Waagner Company in 1895-1896 in Istanbul. High quality in the construction of the church of St.Stefan was assured by the fact that the steel to be used in it had to be subjected to the laboratory tests.

Figure 5.14 shows the dimension of the historic test specimen and the size of the tested samples from the historic tests. These values are compared with those under European standard B S EN 10002-1(2001) acquired on specimens made of a steel sheet 380x80 mm in size and 44 mm in thickness that formed part of the exterior facing of the building and was sampled for recent material investigations [23].

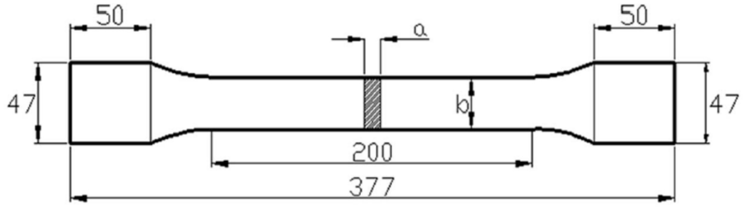


Figure 5.14: Dimension of a specimen for tensile testing [23]

The thickness of the samples may be taken as 10 mm for each sample, on average. The width is 17-18 mm. In addition the overall length is greater, also due to the different manner of clamping the edges of the sample in the measuring device. The most important and most general size for testing, the working length of 200mm has remained unchanged for more than 110 years, and is still used in present day standards.

The analysis shows that the data obtained from the test has a high degree of reliability, both for the reconstruction of the working tensile test diagram and for the qualities of the steels that were used. The chemical composition data according to a spectrometry analysis (SPECTROLAB, X-ray analysis of steel chemical composition with accuracy of 0.1%) and a standard tension test have indicated steel corresponding to grade ST.L 35 with No.1.0208, according to the DIN 17115 .The steel contains 7% carbon, 1% Si, 2%P, 3% Mn, 3% S, 3% Cr, 10% Ni and 15% Cu [23].

Table 5.17: Strength performance of the two types of steel according to the modern tests

		Steel No.1		Steel No.2	
		Test1	Test2	Test 1	Test 2
Yield point	(MPa)	280	256	325	317
Rupture strength	(MPa)	417	388	410	408
Relative elongation after rupture	(%)	10.2	29.7	29.6	30
Relative cross-section shrinkage after rupture	(%)	53	60	58	61

5.4.2 Material properties of old steel riveted bridges in Portugal

This investigation present research work carried out by Jesus et al. (2011), to characterize the mechanical properties and fatigue behavior of materials from ancient Portuguese riveted bridges, namely the Pinhao bridge designed by Gustave Eiffel by the end of 19^{th} century and Luiz I highway bridges designed by Gustave Eiffel in 1886, the Viana Highway Bridge, Trezoi Railway Bridge designed in 1956, Eiffel bridge designed by Gustave Eiffel in 1878 and Fao road bridge designed by Abel Maria Mota by the end of the 19th century.

The experimental program was carried out with materials extracted from all of the mentioned bridges. In order to do the mechanical characterization of original bridge members, test specimens were removed from structural elements and replaced by new ones. A diagonal member with 1500 mm in length and a bracing 1400 mm in length were removed from Pinhao Bridge. A diagonal member with 1600 mm in length was removed from Luiz I bridge. Also, a bracing with 3000 mm in length was removed from Trezoi Bridge. Regarding the Viana Bridge, the highway Darque viaduct was removed and replaced by a new one. The test specimen from Viana Bridge for the experimental work was extracted from a viaduct girder. The specimens were used in chemical and metallographic analysis, hardness measurements, monotonic tensile tests and notch toughness tests.

Tensile strength properties

The tensile strength properties for the various materials under investigation were evaluated according to the European Standard NP 10002-1. Several numbers of specimens extracted from different bridges. The average values of the tensile strength properties are summarized in Table 5.18, namely the ultimate strength, f_u, the yield strength, f_y, the elongation at fracture, *A*, and the reduction in cross section at fracture, *Z*.

In general, the materials exhibit a high ductility, being the material from the Viana Bridge an exception to this trend, since it presents a relative small ductility, which may be justified by the high level of inclusions in the material microstructure. The material from Trezoi Bridge shows higher strength properties, which is expectable since it is closer to modern steels.

Table 5.18: Tensile strength properties

Bridge		f_u	f_y	A	Z
		(MPa)	(MPa)	(%)	(%)
Pinhao	Diagonal	367	284	33	70
	Bracing	355	328	33	70
Luiz I	Diagonal	397	303	21	27
Viana	Darque Viaduct	342	292	8	12
Trezoi	Bracing	464	401	23	66

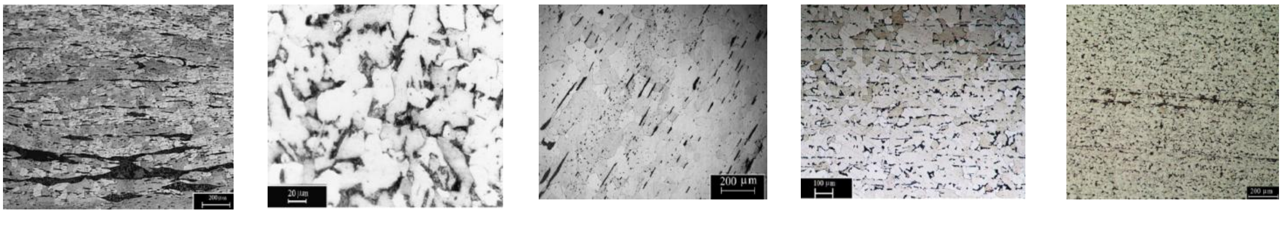
Also, monotonic tensile tests were carried out by using round specimens machined from samples of materials extracted from the mentioned bridges. Main mechanical properties of specimens are shows in Table 5.19.Specimen tested from Trezoi road bridges exhibit the highest strength properties and high ductility. Specimen extracted from Pinhao Bridge show the lowest ductility properties. Highest ductility properties are recognized for Pinhao Bridge. By comparing the results of the tensile test of Pinhao Bridge with other bridges, it shows the highest ductility and very good strength properties. Chemical analyses on specimens extracted from the bridges were assessed by using the spark spectrometry technique. Chemical composition of specimens shows that Trezoi bridge materials have lowest sulphur and phosphorus contents, which is consistent with the age of material. The Trezoi Bridge is a ferritic structural steel, since it has very small amount of carbon. Different chemical compositions, due to the typical heterogeneous microstructures of the materials of the bridges in 19th and 20th century, leads to significant variable chemical compositions. Low carbon content in these materials exhibit the ferrite matrix. Chemical analyses of the samples of Luiz I bridge show the higher carbon content, silicon and manganese than specimens from other bridges.

Chemical analyses present the microstructures of extracted specimens. Figure 5.15 shows that the perlite is observed from the materials of Pinhao and Trezoi bridges.

Table 5.19:Tensile properties and chemical compositions of materials

Specimens	Young modulus (GPa)	Yield stress (MPa)	Ultimate tensile stress (MPa)
Eiffel	193.1	292	342
Luiz	192.7	303	397
Fao	198.7	220	359
Pinhao	-	306	361
Trezoi	198.6	401	464

Material	C%	Mn%	Si%	P%	S%
Eiffel	0.03	0.02	0.13	0.46	0.06
Luiz	0.24	0.26	1.49	>0.15	>0.15
Fao diagonal sample	0.09	0.13	0.06	0.14	0.007
Pinhao diagonal sample	0.06	0.4	<0.01	0.04	0.04
Trezoi bracing sample	0.06	0.34	0.03	0.02	0.02



(a) (b) (c) (d) (f)

Figure 5.15: Microstructure of the materials of the bridges: (a) Eiffel; (b) Luiz I ; (c) Fao ; (d) Pinhao ; (e) Trezoi

Hardness measurement

Hardness of the test specimens are measured by Vickers hardness test according to the procedures of the Portuguese Standard NP711-1. Pinhao Bridge were analyzed, 3 from the diagonal and 3 from the bracing resulting, respectively, the average hardness of 108 HV40 and 116 HV40. For the Luiz I bridge, 3 samples of material from the diagonal were analyzed resulting an average hardness of 158 HV50.Three samples of a bracing from the Trezoi bridge were tested, exhibiting an average hardness of 136 HV40.

Notch toughness testing

The notch toughness of the materials was measured using both Charpy V-notch impact and COD tests. The thickness of the specimens was limited by the thickness of the removed bridges members from which they were extracted. According to Eurocode standard, the minimum allowable Charpy V-notch strength, for a material classified according the EN 10025, should be 27 J at a specified temperature. Only the material from the Pinhao Bridge exhibits acceptable toughness properties, even for current design requirements.

5.4.3 Material Properties of old Swedish and German metal bridges (Tobias Larsson, 2006)

This investigation on mechanical properties of steel and wrought iron in Swedish and German bridges refers to the period that extends from the end of the 19th century to the 1940's.The data base consists on information obtained from tests on metal specimens taken from both Swedish and German bridges and structures. The amount of information from each bridge differed depending on the extent of the evaluation.

For the mechanical properties, the characteristic values are determined by the 5 % fractile of lognormal distribution, also the mean value and standard deviation are accounted for.

In the data base for steel produced before 1901, only material from one bridge was found.33 samples were retrieved from the bridge. According to the Swedish Road and Railway Administration the mechanical strength properties should be determined by BVS 583.11.Table 5.20 shows the average results of mechanical properties of Swedish steel produced before 1901.

Table 5.20: Mechanical properties of Swedish steel produced before 1901

Properties	5 % frac (MPa)	Mean value (MPa)	Standard Deviation	No. of samples
steel				
Yield stress	244	295	31	32
Ultimate stress	404	454	30	32

Data from Germany show the evaluation of material properties of metal produced before 1901 and metal produced from 1901 to 1919.A small number of samples from German bridges constructed with steel and iron made before 1901 are available. Since only 4 samples were available, a fit distribution was not possible. Table 5.21 shows the results of material properties of German steel produced before 1901.

Table 5.21: Mechanical properties of German steel and iron produced before 1901

Properties	5 % frac	Mean value (MPa)	Standard Deviation	No. of samples
Iron				
Yield stress	227	259	19	32
Ultimate stress	264	332	41	32
Steel				
Yield stress	-	249		4
Ultimate stress	-	395		4

Due to the several tests on steel samples taken from Swedish bridges and structures constructed during 1901 to 1919, mechanical properties and fracture toughness with a good basis of evaluation are present in Table 5.22.

Table 5. 22: Mechanical properties of Swedish steel produced between 1901 and 1919

Properties	5 % frac	Mean value(MPa)	Standard Deviation	No. of samples
Steel				
Yield stress	236	278	25	87
Ultimate stress	372	425	32	70
Toughness Temp.-30^{o}C (N/mm)		33	23	31

Data regarding Charpy-V tests are available, but since they were conducted at different temperatures, an evaluation is not possible and therefore the results obtained are not accounted for. Concerning German data, the time period between 1901 and 1919, corresponds to the largest number of tests on mechanical, Charpy-V and fracture mechanic properties for steel and wrought iron. The Charpy-V and fracture mechanics tests were performed at-30^{o} C. Table 5.23 show the mechanical properties of steel and iron in Germany between 1901 and 1919.

Also Table 5.24 shows the properties of Swedish steel contains information about the mechanical, Charpy-V and fracture toughness of steel.

Table 5.23: Mechanical properties of German steel and iron produced between 1901 and 1919

Properties	5 % frac	Mean value (MPa)	Standard Deviation	No. of samples
steel				
Yield stress	242	302	36	494
Ultimate stress	353	431	47	494
Wrought iron				
Yield stress	219	266	28	26
Ultimate stress	273	334	37	26
Steel				
Charpy-V Temp-30^o C (J)	-	5.3	3.1	139
Toughness Temp-30^{o}C(N/mm)	-	54	51	96
Wrought iron				
Charpy-V Temp-30^o C (J)	-	5.2	2.1	8
Toughness Temp-30^{o}C(N/mm)	-	32	26	12

Table 5. 24: Mechanical properties of Swedish steel produced between 1919 and 1940

Properties	5 % frac	Mean value (MPa)	Standard Deviation	No. of samples
Steel				
Yield stress	238	294	34	100
Ultimate stress	348	437	54	62
Charpy-V Temp-20^o C (J)	-	137	298	17
Toughness Temp-30^{o}C(N/mm)	-	288	580	60
Toughness Temp-20^{o}C(N/mm)	-	290	479	74

5.4.4 Chemical properties of steel used in Boco Bridge in Portugal

An experimental investigation in order to analysis the chemical compositions of steel used in the Boco Bridge has been done by Sena Cruz et al.,(2012).The Boco Bridge is located along the Portuguese road EM595-1,breaching the valley of the Cávado river and dividing the regions of Amares and Vieria do Minho, in the district of Braga. This bridge built in between the years of 1909 and 1910 in Hennebique construction system, (Sena-Cruz, 2012).

In order to analyze the chemical properties of steel used in the bridge, a sample of steel was taken from the structure of the bridge to do the X-ray fluorescence spectrometer test and basic carbon element test. Chemical analyses of the test specimen extracted from the bridge are presented in Table 5.25 which reveals mild steel with low content of carbon. The microstructure of the test specimen was observed in SEM, which shows the existence of manganese sulphide inclusions, aligned along the ferrite grain boundaries [35].

Table 5.25: Chemical composition of the steel

Element	C (%)	Mn (%)	S (%)	P (%)	Si (%)	Pb (%)	Fe (%)
Portion %	0.024	0.29	0.043	0.067	0.046	0.096	Remaining part to 100%

6 Evaluation of experimental tests data and standards

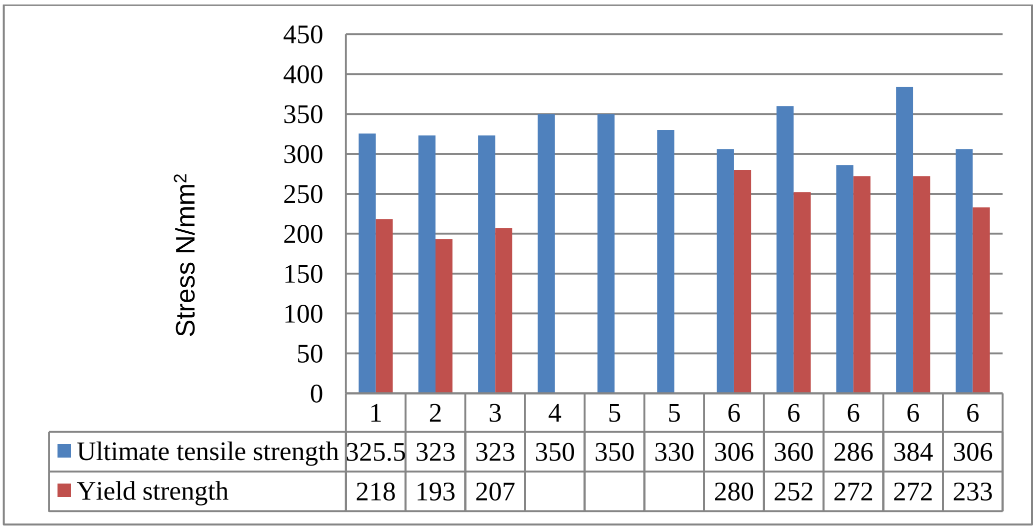
The test results of the metallic materials used in structures built during the 19th and early 20th century are collected from the work developed from different authors of different countries. The results include the average values of chemical and mechanical properties of metal elements used in structures. The assessment of material characteristics concerns the chemical compositions of each element and mechanical properties such as strength, hardness, toughness, etc. Due to the different composition and properties of metallic elements used in structures in different countries and different standard to evaluate the properties, the values of test results are presented in relation to each different country.

In general, for the wrought iron structures were mostly used in the 19th century which studied in previous chapter and for the practical standards and codes in different countries, the average amount of mechanical properties such as tensile strength and yield strength is presenting in Table 6.1.

Table 6.1: Average values of properties for wrought iron samples

type	Year	f_u (MPa)	f_y (MPa)
1		325.5	218
2		323	193
3		323	207
4		350	
5	1886	350	
5	1900	330	
6	1860	306	280
6	1862	360	252
6	1870	286	272
6	1877	384	272
6	1897	306	233

Type 1: Samples from wrought iron bridge in Indiana, USA (eyebars)
Type 2: Samples from wrought iron bridge in Indiana, USA (round bars)
Type 3: Samples from wrought iron bridge in Massachusetts, USA
Type 4:Samples from British wrought iron structure
Type 5:Samples from Swedish wrought iron structures
Type 6:Samples from French wrought iron structures



	1	2	3	4	5	5	6	6	6	6	6
🟦 Ultimate tensile strength	325.5	323	323	350	350	330	306	360	286	384	306
🟥 Yield strength	218	193	207				280	252	272	272	233

Figure 6.1: Average tensile strength and yield strength values of wrought iron structures

Figure 6.1 show the chart of tensile strength and yield strength values of different wrought iron structures described in table 6.1.For the results from the wrought iron structures in USA, the ultimate tensile strength present the same values. As analyzed in previous chapter, difference in values depends to the other properties of the samples such as chemical compositions. In yield strength values for the samples from wrought iron structures, due to the investigation in different structures, different values are presented.

Actually because of the lack of information of wrought iron structures in 19th century, the average values don't show the complete properties of the wrought iron elements in general.

Cast iron elements in different structures examined in order to analyze the mechanical properties. Different practical codes and experimental tests results present the different mechanical properties.

Figure 6.2 show comparison between tensile strength and compressive strength values of different cast iron structures described in Table 6.2.Results shows increase in average amount of tensile strength by the date of construction of cast iron structure. For Swedish cast iron elements, the tensile strength from before 1850 till 1950 shows an increase in average values. But for compression strength, different structures present different values which the Swedish elements and US capitol dome samples shows the lower amount in compression in compare with other structures.

Table 6.2: Average values of Cast iron samples

type	Year	f_u (MPa)	f_y (MPa)	Compressive stress
1			319	640
2		118		685
3		125		540
4		123		680
5	before1850	100		550
5	1850-1900	160		550
5	1900-1950	260		550

Type 1: Samples from Cast iron bridge in Germany
Type2: Samples from cast iron beams and columns
Type3: Samples from cast iron used in US Capitol dome
Type4:Samples from British cast iron structure and codes
Type5:Samples from Swedish cast iron structures based on codes

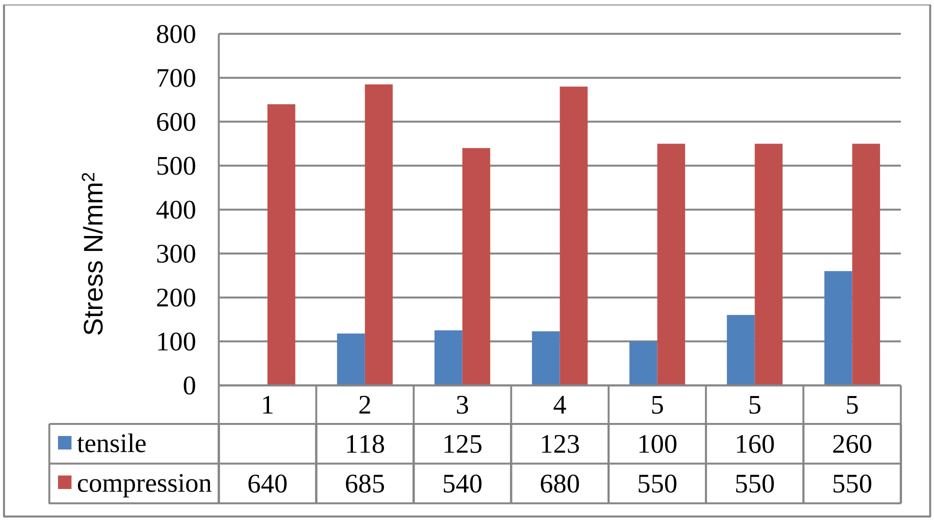


Figure 6.2: Graph of average tensile strength and compressive strength values of cast iron structures

The same investigation on mild steel used in structures in 19th and 20th century present the values for ultimate tensile strength and yield strength. By using different experimental test results and different practical codes of countries, the ultimate and yield strength values shown in Table 6.3.

In Figure 6.3 the results obtained for the French samples from the end of 19th century show the lowest values for tensile strength. In British code also the strength in 19th century samples present the lower values in comparison with the samples from the early 20th century.

In particular, test results according to the British Standard show the increase in amount of yield strength along time. Also the ultimate tensile strength for the structures from the beginning of the 20th century presents higher values in comparison with the structures from end of 19th century.

Table 6.3: Average strength values of steel samples

type	Year	f_u (MPa)	f_y (MPa)
1			295
2		385	322
3	before1906	368	
3	BS15:1906	463	
3	BS16:1912-1941	470	
3	BS16:1948-1961	424	230
3	BS16:1961-1968		240
3	BS968:1962	548	347
4	1886	500	
4	1919	440	
4	1931: ST 37	400	
4	1931:ST 44	470	
4	1931:steel bolts	400	
5	1913-1919	338	436
6	1890	279	415
6	1906	251	392
6	1909	217	415

Type 1: Samples from Church St.Stefan in Istanbul.
Type 2: Samples from Portuguese bridges
Type 3: British standards
Type 4: Swedish codes
Type 5: German codes and structures
Type 6: French steel structures

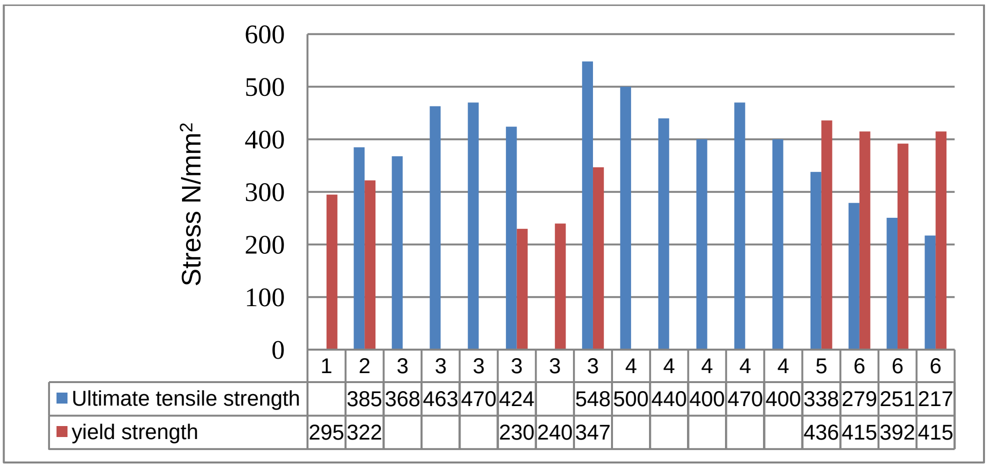


Figure 6.3: Graph of average strength values of steel structures

In Sweden, the evaluation codes BVS 583.11 and the Swedish Railway Administration data base were used to collect result on the characterization of the material properties of cast iron, wrought iron and steel, in different periods. The German data was retrieved from different tests conducted with the University RWTH in Aachen Germany.

Investigations shows the higher yield strength of material in all intervals in data base which presented in the in the table A7 and A8, from before 1901 to 1940,compared to the Swedish evaluation code BVS 583.11.For steel produced before 1901,200% higher values for yield strength and ultimate strength were found. But for the results of materials before 1901, since the values come from just one bridge, it cannot represent the characteristics of all metallic structures and bridges. In the interval 1901-1911 the properties of yield strength and ultimate strength were 34% and 29% higher. In the interval 1919 -1940 the properties of yield strength was 8% higher but ultimate strength show 4% lower values in compare with BVS 583.11.Data collected from experimental tests and practical codes from different counties on cast iron, wrought iron and steel are presented in Appendix.

In Sweden, material properties of different Swedish bridges were analyzed in three intervals. The detailed average values in each year are presented in Appendix. Material characterization from the first interval before 1900 is shown in the Table 6.4.In the first interval before 1900, the average value for yield strength is 295 MPa and the average value for ultimate tensile strength is 454MPa.

In second interval from 1901 to 1919, the values for each year for different structures are presented as a Table A.7 of the Appendix. The graph of values is show in Figure 6.4.For both yield strength and ultimate tensile strength, structures built in the last years of this interval show the higher strength values.

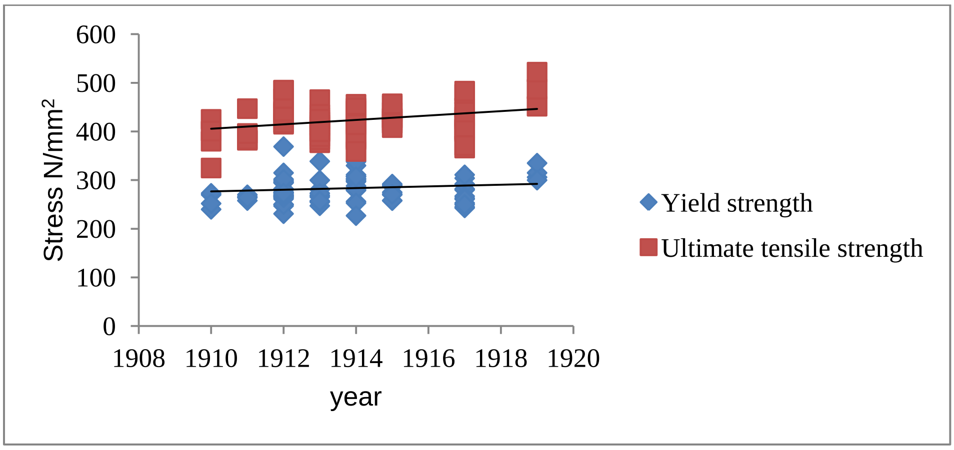


Figure 6.4: Swedish material properties between 1910 and 1919

Figure 6.5 presents the values for Swedish materials' yield and ultimate strength for the interval of time between 1920 and 1939. The detailed values are presented as a table in Appendix. The materials used in the last years of this interval show higher strength values than the materials produced in the beginning of the interval.

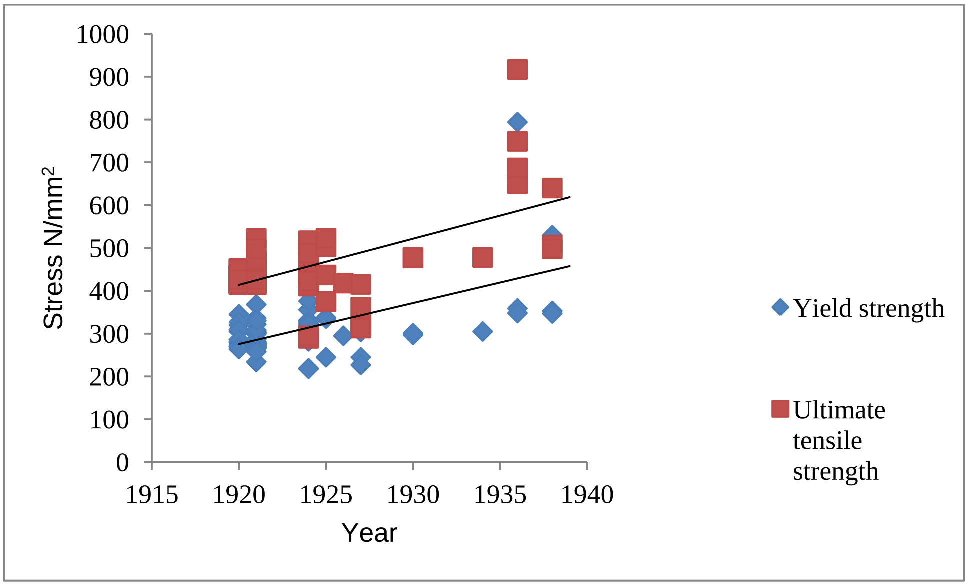


Figure 6.5:Swedish material properties between 1920 and 1939

By comparing the average values of yield strength and ultimate tensile strength for Swedish materials produced in different periods of time, it is clear that strength values from the last interval show the higher values. In the Appendix, the detailed values for each metallic structure and corresponding date of the test are presented. In the data base for steel produced before 1901, only material from one bridge was found. Because of the lack of information for the bridges before 1900, the values presented in data base are not representing of all bridges and structures built before 1900. The average value of the strength is representing the averages from 32 samples. However it shows that the bridges before 1901 can provide much higher material values than specified in the present codes.

Table 6.4: Average strength value for the Swedish data base

Interval	f_y (MPa)	f_u (MPa)	J_c (N/mm)
before 1900	295	454	
1901-1919	283	424	57
1920-1939	307	459	236

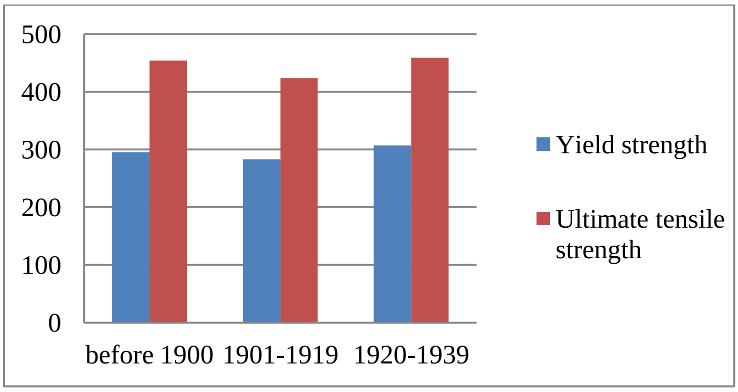


Figure 6.6: Average values of Swedish material properties

The statistics results from Swedish data base for the last interval from 1919 to 1940, shows an 8% higher yield strength in compare with the results from Swedish evaluation codes BVS 583.11.In ultimate strength, the difference shows 4% lower in values for data base in compare with the codes.

For the results before 1901, a comparison of Swedish data base and Swedish design codes shows the 10 to 20% lower values of ultimate strength in data base. The high values for the ultimate strength in Swedish data base before 1900 present the values of 450 up to 500 MPa, but because of the lack of results of experimental tests in this period, it is not possible to do comparison these values with other periods.

The results from material properties of Swedish data base and French data base before 1900 shows the 15% higher amount in yield strength and 30% higher in ultimate strength for Swedish data base.

7 Steel material characterization of the bridge in Terras do Bouro village country in Portugal

The steel material characterization of the bridge made by using the Hennebique system was assessed in the ambit of the present dissertation. The Hennebique Reinforced Concrete Bridge was made in 1909, and is located on the river Man; in the municipality of Terras do Bouro district of Braga, Portugal. The bridge is resting on a stone pillar with a span of 14.1 m and with the guards of concrete and iron.

The bridge was used until 1977, when the city council's Land Bouro built beside it, a few meters upstream, a new bridge. It is now unused and there is no signs of having suffered and modification during the period of use. Figure 7.1 shows the structure of bridge and the place where the specimen was taken.

Figure 7.1: Hennebique bridge

Experimental tests were done in mechanical laboratory of University of Minho is performing in order to determine essential material and mechanical properties of the reinforced bars used in the structure of the bridge using samples extracted from the structure of bridge.

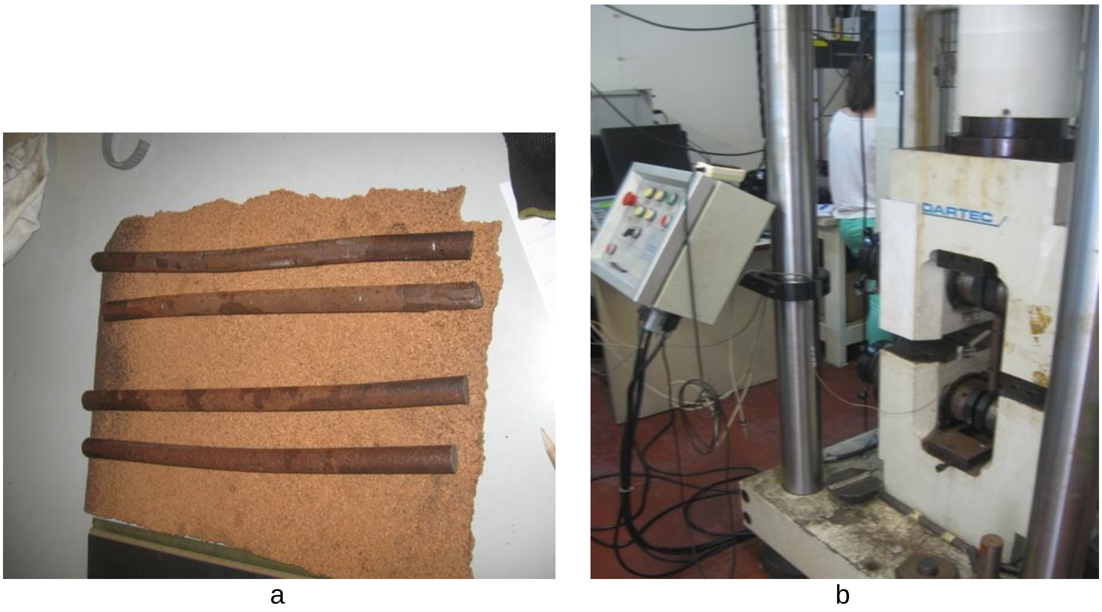
Chemical composition

The Chemical composition of the specimen extracted from the bridge can be analyzed by SEM technique. For SEM analysis, a 5 cm sample was taken from the bar specimen. Because the SEM test is doing in the last moments of presenting this thesis, results of chemical composition of the bar samples will publish later.

Tensile test

Mechanical properties of the bar extracted from the bridge are analyzed on four test samples of the bar. The tensile test specimens can be seen in Figure 7.2 (a). The tests were done in a DARTEC universal tensile test machine (with a maximum carrying capacity of 600 kN) which is shown in Figure 7.2 (b). In these tests, the initial length of the specimens is taken to be equal to the gage length of the test machine. The initial length for all specimens was chosen 20 cm which is equal with the gage length of the test machine. The specimens should be gage marked with a center punch with 20cm gage length near the middle of the specimens. The purpose is to make a reference point for determination of the percent of elongation.

By placing the test specimen in test machine, while the applied uniaxial load is continuously increasing, the elongation, strain, displacement value, load and the velocity of loading is recording. Increasing of the load is applying in a uniform rate.



a b

Figure 7.2: (a) Test specimens (b) Tensile test machine

For each test specimen, after the test by taking the data obtained from test machine, mechanical properties such as tensile strength, modulus of elasticity, strain, stress-strain curve is measured. Measurement of ultimate tensile strength of each specimen is doing by dividing the maximum load sustained during the tensile test by the cross-section area of the bar.

Figure 7.3 shows together the specimen placed in the test machine, the clip gage used to the test specimen and specimens after the tensile tests.

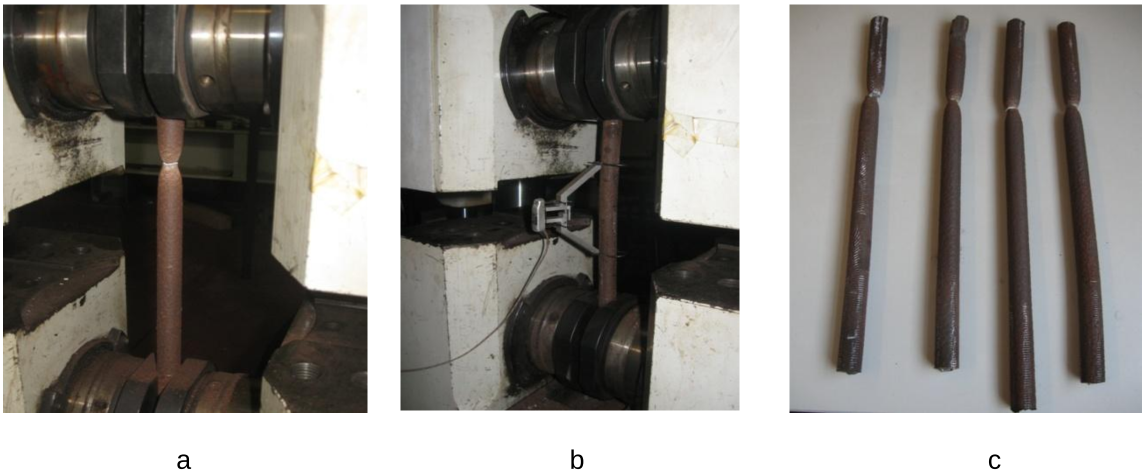


Figure7.3: (a) Specimen during test (b) Clip gage (c) Specimens after test

For specimen No.1, the maximum load recorded 132.24 kN. The following calculation present the area of the bar specimen and ultimate tensile strength.

Cross- section area of specimen No.1: $A_1 = \frac{\pi}{4} d^2 = 271.716 \text{ mm}^2$

Specimen No.1: Ultimate tensile strength $\sigma = \frac{F}{A} = \frac{132.2399 * 1000}{271.716} = 486.69$ MPa

By using the data obtained from the tensile test results, other properties such as yield strength, modulus of elasticity is presenting in the in the graphs. The modulus of elasticity, E, was calculated by drawing the stress-strain graph, and then evaluating the slope of the graph in elastic branch of this curve.

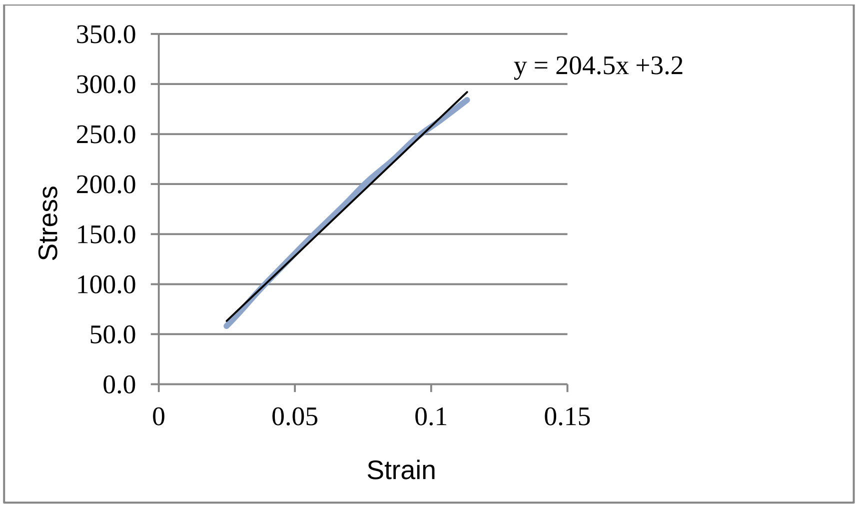


Figure 7.4: stress-strain line equation in elastic part for specimen No.1

The equation y=204.5X+3.2 is the stress-strain equation of the graph. The value of 204.5 (GPa) is presenting the value of modulus of elasticity.

By using 0.2% offset yield strength of stress-strain graph, the yield stress of the test specimen is obtained. Using the data from the test result and the graph in Figure 7.4, the value of yield stress is 424.76 MPa in the point which strain value is 0.3628. Table 7.2 resumes the mechanical properties obtained from the tensile test result of specimen No.1:

Table7.1:Mechanical properties of specimen No.1

Specimen		No.1
d	(mm)	18.6
Area	(mm^2)	271.7
Load Max	(kN)	132.2
Lo (initial length)	(mm)	200
Lf (elongated length)	(mm)	217
Ultimate Tensile Strength	(MPa)	486.7
Yield Strength	(MPa)	424.8
E	(GPa)	204.5

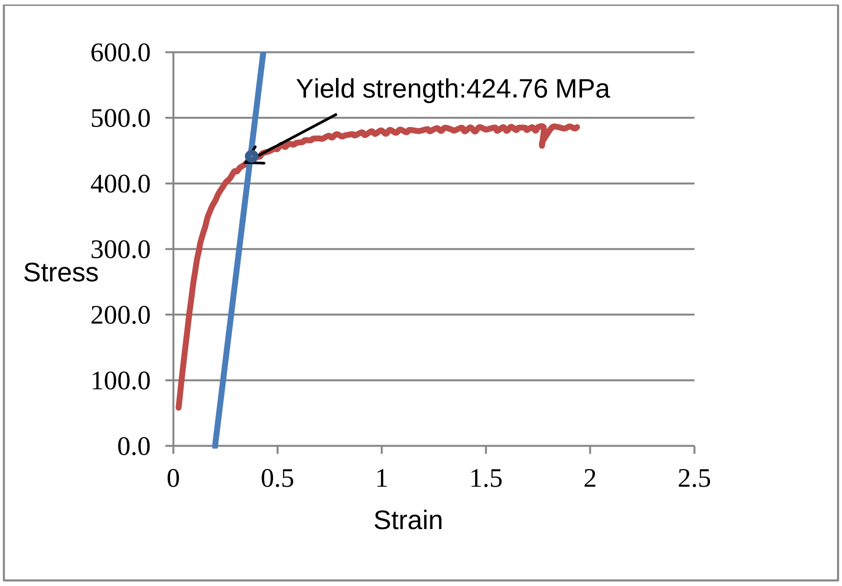


Figure7.5:Yield stress value of specimen No.1

The same tensile test procedure for specimen No.2 is done but because of high temperature of the test machine, during the test, it was stopped during loading on specimen. After one day, the test repeated for the specimen No.2. The same procedure is done for the results obtained from the test. The maximum load recorded is 112.91 kN. The following equations present the cross-section area of specimen and the ultimate tensile strength.

Cross-section area of specimen No.2: $A_2 = \frac{\pi}{4}d^2 = 271.716\ mm^2$

Specimen No.2: Ultimate tensile strength σ = $\frac{F}{A} = \frac{112.9069*1000}{271.716}$ = 415.533 MPa

By using the data obtained from the tensile test results, other properties such as yield strength, modulus of elasticity is presenting in the in the graphs. The modulus of elasticity, E, was calculated by drawing the stress-strain graph, and then evaluating the slope of the graph in elastic limit presents the Modulus of Elasticity.

The equation y=188.3X+2.0252 is the stress-strain equation of the graph. The value of 188.3 (GPa) is presenting the value of modulus of elasticity.

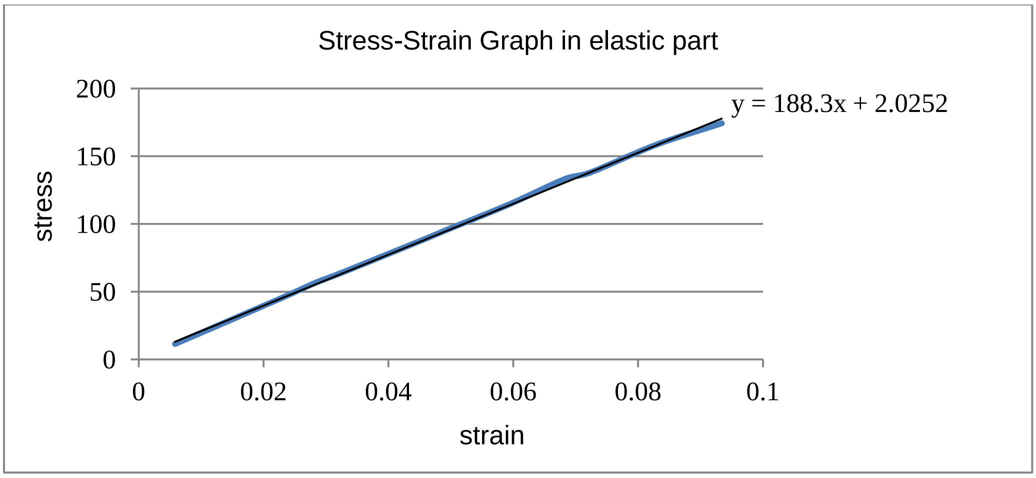


Figure7.6: stress-strain line equation in elastic part for specimen No.2

By using 0.2% offset yield strength of stress-strain graph, the yield stress of the test specimen is obtained. Using the data from the test result and the following graph, the value of yield strength is 345.75 MPa in the point which strain value is 0.3826.The decrease of the amount of mechanical properties for the specimen No.2 is because of the problem occurred during the test, which was stopping the test because of the high temperature of the test machine. Table 7.3 resumes the mechanical properties obtained from the tensile test result of specimen No.2:

Table 7.2:Mechanical properties of specimen No.2

Specimen		No.2
d	(mm)	18.6
Area	(mm^2)	271.72
Load Max	(kN)	112.91
L_o (initial length)	(mm)	200
L_f (elongated length)	(mm)	231
Ultimate Tensile Strength	(MPa)	415.5
Yield Strength	(MPa)	345.75
E	(GPa)	188.3

For specimen No.3, the maximum load was recorded 114.79 kN. The following calculation present the area of the bar specimen and ultimate tensile strength.

Cross- section area of specimen No.3: $A_1 = \frac{\pi}{4} d^2 = 277.59\ mm^2$

Specimen No.3: Ultimate tensile strength $\sigma = \frac{F}{A} = \frac{114.7927*1000}{277.59} = 413.533$ MPa

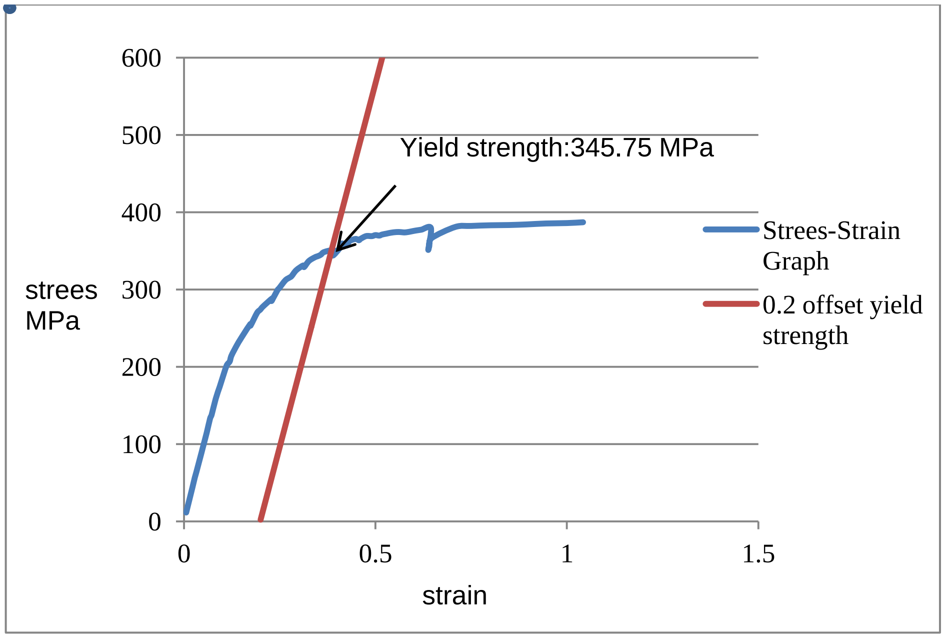


Figure 7.7:Yield stress value of specimen No.2

By using the data obtained from the tensile test results, other properties such as yield strength, modulus of elasticity is presenting in the in the graphs. The modulus of elasticity, E, was calculated by drawing the stress-strain graph and then evaluating the slope of the graph in elastic branch of this curve.

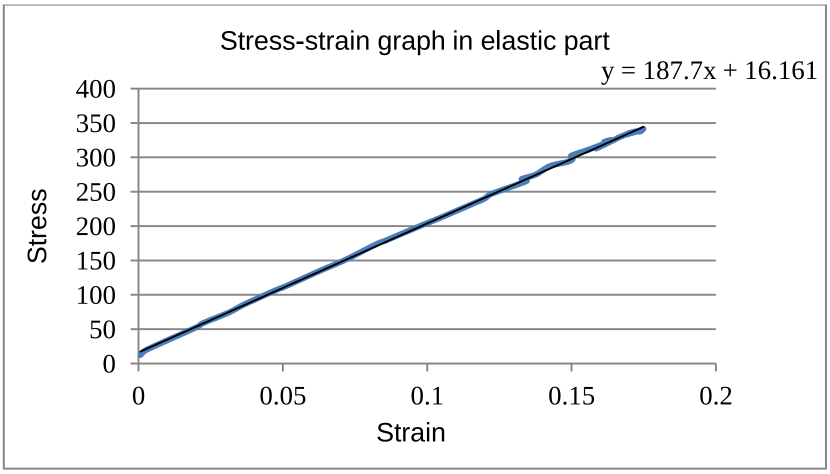


Figure 7.8: stress-strain line equation in elastic part for specimen No.3

The equation y=187.7+16.161 is the stress-strain equation of the graph. The value of 187.7 (GPa) is presenting the value of modulus of elasticity.

By using 0.2% offset yield strength of stress-strain graph, the yield stress of the test specimen is obtained. Using the data from the test result and graph in Figure 7.8, value of yield strength is 342.66 MPa in the point which strain value is 0.374.Also the Table 7.4 resumes the mechanical properties obtained from the tensile test result of specimen No.3:

Table 7.3:Mechanical properties of specimen No.3

Specimen		No.3
d	(mm)	18.8
Area	(mm^2)	277.59
Load Max	(kN)	114.79
L_o (initial length)	(mm)	200
L_f (elongated length)	(mm)	235
Ultimate Tensile Strength	(MPa)	413.5
Yield Strength	(MPa)	342.66
E	(GPa)	187.7

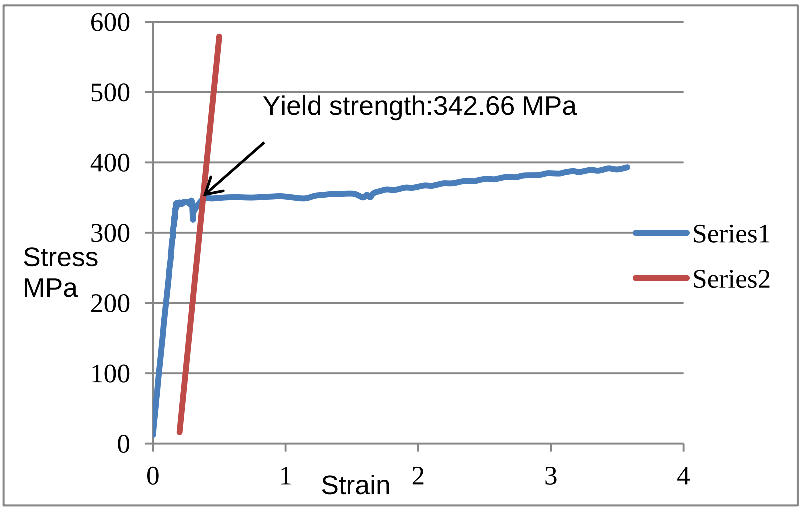


Figure 7.9:Yield stress value of specimen No.3

For specimen No.4, the maximum load was recorded 117.87 kN. The following calculation present the area of the bar specimen and ultimate tensile strength.

Cross- section area of specimen No.4: $A_1 = \frac{\pi}{4} d^2 =$ 274.65 mm^2

Specimen No.4: Ultimate tensile strength σ = $\frac{F}{A} = \frac{117.8691*1000}{274.65}$ = 429.16 MPa

By using the data obtained from the tensile test results, other properties such as yield strength, Modulus of Elasticity is presenting in the in the graphs. The modulus of elasticity, E, was calculated by drawing the stress-strain graph, the slope of the graph in elastic branch of this curve.

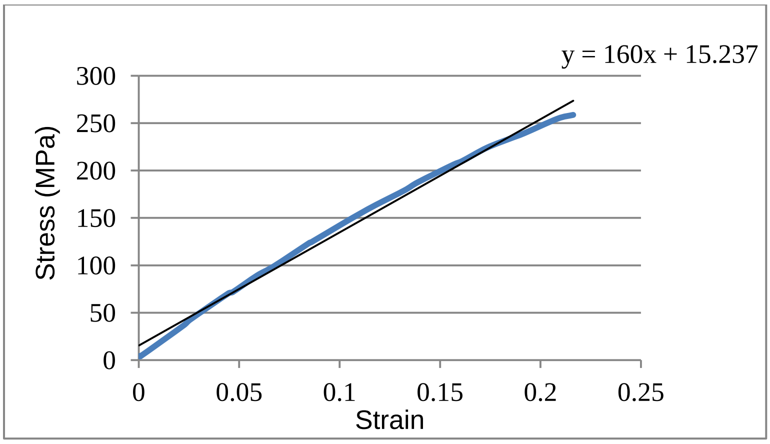


Figure 7.10: stress-strain line equation in elastic part for specimen No.4

The equation y=160x+15.237 is the stress-strain equation of the graph. The value of 160 (GPa) is presenting the value of modulus of elasticity.

By using 0.2% offset yield strength of stress-strain graph, the yield stress of the test specimen is obtained. Using the data from the test result and Figure 7.10, the value of yield strength is 334 MPa in the point which strain value is 0.4786. Table 7.5 resumes the mechanical properties obtained from the tensile test result of specimen No.4:

Table 7.4: Mechanical properties of specimen No.4

Specimen		No.4
d	(mm)	18.7
Area	(mm^2)	274.65
Load Max	(kN)	117.87
L_o (initial length)	(mm)	200
L_f (elongated length)	(mm)	221
Ultimate Tensile Strength	(MPa)	429.16
Yield Strength	(MPa)	334
E	(GPa)	160

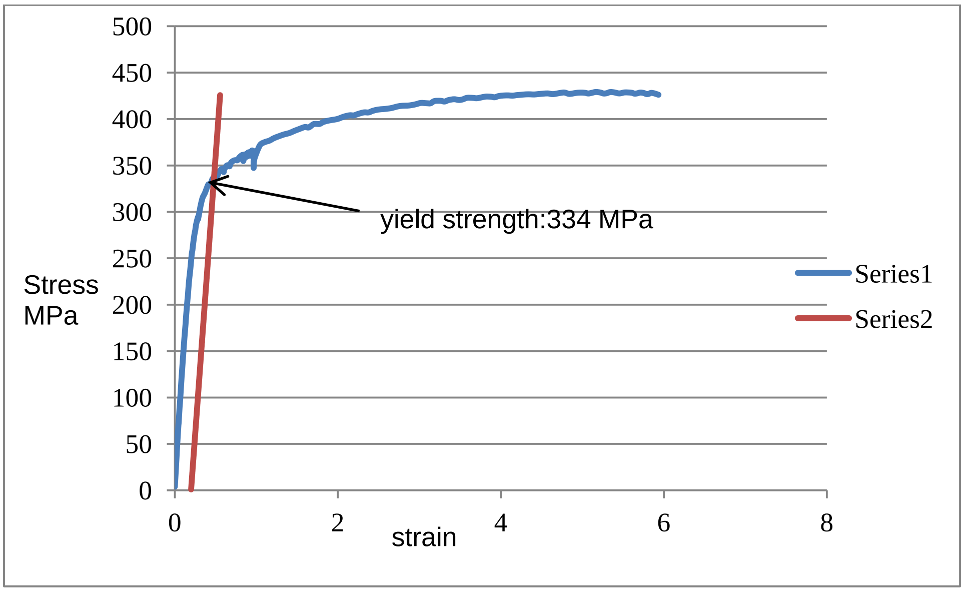


Figure 7.11:Yield stress value of specimen No.4

Mechanical properties results from all test specimens are presenting in Table 7.5.The average value for Ultimate tensile stress of the test specimens is 436.5 MPa and the average values for the yield stress is 361.9 MPa and the average values for young's modulus is 185.2 GPa.

Table 7.5 : Average mechanical properties values for steel bar specimens of the bridge

Test specimen	d (mm)	Area(mm^2)	Max Load (kN)	Ultimate Tensile Stress (MPa)	Yield Stress (MPa)	E (GPa)
No.1	18.6	271.7	132.2	486.7	424.8	204.5
No.2	18.6	271.7	112.9	415.5	345.7	188.3
No.3	18.8	277.6	114.8	413.5	342.7	187.7
No.4	18.7	274.65	117.9	430	334	160
Average Value	18.7	273.9	119.5	436.5	361.9	185.2

Due to the original deformation of bar sample tested in the tensile machine, the material properties obtained from the specimens in this investigation cannot totally represent the properties of whole steel used in the structure of bridge. The average values of the results of 4 test specimens shows very close values to the range of general steel elements structures at the beginning of 20th century.

In general, in order to obtain the complete results from tensile test on steel bars of the bridge, more specimens from different parts of the bridge is necessary.

Also, to complete the evaluation of material properties of steel bars in bridge, different types of mechanical, physical and chemical tests are needed.

8 Conclusion

8.1 Final remarks

This thesis is developed with the goal of evaluating the material properties of three traditional metallic materials used in the structures of 19th and early 20th century: cast iron, wrought iron and early steel elements. The application of these metallic materials in construction and their typical mechanical and chemical properties are given in the first chapters.

For most of the steel/iron structures that were built in 19th century and in the beginning of 20th century, the information about the construction sequences and procedures and the information about the steel/iron elements fabrication is scarce. The detailed material characteristics also need to be studied: chemical composition, microstructure, strength values and other chemical or physical properties. Several experimental tests performed by different authors on metallic structures built in the referred period were investigated in order to obtain average values of properties. Test results obtained on cast iron, wrought iron and early steel structures (buildings and bridges) is collected.

Evaluation of existing test results is necessary to define the overall characteristics of steel/iron used in these structures. It is not possible to do a complete assessment on these metallic materials because of the few structures investigated in this thesis. However, some comparison can be done with the data collected from different experimental research sources presented.

Also, the results of the experimental test performed on steel bars collected in an old Portuguese Hennebique reinforced concrete bridge show that the evaluated mechanical properties average values are comparable to other steel structures investigated by different authors.

8.2 Future work

Further investigation is needed to collect more experimental test results on cast iron, wrought iron and early steel samples collected in metallic structures built during the 19th century and early 20th century. Also a chronology for the experimental test data collected is needed. It would also be interesting to establish some comparison of material characteristics between different countries.

In order to obtain the exact properties of steel bars used in the bridge located at Terras de Bouro, more test specimens from different elements and parts of the bridge are needed. Collecting specimens from other early concrete structures would also be interesting, in order to establish some comparison between various structures built in this period.

Appendix

Table A.1: Material properties of Swedish soft steel, [43]

Year	Ultimate strength (MPa)	δ (%)	Comments
1900	380-440	>22	Prime quality of P<0.08% and for rivets S < 0.06%
	310-370	>28	Rivets
	360-430	>22	Remaining material
1901	380-440	22	Prime quality of P<0.08%
	380-440	20	Remaining material P<0.08%
	310-370	28	Rivets P<0.08%
1911	430-530	-	5<t<8
	430-510		8<t<28
			Class A
	360-450	-	5<t<8
	360-430		8<t<28
			Class B
	330-410	-	5<t<10
	330-390		10<t<28
			Rivets

Table A.2: Material properties of Swedish wrought iron [43]

Year	Ultimate strength (MPa)	δ (%)	E (Gpa)
1886	300-400	10-20	-
1900	290-330	>20	-
	330	12	-
	350	10	-
1901	-	-	210

Table A.3: Material properties of Swedish cast iron [43]

Year	Ultimate strength (MPa)	δ (%)	E (Gpa)	
1886	>700	-	-	In compression
1901	700	60	100	In compression
	120	-	100	In tension
1911	>700	-	-	In compression
	>120	-	-	In tension

Table A.4: Material properties of old grey cast iron elements in Sweden retrieved [42]

Ultimate tensile strength(MPa)	Ultimate tensile strength(MPa)	Ultimate tensile strength(MPa)	Elasticity Modulus	Compressive strength	Carbon content	Acoustic velocity
Till before 1850	1850-1900	1900-1942	(GPa)	(MPa)	(%)	(m/s)
80-120	120-180	120-400	85-130	320-780	3-3.5	3.8-4.9

Table A.5: Swedish material properties of mild steel [43]

Year	f_u (MPa)	δ (%)
1886	450-550	10-25
1919	>440	
1931	360-440 430-510	>20
	370-440	>20
	330-390	>25

Table A.6: Swedish bridge properties before 1901 [26]

Vindelalven	year	f_y (MPa)	f_u (MPa)
Vindelalven	1896	311	464
Vindelalven	1896	322	472
Vindelalven	1896	377	458
Vindelalven	1896	328	425
Vindelalven	1896	373	509
Vindelalven	1896	353	509
Vindelalven	1896	324	454
Vindelalven	1896	376	442
Vindelalven	1896	279.1	438.9
Vindelalven	1896	290.5	490.8
Vindelalven	1896	266.6	422
Vindelalven	1896	296.3	481.2
Vindelalven	1896	266.1	421.1
Vindelalven	1896	280.4	476.3
Vindelalven	1896	284.6	441.1
Vindelalven	1896	273.6	464.6
Vindelalven	1896	274.2	443.3
Vindelalven	1896	302.7	492.1

Vindelalven	1896	260.6	424.5
Vindelalven	1896	276.6	479.8
Vindelalven	1896	250.5	382.4
Vindelalven	1896	276.6	450.6
Vindelalven	1896	274	417.2
Vindelalven	1896	277.2	487
Vindelalven	1896	281.6	434.1
Vindelalven	1896	289.3	492.7
Vindelalven	1896	281.8	431
Vindelalven	1896	281.5	470.4
Vindelalven	1896	270.4	419.3
Vindelalven	1896	287.9	481.3
Vindelalven	1896	279.4	430.8
Vindelalven	1896	277.6	450.4

Table A.7:Material properties of Swedish bridges during 1901-1919 [26]

Bridge name	Year	f_y (MPa)	f_u (MPa)	*Jc* (N/mm)
Bjuran	1910	270	325	15.8
Bjuran	1910	273	425	17.7
Bjuran	1910	240	380	20.1
Bjuran	1910	252	401	29.6
Skelleftea	1911	266	382	11
Skelleftea	1911	270	447	14.3
Skelleftea	1911	258	384	17.8
Skelleftea	1911	264	396	20.7
Forsmo	1912	264	415	
Forsmo	1912	295	439	
Forsmo	1912	268	418	
Forsmo	1912	369	485	
Forsmo	1912	267	445	
Forsmo	1912	282	437	
Forsmo	1912	280	442	
Forsmo	1912	297	468	
Forsmo	1912	315	485	
Forsmo	1912			53
Forsmo	1912			5.5
Forsmo	1912			45

Forsmo	1912			29
Forsmo	1912			43.5
Forsmo	1912			5
Forsmo	1912			2.5
Forsmo	1912			5
Forsmo	1912			3.8
Forsmo	1912			3.3
Forsmo	1912			49
Forsmo	1912			67
Forsmo	1912			24
Forsmo	1912			2.3
Forsmo	1912			53
Forsmo	1912			
Forsmo	1912			
Forsmo	1912			
Forsmo	1912	247		
Forsmo	1912	266.8		
Forsmo	1912	261.4		
Forsmo	1912	266.8		
Forsmo	1912	250		
Forsmo	1912	270		
Forsmo	1912	274.4		
Forsmo	1912	231		
Forsmo	1912	250		
Forsmo	1912	275.6		
Forsmo	1912	299.4		
Forsmo	1912	264.1		
Forsmo	1912	273.5		
Forsmo	1912	294.6		
Forsmo	1912	270		
Forsmo	1912	281.6		
Forsmo	1912	301.8		
Forsmo	1912	273.3		
Gidealvsbron	1913	433	465.6	
Gidealvsbron	1913	385.8	428	
Gidealvsbron	1913	268.7	398.4	
Gidealvsbron	1913	338.7	410.8	
Gidealvsbron	1913	265.5	376.9	
Gidealvsbron	1913	280.8	383.2	

Gidealvsbron	1913	247.4	389.7	
Gidealvsbron	1913	410.4	413.9	
Gidealvsbron	1913	299.9	435.4	
Testeboan	1913	273	420	
Testeboan	1913	257	425	
Testeboan	1913	255	400	
Testeboan	1913	257	400	
Sikfors	1914	288	433	55.7
Sikfors	1914	279	419	51.7
Sikfors	1914	299	439	64.5
Sikfors	1914	311	442	61.3
Sikfors	1914	308	433	121.5
Sikfors	1914	297	431	
Dingelsundsadran	1914			29
Dingelsundsadran	1914			24
Dingelsundsadran	1914			41
Dingelsundsadran	1914			70
Dingelsundsadran	1914			40
Dingelsundsadran	1914			27
Dingelsundsadran	1914	302	443	
Dingelsundsadran	1914	303	456	
Dingelsundsadran	1914	256	387	
Dingelsundsadran	1914	281	383	
Dingelsundsadran	1914	330	427	
Dingelsundsadran	1914	338	448	
Dingelsundsadran	1914	253	417	
Dingelsundsadran	1914	227	359	
Dingelsundsadran	1914	307	414	
Dingelsundsadran	1914			
Dingelsundsadran	1914			
Dingelsundsadran	1914			
Landafors	1915	275	428	
Landafors	1915	258	422	
Landafors	1915	270	417	
Landafors	1915	290	454	
Landafors	1915	288	440	
Landafors	1915	271	427	
Landafors	1915	292	457	
Landafors	1915	258	416	

Landafors	1915	271	408	
Landafors	1915			16.1
Landafors	1915			277.4
Landafors	1915			634.4
Landafors	1915			14
Landafors	1915			10.5
ostfors-Faluan	1917	280	366	
ostfors-Faluan	1917	304	477	
ostfors-Faluan	1917	263	399	
ostfors-Faluan	1917			45
ostfors-Faluan	1917			10.7
ostfors-Faluan	1917			325
ostfors-Faluan	1917			
ostfors-Faluan	1917			
ostfors-Faluan	1917			
ostfors-Faluan	1917	282	430	
ostfors-Faluan	1917	243	405	
ostfors-Faluan	1917	253	449	
Bergsgardsan	1917	292	425	
Bergsgardsan	1917	267	402	
Bergsgardsan	1917	261	405	
Bergsgardsan	1917			36.5
Bergsgardsan	1917			30.1
Bergsgardsan	1917			56
Bergsgardsan	1917	245	371	
Bergsgardsan	1917	311	483	
Bergsgardsan	1917	250	440	
Bergsgardsan	1917			
Bergsgardsan	1917			
Bergsgardsan	1917			
Bergsgardsan	1917			
Banforsan	1919	306	452	
Banforsan	1919	315	487	
Banforsan	1919	335	522	
Torne alv	1919	300		20

Table A.8: Material properties of Swedish bridges during 1920-1940 [26]

Bridge name	Year	f_y (MPa)	f_u (MPa)	Jc (N/mm)
Nissan	1920			
Nissan	1920			
Nissan	1920			
Nissan	1920			
Lagan/Knared	1920	345	433	
Lagan/Knared	1920	305	436	
Lagan/Knared	1920	320	433	
Lagan/Knared	1920	309	418	
Lagan/Knared	1920	327	435	
Lagan/Knared	1920	309	438	
Lagan/Knared	1920			386
Lagan/Knared	1920			407
Lagan/Knared	1920			447
Lagan/Knared	1920			432
Lagan/Knared	1920			373
Lagan/Knared	1920			398
segea	1920	282	433	
segea	1920	271	415	
segea	1920	276	436	
segea	1920	269	416	
segea	1920	280	433	
segea	1920	280	418	
segea	1920			519
segea	1920			550
segea	1920			233
segea	1920			534
segea	1920			219
segea	1920			350
Mora	1921	271	452	
Mora	1921	286	450	
Mora	1921	270	415	
Mora	1921	264	426	
Mora	1921	265	430	
Mora	1921	275	436	
Mora	1921	270	417	
Mora	1921	276	418	

Mora	1921	273	452	
Mora	1921	302	442	
Mora	1921	300	442	
Mora	1921	305	447	
Mora	1921	273	416	
Mora	1921	270	419	
Mora	1921	268	414	
Mora	1921	279	430	
Mora	1921	276	427	
Mora	1921			389
Mora	1921			473
Mora	1921			124
Mora	1921			111
Mora	1921			23
Mora	1921			483
Mora	1921			433
Mora	1921			469
Mora	1921			70
Mora	1921			57
Mora	1921			40
Mora	1921			66
Mora	1921			83
Mora	1921			80
Mora	1921			18
Mora	1921			41
Mora	1921			65
Mora	1921			468
Mora	1921			490
Mora	1921			470
Mora	1921			491
Mora	1921			460
Mora	1921			395
Mora	1921			366
Mora	1921			87
Mora	1921			361
Mora	1921			98
Mora	1921			430
Mora	1921			94
Mora	1921			21

Mora	1921		20
Mora	1921		18
Mora	1921		445
Mora	1921		341
Mora	1921		401
Mora	1921		287
Mora	1921		349
Mora	1921		468
Mora	1921		470
Mora	1921		490
Mora	1921		395
Mora	1921		460
Mora	1921		491
Mora	1921		87
Mora	1921		361
Mora	1921		366
Mora	1921		94
Mora	1921		98
Mora	1921		430
Mora	1921		18
Mora	1921		20
Mora	1921		21
Mora	1921		341
Mora	1921		401
Mora	1921		445
Mora	1921		287
Mora	1921		349
Mora	1921	276	389
Mora	1921	276	473
Mora	1921	268	23
Mora	1921	268	111
Mora	1921	268	124
Mora	1921	273	433
Mora	1921	273	469
Mora	1921	273	483
Mora	1921	302	40
Mora	1921	302	57
Mora	1921	302	70
Mora	1921	270	66

Mora	1921	270		80
Mora	1921	270		83
Mora	1921	278		18
Mora	1921	278		41
Mora	1921	278		65
Mora	1921	234		
Mora	1921			
Mora	1921			
Mora	1921	280		
Mora	1921			
Mora	1921	281		
Mora	1921	336		
Mora	1921	330		
Mora	1921			
Mora	1921			
Mora	1921	277		
Mora	1921	299		
Mora	1921	287		
Mora	1921			
Mora	1921			
Mora	1921	265		
Mora	1921			51
Mora	1921	258	469	54
Bergforsen	1924	322	469	
Bergforsen	1924	368	522	
Bergforsen	1924	308	474	
Bergforsen	1924	331	498	
Bergforsen	1924	327	510	
Bergforsen	1924	331	470	29
Bergforsen	1924	282	469	70
Bergforsen	1924	356	506	
Bergforsen	1924	376	517	52
Bergforsen	1924	320	436	
Bergforsen	1924	329	488	
Erikslund	1924	219	289	
Erikslund	1924	218	295	
Erikslund	1924	306	432	
Erikslund	1924	304	437	
Erikslund	1924			501

Erikslund	1924			532
Erikslund	1924			327
Erikslund	1924			45
Erikslund	1924			127
Erikslund	1924			112
Kyrkviken	1925	314	411	
Kyrkviken	1925	315	412	
Kyrkviken	1925	323	423	
Kyrkviken	1925			11.1
Kyrkviken	1925			16.5
Kyrkviken	1925			614.2
Kyrkviken	1925			17.1
Kyrkviken	1925			12.7
Myskjean	1925	335	437	
Myskjean	1925	366	503	
Myskjean	1925	363	523	
Myskjean	1925			16.1
Myskjean	1925			14.7
Myskjean	1925			22.9
Myskjean	1925			6.1
Alsan	1926	337		36.4
Alsan	1926	337		39
Alsan	1926			47.1
Krokom	1927	245	375	
Krokom	1927	295	418	
Krokom	1927			323
Krokom	1927			197
Krokom	1927			469
Krokom	1927			343
Krokom	1927			603
Krokom	1927			717
Krokom	1927			783
Krokom	1927			776
Krokom	1927			30.7
Krokom	1927			28
Petreboda	1930	245	320	
Petreboda	1930	227	313	
Petreboda	1930		362	
Petreboda	1930	304	415	

Petreboda	1930			54
Petreboda	1930			74
Petreboda	1930			21
Petreboda	1930			30
Petreboda	1930			92
Petreboda	1930			45
Skidtraskan	1934			16.8
Skidtraskan	1934			35.3
langstraskan	1934	297	477	11.3
langstraskan	1934	301	477.5	17.6
langstraskan	1934	305	478	31.4
onnerupsbacken	1936			390
onnerupsbacken	1936			436
onnerupsbacken	1936			329
onnerupsbacken	1936			87.6
onnerupsbacken	1936			104
onnerupsbacken	1936			84
Norde alv	1938	359	650	
Norde alv	1938	348	687	
Norde alv	1938	655	749	
Norde alv	1938	794	917	
Norde alv	1938	530	640	
Norde alv	1938			
Norde alv	1938			
Norde alv	1938			
Norde alv	1938	353	507	
Norde alv	1938	347	498	
Norde alv	1938			
Norde alv	1938			
Norde alv	1938			
Norde alv	1938			
Norde alv	1938			
Norde alv	1938			
Sodra Kannickean	1939			390
Sodra Kannickean	1939			436
Sodra Kannickean	1939			329
Sodra Kannickean	1939			87.6
Sodra Kannickean	1939			104
Sodra Kannickean	1939			84

Table A.9: French material properties [42]

	Material	year	f_y (MPa)	f_u (MPa)	Charpy-V (J)	Test Temp(^{o}C)
St.Denis	Iron	1897	234	336	18	20
St.Denis	Iron	1897	231	276		
Les Fades	steel	1909	217	381	21	0
Passerelle	Iron	1860	280	306	15	20
Pont suchard	Steel	1906	285	403	27	20
St Andre	Iron	1870	272	286	6.7	20
Ponte de fer	Iron	1877	275	384	18	20
Sabart	Iron	1877	268	378	14	20
Andour a Bayonne	Iron	1862	252	360	6	20
Ponte des Termes	Steel	1890	279	415	34	20

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