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Master's Thesis

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Investigation of the Use of Iron in Construction from Antiquity to the Technical Revolution.

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ABSTRACT

In the context of this dissertation, the use of iron in construction has been investigated. By examining the information available from ancient and modern treatises on the subject, this work examines practices and concepts associated with iron in civil construction from its inception in antiquity to its universal acceptance by designers and observers alike in the Industrial Revolution.

Iron has always been closely linked to innovation and development in the world of civil construction since first being introduced as a technological solution. Despite high cost and labour demands, it held its place as a valuable structural tool, providing solutions to needs not satisfied by ordinary structural practices in masonry and timber. As efficient production methods and increased market demand made iron a more common commodity, its use spread rapidly in terms of extent and daring, allowing longer spans and acting as an incentive to improve the material itself. The Industrial Revolution is the pinnacle of iron use in historical construction, gracing the world with a wealth of architectural heritage in, or incorporating, iron.

Centuries of application experience have provided designers with extensive knowledge on the properties, strengths and weaknesses of structural iron, as well as the means to inspect and counteract those deterioration mechanisms most detrimental to its integrity and fabric. This knowledge forms the basis for the restoration practices of historical iron applied today.

An early application of iron in construction is its incorporation in ancient Greek monumental architecture as a reinforcing element and, more commonly, as a hidden substitute of mortar. Being the product of centuries of development, it was used as a means to relieve stresses from stone, support otherwise unstable assemblages, prevent structural movement and bind blocks together to provide monolithicity. Its performance under static and dynamic loading has recently been investigated in both experimental and numerical investigation.

The restoration projects of the Athens Parthenon include full restoration of iron connecting elements, including controlling and halting the damage caused by faulty application of iron members in previous efforts. However, the structural effect of these new connections has only been investigated on a local rather than a global level, going against modern restoration concepts. Despite this approach being necessary due to computational shortcomings at the time the current restoration plans were compiled, it is a restoration issue that warrants further investigation.

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RESUMEN

Investigación sobre el uso del hierro en construcciones desde la antigüedad hasta la revolución técnica

En el contexto de la presente disertación, el uso del hierro en construcciones ha sido investigado. Mediante el estudio de antiguos y modernos documentos disponibles sobre el tema, este trabajo examina prácticas y conceptos asociados con el hierro en construcción civil desde su uso en la antigüedad hasta la universal aceptación por los diseñadores, así como de observadores, en la Revolución Industrial.

El hierro ha sido siempre relacionado con la innovación y desarrollo en el mundo de la construcción civil desde que fue introducido como una solución técnica. A pesar del alto costo y trabajo necesario para su implementación, el hierro es una herramienta estructural muy importante, proveyendo soluciones a necesidades no satisfechas por prácticas estructurales ordinarias en la albañilería y madera. Debido a métodos eficientes en su producción y al aumento de la demanda en el mercado del hierro, el hierro se ha convertido en una herramienta utilizada comúnmente con un rápido crecimiento, permitiendo mayores longitudes libres entre elementos verticales.

Siglos de experiencia con la aplicación del hierro ha provisto a los diseñadores el conocimiento de las propiedades, resistencia y debilidades del hierro estructural, así como la necesidad de inspeccionar y determinar los mecanismos de deterioración más importantes para su integridad y fabricación. Este conocimiento establece la base para prácticas de restauración del hierro aplicados en la actualidad.

Una temprana aplicación del hierro en construcción es la incorporación en antiguos monumentos griegos como refuerzo de elementos y, comúnmente, como una oculta sustitución del mortero. Siendo un material desarrollado a lo largo de los siglos, ha sido usado para reducir esfuerzos producidos en roca, como soporte de elementos estructurales inestables, previene desplazamientos y logra crear bloques monolíticos. Su comportamiento ante cargas estáticas y dinámicas ha sido recientemente investigado con investigaciones numéricas y experimentales.

Los proyectos de restauración del Partenón en Atenas incluyen una restauración completa utilizando elementos conectores de hierro debido a la mala aplicación del hierro en intervenciones pasadas. Sin embargo, el efecto estructural de estas nuevas conexiones ha sido investigado únicamente a un nivel local y no globalmente, estando en contradicción con los conceptos modernos de restauración. Debido a que este efecto tiene que ser analizado con herramientas computacionales, es necesario que se realice mayores investigaciones.

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ΠΕΡΙΛΗΨΗ

Διερεύνηση της Χρήσης του Σιδήρου στην Κατασκευή από την Αρχαιότητα εώς την Τεχνολογική Επανάσταση

Στα πλαίσια αυτής της εργασίας, διερευνήθηκε η χρήση του σιδήρου στις κατασκευές. Μελετώντας τις πληροφορίες παρεχόμενες από αρχαίες εώς και σύγχρονες εργασίες στο θέμα, η εργασία εξετάζει μεθοδολογίες και αντιλήψεις σχετικές με το σίδηρο στις κατασκευές πολιτικού μηχανικού από τις απαρχές τους στην αρχαιότητα μέχρι και την καθολική αποδοχή του υλικού από σχεδιαστές και κοινό κατά την Βιομηχανική Επανάσταση.

Ο σίδηρος ήταν ανέκαθεν στενά συνδεδεμένος με την πρωτοπορία και τις εξελίξεις στον κόσμο των κατασκευών. Παρά το υψηλό οικονομικό, παρέμεινε ως ένα πολύτιμο δομικό εργαλείο, παρέχοντας λύσεις σε ανάγκες μή καλυπτόμενες από συνήθεις πρακτικές της τοιχοποιίας και του ξύλου. Με την έλευση αποδοτικότερων μεθόδων παραγωγής και την ανάπτυξη της ζήτησης για σίδηρο, η χρήση του απλώθηκε ραγδαία, επιτρέποντας μεγαλύτερα ανοίγματα και οδηγόντας σε βελτίωση του υλικού. Η Βιομηχανική Επανάσταση αποτελεί το αποκορύφωμα των σιδηρών κατασκευών, χαρίζοντας στον κόσμο έναν πλούτο αρχιτεκτονικής κληρονομιάς.

Αιώνες πρακτικής εφαρμογής έχουν ώς αποτέλεσμα ενδελεχή γνώση των ιδιοτήτων, πλεονεκτημάτων και μειονεκτημάτων του δομικού σιδήρου, καθώς και των μεθόδων διερεύνησης και διόρθωσης των σημαντικότερων για την δομική και καλλιτεχνική ακεραιότητα μηχανισμών διάβρωσης. Αυτή η γνώση αποτελεί τη βάση των πρακτικών επεμβάσεων στον ιστορικό σίδηρο.

Μια πρώιμη εφαρμογή του σιδήρου στην κατασκευή είναι η ενσωμάτωση στην Αρχαία Ελληνική αρχιτεκτονική ώς μέσο ενίσχυσης του λίθου και ώς συνδετικό στοιχείο. Όντας αποτέλεσμα αιώνων ανάπτυξης, χρησιμοποιήθηκε για την ανακούφιση του λίθου από υψηλές τάσεις, τη στήριξη και συγκράτηση των λίθων. Η δομοστατική συνεισφορά του σιδήρου είναι αντικείμενο μελέτης πλήθους πειραματικών και αριθμητικών προσεγγίσεων, κατά κύριο λόγο πρόσφατων.

Στην αποκατάσταση του Παρθενώνα προβλέπεται ανακατασκευή των σιδηρών συνδετικών στοιχείων. Εντούτοις, η δομοστατκή λειτουργία τους δεν είχει πλήρως διερευνηθεί κατά τη σύνταξη των μελετών και δεν αποτελεί παράμετρο σχεδιασμού των επεμβάσεων στην κατασκευή ως όλον. Οι νέες παρατηρήσεις πάνω σε αυτό το αντικείμενο ωφείλουν να δράσουν ως κίνητρο για επιπλέον έρευνα και, ενδεχομένως, τροποποίηση της μεθοδολογίας επεμβάσεων.

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TABLE OF CONTENTS

1. INTRODUCTION

1.1 General

Iron is an integral part of human history, as can be safely argued by the technical capabilities opened up to artisans, craftsmen and architects by its becoming available, which warranted an entire age to be named after it. Until then, iron was a divine gift, a blessing from the heavens, which we now know to have been meteoric iron, and which the ancient people from all over the globe went to great lengths to make use of when available. Equally divine was the gift of iron making from abundant terrestrial sources, a testament to the effect it had on many societies' technological capabilities and their capacity to work the earth, carve rock and wage war.

If iron was quick to be adopted for the construction of tools and weapons and for ornamental or status purposes, it lagged far behind masonry and timber in architecture until quite recently. Despite their relative scarcity in the ancient world, civil engineering works built in iron, or incorporating iron in their architectural and mechanical fabric, that are today designated as pieces of cultural heritage, span the period of time from within a few centuries after its discovery to the present day, uninterrupted from a chronological perspective and as yet unchallenged in significance compared to other metals. Its applications account for the crushing majority of metals used in all technical fields dealing with the construction of vernacular buildings, monumental structures and infrastructure, the result being that iron is a key material of historical and, especially, industrial heritage. In fact, the onset of the Industrial Era is closely linked to the capability of producing iron at an industrial level and many of the technological and scientific efforts of the time are associated with the development of iron production techniques. Not to be overlooked, furthermore, is the role of iron production in later history as an economy shaping element, being a multifaceted industry that directly extends to the development of transportation and trade.

Iron architecture, born out of technological innovations and the necessity to address new architectural needs and problems, brought about significant changes in the world of construction. Science overcame architectural tradition, an approach that was soon afterwards adopted for all types of civil construction.

1.2 Objectives

The general objective of this dissertation is to analyze and conclude on the use of iron as a construction material in historical structures, both as an original structural part and as a later addition in restoration efforts. The historical span of the work covers the period from antiquity, when iron was introduced to civil construction, to the Industrial Revolution, of which iron was an integral part and during which it was elevated to the popularity status it still enjoys today in the world of construction. A better understanding of iron in terms of historical production methods, application types and their structural significance, as it relates to the intended and actual role, is sought in an effort to determine the most appropriate inspection methods, interpret their results and lead to effective intervention methods, relevant to the character of the structure and addressing structural problems typically faced by them. For this purpose, a brief outline of major pathology types, inspection methods and restoration practices of historical iron is also offered, as a complement to aspects of historical iron use.

Having established a better understanding of iron use in construction under a wide scope, a more focused investigation of a specific era will be conducted, identifying the particular characteristics associated with it. The era to be examined is that of Greek antiquity, roughly from the 7th century BC until the Hellenistic era in the 4th century BC, a period during which iron use in monumental architecture was constantly improved. The geographic expanse of the typologies examined, as adopted and spread by the Romans, covers much of the Mediterranean coast, making them a significant early application example of iron.

The research will be mostly based on information drawn from a wide variety of bibliographical sources, including books of technical and archaeological content, monument restoration studies, ancient and modern architectural treatises, scientific papers, ancient building rules and modern design regulations dealing with the subject of iron use in construction and restoration. The wealth of available literature is a testament to the effect iron had on historical architecture and to the reaction offered by the experts of every era and profession, ranging from enthusiasm, controversy to outright rejection. A number of characteristic examples in which iron was used in an innovative way will also be briefly presented, citing construction and restoration issues that arose from iron use as presented in the available literature and, occasionally, as witnessed by site visits.

The specific objective of the dissertation is the investigation of a specific case study of a historical building in which iron was systematically and rationalized implemented; the Athens Parthenon is a building which presents a multitude of study topics concerning iron as an original material and as a restoration solution. Conservation problems caused by iron related pathology in the structure are a constant technical concern for architects and engineers involved in the restoration projects of the Parthenon. Therefore, by study of available historical and technical data a critical appreciation of current restoration practices of or involving iron in the monument is offered in order to verify their compliance with modern restoration theory. Similarly to the general approach adopted for the other study subjects in this thesis, research on available documents will provide the bulk of the information for the case study, augmented by site visits and interviews with the personnel involved in the documentation and structural restoration of the monument.

2. HISTORY OF THE USE OF IRON IN CONSTRUCTION AND RESTORATION

2.1 Genesis of Iron Use

The advent of iron production brought the onset of the Iron Age, signalled by the replacement of copper by iron in tools, weapons and other implements, as soon as it could be produced in sufficient quantities. Chronologically, it occurred sometime after 2000 BC, although iron had been used in small quantities since prehistory, with meteoric iron being the main source of the material. However, the primary sources of iron are the abundant iron ore deposits in the earth's crust, otherwise known as terrestrial iron [20].

Iron was first produced in south-west or south-central Asia, perhaps in the Caucasus region or in India. The debate on where iron production was first achieved has yet to be settled. In any case iron produced by iron ore is distinguished from meteoric iron by its noticeably lower nickel content; meteoric iron may contain up to 10% nickel [2].

Shortages in copper and tin during the late Bronze Age led smiths to the adoption and exploitation of the more abundant iron ores for supplies of materials and, subsequently, to the development of iron smelting techniques throughout much of the ancient world. The reason for the simultaneous development of iron smelting in several different geographical locations is owed to the collapse of copper trade routes, which affected many of the ancient world's nations. While largely replacing copper for the construction of most tools and weapons, iron did not lead to its complete abandonment, mostly because early iron was not superior in strength.

2.2 History of the Development of Wrought Iron

2.2.1 Origin

The word "wrought" is possibly derived from "worked", meaning the hammering process associated with its production. Wrought iron is the "iron" that is referred to throughout western history, with very few exceptions [20].

2.2.2 Historical Production Techniques

The smelting of iron in bloomeries, as inherited from the copper and tin smelting developed in the Bronze Age, began in India, Anatolia or Caucasus in 2000 BC and consisted of separating iron from its oxides, since metals were usually mined in some form of ore. The carbon monoxide produced by the consumption of the charcoal fuel reduces iron oxides to metallic iron. The reduction of the common iron ore hematite is presented in the following reaction:

$2C + O_2 \rightarrow 2CO$

$3CO + Fe_2O_3 \rightarrow 2Fe + 3CO_2$

The product of this process is a spongy bloom of iron and slag, which are subsequently separated by forging to produce wrought iron. Another reason for making forging necessary was that the temperatures developed in the bloomery were not high enough to melt iron itself, but only make it malleable. The process was repeated until the slag was removed as much as possible, making it a long and costly process, requiring much manual effort and timber fuel. Crushed seashells or limestone (forge flux) where sometimes added to the mix to facilitate the process and to remove chemical impurities [20].

The bloomery process in principle remained largely unchanged for centuries, especially in Europe, with the only significant alteration being the adoption of water power for the bloomery bellows in the Middle Ages. Smelting using coal or coke instead of charcoal was only achieved in the 1700s by the introduction of processes known as potting and stamping. The final direct processes of wrought iron production were the shingling and the rolling process. It was the rolling process, introduced in the 1830s, that allowed the shaping of wrought iron members in sufficient quantities to make it a reasonable choice for structural material with the commercial fabrication of T- and I-beams, which came to replace their heavy and brittle cast iron predecessors, by 1845. The reduction of the necessary material for a particular solution compensated for the increase in its price. Interestingly, the first major applications of continuous rolled wrought iron beams were in the shipbuilding industry, which were afterwards imported to civil construction [47].

Following the introduction of cast iron production techniques in Europe, indirect methods were also developed. The osmond process was developed in the early 13th century, which involved the decarburization of pig iron to produce wrought iron. However, it was replaced from the 15th century by finery processes, of which there were two versions, the German and Walloon. They were in turn replaced from the late 18th century by puddling (stirring molten pig iron in the open air), with certain variants such as the Swedish Lancashire Process. Puddling generally supplied the material for rolling mills. Finally, after the introduction of the Bessemer process for steel production, the Aston process was developed to produce cheap wrought iron from molten steel taken from a Bessemer converter.

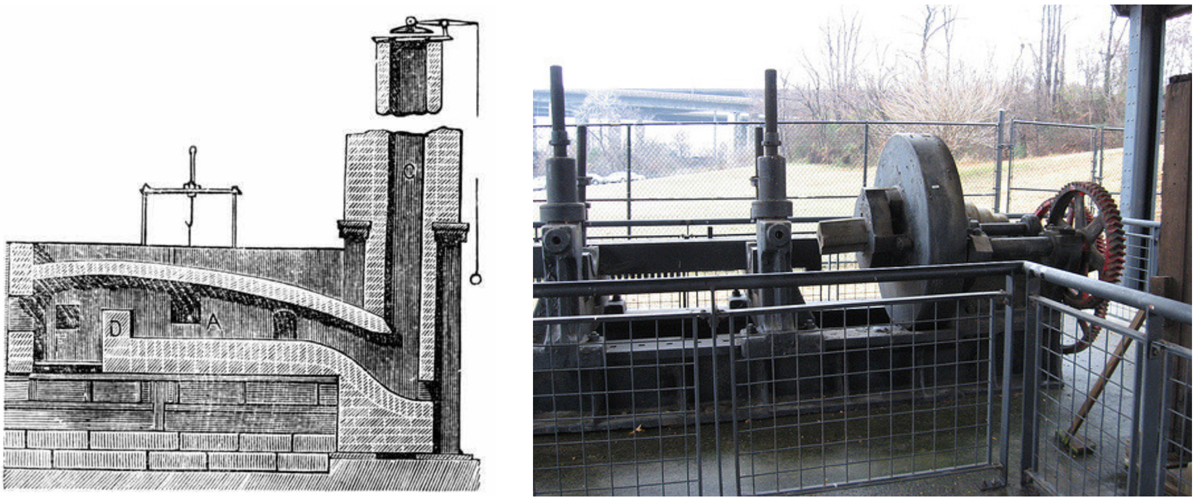


Figure 2.1: Iron puddling furnace and iron rolling mill for beam manufacture [43].

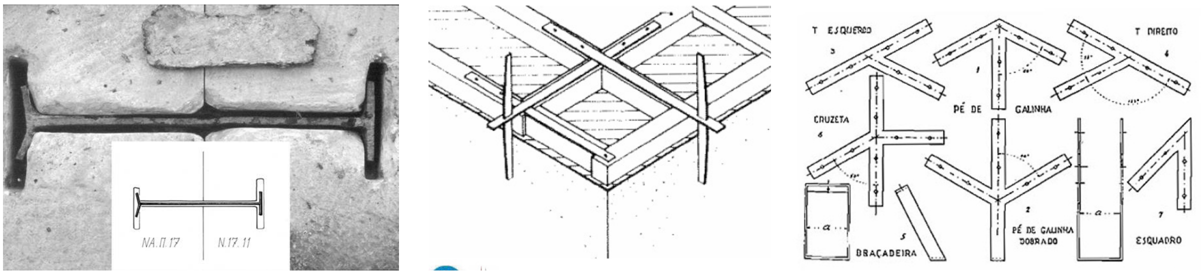
In China, iron smelting was possibly never used as in other geographical areas because of the very early technological developments in the production of cast iron and its decarburization into wrought iron. An early type of blast furnace was used from 500 BC onwards to produce cast iron, which was then decarburized into wrought iron by heating it in open air for several days. Another innovation was an early form of puddling which was used to produce wrought iron from pig iron from about 200 BC. Finally, the Chinese were the first to implement water powered bellows for their furnaces and knew how to use coke instead of charcoal from as early as the 11th century AD [3].

2.3 History of the Use of Wrought Iron in Construction

2.3.1 Historical Applications

Iron was virtually unheard of for the construction of main structural elements until the Industrial Revolution. Until then it provided builders with solutions in structural details and as a local strengthening measure. Vitruvius mentions the use of iron as a structural element in the construction of walls as a means of bracing the outer courses of multi-leaf brick and stone masonry by the use of iron clamps covered by cast lead [4]. Finally, it was used in masonry for securing portions that were prone collapse otherwise, such as cornices, parapets and copings. Apart from that, it was only used as a material for the construction of mechanical equipment and tools.

It was mainly used for nails and straps in timber roof structures. Wrought iron was also used as a secondary structural element in the ancient monuments of ancient Greece and Rome. Iron tensile connections and shear dowels were placed in the interfaces between stone blocks to enhance structural performance and prevent small relative movement. The connections were covered by casting lead in the slit in order to protect the iron from corrosion and minor vibrations. Iron use in this reinforcement procedure was a development from timber or brass connections covered with cast lead or tar applied in earlier temples. The Romans extended this application to dry-set masonry arches and domes, even using iron in a way similar to modern rebars in concrete [5]. Having lost the complete understanding of this technique in later years, iron tying members were widely used, in faulty applications and often unprotected, in restoration works on ancient monuments and other masonry structures. The combination of mechanical action on and corrosion of the iron members often led to the damage of the iron members and, subsequently, of the surrounding material. Since then, easily corroded materials, like iron, are considered an ill choice for restoration projects.



(a) (b) (c)

Figure 2.2: (a) Tension connecting element in ancient monument, (b) anchored tie in masonry structure, (c) nailed connecting plates in timber roof trusses.

One of the oldest constructions made of wrought iron is the iron pillar of Delhi, built at least 1600 years ago and surviving to this day with very little sign of corrosion. It has been argued that the pillar, standing nearly 7m tall, was one of the pillars supporting a temple structure, which would make it the oldest of its kind. It is made of 98% wrought iron of pure quality and is a testament to Indian ironworking skills [6].

Figure 2.3: Iron Pillar of Delhi [6].

During the middle ages, some examples of iron as an original structural component, as opposed to being a later addition, can be discovered in large buildings but not in vernacular architecture. The Palace Chapel of Aachen in Germany, from the 8th century, employs iron ring beams and interconnected iron bar anchors embedded in the masonry at the base of the dome. Other Romanesque buildings in Germany, like the Speyer cathedral, were discovered to have employed iron clamps and dowels between stones. These techniques were probably an important early influence in French Gothic cathedral architecture, in which iron played a more consistent and clearly defined role as tensile and shear reinforcement of masonry assemblages [7].

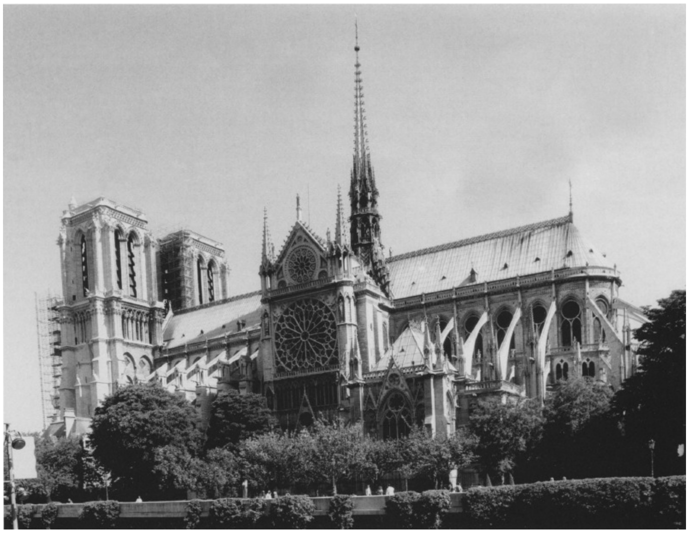


Figure 2.4: Notre Dame de Paris. Iron was used extensively both initially and in restorations [10].

When the demands of skeletal Gothic architecture made doweling necessary, iron members became more widespread. It also coincided with the advent of more efficient iron production techniques and the establishment of a robust iron trading market in 12th century Europe. It could be argued that the increase in availability of the material allowed architects to pursue more daring forms through a more rationalized and engineered use of the materials at hand [7].

Following the Industrial Revolution, structural members made of wrought iron could be produced. The use of wrought iron in that era coincides with the advent of rationalized, engineered designs of structures, where the forms are dictated by structural requirements rather than architectural rules. A further explanation for the spreading of the use of structural analysis tools (bending and truss theory) going hand in hand with the use of iron is the fact that iron was still a very expensive material and had to be optimally used.

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 rebars in form and function, in the construction of the Paris Pantheon in 1790. Spurred by confidence in the new material, load bearing masonry assemblages (piers and domes) were designed exceedingly slender. Additionally, jack arches were hollowed out to reduce weight, relying on the reinforcement to carry the load, but essentially functioning as ties to the overlying arches. A variety of causes (second order phenomena, masonry creep and iron corrosion) have taken their toll on the structure, despite investigation and experimental efforts undertaken to support the designers' decisions [8].

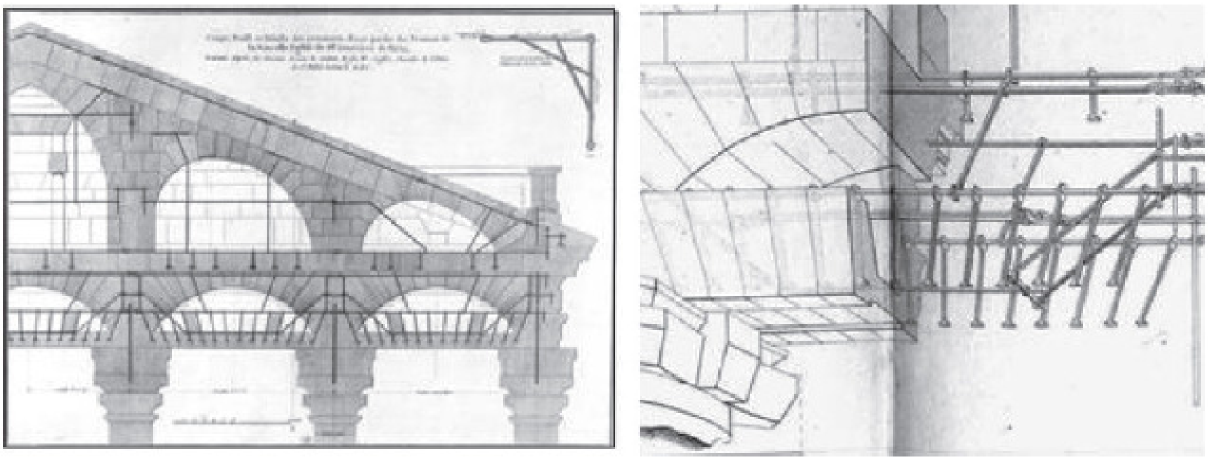


Figure 2.5: Paris Pantheon iron reinforcement of jack-arches [8].

Wrought iron members are formed by riveting plates, since the material is not always suitable for welding. The riveted connections had to be very well detailed and required highly skilled manpower at the same time. The riveted connections were a significant change from the carpentry connections between elements which were used in both timber and cast iron architecture. Structural applications include bridges, cables, high-rise buildings, industrial roof trusses, beams and girders. A most famous example of the Industrial era is the Eiffel tower of Paris (1889), made entirely of prefabricated wrought iron members and rivets [9].

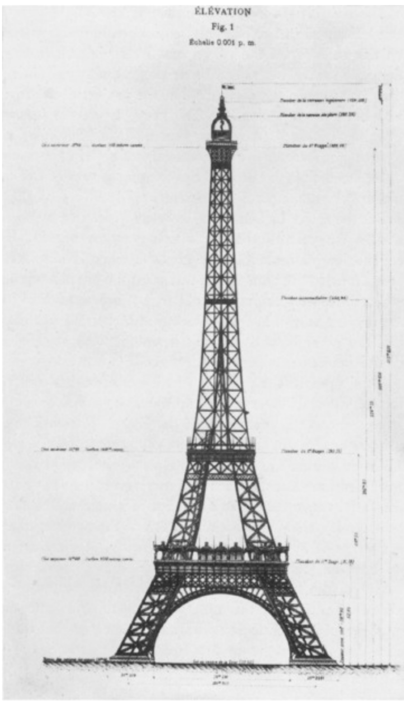


Figure 2.6: The Eiffel Tower of Paris [9].

2.3.2 Extent of Use

Wrought iron was not the material of choice for main structural members in antiquity. Timber, stone and brick were universally preferred. Only after the introduction of cost effective production techniques could it be extensively implemented for structural purposes. It should be noted, however, that the use of wrought iron, and cast iron previously, in civil construction met with much public and professional resistance initially, until it was proven that it could be safely and economically used. In fact, wrought iron became the most popular construction material between 1850 and 1890 for the erection of high-rise buildings and long-span bridges. Even then, only industrialized, iron producing states, like industrialized European countries or the United States could make full use of the material or export the technology to other areas. Even so, the structural achievements of the era comprise an important body of cultural heritage.

The Eiffel Tower is the significantly first and chronologically last outcome of France's widespread adoption of wrought iron as the material of choice for the construction of high profile buildings and infrastructure construction.

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

2.4 History of the Development of Cast Iron

2.4.1 Origin

Cast iron was first produced in China, possibly as far back as the 6^{th} century BC, making it a much newer invention than wrought iron. Even though wrought iron was first produced many centuries before, it apparently could not be cast because ancient furnaces were incapable of producing the required temperatures, at least not without prohibiting cost. However, the Chinese had developed melting equipment capable of producing greater draft than hitherto had been possible. This allowed the production of an iron alloy that could be cast.

2.4.2 Historical Production Techniques

The main reason for the success of the Chinese in being able to produce cast iron was that they reduced iron oxide by heating it in the presence of an excess amount of carbon, apparently in the form of charcoal. This procedure resulted in a soft, pure iron with a melting point of 1530^0C. The iron was then carburized, reducing its melting point to about 1170^0C, thereby making it easier to melt in their high draft furnaces, which could be considered early examples of blast furnaces. The resulting material could be cast in moulds, thus bypassing the lengthy and costly process of forging and therefore significantly reducing cost.

Additional references indicate that the Chinese used some high phosphorus coal along with high phosphorus iron ore as charge materials. These materials, by lowering melting temperatures, reduced the amount of blast needed to melt the iron and thus facilitated the production of the material. Another production method is the re-melting of pig iron in furnaces with the addition of scrap iron or steel. All the aforementioned methods produce what is called grey cast iron, the most common type.

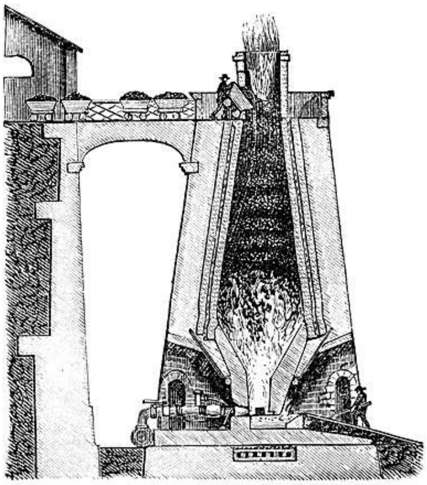


Figure 2.7: Blast furnace [43].

Slight alterations in the production process result in a variety of cast iron types. White cast iron is distinguished from grey cast iron by the inclusion of carbon in the form of cementite rather than graphite or the inclusion of Chromium. Malleable iron is obtained by heat treatment of white cast iron at about 900 ^{0}C. Finally, ductile cast iron is obtained by the addition of Magnesium or Cerium to the alloy. Historically, however, grey cast iron is predominant in civil construction and the other types of cast iron were mostly developed and applied after the use of wrought iron and steel had generally prevailed.

Regardless of the particulars of every individual technique, the steps involved usually included smelting and fluxing of the ore, refining after smelting and, finally, casting of the alloy, typically in sand moulds. Before smelting, the ore was often weathered and washed for several months before use, removing many of the impurities, and then crushed before being put in the furnace.

The latest advances in cast iron production were the discovery and production of coke as smelting fuel, which reduced cost and enhanced the mechanical properties of the product, and the production of ferrosilicon as an additive to the cast iron alloy.

2.5 History of the Use of Cast Iron in Construction

2.5.1 Historical Applications

Many applications for this cast iron were made possible by improvements in melting equipment and techniques as well as great progress in the art of moulding. Several civil engineering applications employed cast iron from time to time, including iron chain suspension bridges, the first of which were constructed by the Chinese in 56 AD. Another early example of cast iron in civil works was as a supporting element in Chinese Pagodas and other buildings. This sort of construction may have appeared as early as the 6^{th} century AD during the Sung dynastic period or even before that.

However, iron was not generally cast in what might be called "substantial quantities" in Europe until the fourteenth century AD. Aided by improvements to the blast furnace and refinements on silicon control, the quality and production rates of cast iron increased steadily and allowed for a more widespread use of the material in construction.

With the advent of more efficient production methods which allowed the manufacture of large members, cast iron was used as a material in civil construction more frequently. A good example of its application is the Iron Bridge of Coalbrookdale, England (1779), the first metal bridge, which spans 30m and survives to this day. The amount of iron used in the construction (380 tonnes) is equal to the annual output of an ironworks at that time, but it proved that cast iron could indeed be used for structural purposes on its own. The arched shape is meant to make maximum use of the material's high compressive strength while attempting to avoid tension in all members [11]. Subsequently, many bridges and aqueducts were built of cast iron, composed of arches resting on masonry piers, very similar to the design of masonry arch bridges. Structural element connections were initially similar to carpentry joints formed during casting and secured by cast iron wedges. Iron architecture would remain heavily indebted to traditional materials and techniques for at least a few decades. Fitted joints remained commonplace in cast iron lattices, only occasionally utilizing bolted connections, usually made of a different material, such as wrought iron.

Figure 2.8: The Iron Bridge of Coalbrookdale.

Buildings were also constructed using cast iron members for pillars. It was a good alternative to thick masonry walls, since it allowed for larger openings and greater heights, even though some architects used it in the form of slender walls so as to not make a complete break from masonry forms. The first examples of this sort of construction were mixed iron-masonry structures, which eventually evolved into skeletal load bearing systems of rows of columns and beams embedded inside brick masonry assemblages, very similar to today's architectural solutions. Ribbed domes, which function in a manner closely related to arches, were also constructed in the 19th century. A very famous example of cast iron architecture was the Crystal Palace, England (1851), which covered an area of 92.400m^2. The choice of just cast iron for the structural components of the building indicates the familiarity with the material that designers had achieved by that point. The structure was later destroyed in a fire, raising several questions concerning the fireproof properties of cast iron buildings. Despite that particular failure, pillars and roof trusses made of cast iron remained in extensive use.

Figure 2.9: The Crystal Palace.

2.5.2 Extent of Use

Because of its low tensile strength, the use of cast iron was not particularly spread in civil construction until the Industrial Revolution. Compressed members were still made of masonry assemblages. Additionally, wrought iron was preferred because it allowed the construction of elements under tension, like ties and connecting plates in timber trusses. Nails were also made of wrought iron because of its more ductile behaviour. Regardless, a wave of cast iron use in construction developed, because of the material's low cost, high compressive strength and corrosion and fire resistance. Members could be standardized and prefabricated easily due to the material's castability. Factories, which required large open spaces and spans to accommodate machine equipment, were often constructed using cast iron pillars and it became the material of choice for the construction of greenhouses. Arched shapes built of masonry and proven to be stable from practical experience could be formed by cast iron members, thus immediately offering a wide range of applications.

Cast iron possesses superior corrosion resistance to wrought iron, owing to its higher carbon and silicon content. In coastal cities this particular advantage led not only to cast iron being favoured over the use of other iron alloys but also to numerous examples of original 19th century cast iron architecture to survive to this day.

Despite the important early achievements in cast iron building, the cast was not initially favourably received, seen as a too sudden abandonment of traditional masonry architecture and methods. However, the development of the railroad, beginning at the start of the 19th century, demanded the construction of bridges with high load bearing capacity and short construction times. This demand could be satisfied by the use of cast iron members, which were much less bulky than masonry members. Cast iron beams were in the early days of its application actual rails, which were abundant due to its adoption in railroad engineering [14].

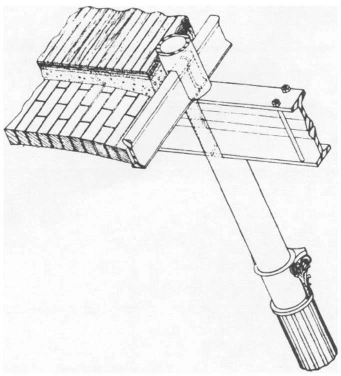


Figure 2.10: Construction detail of cast iron column-wrought iron tie rod-wrought iron beam and brick jack arch in an 18th century industrial building [47].

England in the first half of the 19th century is a most fitting example of the extent of use of cast iron in civil construction. The low cost and high availability of cast iron propelled by a prospering industry, made wrought iron a secondary choice for engineers. The fact that it was considered fireproof also helped to widen its range of applications, replacing structural timber in industrial buildings despite its higher cost. This trend was begun with the adoption of cast iron for the construction of textile mills in late 18th century England, a period in which fires in textile industry facilities were a very frequent phenomenon [15]. The application of cast iron followed the aesthetic and functional transition in Britain from Baroque to Rococo; the transition from drama to austerity and mechanisation. By the 1840s, the word iron itself had come to denote cast iron in the British Isles.

Cast iron was also used in the construction of some of the latest examples of post-lintel structures, which where composed of cast iron pillars and wrought iron beams. These buildings coincide with the gradual replacement of cast iron by wrought iron in civil construction after the 1850s and indicate an effort for optimal use of both materials.

Figure 2.11: Timber roof purlin (depth increased in the support), wrought iron riveted edge beam and cast iron decorative brackets and column.

The rise in popularity of cast iron for the needs of the railroad infrastructure, namely the construction of bridges, was probably as rapid as its decline. Cast iron bridges experienced sudden and disastrous failures, owing to the mechanical shortcomings of the material. Many cast iron bridges belonging to railroad networks were dismantled for fear of collapse. They were eventually replaced by wrought iron and, subsequently, steel bridges.

2.6 History of the Development of Steel

2.6.1 Origin

Production of steel was achieved, initially in very small quantities, at roughly the same time iron smelting was introduced. The oldest specimens were found in Anatolia and date back to roughly 2000 BC.

2.6.2 Historical Production Techniques

Steel was initially produced in a manner similar to wrought iron: by smelting in bloomeries but with the addition of carbon in the bloom which was then forged. Finally, the forged product underwent quench hardening, a form of heat treatment. As was the case with wrought iron, the productivity of steel producing bloomeries was increased by the use of hydraulic and wind power for the furnace bellows. Despite that, the quantities produced allowed it to be used only for small, and highly prized, objects.

By the 1st century BC, the Chinese were able to produce steel by melting together wrought and cast iron. Chinese steel output was bolstered by the development of decarburization techniques under a cold blast applied on pig iron from the 11th century AD onwards.

The cementation process was introduced in the early 16th century in Italy or Bohemia and involved the carburization of wrought iron. The process involved wrought iron being packed with powdered charcoal in many layers and heated for several days until the iron had absorbed the desired amount of carbon. This step was repeated several times and the resulting alloy mass was forged to the desired shape (inhomogeneous blister steel) or formed in a crucible (homogeneous crucible steel).

The Bessemer process was introduced in 1858 in England and allowed for the first time the mass production of relatively cheap steel. It was achieved by melting pig iron and reducing its carbon content by blowing compressed air through it. By manipulating the chemical intricacies of the production process, steel of higher quality than previously achieved could be easily produced. This was due to the fact that the Bessemer process required pig iron obtained from phosphorus-free ores, which were scarce. The addition of limestone removed phosphorus impurities and resulted in the method known as the basic Bessemer or Thomas basic process in 1876, in which any iron ore could be used.

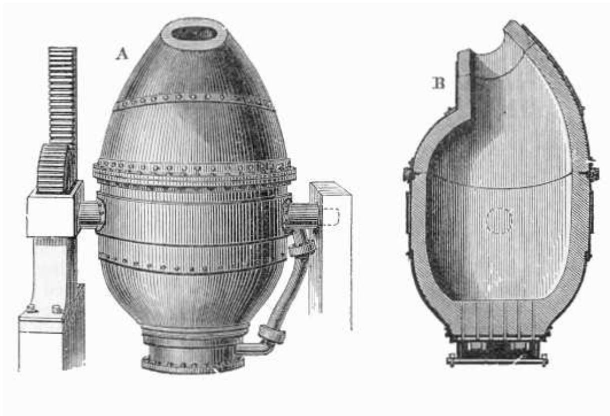


Figure 2.12: Bessemer converter [44].

The open-hearth process was developed in the 1860s in Germany and rivalled the Bessemer process in productivity and product quality. It involved the addition of wrought iron or iron oxide to molten pig iron. It was slower than the Bessemer process but allowed for a more precise chemical control during production. Similarly to the basic Bessemer process, the addition of limestone removed chemical impurities in a modified process called the basic open-hearth process.

2.7 History of the Use of Steel in Construction

2.7.1 Historical Applications

The application of steel as a structural component had to wait until the introduction of the Bessemer process, since until then it was an expensive and scarce material. After the production of steel in an industrial level was possible, structural steel members were 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.

Figure 2.13: Forth Railway Bridge (1890). First major British structure made entirely of steel.

From the second half of the 19th century onwards, engineers started experimenting with the new material. Early examples of its use include the International Exhibition buildings in Paris in, which were initially constructed with mixed steel-cast iron systems. Skeletal structures made entirely of steel soon became fairly common [16].

From the late of the 19th century, welding became a part of 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.

2.7.2 Extent of Use

Steel production procedures like the cementation process were energy- and labour-intensive, making steel an unrealistic choice for structural purposes. When the Bessemer process was introduced, the cost of steel production plummeted to about the same as that of wrought iron. Due to the superior properties of steel over those of wrought iron, the former had replaced the latter in virtually every civil application within a few decades and has not been replaced since.

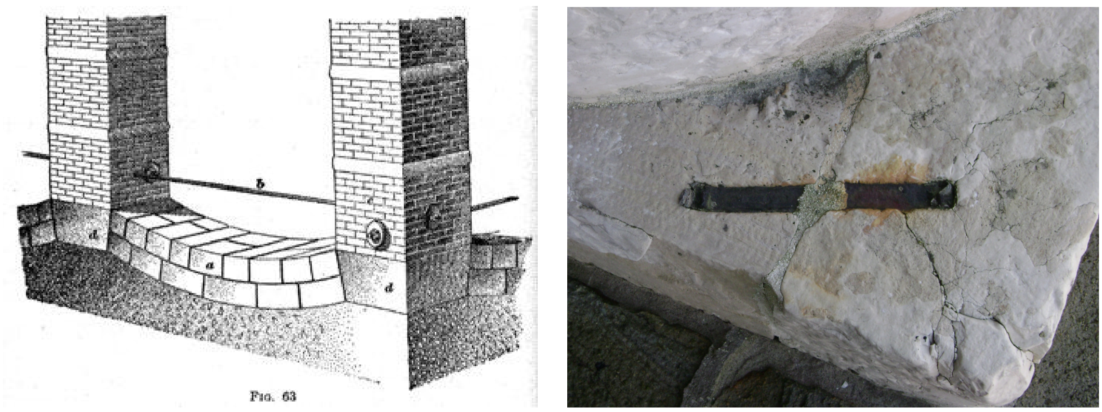
Similarly to the way Britain had pioneered the use of cast iron and France the use of wrought iron in civil construction, most innovations regarding the structural use of steel for major engineering projects were made in the USA, starting from the 1900s.

2.8 Iron as a Restoration Material

2.8.1 Historical Use

The most obvious shortcoming of masonry is its negligible tensile strength. This was well known since antiquity and dictated the forms that could be achieved with stone and brick. When the structural function of masonry was disrupted and cracks would appear it was common practice to bind cracks with wrought iron elements which functioned mainly in tension and shear. Tie rods for bracing against the in-plane opening of arches and exterior walls from out-of-plumb collapse are even more widespread. Usually, no particular effort was made to conceal the use of iron in structural reinforcement, apart from the occasional invisible anchoring of tie rods.

Iron plates and dowels were frequently utilized in the strengthening and propping of timber structures, truss joints for the most part.



(a) (b)

Figure 2.14: Historical wrought iron reinforcement in masonry (a) tie rod, (b) clamp.

In early Gothic cathedrals, when the ribbed forms and large openings for windows started becoming the norm, timber elements were utilized for the bracing of arches, as had been the usual method for Romanesque buildings. Soon it had become apparent that traditional timber members did not have the necessary load bearing capacity to accommodate the thrust of the piers. These were replaced by wrought iron beams in an intervention that could be characterized as a strengthening intervention [7].

Until the beginning of the Industrial era, roofs were generally built of flammable materials, like timber trusses covered with thatched roofs. Following fire incidents in industrial buildings, which contained industrial machines and flammable materials, it became apparent that fireproofing of manufacturing and storage spaces was necessary. In existing buildings this meant that timber roof trusses and thatched roofs had to be replaced by cast iron trusses, or cast iron beams for the intermediate storeys, and brick masonry vaulting or jack-arches. This was, however, a short lived intervention endeavour, due to the high cost in material and lost work hours as well as the eventual adoption of cast iron members for all new industrial buildings [15].

Similar alterations started being implemented in the late 19th century, with the replacement or strengthening of timber roof trusses by steel trusses in industrial buildings.

Following the first cast iron bridge disasters, measures were taken to replace or strengthen existing bridges, mainly those belonging to the railway networks. Wrought iron trusses, beams and shims were utilized in several strengthening interventions, which proved for an inappropriate decision or rather an erroneous and ill-designed attempt. The interventions were meant to provide strengthening to the members and to reduce vibrations and the opening of cracks. The result was further bridge failures, like the Dee rail bridge disaster in 1847 or the Tay rail bridge disaster in 1879, both occurring within two years of completion.

On the subject of iron as a restoration material, architects and engineers had widely differing opinions. Leon Battista Alberti preferred the use of copper to iron ties to bind weak walls to strengthening additions [69]. Giuseppe Valadier, the Italian architect and archaeologist belonging to the archaeological restoration school, was completely against it, citing the structural degradation of the original material due to iron corrosion. Mallerville, of the stylistic restoration school, was opposed to it in the case of the consolidation of the Rouen cathedral. Eugène Viollet-le-Duc, the French Gothic revivalist also of the stylistic school of restoration, was open to its use in monumental buildings, but not without expressing some concern on compatibility issues between iron and traditional materials [71].

2.8.2 Modern Use

Modern restoration may be distinguished from traditional approaches to restoration by the advent of charters, the first one being the Athens Charter in 1931. One of the key issues stressed in the Charter is the embracement of new technologies in the restoration of historic construction. This meant primarily the use of iron, steel and reinforced concrete, which contains steel bars, was completely justified and, indeed, encouraged. The adoption of these modern materials in many restoration projects led to the restorations being a source of significant damage. The compatibility problems of iron with brick and stone, known since antiquity, were disregarded due to a faith in new technologies and methods. Examples of erroneous applications of iron in restoration include the ancient monuments of the Athens Acropolis at the beginning of the 20th century, in which Balanos made heavy use of clamps and dowels to bind stone fragments together or secure different stone elements from relative movement, and the Barcelona cathedral, where steel ties, mainly clamps and rings were placed in the late 19th and in the early 20th century in the façade and Cimborio respectively. The main problems (loss of architectural fabric and the iron itself) were caused by corrosion and expansion of the iron elements in conjunction with mechanical strain within a few years after they were placed. Such iron elements have been removed from both monuments, in costly and time-consuming restoration works, which involved dismantling and reconstruction of large portions of the structures. However, since authenticity issues in ancient monuments and structural analysis of the Barcelona Cathedral have determined that the elements are essential, they have been replaced by titanium members in the case of the Parthenon and CFRP and titanium members in the cathedral.

(a) (b)

Figure 2.15: Damages due to iron use in monument restoration (a) Parthenon, (b) Barcelona Cathedral (photos A. Drougas).

Despite the negative initial experience in the use of iron in modern restoration, following the disasters of World War II, reinforced concrete, steel and iron were used extensively in the reconstruction efforts on European monuments and vernacular structures because of the urgency and the sheer amount of works that needed to be carried out in conjunction with the dire financial position most countries found themselves in after the conflict. Restoration theory became a secondary issue to urgency due to the circumstances [71].

The blind usage of materials and methods was strongly criticized after the formation of ICOMOS and the publication of the Venice Charter in 1964. Compatibility issues between old and new materials were given a substantial part and scientific rationalization in the design of interventions following the formation of ISCARSAH in 1996. Since then, the systematic use of iron in restoration has been largely abandoned. Instead, other metals have assumed its role, with stainless steel and titanium being prime examples. These are adopted when tying, confinement or propping are necessary measures, either permanently or as a short term solution.

Figure 2.16: Temporary propping of drum column at the temple of Zeus at Nemea with steel members [65].

Compatibility is a key issue in the use of any material as a means of intervention on a historic structure. A qualitative, comparative illustration of compatibility of new with historic material in conjunction with durability is presented in the following table. It is interesting to note that steel is the only intervention material that can be used on any type of historic fabric, even to a limited extent. At the same time, many of the compatibility problems of reinforced concrete are related to steel reinforcement corrosion and its effect on the surrounding historical material.

Table 2.1: Degree of compatibility of reinforcing with historic material [71].

Degree of compatibility		Reinforcing Material						
		Earth	Stone	Wood	Brick	Steel	Concrete	Polymers & FRP
Historical Material	Earth masonry	HIGH	LOW	MEDIUM	LOW	LOW	LOW	HIGH
	Stone Masonry	NULL	HIGH	MEDIUM	LOW	MEDIUM	MEDIUM	MEDIUM
	Wood	NULL	NULL	HIGH	NULL	MEDIUM	NULL	MEDIUM
	Brick Masonry	NULL	LOW	LOW	HIGH	LOW	HIGH	HIGH
	Steel	NULL	NULL	NULL	NULL	HIGH	NULL	NULL
	Concrete	NULL	NULL	NULL	NULL	MEDIUM	HIGH	HIGH

Contemporary examples of steel incorporated in the strengthening of structures made of the above materials are: confining straps in adobe buildings, tension ties in brick and stone masonry arches, carpentry joint reinforcement with steel plates in timber trusses, bracing trusses in damaged reinforced concrete frames and replacement of members in steel structures. Furthermore, steel frames are regularly employed in the bracing of masonry structures during dismantling and reconstruction works, during which the frame offers a working platform for the project and a bracing mechanism for the whole structure while at the same time preserving the profile of the masonry structure for the observer until the repairs are complete, at which point the frame can be removed. The Cimborio of the Barcelona cathedral is an example of such an application.

2.9 Further Aspects of Historical Iron Production and Use

2.9.1 Production Rates and Costs

As mentioned in the above passages, iron production before the Industrial Revolution was a fairly limited affair in terms of product amount. At the same time, production methods were labour- and cost-intensive and lengthy processes requiring plenty of fuel. Individual aspects of the various aforementioned processes are investigated in the following segments.

Ancient bloomeries produced very limited iron and steel quantities, about 1kg per firing. By the middle ages a bloomery charge could be no more than 15kg and with the introduction of waterwheels for the bellows this was increased to 300kg per firing. This quantity was never increased because of the advent of more efficient production methods. Wrought iron could be produced in a matter of hours, while steel required heating for up to several days. Finally, the time and effort for forging need to be added to the total.

Until the discovery of coke, large amounts of timber fuel were spent in the firing process causing excessive deforestation. Coke freed the iron industry from forest growth and spared large woodland areas. However, the iron industry would be from now on linked to mining not only for iron ore but for fuel as well.

The puddling process for wrought iron and steel production could average between 360 and 410kg per firing, which took about 4 to 5 hours of pre-heating and about an hour of heating of the pig iron in a higher temperature [82]. Obtaining the final shape in a crucible or through rolling significantly sped up the process compared to forging. However, crucible steel required three additional hours of firing and a greater amount of coke.

The production of pig iron was critical during the Industrial Age for the production of all iron alloys, since both wrought and cast iron, and later steel, were derived indirectly from pig iron. In Britain, for example, pig iron production increased from 23,000 tons per annum in the middle of the 18th century to 400,000 less than a century later.

The cementation process required 3 tonnes of coke per ton of steel and could fetch up to 16 tonnes in a single firing. The time required for pre-heating could be as long as one week. The Bessemer converter had the capability of producing 25 or more tonnes of steel in about 30 minutes. The open hearth process required a few hours to be executed but could fetch 50 to 100 tonnes of steel, and in special cases up to 500 tonnes, in a single firing. These methods resulted in the production costs for steel to plummet by 1900 to just 10% of what they had been 40 years before and 6 times cheaper than what the price of wrought iron had been at the same time period.

Early cast iron production rates were probably comparable to those of wrought iron. Production rates of blast furnaces in the 15th century were 1200÷1500 kg/day, in the 16th 1700÷1800 kg/day and in the 17th 1800÷2100 kg/day. The maximum productivity attained in the 18th century was 360 tonnes per year [11].

2.9.2 Design and Analysis Methods

A few general trends can be noticed when examining the development of iron production and historical building technology.

Innovations which resulted in faster and cheaper iron production were soon afterwards followed by modifications in traditional structural systems and techniques. Iron found its place in historical construction often by replacing other materials like timber. Additionally, new systems were developed in order to make use of the new material.

At the same time, rapid developments in the technical world overall, in which iron played no small part, required the application of new architectural solutions which stretched the capabilities of traditional systems (fireproof structures, train stations, long span bridges, exhibition halls etc.). Iron became the material designers turned to for meeting these ever-increasing requirements.

During the Industrial Revolution, traditional design methods based on geometrical rules and a modest understanding of the properties of materials were no longer sufficient. Meanwhile, the prices of iron products, and especially bulky structural members, were still very high. These conditions made necessary for designers to adopt a more rationalized approach of analysis and design of structures in an attempt to obtain the most appropriate solutions which address new structural problems with an optimal limitation of used material [11].

In 1747, École Nationale des Ponts et Chaussées, the first truly modern engineering school, was founded in France. In 1819, Claude-Louis Navier produced the mathematical expressions of the theory of elasticity in an easily usable form and expressed the elastic modulus independently of the cross section’s second moment of inertia in 1826, thus setting the foundations of modern structural analysis. Mathematically solved problems of the bending theory were for the first time introduced to the analysis and design process of civil construction [11]. At the same time, British engineers got their technical education mainly through an apprenticeship under an experienced engineer, with formal education being a secondary matter. This dichotomy can explain the adoption of different materials and methods by engineers in those two countries: French engineers pioneered the use of wrought iron in trusses and girders in an innovative and rationalized fashion while British engineers used cast iron in traditional forms, such as arches [18].

Design approaches adopted by engineers were necessarily limited to those allowed by the amount of knowledge provided by material testing capabilities. For instance, until the 1860s, the measurement of the elastic limit was not directly possible due to the absence of testing equipment of sufficient accuracy. Therefore, engineers were forced to design on the basis of ultimate tensile strength with the application of safety factors which yielded design values of 10%÷40% of the ultimate strength for wrought iron and steel. The advent of testing machines capable of measuring the elastic limit of materials in 1865 was a significant step forward in material science with considerable effect on civil engineering.

In the late 19th century, following the introduction of steel production techniques, interest in material testing rose sharply, especially in the United States. Laboratory installations which allowed the testing of full-scale members, rather than just specimens, became available in the 1880s, making important contributions in the understanding of the behaviour of beams, chains and cables. Confidence in the material rose as a consequence.

The optimal limitation of used material was considered not only in terms of the iron itself but also in comparison with stone and brick. The use of hollow cast iron piers in bridge construction, for example, resulted in a 99% volume reduction of material. The financial and logistic benefits in lowering on-site labour and transportation expenses were well received by engineers. A further rationalization and optimization of the building process, closely associated with iron production methods, was the prefabrication of structural members, starting with cast iron moulds made of sand which could be reused.

The synergy between science, engineering, technical education, fabrication methods and managing resulted in the formation of the modern building industry. It also signalled the split of art and science in two different, yet complementary, disciplines as far as construction is involved.

2.9.3 Structural Systems

The first wrought iron members, working mainly under tension, were of simple geometry; clamps, dowels, straps and rings of circular or slender rectangular cross-section. Dimensions were concluded on not based on some design process but rather on the simple knowledge of iron's capacity for bearing tension and shear. Elements were designed according to traditional practice rules and trial and error. An example of this is the dome of St. Paul's cathedral in Rome, which was strengthened by a number of rings, ranging from 3 to 9 from time to time, depending on the development of the cracking patterns observed on the structure.

Early cast iron members were designed to function under compression. Arches composed of slender ribs were the most common system for building over spans. The brittle character of the material was taken into account for the design of members under flexure by neglecting tensile strength. Through basic calculations coupled with applications and experiments, the most favourable cross-section geometry for cast iron members under flexure was found to be the inverted-T shape with a thick web; the object was to lower the neutral axis in a deflected member as much as possible in order to maximize the resisting moment. This particular shape, first explained in detail in Eaton Hodgkinson's treatise "Theoretical and Experimental Researches to Ascertain the Strength and Best Forms of Iron Beams" in 1830, was soon greeted with near universal acceptance [17].

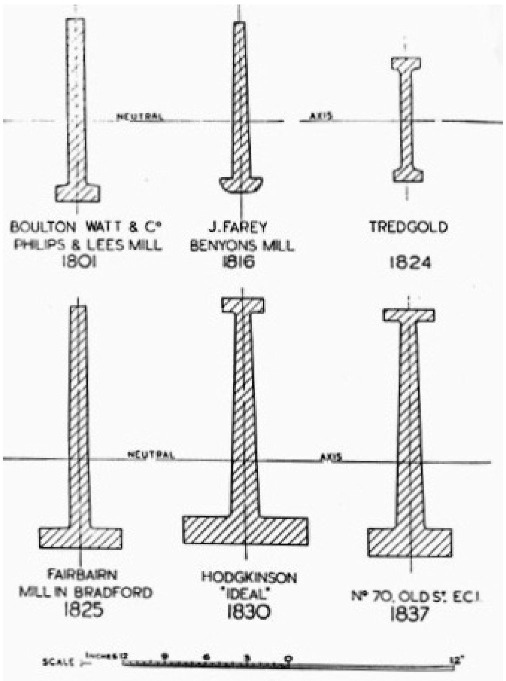


Figure 2.17: Development of cast iron beam cross-sections.

Early publications on cast iron behaviour, however, do not always indicate an accurate understanding of the material's behaviour. Thomas Tredgold, in his 1824 treatise "Practical Essay on the Strength of Cast Iron" had assumed orthotropic behaviour of cast iron, possibly misled by his practical experience with timber, thus concluding that the ideal cross-section was the double-T, which would maximize the moment of inertia and place the neutral axis at the centroid, thus simplifying calculations. While his assumption was fundamentally flawed, his conclusions formed the basis for wrought iron and steel member design in the following years. However, cross section types for wrought iron were more limited by the production processes available. Rolling allowed the fabrication of the advantageous double-T section, which immediately became more popular than the previous wrought iron bulb-T (essentially shaped like, and possibly derived from, an inverted rail) [47].

The advent of structural wrought iron led to the partial abandonment of arched shapes under compression for spans and to the more widespread adoption of girders and trusses. However, arched trusses and frames resting on inclined piers became common for bridges with spans up to 400m. Timber trusses had been in use since antiquity in highly developed forms, the Arsenale of Venice being a prime example of truss design optimization through time. However, new demands and the capabilities of wrought iron brought about an extremely rapid progress in the field. In both long span bridges and building roofs the three hinged arch were the iron truss system that maximized covered spans. For example, the Dirschau truss bridge reached a span of 131m with a weight of 8.3t/m [21].

Apart from truss structures, girders and tensile structures rose in importance for the spanning of distance. Hinged girders, box girders and continuous and Gerber beams were introduced for iron structures and later adopted and applied by engineers for other materials, like reinforced concrete and applied mainly for intermediate spans. The Britannia Bridge was built utilizing whole-body box girders with longitudinal stiffening reinforcement, reaching a span of 142m and having a weight of 12.5t/m. The first modern tensile structures were suspension bridges in Britain in the 1820s, which utilized wrought iron chains. Cables made of wrought iron and later steel soon followed [21].

Prestressing of beam-shaped structural elements with steel cables was first conceived and experimentally attempted for steel beams in the early 20th century in order to increase load-bearing capacity and reduce deflection for large spans. Technological limitations and application obstacles regarding the material properties and the composite function of the beam and cable system caused this innovation to fetch poor performance results, thus not finding its way into the technical world. But even before this attempt, prestressing in the modern sense had been attempted more successfully in the cast iron skeleton of the Crystal Palace, cast iron suffering from the same low tensile strength as concrete. This method was later reinvented for application in concrete structures with far more positive results, resulting in a wide range of applications for beams and slabs. The practical experience in concrete allowed for a more successful, but still somewhat uncommon, application of the method for steel members in more recent years [22].

2.9.4 Attained Spans and Heights

The use of iron as a secondary reinforcement element first and as the primary structural material eventually has contributed in a variety of ways to the increase of covered span and attained height of civil structures.

Continuity connections in timber members, in the form of doweled connections made of wrought iron straps and pins, were a development from, and usually employed in conjunction with, carpenter’s connections that increased the spans attainable by timber structures, mainly in roof systems by overcoming the size limitations of wooden logs. Early examples of such connections can be found in ancient Egyptian architecture. These applications also allowed for the maximum pre-industrial spans to be attained in both building and bridge structures. These spans were eventually surpassed by the application of iron as a main structural element within a few decades following the construction of the Iron Bridge.

The surpassing of the maximum spans covered by masonry arches had been achieved by 1815, with the construction of the Union Bridge in England. From then on, progress in that regard was extremely rapid, especially with the advent of the earliest modern suspension bridges.

The transition from Romanesque to Gothic cathedral architecture serves as another example of the application of iron in an effort to surpass previously attained spans and heights and to maximize the area of openings using masonry as the base structural material. Skeletal constructions with slender members allowed for greater heights and spans, but also allowed narrower margins for error in the design. Architects relied on iron dowels between stones in piers, arches, vaults and even foundations to widen those margins, make up for the uncertainties involved in historical building techniques and increase safety. The replacement of timber ties with iron ones was a further development in that regard.

Dome building up to the 19th century had not progressed in terms of clear opening since the construction of the Rome Pantheon 17 centuries before. More sophisticated clamping systems utilizing iron dowels and tensile connections did not provide enough confidence to architects to attempt to surpass the Pantheon's dimensions. This situation started changing when cast iron ribs began being employed in the late 18th century in an effort to reduce their weight, which even with the construction of multi-layered systems was very significant, and this development was soon followed by the building of longer spans. The innovative use of cast iron in dome building was greeted with significant resistance, as was the case with the U.S. Capitol Dome, leading the architects to painting the cast iron to resemble marble. However, iron did eventually lead to surpassing the pantheon's span with the construction of the Devonshire Royal Hospital in 1881.

The average height of structures was steadily increased by reliance on iron members, but the maximum attained height by any structure was abruptly increased nearly twofold with the completion of the Eiffel Tower.

Iron, coupled with the closely related advent of structural analysis techniques, became the material that helped surpass all previously attained dimension landmarks less by risk-taking and more by adopting a rationalized approach in engineering.

2.9.5 Mechanical Properties

The mechanical characteristics 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 the technological aspects of iron production.

The capability of decreasing or orienting slag inclusions in more than one direction reduced the inhomogeneity of the final product. Whereas bar wrought iron had slag grains running in one main direction, plate iron, made of cross piling iron bars, had about the same ultimate tensile strength and ductility along the grain and a reduction of less than the typical 15% across the grain for bar iron [23].

The improvements through time can mainly be observed in examining structural and reinforcement steel strength during the 20th century. The advances in material science, chemistry and industrial manufacturing methods not only yielded material of better properties but also inspired a confidence in the material, both of which can be witnessed even today in the recommendations for historical strength steel in design codes. An example of this is the FEMA 356 standard in its specifications for the estimation of lower bound strength of historical iron and steel [24].

3. HISTORICAL APPLICATION OF IRON – ANCIENT GREEK MONUMENTS

3.1 General

From a preliminary examination, ancient Greek temple architecture may seem to be comprised simply by a piling up of cut stone blocks. This position was held by several qualified observers for centuries. This couldn't be further from the truth, given the meticulous nature of the stone cutting process and the thousands of concealed connecting elements made of iron that secure these stone blocks from relative movement located in every temple. Extensive studies on these connecting elements have been performed over the past century, beginning from an archaeological perspective, moving to an architectural interpretation and finally elaborating on an engineering and scientific approach, mostly in the past few decades, which is still unfolding. The investigation of the structural role of these connections has lagged behind the study of their historical, architectural and chemical aspects. Despite this deficit in understanding them fully, many past preservation projects have rushed towards their, sometimes careless and ill-conceived, restoration often based on approaches and materials appropriate to new structures.

This chapter offers a summing up of the most significant information available on the iron elements used in ancient Greek temples, beginning from the production process and chemical properties up to a description of application types and their development through time. A critical stance towards restoration practices, and examples thereof, is offered.

3.2 Iron Production in Ancient Greece

3.2.1 Introduction of Iron in Ancient Greek Territory

Based on the available archaeological findings, ancient literary references and merchant records from neighbouring states a number of different theories concerning the introduction of iron in Greece have been proposed over the past several decades. Many of these sources indicate towards its introduction in the area by forceful export from Cyprus in the southeast and over the Aegean see in the east (the Caucasus region lies in that direction and in relative proximity), since discovered iron weaponry comprise the majority of the most ancient findings made of the material in question. Iron swords and spearheads have been discovered in the Aegean area that date back to the 11th century and are of definitely eastern typology. The discovered iron implements that follow these findings tend to outnumber the copper ones from that point on [25].

For the Greeks, the mythological birthplace of iron was, as with copper, the island of Crete and Phrygia in the southeast or the island of Samothrace in the northeast. The ancient Greek word for steel is «χάλυψ», which took its name from the people known as Χάλυβες that resided in the northern part of Asia Minor, and which Aeschylus calls «σιδηροτέκτονες» (iron-builders). Trade records indicate a robust iron trading relationship with states in the Caucasus region, which they called «σιδηρομήτωρ αία» (motherland of iron) [30].

As far as local production is concerned following the import of iron production technology, iron implements seem to be mostly limited to domestic items, agricultural tools and decorative items. Copper was possibly considered superior to iron for arms and armour even during Homer's time in the 8th century. In fact, there is evidence of extremely slow development or improvement in iron smelting and forging techniques in Greece from the 11th to the 7th century, at which point a second wave of influence may have spread from central Europe to the Balkan Peninsula [26].

A possible indirect indication of the introduction of steel in the area are the stone cutting tool marks discovered in the marble of monuments, theatres and other major stone buildings from the 7th century onwards as well as the opening of tunnels and mining shafts of greater length and width than previously attained. It is interesting to note that this technological development coincides chronologically with the proposed central European influence wave. However, there are earlier literary references to a process that closely resembles steel quench hardening from one century earlier, the technical aspects of which cannot be determined by that source alone. Direct evidence of steel tools is hard to come by, since after oxidation of a specimen it is extremely difficult to distinguish between iron and steel [30].

There are references that a type of heat welding of iron pieces could be achieved to some degree. Ancient Greeks were also familiar with the fact that iron production techniques mainly involved the forging of the material, but there are references of melting and casting of iron masses in moulds. However, heat welding and casting, and their results, achieved in Ancient Greece can in no way be compared to the developments in welding or cast iron technology as are known today [30].

3.2.2 Iron Production Techniques

The majority of the information presented in the following segment concerns the iron producing practices employed in the Laurium area, where extensive research on the subject has been carried out. Iron production in different geographical areas did not differ significantly [31]

For the production of wrought iron, ancient Greek metallurgists of the 6th-5th century used a variety of furnaces. Short furnaces, sometimes partially embedded in the ground, were used for mundane items, in which high quality was not of prime importance. Initially, the iron ore was reduced by a preliminary thermal treatment, followed by its placement in the furnace. The resulting spongy bloom was finally worked with elongated hammers and forged in order to remove slag and to shape it into various shapes. However, when iron of superior quality was required, as, for example, the one for structural elements, a different type of furnace was used, mainly distinguished by its increased height and a series of technological improvements.

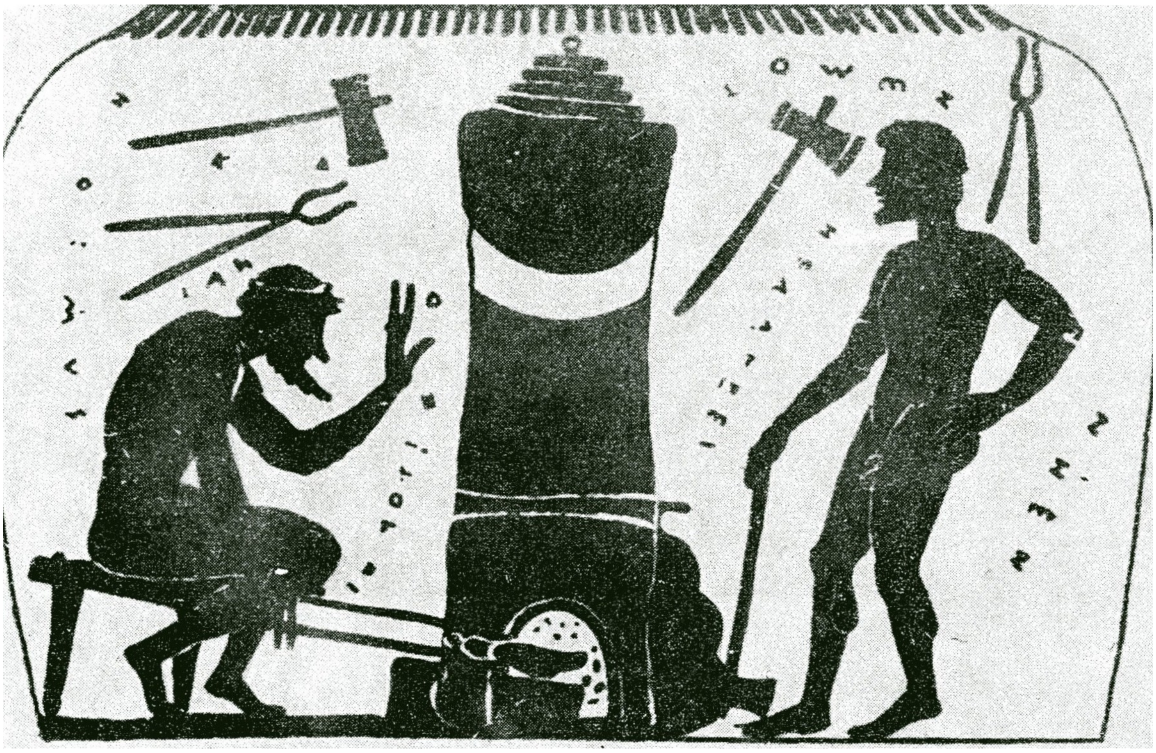


Figure 3.1: Iron reduction furnace from a 6^{th} century amphora [31].

These furnaces were tall shafts, constructed entirely above ground. A number of different modifications of a base type of the same furnace were devised, depending on the metal to be produced (iron, lead-silver alloys etc) and the type of process to be carried out (smelting, melting etc). The furnaces for iron production were estimated at 80÷120cm high, having a diameter of about 15cm at the bottom, which was slightly concave. The stone used for its construction was schist, internally lined with some type of clay based material for increased fireproofing. The overall shape of the furnace resembles a crucible. Located near the base of the shaft were a number of nozzles, through which the necessary draft was provided by manually operated bellows.

The production process started with a preheating of the furnace. It was filled to a large degree with timber fuel initially and charcoal later. The bellows were used to gradually increase the temperature in order to dry out the fuel and, finally, to ignite it. Subsequently, the furnace was steadily supplied with charcoal in order to keep it to a height of 40÷50cm and maintained the temperature at a high level. Finally, the iron ore was placed in the furnace, mixed with more charcoal. The estimated amount of charcoal in the mix is 70% of that of the iron ore to be reduced. In the Laurium area, the ores primarily used were hematite and limonite, and were considered of quite higher than average quality. It is probable that quantity of ore added was such as to completely fill the furnace, which facilitated a more thorough preheating of the load from the rising smoke. The top of the ore-charcoal load was covered by placing pieces of schist to reduce heat losses from upwards draft. At the top of the furnace, a ceramic amphora with a removable cover was placed for further heat proofing.

After loading, the firing process required 6÷10 hours, at the end of which the spongy bloom had descended, without melting, to the bottom of the furnace, where it formed a hemispherical mass with a concave upper surface. The furnace was left to cool down and, finally, the bloom was removed, either from the top of the shaft or from a possible side opening at the bottom.

Slag inclusions were removed by forging at 1200^{0}C, requiring the reheating of the bloom in a second type of furnace fuelled by charcoal. The bloom, handled with long tongs, was placed in the fired charcoal until the slag reached melting temperature, at which point the forging would commence for slag separation and shaping.

Steel was produced by carburization of the forged bloom taken from the second described furnace. The process utilized was similar to that later employed in the creation of Damascus steel. Thin iron plates were carburized within a few hours by being placed along with powdered charcoal in a sealed amphora, which, in turn, were placed in pottery firing furnaces and heated to $800{\div}1000^{0}$C. The carburized sheets were folded and forged repeatedly for merging. This resulted in the final product being composed of, in the typical case, 2÷3mm thin alternating layers of soft iron and hard steel.

3.2.3 Financial and Social Importance of Iron

Like in all ancient cultures, iron production was an economically significant process, costly and time-consuming but necessary for development. The slave labour mobilized for its production did very little to lower the prices of products. The high costs required that iron production, supply for public projects (such as temples) and the manufacture of implements be strictly supervised, regulated and controlled. According to the already rigid public project laws, this meant that public contracts were composed, which stipulated that the architect should supervise the production and placement of the iron in order for it to comply with architectural rules specified by the client (generally the state). Such contracts, as well as contracts related to connections made of other metals, have survived to this day, as they were carved in stone tablets to be accessible by the public.

When local iron ore deposits were deemed unsatisfactory for structural members, owing to unwanted chemical inclusions, architects did not hesitate to purchase and import iron ore mined from purer deposits. This was a practice also common in selecting the appropriate stones for a particular monument, indicating that the preoccupation with choosing the right materials did not stop with stone but was extended to iron as well.

Despite the efforts related to every step of iron production, connecting elements were of secondary architectural and financial importance in the construction of temples. The production and transportation of the stone blocks, both of which made heavy use of iron and steel implements for mining, shaping and lifting, was a more crucial and expensive affair [33].

3.3 Iron in Ancient Greek Temples

3.3.1 General

For the sake of immobility of superstructure stones from their final positions, two general types of connections were utilized in the load-bearing elements (columns, walls etc) of monuments, scarcely in archaic times and with increasing frequency with the passage of time: connections with stones in the same course (horizontal connection) and with those of the underlying course (vertical connection). They are the more widespread and comprehensively documented examples of iron use in ancient Greek monuments, as well as those that follow more specific architectural rules. They were also the only iron structural elements that were completely incorporated in monumental architecture [30].

Ancient Greek stone masonry was laid dry for all structural elements, relying on friction developed across flat surfaces for securing stones from movement and on these iron connecting elements as a further bonding agent, as a means of preventing small movement and as practical aid in the stone laying process.

Two more types of iron applications may be identified in ancient Greek temples: stone reinforcement and secondary structural and non-structural elements. The first type was mostly applied as an innovative solution to observed progressing failures and is not particularly commonplace. The second refers to relatively common applications without, however, a critical structural role [30].

The different types of iron elements developed independently from one another, even though originating from the same type of building. Dating of monuments from the type of elements used in its construction can often lead to inaccurate conclusions, especially since they may had been replaced through the course of the monument’s history.

3.3.2 Archaeological Findings

Historical references to iron used in monuments are very limited; observers focused more on the stonework. However, there are references to clamps, dowels and most other applications to be found in ancient literature and public documents, especially building contracts [30].

Actual iron specimens dating back to the original structures are rare, depending on the type of element and the structure type. Reinforcement bars are almost impossible to survive to this day, but connections protected by cast lead may be found practically intact, especially if they are still in the mortise. In any case, the footprint of these elements on the structure can be detected and excavations in the vicinity may produce positive results. Still, if any findings are produced, their archaeological and chemical study usually takes precedence over the investigation of their mechanical properties.

The mortises and grooves in which the elements were placed and anchored serve as the first indication that some sort of connection or reinforcement was indeed used in the structure. The type of connection may usually be determined by the shape of these mortises and grooves. Chemical traces of rust can be found, which would provide positive identification of iron as the material of these elements over timber, lead or copper. In some instances, iron amalgamated in the stone mass can be discovered, as well as imprints on the surrounding material created by stressed elements.

3.3.3 Horizontal Connection

Following their placement in their final positions, stones were bonded to each other by simple friction (mostly in foundations) or, more commonly by one or more connecting elements on the upper part of their faces. These connections were called “bonds” by the ancients, and were placed in specially prepared mortises. A variety of shapes for the connections, along with several changes in the material, were utilized as the method developed. As a general rule, no more than one type of connection was used in a single monument, but there are exceptions [32].

Some of the first examples from which this method was derived are from the mid-Minoan period in Knossos, during which dovetail shaped elements made of timber, roughly 0.28 · 1.10m in dimension, the typology of which was possibly imported from Egypt, were used to secure the outer courses of three-leaf stone masonry with a rubble infill. The Knossos palace utilized such devices, which were oriented perpendicularly to the wall surface, and not longitudinally. Later, in the Mycenaean period, in domed tombs and other Cyclopean structures made of large cut stones, similar connections were sparingly used, such as in the Treasury of Atreus. During the 7th century, a more frequent use of connections is noticed, followed by some technological developments in shape and materials.

From the 6th century onwards, dovetails had become particularly widespread, but where by then constructed entirely of lead. They were mainly used in monuments made of limestone blocks, and were placed not by casting lead in the mortise but rather by shaping the elements according to the dimensions of the mortises and being thrust into them, this being allowed by the softness of the lead. Examples of such devices have been discovered in archaic Delphi findings.

Soon afterwards, lead dovetails were internally reinforced by a wrought iron bar of rectangular or circular cross-section whose ends were bent until perpendicular to the upper surface of the stones to be connected and protruded from the lead mass, giving them an elongated Π-shape. The mortises were fitted with openings to accommodate the protruding iron edges. These connections were applied mainly in marble archaic monuments, and were apparently constructed by placing the iron in the mortise and casting the lead over it and their length could reach 0.56m, as was the case in Delphi. There is evidence of existence of this method since the Mycenaean period. The technique of lead casting in the mortise itself which was later adopted was possibly imported from Babylonia, where it had been in use since at least the 7th century. The purpose was to protect from corrosion, absorb small vibrations and assist in the anchoring of the element in the mortise. The suggestion of absorbing vibration could only stand in case small gaps were predicted in the cast lead mass, because the mortise and the overlying member would completely confine the lead and prevent expansion.

Connections of a double-Γ shape (two types: with legs facing the opposite or, more rarely, same horizontal directions) made of iron first appeared in the 7th century and were occasionally used in combination with dovetails. They were extensively used throughout the 6th and early 5th centuries.

Double-T connections made of iron and covered with lead cast in the mortise, with the flanges extending horizontally, although dominating stone construction during the classical era, date back to roughly the same time as dovetails. They remained in constant use well into the Hellenistic era. Their length varied and often reached 0.70m or more. A number of modifications on the basic design exist, some examples of which are the web extending beyond the flange and a thickening of the web at roughly its midpoint. Apart from being anchored along two horizontal surfaces, double-Ts were sometimes anchored along one vertical and one horizontal surface, which required the element (often of considerably greater length than usual) to be twisted by 90^0 at the midpoint of the web. The Parthenon was fitted with such connections.

Π-shaped connections, known as arches, made of iron or copper with the flanges extending downwards appeared in the 6th century, placed in dovetail mortises and covered with cast lead. The mortises had become Π-shaped as well by the end of the 5th century. This configuration had largely replaced the double-T connections by mid 4th century, after a period of parallel application, sometimes in the same structure, with the foundations being secured with double-Ts and the superstructure with Π-shaped elements, perhaps due to a change of plan while the construction had already began. These connections remained in use during both the Hellenistic era and the entire Roman period, making them the most widespread in terms of number of applications and geographic expanse by far.

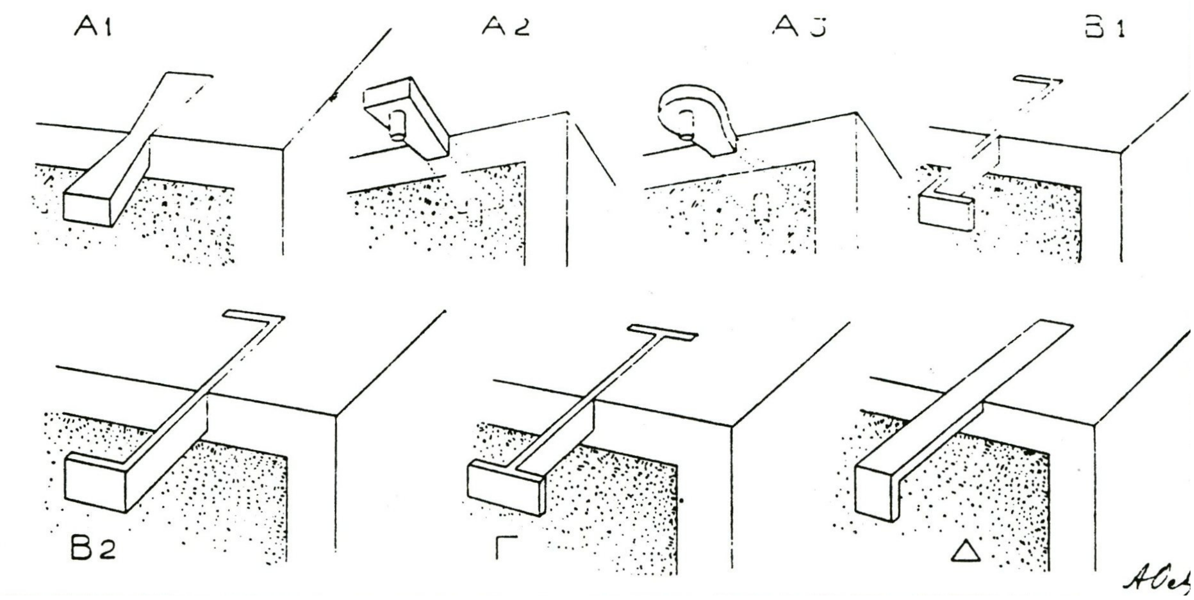


Figure 3.2: Development of horizontal connection elements [30].

For all the aforementioned connection types, it should be noted that in the final configuration of the building, the horizontal connecting elements were generally concealed by overlying stones. In positions where the top surface of the stones was bare, such as in the stylobate between two columns, no connections where placed. In the handful of known exceptions, the bare parts of the stylobate were connected with dovetails or other purely decorative elements of very little structural significance. This serves as evidence of the preoccupation of architects to conceal iron members or not to use them at all in cases where they would be visible.

Horizontal connection was very thorough at the intersection points of horizontal structural elements, such as walls, architraves or grid-like foundations. Horizontal connecting elements were used in non-standard ways in a number of instances. When a stone block was discovered to be suffering from a previously undetected discontinuity which may develop into a crack, a number of elements, such as double-Ts were placed to bridge the crack in case the block was eventually deemed fit for use. Typical such examples may be found in column capitals, which work primarily in compression, but nothing similar was attempted in members under flexural loads, such as architraves. Finally, they were utilized for securing precariously placed members, especially slender sculpted slabs standing upright at the gables, from out-of-plumb collapse.

Horizontal connection with iron-in-lead elements was applied almost universally to temple structures, but was also used for all major projects; permanent stone fortifications are an example of major structures, in which the use of iron was not mitigated by the fact that the quantities of reliable material required were considerable.

3.3.4 Vertical Connection

The earliest found mortises intended to hold vertical connection elements of square cross section, possibly made of timber, were located in the upper surfaces of large cut stones in a number of Minoan palaces. They were called «γόμφοι» (pegs) by builders, and were a rather late and slower development, compared to horizontal connections. Mycenaean monuments, being composed of smaller irregular stones, did not make use of such or any other doweling. Archaic monuments also did not contain dowels until the mid-Archaic period. Even then, dowels were not placed in the foundations, but only in the superstructure. The general typology of dowels remained more or less steady, half of the element being placed in a mortise in the upper surface of the underlying stone and the other half in the lower surface of the overlying stone [30].

Dowels were initially made of timber, then copper and, finally, iron. Timber remained in use for dowels in drum columns, but it has been argued that they were used mostly to assist builders in the placing of the drums, and thus were not intended to provide any shear reinforcement. Iron dowels with the same function have been found in drum columns in Roman monuments. However, some timber dowels with a lead protective casting have been discovered in stylobates, in which the dowels are normally made of iron.

Three shapes of iron dowels are the most common and account for the majority of known applications and are of particular importance for the construction of the walls of ancient temples. The most common is the rectangular plate-like dowel with typical dimensions of 1÷1.5cm thickness, 5÷8cm width, which ran along the length of the wall, as a rule, and 5÷10cm height. The mortises in the upper stone were carved in the face surface, so that after placing the dowel in the lower stone, its upper half protruding, the overlying stone could be pushed into place. Variations of this typology are dowels which are placed in mortises carved in two overlying stones instead of one, thus being of twice the usual length, and are found near wall corners, as a rule. All these dowels were covered by cast lead while in the mortise, which, if inaccessible after the placement of the overlying stone, was reached by carving channels in the vertical joint leading to it. T-shaped and Γ-shaped dowels, of roughly the same dimensions as the rectangular dowels, were also used for the bracing of stones located in external and internal corners respectively, but are only common in classical era monuments.

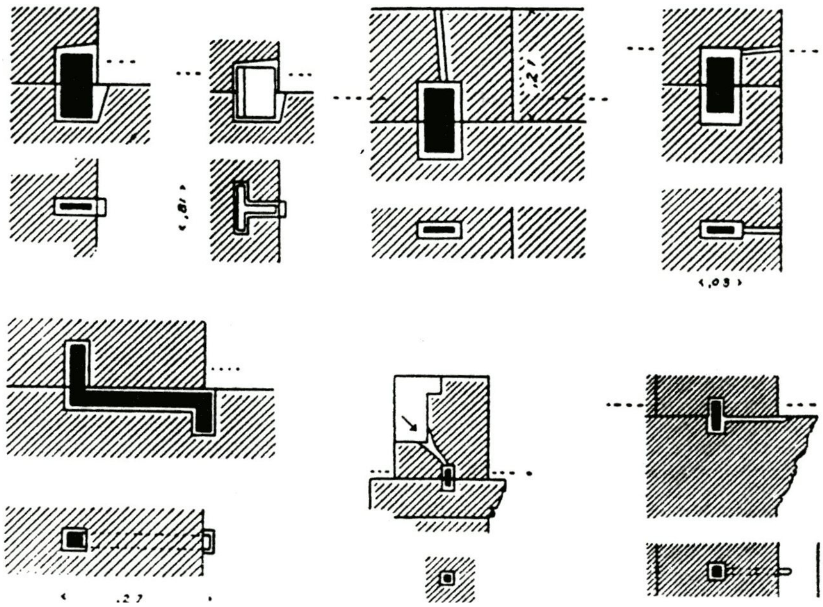


Figure 3.3: Dowel types and lead casting channels [27].

As a final note, iron dowels were also sometimes utilized in the shear reinforcement of joints between the pedestals of large statues and the stone floors on which they were placed. For this purpose, rectangular and T-shaped dowels were used, protected by cast lead in the usual manner, sometimes in the original setup and sometimes as a subsequent reinforcement [28].

3.3.5 Structural Reinforcement

Iron elements were used in monuments in a variety of ways which generally tend not to follow ancient architectural rules but were apparently attempts at making slight alterations to the function of structural elements, to strengthen weaknesses, secure against the opening of joints, relieve stresses from heavily compressed areas or offer a degree of redundancy when the strength of the material was not certain. It is not entirely certain if these solutions evolved from previous similar attempts with timber, but the shape of the iron members (long beams of mostly rectangular cross section) seems to suggest that.

Reinforcing iron was generally adopted when special structural conditions demanded it or when the architectural design called for members of heavier proportions than usual, which may had been previously unattempted [27].

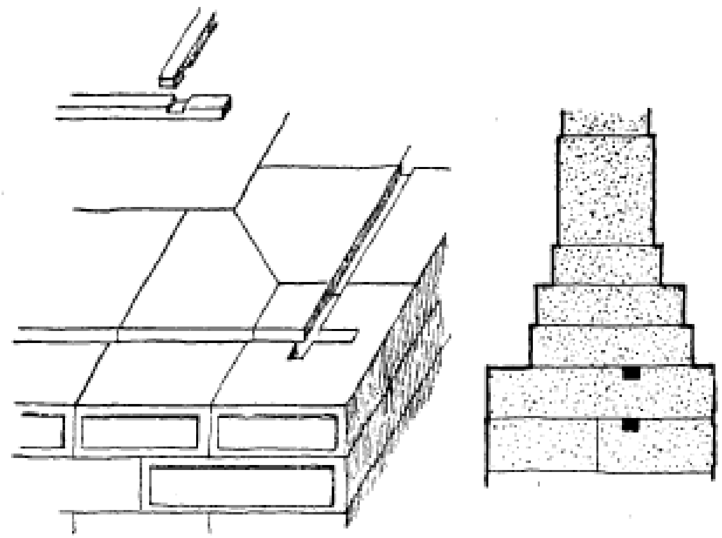


Figure 3.4: Foundation reinforcement at the Theban treasury [27].

As a reinforcing element, iron bars were sometimes used, both in the foundations and the superstructure of stone monuments. These bars were of square or rectangular cross section and were concealed by being placed in carved grooves, which serve to recognise them in archaeological surveys. The crepida of the Theban Treasury at Delphi, constructed of limestone blocks, was reinforced in two levels by such bars with a cross section of $10 \times 8cm^2$, which ran along much of the outer lengths of the structure, were bonded together at the edges by a joint similar to carpenter's joinery and secured the foundation from outwards expansion by providing a sort of confinement. Additionally, the superstructure was doweled to the beams for added rigidity. The building was founded near a steep slope and a small river that flooded frequently, thus probably causing concern to the architect, who decided to apply this strengthening method [27].

A good example of superstructure reinforcement with iron is the temple of Zeus at Acragas. The architraves were exceptionally long, making the spanning of the gap by one stone only impossible. The vertical joint between the two stones at the middle of the architraves would clearly make them unstable without support or partially stable at best as two piece jack arches. This was provided by a rectangular iron beam at the lower surface of the architrave, its groove extending just enough for the beam to bridge the free span, giving it a total length of about 4.3m. A total of 38 such beams were placed and were possibly covered by cast lead while the architrave still lay in the ground and concealed by stucco after placement. A similar application was discovered in a lintel supporting a small wall at the Erechtheum [27].

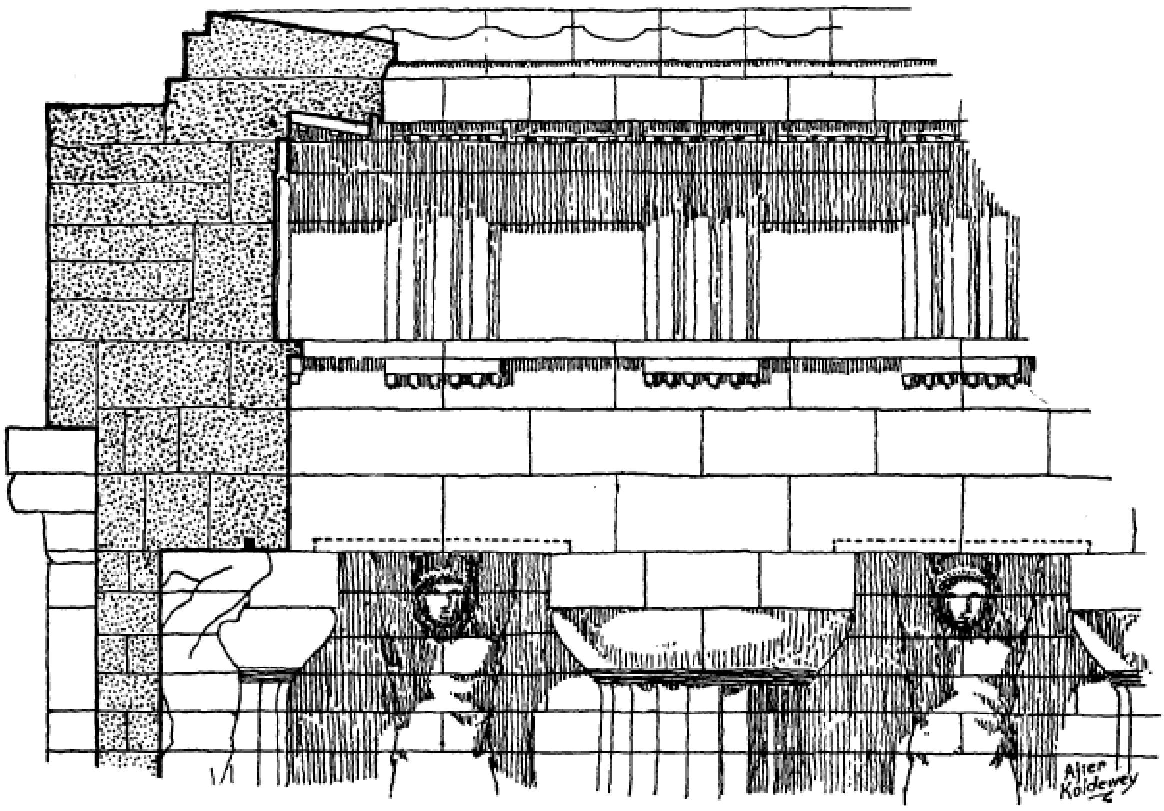


Figure 3.5: Architrave reinforcement at Zeus at Acragas [27].

Another example of iron reinforcement, but quite different in its conception and function, was utilized at the Propylaea in Athens. Coffer slabs made of marble were a relatively new affair at the time and it was attempted by architects for them to resemble the timber roofs they had replaced. To reduce the stresses applied to the architraves, an innovative solution was attempted. Deep grooves were cut at their top surface and inside the grooves, rectangular iron beams were placed, which spanned about 1.7m, making them end at about 1m from the edges of the capitals, onto which the transversal ceiling beams were supported. The groove was of such depth that in its deflected shape under the weight of the ceiling beams the iron beam would not touch and, therefore, load the architrave. Since testing the interlocking of small stone assemblages on the ground before placing them in their final positions on the actual structure was common practice, it is not unreasonable to assume that this and other similar setups making use of iron were also tested before application to verify their behaviour. This setup shifted the weight of the ceiling beams closer to the supporting capitals, thus reducing the strength demand in the architrave to 33% and its deflection by 25%, which was loaded solely by its self weight near the mid-span. A total of 16 such beams were used in the structure, in which, in the effort to eliminate any possible contact between them and the architrave, lead casting was possibly not applied.

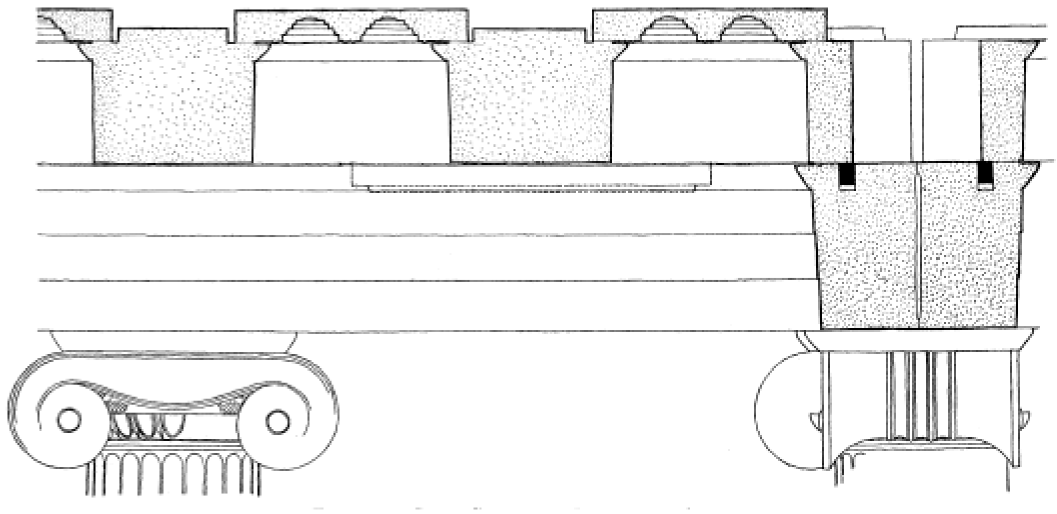


Figure 3.6: Beam reinforcement of the Propylaea [27].

A hypothesized, but not proven to have existed, iron reinforcement in the form of rectangular beams may have been employed at the coffer slabs of the temple of Apollo at Bassae. The ceiling beams were hollowed out to a U-shape to reduce their weight and to accommodate iron beams, from which they would be hanged by means of straps. The fact that the usual stiffening of beams by adding a ridge at their upper, invisible from bellow, part was known but not used seems to support the hypothesis. However, that hollowing out beams and coffer slabs for weight reduction without any further strengthening was also standard practice and the fact that no trace of iron has been found weaken the hypothesis, possibly inspired from construction methods utilized when the hypothesis was postulated.

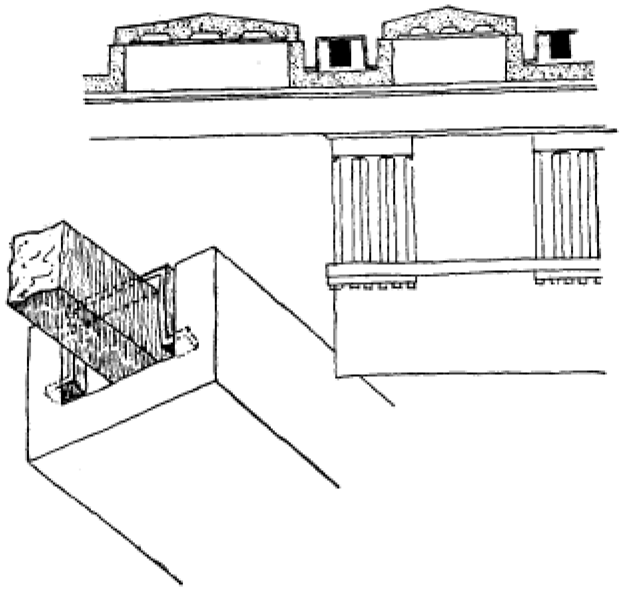


Figure 3.7: Roof reinforcement at Bassae [27].

3.3.6 Other Uses

Iron was used to provide cantilevers for the support of other structural members or heavy statues which would otherwise overload sensitive areas, such as stone cantilevers, in flexure. Both single and double cantilevers were built and were secured in other stones by superimposed weight or by being bent upwards and bonded by assuming a looped shape behind them. The iron cantilevers were placed over carved grooves so that when deflected under loading they would not touch the stone beneath, in a manner similar to the iron beams in the Propylaea ceiling. Despite being exposed in many instances, they would not be visible, being situated at great height, and it is not clear if any protective lead coating or any other corrosion protection method was applied.

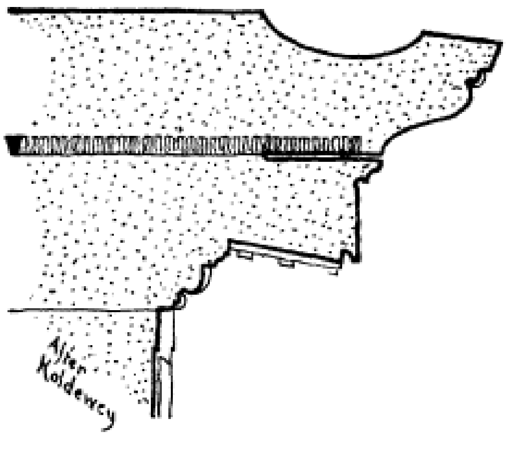


Figure 3.8: Iron supporting stone cantilever at cornice at temple of Castor and Pollux at Acragas [27].

During the process of temple wall construction a method for securing stones from movement was applied which made use of iron members dissimilar to the usual horizontal and vertical bonding and unique in their function. After doweling and lead casting had taken place, a single small bracing element was forced in order to be placed in a buttressing position and supported in small mortises, thus preventing small movements of the stone along the length of the wall until the neighbouring stone was placed. This arrangement was introduced in archaic structures and maintained during the classical era, but discontinued from the 4th century. The unique characteristic of these connections, dubbed «παράγομφοι» (side pegs) due to their being placed alongside vertical connections, is that they are the only element, iron or otherwise, in ancient temples that was placed in such a manner so that it was essentially prestressed. However, despite being important during the construction process, their role after completion of the structure is probably of small importance since there is no way to inspect them or ensure that they would stay in their original place [30].

3.4 Structural Role of Iron in Ancient Monuments

3.4.1 General

Documentation of ancient monuments and material science has demonstrated that the ancient Greeks had greatly underestimated the strength properties of stone, leading to oversized walls and columns in which very small stresses are developed. This cannot be said of their use of iron in the same structures. Connections and reinforcements are of very small size compared to the stone members they were meant to secure in place or support, despite their rather large absolute dimensions. Three possible explanations have been proposed: confidence in the strength of iron, reluctance to rely on its strength altogether or an effort to ensure that the iron members rupture before the surrounding stone, which is more expensive and architecturally important.

In order to address the issues concerning the actual structural role of iron in ancient monuments and to determine the result that ancient architects strove to achieve with its use, numerical calculations and experiments have been carried out, the extent of which is, unfortunately, far smaller than that for other, more common types of structures. Furthermore, the bulk of these investigations supersedes the finalization of modern restoration project plans and their execution, a logical jump inconsistent with restoration theory principles as have been applied in other monuments.

3.4.2 Static Loading

Iron members for the horizontal and vertical connection of stones in ancient monuments are used in such a way so that in the steady state of the structure, under static loads, they remain unstressed. The additional fact that ancient monuments tend to not incorporate asymmetric shapes, discontinuities and horizontal loads means that the resistance of the connections is only activated in the event of relative structural movement between two stones when the friction bond between them is overcome, which is normally the result of a dynamic excitation and not a static load. Connections would also be activated in case of foundation movement resulting from, for example, differential settlement. As a consequence, the structural function of connections remains unaltered regardless of the state of the monument; whether a monument is complete or in any degree of ruinous state is not significant in the steady state.

Experimental and numerical approaches have been pursued in the investigation effort of the behaviour of clamps and dowels, as well as that of their anchoring area. As these were part of the validation of design concepts and principles affected in the recent restoration project of the Parthenon, they are presented in more detail in the respective chapter.

As far as reinforcing elements are concerned, simple static analyses have shown that iron reinforcement members, when the geometry of the structure is intact, would have been loaded very near their elastic limit, up to a level that is usually avoided in modern structural design [30]. However, the vast majority of ruins suffer from collapses of their upper parts, resulting in a significant decrease in vertical gravity loading from self weight, which would mean that new iron elements would be stressed to a much smaller degree.

3.4.3 Dynamic Loading

Ancient Greek monuments tend to exhibit a certain degree of resistance against seismic loads in their intact form. Part of this resistance may be attributed to the iron connections between stones. Archaeological evidence testifies that temples with connections often fared better through the ages than temples without connections in seismic areas [30]. Experimental and numerical investigation of the contribution of connections to the seismic resistance properties of ancient monuments has only recently been attempted, while the behaviour of reinforcements in that regard has not been investigated at all. The effects of dynamic loading on ancient monuments is of particular significance to iron connecting elements for the reason that the response is highly non-linear [40]; residual displacements are practically always manifested, leading to the connections remaining deformed and stressed if not ruptured in the event.

The role of clamps in the seismic response of ancient monuments has been investigated by shaking table tests performed quite recently, in which scaled block masonry assemblages resembling parts of actual monuments were subjected to seismic excitation in order to assess their role, often as part of a wider parametric investigation [36]. These experiments have demonstrated that drum columns are structurally more stable and less sensitive to seismic parameter changes when connected with architraves. However, architraves are usually the part of the structure most prone to collapse, since anastylosis efforts don’t include the restoration of overlying members, in most cases. Therefore, the clamps in architraves are restored to increase safety in that regard. Indeed, the sliding of the architraves is significantly reduced by this restoration, resulting in smaller residual displacement. Clamping of the architraves may, however, increase the response of the drum columns. Overall, however, the performance of the assemblages is improved in terms of safety against collapse when clamping is implemented.

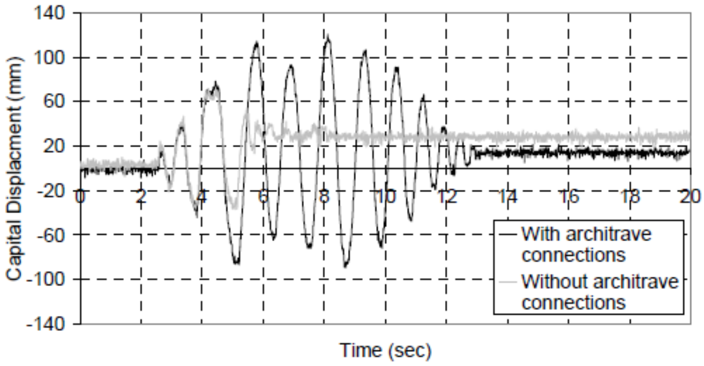


Figure 3.9: Experimental setup with clamped architraves and response comparison [36].

Numerical approaches utilizing both the Finite and Distinct Element Methods have been employed in several different occasions [34, 35, 37, 38, 39]. These either mainly focus on the overall effect of clamps and dowels in the earthquake resisting capacity of monuments and are, consequently, represented in a simplified manner, either as bilinear springs or as contributing to the cohesion of joints, which is initially null, in the mechanical model for friction. As far as clamped architraves connecting drum columns are concerned, similar results as in the experimental approach have been reached; failures are less probable when connections are utilized but an increase in the response of the column is probable. However, dowels between the architraves and the column capitals have no significant effect on the response. Yielding and rupture of clamps may occur in strong motion events, which, accompanied by residual displacements, can reduce the overall seismic resistance of the monument or assembly for future earthquakes.

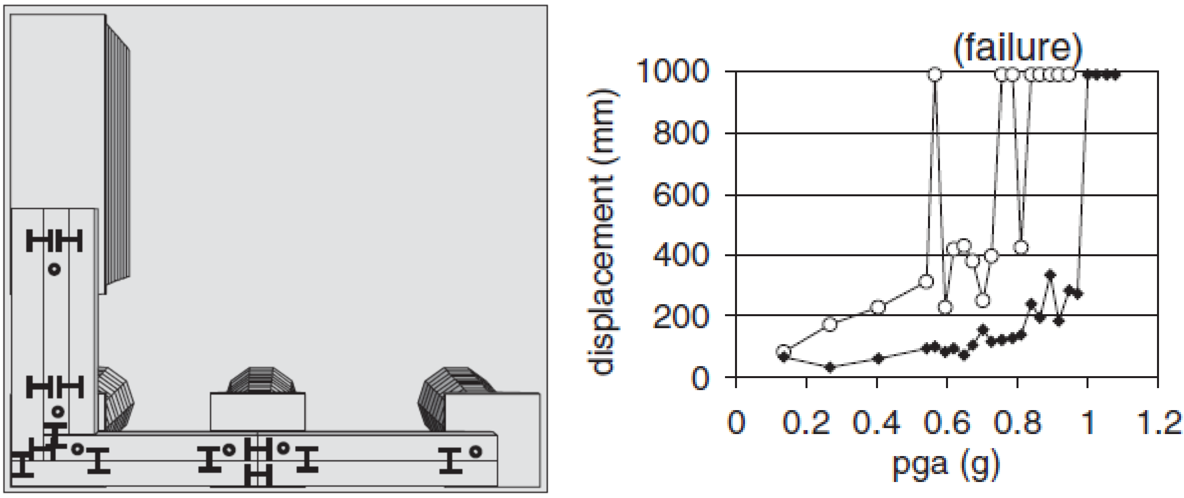


Figure 3.10: Model of clamped and doweled architraves and comparison of results between free and clamped architraves [39].

Free standing wall sub-assemblies exhibit a behaviour distinctly different to that of free standing drum columns. This discrepancy is owed to the geometry of the walls, which span in one plane, and the more thorough interlocking between stone walls, especially in wall systems of alternating header and stretcher courses. As a result, they respond to seismic loading by whole body out-of-plane rocking with only secondary relative sliding and rocking of individual stones or groups of stones. Opening of vertical joints is exceptionally small, forcing clamps to work, and possibly yield and fail, primarily in shear and remain virtually unstressed in tension. This is true even for the outer, unrestrained stones in the in-situ assembly. However, relative displacements between two consecutive stones in the same course are much smaller than those between stones in two consecutive courses [41]. Therefore, dowels are much more vulnerable than clamps in shear in wall structures, as can be also witnessed by documentation of damages in monuments. Similar conclusions have been reached from the analysis of complete walls, in which the wall architraves are again the most vulnerable part of the structure [35].

Despite the meticulous connection of wall stones with a variety of connecting elements, the mode of response of free standing walls is such that clamps and dowels complement the seismic resistance of the assembly to a very small degree, while parametric investigation has clearly illustrated that the response is more sensitive to other parameters, such as existing damage. While in some cases they may reduce residual displacements in the upper courses somewhat, maximum deformations are not decreased and the risk of collapse is not mitigated. By considering the contribution of dowels to the shear resistance of horizontal joints in walls as an equivalent cohesion value, equal to the strength of the dowel over the area it secures, in a Mohr-Coulomb friction model it can be concluded that the majority of the resistance is governed by the friction angle multiplied by the self weight of the overlying stones, except for the very upper courses [41].

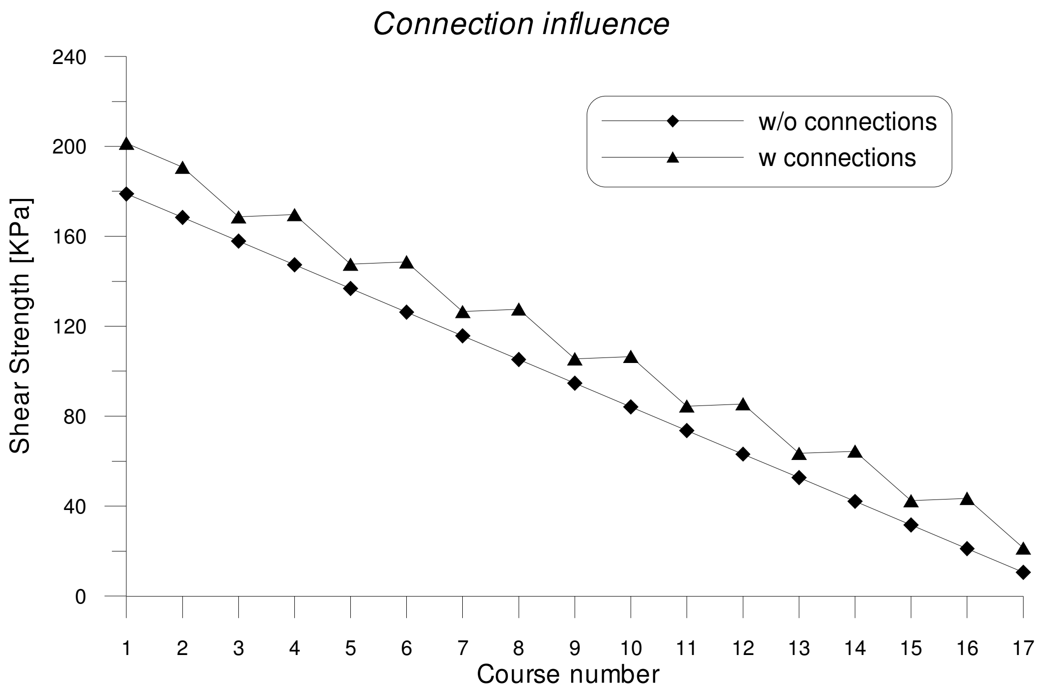


Figure 3.11: Equivalent shear strength contribution of dowels to the horizontal joints of the walls of the Parthenon [41].

3.4.4 Effect of Iron on Architecture

Structural iron in ancient Greek monuments can be associated with a number of architectural alterations that were otherwise either not possible or simply not attempted. It allowed for the spanning of larger distances between vertical supports by reducing weight or providing mid span support. It provided with a means of counteracting adverse conditions which might otherwise had made a structure unsafe. It relieved stresses from the stone, in the use of which ancient Greeks were quite timid. Finally, it allowed for a last minute reinforcement of a stone block in case of uncertainty concerning its structural integrity, which could spare the project from additional costs in mining, shaping and transportation of a new stone member. Therefore, it is not unusual that iron had become fully incorporated in ancient Greek monumental architecture by at least the classical era.

3.5 Iron as a Restoration Material in Ancient Monuments

3.5.1 General

Iron has been employed in restoration works carried out on ancient monuments in a wide variety of ways, some faithful to the original function of iron in the structure and others introducing iron in entirely new structural roles. It is clear that these methods could and have been applied not only in ancient monuments but also in neoclassical buildings or any other type of structure with structural components similar to ancient ones (drum columns, stone lintels etc).

3.5.2 Historical Applications

A widely applied restoration technique involving iron was the replacement of original connecting elements with new ones made of iron or steel, and has been in constant use since antiquity. Corrosion protection with lead was attempted in some instances, sometimes being replaced by the application of mortars of varying compositions. This restoration procedure often requires the repair of the original mortise or the carving of a new one. The longevity of this intervention in recent projects was extremely short (a few decades) because of the rapid corrosion damage these new members suffered, especially in monuments situated in marine climates and polluted atmospheric conditions. However, connections protected by cast lead exhibited noticeably greater durability.

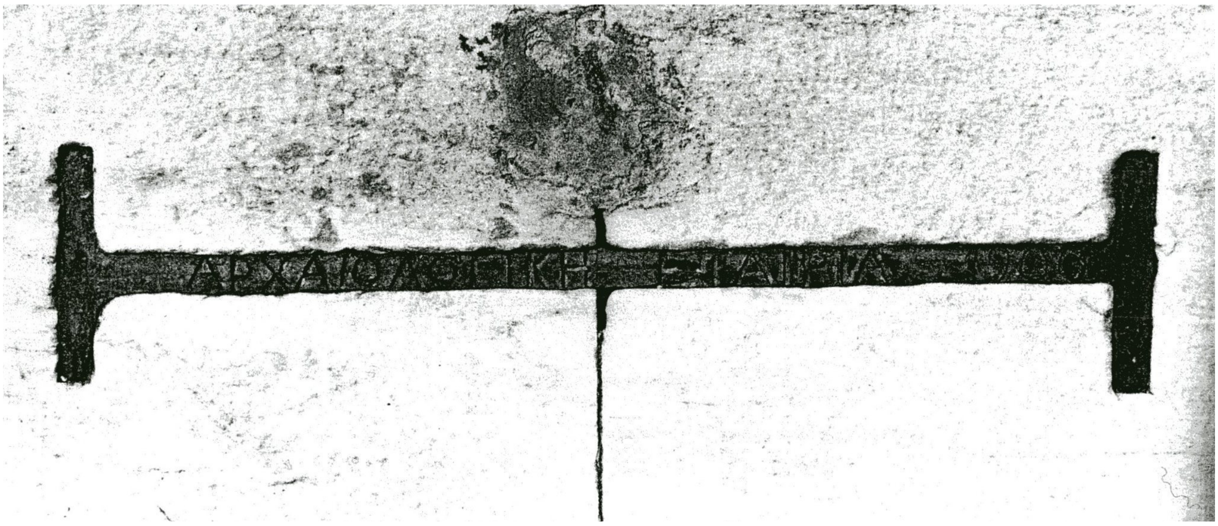


Figure 3.12: Iron clamp from 1900 with cast lead coating in the Parthenon [42].

The joining of fragmented stone members with both externally and internally anchored iron and steel rods to restore their integrity is a technique initially greeted with acceptance due to the confidence of engineers in the material and the construction methods associated with it. In some of the earliest applications, lime mortar was used to complete the member and supported to the stone with iron. Additionally, permanent external frames, straps or hidden beams made of iron and steel for the bracing, confinement, support or suspension of stone members, sometimes as a replacement of original reinforcement, when stability was a concern were also widely used. These members were sometimes covered by cement mortar for concealment, as was the case in some of the monuments in the Athens Acropolis. This method, possibly influenced by the discovery and study of original such members in structures and by the fact that it was one of the standard construction practices in late 19th

century masonry buildings, was introduced to ancient monuments with a great detriment in the long term, since not only structural authenticity was sacrificed but mainly because of the extent of corrosion damage caused by the added deteriorated members. Metallic frames can usually be dismantled and removed, but it may prove to be quite challenging and costly to extrude anchored rods from fragmented members.

Iron in the form of reinforced concrete bars was also extensively used in some reconstruction efforts since the early 20th century. Reinforced concrete blocks were used to replace missing members or complete partial ones. Some examples include the construction of missing drums in columns and beams replacing architraves. Faulty execution and poor compatibility between old and new materials and methods were the cause of significant damage to the monuments and the marring of their artistic value, usually in an irreversible manner. Despite that, reinforced concrete has been used in restoration projects carried out after the documentation of the damage in other monuments and the advent of the Venice Charter; an example is the temple of Zeus at Cyrene, Libya.

Figure 3.13: Steel frame (Erechtheum) and reinforced concrete (Zeus at Cyrene) in ancient monument restorations.

Finally, iron nails for the mechanical pinning of detached segments of stone, mostly from sculptures and other decorative elements of reduced structural importance, were used in large quantities in older restoration projects, not following the practice followed by, for example, fresco restorers, who shunned iron pins and preferred copper ones to avoid expansion due to corrosion.

Concerning many of the restoration methods involving iron that were introduced and applied in the late 19th and early 20th century, it should be noted that they were techniques developed over a period of time much shorter than that over which the ancient practices were developed and adjusted until proven by practical experience to be appropriate, as was illustrated in a previous segment. Assuming a stance of confidence in the capabilities of materials without prior verification led to significant structural deterioration and artistic value loss in many monuments.

3.5.3 Modern Applications

The damages caused by iron and steel in older restoration projects on ancient monuments demanded the introduction of new techniques and perhaps new materials to the anastylosis efforts. In fact, significant effort is spent in newer restorations to undo the damage caused by iron and to remove corroded and fractured iron members from stones.

Methods applied with the use of iron and steel, such as the joining of fragmented members with rods, mechanical pinning, replacement of connections, completion of partial members with new pieces were largely reinvented by the replacement of iron and steel by titanium in most cases and stainless steel in some. Propping with steel frames is still used, but not as a permanent solution. Finally, confinement with steel straps is sometimes utilized, but given the very low stresses developed in columns, especially if the superstructure is not reconstructed, the necessity for such an intervention is probably not justified.

4. PROPERTIES OF IRON

4.1 General

The subject of the properties of iron alloys is a well researched subject, even spreading to the field of historical structures, and is not a specific focus in this thesis. The following segment offers a general overview of the more significant properties of iron, focusing on those most relevant to civil engineering structures, but also presenting how these properties made them appropriate for historical structural applications.

4.2 Chemical, Physical and Mechanical Properties of Iron

Iron is the fourth most abundant element in the earth's crust, its abundance making it the most used metal, in civil construction or otherwise, constituting 95% of all metal used worldwide. It is element number 26 in the periodic table and some of its physical and chemical properties are as follows:

Table 4.1: Chemical and physical properties of pure iron.

Density	7.874 g/cm^3
Melting Point	1811 K
Magnetic Order	Ferromagnetic – 1043 K
Electrical Resistivity	96.1 nΩm
Thermal Conductivity	80.4 Wm^{-1}K^{-1}
Thermal Expansion	11.8 µm m^{-1} K^{-1}
Speed Of Sound	5120 m/s

Pure metallic iron is characterized by its high strength, relative softness and tendency to revert to its most common form, which is some type of iron oxide or carbonate like magnetite (Fe_3O_4), hematite (Fe_2O_3), goethite (FeO(OH)), limonite ($FeO(OH)\cdot nH_2O$) or siderite ($FeCO_3$). The elastic and strength properties of pure iron are presented in the following table:

Table 4.2: Elastic and mechanical properties of pure iron.

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

Figure 4.1: Iron ore hematite.

The most common contaminants in iron ore are silicon, phosphorus, aluminium and sulphur.

To bypass the natural shortcomings of pure iron, it is not used in its metallic form but in some type of alloy in which the chief contaminant is carbon. The chemical compositions of some types of commercially available iron are presented in the following table:

Table 4.3: Chemical composition of some forms of iron [72].

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	0.25-3.5
Carbon Steel	98.1-99.5	0.07-1.3	0.3-1.0	0.02-0.06	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 alloy. The following figure is 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.

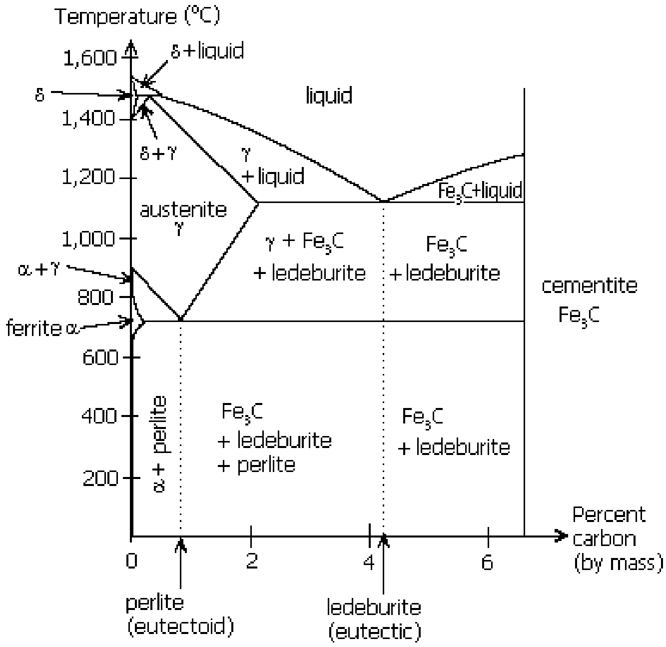


Figure 4.2: Equilibrium diagram for combinations of carbon in a solid solution of iron.

4.3 Wrought Iron

The properties of wrought iron are chiefly governed by its low carbon content and the slag inclusions in the alloy. Its main elastic properties depend on the time in history when the alloy was produced; newer alloys have superior strength properties. Although historical wrought iron specimens from the same time period will tend to be rather consistent in their strength characteristics, ductility will tend to fluctuate more widely, depending on the distribution of the ferrite matrix and the condition of the fibrous microstructure in the material. The number of workings which a wrought iron mass undergoes is an important factor in the final material properties; repeated workings decrease and distribute slag inclusions evenly, producing material of higher quality, but can also produce imperfections in complex shapes if the number of workings exceeds 6. Some typical property values of wrought iron alloys are presented in the following table:

Table 4.4: Elastic properties of wrought iron [73].

Ultimate Tensile Strength	234÷371 MPa
Ultimate Compression Strength	234÷372 MPa
Ultimate Shear Strength	193÷310 MPa
Yield Point	159÷221 MPa
Young's Modulus in Tension	193 GPa
Melting Point	1540 ^{0}C
Specific Gravity	7.8

Due to the forging process associated with the production of wrought iron, thin grains of impurities are formed within the alloy mass, especially when it undergoes treatment by faggoting. In this case, the resulting members exhibit a slight anisotropy, with strength across the grain being about 15% lower than that along the grain. The presence of the grains also introduces some anisotropic behaviour along their length; the compressive strength may be slightly lower than the tensile strength due to buckling of the grains when subjected to compression, in a manner similar to the behaviour of timber.

Wrought iron lacks the carbon content necessary for hardening through heat treatment, but in areas where steel was uncommon or unknown, tools were sometimes cold-worked (hence cold iron) in order to harden them. An advantage of its low carbon content is its excellent weldability compared to cast iron. Furthermore, sheet wrought iron cannot bend as much as steel sheet metal (when cold worked). Wrought iron can be cast with modern technology, however there is no engineering advantage as compared to cast iron; cast iron is much easier to produce and thus cheaper, so it is exclusively chosen over wrought iron for casting purposes.

Due to the variations in iron ore origin and iron manufacture, wrought iron can be inferior or superior in corrosion resistance compared to other iron alloys. There are many mechanisms behind this corrosion resistance. Chilton and Evans found that nickel enrichment bands reduce corrosion. They also found that in puddled and forged and piled the working over of the iron spread out copper, nickel and tin impurities, which produce electrochemical conditions that slow down corrosion. The slag inclusions have been shown to disperse corrosion into an even film to resist pitting but, at the same time, can act as pathways to corrosion. Other studies show that sulphur impurities in the wrought iron decrease corrosion resistance, but phosphorus increases corrosion resistance. Environments with a high concentration of chlorine ions also decrease wrought iron's corrosion resistance.

Wrought iron has a rough surface so it can hold platings and coatings better. For instance, a galvanic zinc finish is approximately 25÷40% thicker than the same finish on steel, thus further increasing its anti-corrosive advantages of the former over the latter.

4.4 Cast Iron

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 shapes alike. It also has excellent machinability, resistance to deformation, and wear resistance making it an engineering material with a wide range of applications, including pipes, machine and car parts, such as cylinder heads, blocks, and gearbox cases. It is resistant to destruction and weakening by oxidization and has good fire resistance, both major factors to be considered in its application. Finally, it has very high compressive strength, comparable to that of mild steel. It is easy and cheap to produce, its cost being a fraction of that of wrought iron or steel.

It has a low melting point of about 1200 ^{0}C or about 300 ^{0}C less than 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.

Several types of cast iron alloys are commercially available:

Grey Iron

The term “cast iron” itself usually refers to grey cast iron, or simply grey iron. It is an alloy of carbon, silicon, and iron, containing from 1.7 to 4.5% C and 1 to 3% Si. It includes some carbon in graphite flakes or nodules, which gives it energy absorption capabilities, made possible by the internal friction of the graphite flakes.

White Iron

White iron has a lower silicon content than that of grey iron and contains carbon in the form of cementite (Fe_3C) instead of graphite. This results in higher bulk hardness but lower toughness (resistance to fracture). White iron requires fast cooling rates, limiting the maximum size of cast members. It can also be produced with a chromium content, which allows for lower cooling rates, and therefore larger sizes, of cast members.

Malleable Iron

Malleable iron is essentially heat-treated white iron. The resulting material has properties similar to those of mild steel. At the same time, it has the member size limitations of white iron.

Ductile Iron

When minute quantities of magnesium or cerium are added to the alloy the result is ductile iron. Ductile iron has properties similar to those of malleable iron but without the cooling time limitations.

Table 4.5: Properties of cast iron varieties [45].

Type	Yield Strength [MPa]	Tensile Strength [MPa]	Brinell Hardness
Grey	-	170	180
White	-	170	450
Malleable	220	360	130
Ductile	365	480	170

Being characterized by high compressive strength and structurally insignificant tensile strength, cast iron was a reasonable alternative to masonry assemplages.

4.5 Steel

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

The hardness, strength and ductility of steel depend on the elements (carbon, chromium, manganese etc) and their percentile participation in the final alloy. Higher carbon contents produce 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 of stainless steel (about 18%). Contaminants like phosphorus and sulphur increase its brittleness requiring steps to be taken for their removal during production. The effect of carbon content in strength and hardness is given in the following figure:

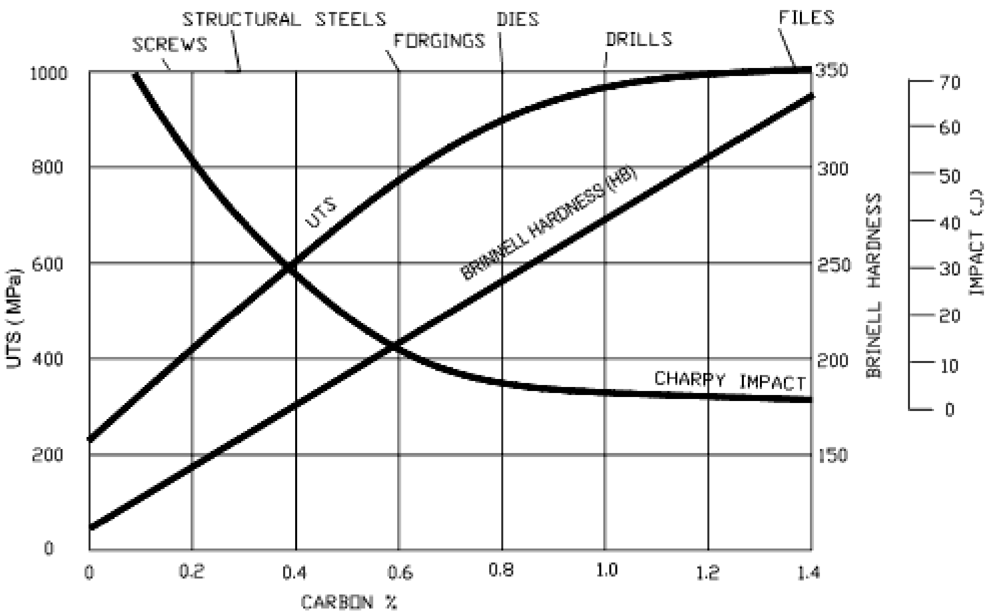


Figure 4.3: Carbon content's effect on steel properties.

It is evident that the technological capability of controlling the carbon content of the final product was and still is of prime importance in the steel industry. Control over chemical intricacies in the production is at least as important as the capability to mass produce, as exemplified by the eventual replacement of the Bessemer process by the open-hearth process.

5. MATERIAL IDENTIFICATION

5.1 General

One of the important issues during the investigation of an iron structure or tool is the determination of the alloy type of which it is made; wrought iron, cast iron or steel. In the case of civil construction, this issue is simplified some by taking into consideration the aforementioned information on the history of iron use. Being familiar with the basics of iron construction history, this determination can be made instantly with very small possibility of error. There are, however, exceptions to these rules.

The age of the structure is a strong indication of the possible alloy used; between 1800 and 1850 cast iron was the most used material, between 1850 and 1900 wrought iron was dominant and in subsequent years steel was practically the only alloy used for new structures. Knowing the time in which the structure was built offers a very strong indication which may even make further investigation unnecessary.

A second indication could be the geographic location of the structure under consideration. As has been mentioned earlier, cast iron use was favoured in Britain from the very start of the Industrial Age until well after the advent of more efficient wrought iron production techniques. At the same time, French engineers favoured wrought iron use for most applications as soon as it became widely available. Historical iron structures located in either of those two geographical locations, or locations where their particular technical practices were exported to, should be more easily identifiable due to the familiarity of forms and application techniques. Similarly, in many locations of the United States a technological jump occurred from timber directly to structural steel, especially in bridge engineering. Infrastructure buildings made of metal are probably made of steel in the North American continent.

In the case of systems containing more than one type of alloy the identification procedure becomes much more significant for the documentation of a historically significant structure. Combinations of two or even three different alloys was far from uncommon, as presented in previous segment, and correct preservation practice requires the identification of the structure and purpose of those mixed iron systems.

Figure 5.1: Upper chord pin-and-eyebar connection in an 1881 Whipple Phoenix Truss. The eyebars and compression sections are wrought iron, the joint blocks are gray cast iron, and the pins are wrought iron on the upper chord and steel on the lower chord [46].

5.2 Wrought Iron

5.2.1 General

Wrought iron identification can be performed, as with all alloys, with either visual inspection or instrumental methods, both destructive and non-destructive. Wrought iron can fairly easily be told apart from cast iron from the slenderness of the members, which are formed of riveted or sometimes heat welded iron plates. Cross-sections are usually symmetric across the main flexure axis, such as double-T sections. Wrought iron members exhibit material delamination and corrosion at the edges. One problem is identifying wrought iron from mild steel. Some observational and destructive methods of identification, including both traditional practices and modern techniques are presented in the following segment.

5.2.2 Spark Test

When ground with a high speed grinder, the carbon free portion of a wrought iron surface will throw long sparks with heavy heads and few branches. The test works by providing an approximation of the carbon content. It helps to have a set of samples of different iron alloys because spark test results may vary significantly in appearance depending on the speed, coarseness and press applied to the grinding wheel. Note that pure iron or very low carbon iron will spark the same as wrought iron. Some preparation and cleaning of the surface is necessary but apart from that it is a non-invasive process that can be applied in-situ [46].

Figure 5.2: Spark test pattern for wrought iron; long yellow streaks becoming leaf-like before expiring.

The spark test constitutes a very reliable identification practice that has been in constant use for a very long time, being applied in the identification of iron structures for the past 100 years. It is, therefore, not only a useful tool in the investigation of historical iron structures but also a historical practice worthy of preservation in itself as a technical method closely associated with the heritage of iron construction and application.

5.2.3 Breaking Test

This destructive test, otherwise known as the nick-break test, consists of extracting a specimen (for example a square bar, 1.5cm^2 sectional area), sawing about half way through and subjecting it to flexure until failure. The break will show the fibrous grains of wrought iron, similar to wood, to which the material's slight anisotropy is owed. The better the quality of the wrought, the finer the grains will be. A fresh fracture also shows a clear bluish colour with a highly silky lustre. In triple refined wrought iron it may be difficult to distinguish through this test. Extraction of specimens from critical areas of interest on a structure might be hazardous for structural safety [71].

The breaking test is another example of investigation method with a long history of application. The accumulated experience in this particular area, applied in a rationalized approach since at least as early as 1850, serves to make the breaking test an investigation method of some significance.

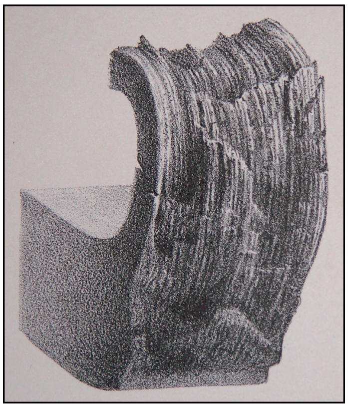


Figure 5.3: Wrought iron bar after breaking test [49].

5.2.4 Etching or Rust

Old rusted wrought iron clearly shows the grains and looks a lot like rotten wood. A heavy etch will do the same. Again, coarse wrought iron will be easier to distinguish than fine. It is, practically, a non-destructive test that can be applied in-situ. As a primarily visual method, it has been in application in civil construction since the need for wrought iron identification first arose.

5.2.5 Hardenability Test

Wrought iron does not harden when quenched. Even mild steel will quench hard enough to blunt a good centre punch. Note that low carbon steels require higher temperatures than the non-magnetic point to harden. The test requires a temperature of +300°F or an orange heat applied on extracted specimens and performed on appropriate facilities.

5.2.6 Forgeability Test

This requires experience but is potentially almost as reliable as the other tests. Experts can tell very low carbon steel from wrought and pure iron by the feel under the hammer. It is a historical method, largely obsolete.

5.2.7 Microstructure Investigation

Wrought iron can be identified by microscopic metallographic investigation; the ferrite matrix, the slag distributions and the near absence of pearlite help identify the alloy. It can be performed in the field [46].

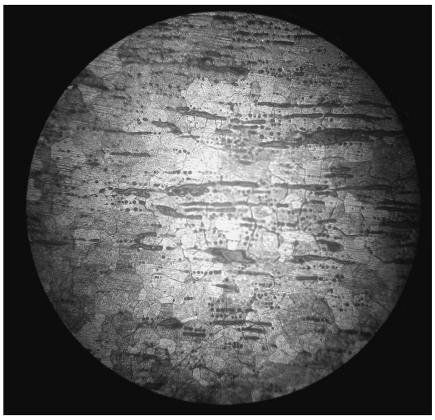


Figure 5.4: Wrought iron microstructure from in-situ investigation [46].

5.2.8 Chemical Analysis

By measuring the contaminants in an iron alloy, the material type can be determined. Modern chemical analysis methods can be effectively and accurately performed both in-situ on members and in the laboratory on very small samples. Wrought iron in particular can be identified by carbon content and slag inclusions. Additionally, phosphorus and sulphur inclusions will mostly fall within certain margins, depending on the age of the alloy. In-situ chemical analysis can be performed with specialized optical emission spectroscopy instruments [46].

5.3 Cast iron

5.3.1 General

Cast iron members are often easy to recognise by just visual inspection. This is because cast iron members are generally more massive than wrought iron or steel members and are arrayed to carry mainly compressive loads and not tension. Members subjected to bending moments, like beams, are usually of the non-symmetric shape proposed by Hodkinson and presented in a previous segment. They also typically have rough surfaces from the sand moulds they were cast in, have rounded internal corners and square external corners and are usually of a hollow round overall shape. Sometimes, blowholes, flashings, mould lines and casting flaws can be found in large members, serving as an indication of the alloy which can be traced back to the manufacturing process. Finally, casting tends to produce members of much more uniform appearance than wrought iron and the joints and connections are either carpentry or bolted joints.

Just like wrought iron, cast iron can be identified by instrumental investigation and testing. The type of cast iron used in construction is grey iron, making distinguishing from different types of cast iron after the preliminary identification unnecessary.

5.3.2 Spark Test

The spark test on grey iron surfaces produces small, repeating sparks of red to straw colour, noticeably shorter than those produced by wrought iron.

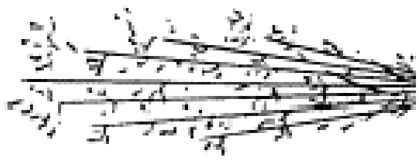


Figure 5.5: Spark test pattern for grey iron.

5.3.3 Breaking Test

The fracture surfaces of cast iron specimens are characterized by a dark grey to black colour, owed to the graphite content, with a clearly crystalline structure. The main developing crack is deflected by the graphitic flakes present in the alloy.

5.3.4 Microstructure Investigation

The crystalline structure of grey iron can be observed by field metallography methods.

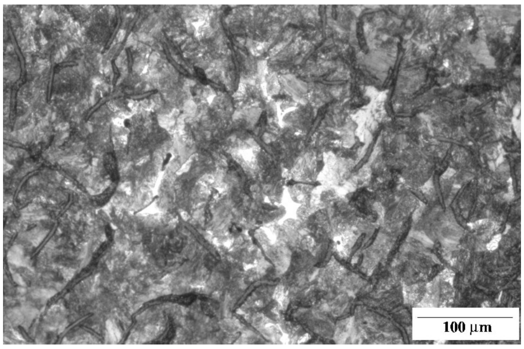


Figure 5.7: Crystalline structure of grey cast iron.

5.3.5 Chemical Analysis

Cast iron can be identified by its high carbon content. As an added characteristic, early European structural cast iron usually has a rather high percentage of silicon.

5.3.6 Hardness Testing

Cast iron, being characterized by very high hardness, can be identified by hardness testing methods, such as sclerometre investigation, which can be performed on in-situ members with a minimum of interference to the structure. Results cannot offer a positive identification but are, nevertheless, a strong indication of the type of alloy; cast iron will have a significantly higher hardness than wrought iron or mild steel.

5.4 Steel

5.4.1 General

Being much newer in conception and execution, structures made of steel are usually adequately documented and particular effort is not necessary to identify the material used. However, identifying steel from wrought iron in mixed iron systems, where steel was used for the construction of certain members, connections or inadequately documented strengthening interventions, might be an issue of some importance.

5.4.2 Spark test

The spark test pattern on mild steel is varied in the spark lengths produced, with small leaves and some fork-like sparking at the end.

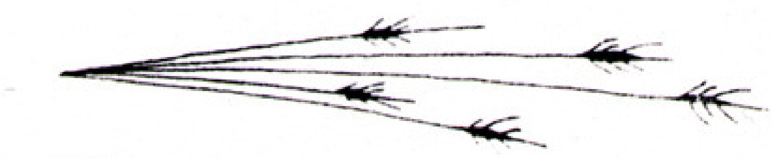


Figure 5.8: Spark test pattern for mild steel.

5.4.3 Breaking test

Steel bars subjected to the breaking test produce a smooth fracture surface, easily distinguishable from wrought iron's fibrous surface.

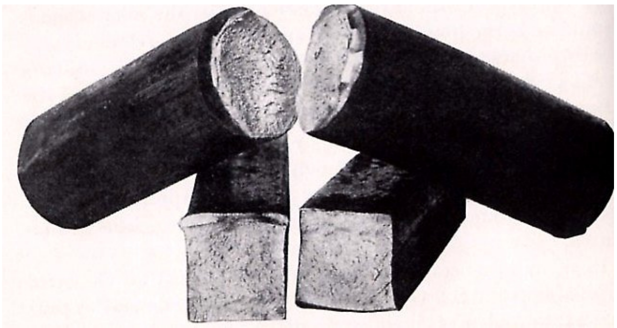


Figure 5.9: Steel bars after breaking test.

5.4.4 Microstructure Investigation

Field metallography on steel members reveals a combination of pearlite and ferrite structures. The fibrous structure that characterizes wrought iron is absent; steel is crystalline in structure and orthotropic in behaviour.

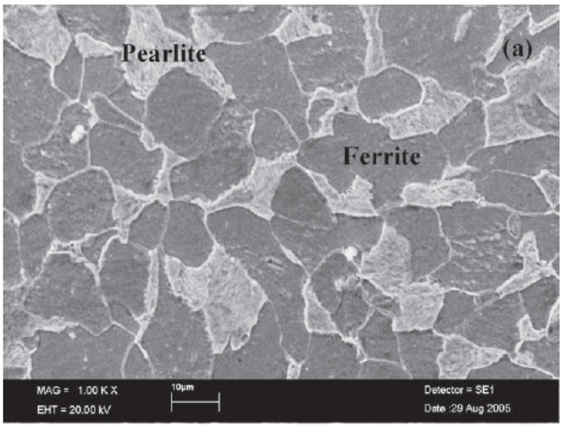


Figure 5.10: Microstructure of mild steel [48].

5.5.5 Chemical Analysis

Apart from the carbon content, the main contaminants of structural steel are manganese, sulphur and phosphorus. The carbon content is usually evidence enough to distinguish steel from wrought iron, but the absence of slag can also serve to identify the alloy.

6. DETERIORATION

6.1 General

As with most structural materials, the sources of iron pathology, both on the level of the material itself and that of individual members and the iron structure as a whole, can be identified and placed in one of several general categories:

- Mechanical: excessive loading, buckling, fatigue etc.
- Chemical: acid attack, alkaline attack etc.
- Electrochemical: corrosion.
- Physical: thermal variation, freeze-thaw cycles, fire etc.
- Inherent: material impurities, faulty structural arrangement etc.
- Biological: fouling, deposits etc.

In terms of percentage of affected material in a structure, electrochemical deterioration is the most prominent, followed by chemical and mechanical deterioration; corrosion affects all iron surfaces and propagates in depth. In terms of development speed, the mechanisms, from most to less rapid, are mechanical, chemical and electrochemical deterioration; mechanical failure occurs the instant the strength of the material is overcome. Finally, in terms of frequency, the mechanisms, from most to less frequent, are electrochemical, mechanical and chemical deterioration mechanisms; iron corrodes practically always in an effort to revert to its natural oxide form in which it is found in nature [50].

The peculiar characteristic of most of the deterioration mechanisms that affect iron microstructure is that they aggravate or act in combination with corrosion, making it the main source of damage in iron structures. This is especially true for historical iron, which has undergone the effects of various deterioration mechanisms over a long period of time, mostly unprotected or with inadequate and ill-conceived protection attempts.

In the following segments, a series of selected deterioration mechanisms relevant to historical iron structures is presented and analyzed.

6.2 Mechanical Deterioration

A significant problem of early cast iron structures is the poor fatigue behaviour of structures made of this specific material. This shortcoming was not initially fully understood by engineers and, coupled with its widespread application under pressure for the development of a railway infrastructure requiring large span bridges, it became a major technical issue drawing the attention of the era's designers and researchers. When stressed beyond its elastic limit repeatedly, cast iron will fracture and fail in a brittle manner. Wrought iron, although possessing satisfactory ductility and deformability capabilities, may develop brittle fractures under similar conditions of cyclic loading, originating from areas of stress concentration or geometrical defects in a member. These defects can be generally traced back to the fabrication and treatment process of the member. Brittle failures associated with fatigue in historical iron bridges subjected to modern road and railroad traffic loads is a matter of high importance from a technical, economical and historical standpoint.

Historical structures often suffer from structural movement, differential settlement, collapse mechanism development in arches and sagging. When iron connecting elements, such as ties, rings and dowels, are used, they may be stressed beyond their ultimate strength and fail, especially in the case of violent application of movement (earthquake or explosion). Ancient monuments in particular, with their low iron-stone ratio, meaning that large volumes of stone are connected with a small amount of iron reinforcement, are vulnerable to this sort of failure of their connecting elements. Loss of anchorage in masonry can also lead to brittle failure of members such as ties due to pull-out under tension, in which case not only the element itself is compromised, but also larger portions of the structure might be facing the hazard of collapse.

Mechanical failure is normally not associated with any changes in the material's chemical composition or properties, unlike most of the other deterioration mechanisms. They are usually not diffused, but rather concentrated on specific strained areas of the structure or member. Mechanical failure can be easily spotted, in most cases, with visual inspection, as it is associated with cracking and member continuity disruption.

6.3 Chemical and Electrochemical Deterioration

Of special interest in terms of structural importance and appearance frequency in historical iron structures are the process and the effects of corrosion, especially since it was shown that corrosion affects all iron alloys to some extent and causes chemical alterations, property changes and damage to a large percentage of the total material.

Iron is located low in the electromagnetic series, thus being susceptible to corrosion when in contact with water and oxygen or another more noble metal. Iron does not form a passivation layer like other metals do, but corrodes uniformly. Additionally, historical iron, being generally not homogeneous and having impurities and irregularities, which cause differences in the oxygen concentration in even small surfaces, iron may corrode even in the absence of water and oxygen. However, atmospheric corrosion remains the most common. Residual stresses and stress concentration due to inhomogeneity may be the cause for stress corrosion and, subsequently, brittle failure of iron in tension.

Corrosion may produce a number of different products, depending on the oxidation state of the iron in the affected alloy mass, which generally tend to cause an increase in volume of the corroded specimen. These may be identified by chemical analysis or, in some cases, visual inspection. The following table summarizes some facts about iron corrosion products.

Table 6.1: Most common iron corrosion products.

Formula	Colour	Oxidation State	Structure / comments
$Fe_2O_3.H_2O$ or $Fe(OH)_3$	red brown	Fe3+	Hematite
Fe_3O_4	black	Fe2+/3+	Magnetite/lodestone
$Fe(OH)_2$	blue/green	Fe2+	Soluble, the colour going from yellow to green and blue by changing the pH of the solution from acidic to very basic
FeO	black	Fe2+	Pyrophoric

The progress of iron corrosion can be monitored by measuring percentile weight loss of dated specimens. It has been suggested that iron corrosion rate follows a parabolic law, with the tendency of rate increase in more recent times. A study involving the investigation of extracted steel specimens from the restoration works on the Erechteion in the Athens acropolis performed by Pittakis (1837-1843) and Balanos (1898-1940) as well as rebars extracted from demolished reinforced concrete structures built in Athens during the 1950s clearly illustrates this rate increase, which may safely be attributed to the increase in atmospheric pollution due to the rapid industrialization of the Athens region. The pollution came to add to the severity of the area's marine environment [50].

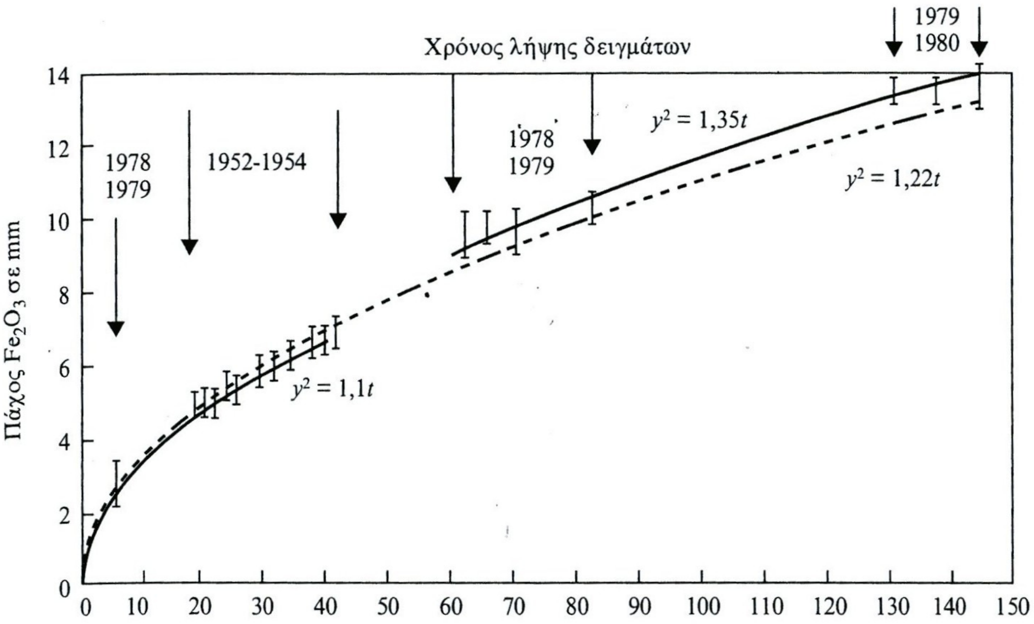


Figure 6.1: Iron corrosion rate in the Athens region; F_2O_3 depth in mm vs. specimen age [50].

Grey cast iron can be affected by graphitization. It is a form of anaerobic corrosion in acidic soils or seawater. Graphite, iron, silicon act as electrodes and the iron matrix is dissolved. Graphitization is not particularly common [71].

6.4 Biological Deterioration

Iron is susceptible to microbial attack, mainly from bacteria. These bacteria are mostly sulphate-reducing and require the absence of oxygen, therefore making the corrosion of iron in anaerobic conditions very likely. Metal sulphide deposits on an iron surface serve as an indication that bacterial corrosion is possibly in development. It can also be identified by its tendency to produce mainly needle-like corrosion. Additionally, deterioration similar to pitting corrosion may occur in cast iron members, in which selective leaching of the iron in the alloy results in there remaining a graphite matrix of low mechanical strength. Galvanic corrosion may be caused or aggravated by the deposits formed by some bacterial colonies [50].

6.5 Deterioration of Historical Materials due to the Presence of Iron

The nature of the deterioration mechanisms that characterize iron is such that it affects the structural integrity and historical fabric of its surrounding material. Several common deterioration types, especially in masonry, can be attributed to the presence of iron in a structure.

Corroded iron insertions in masonry assemblages cause several types of cracking patterns, their severity increasing accordingly with the level of corrosion, lack of expansion tolerance, difference between the thermal expansion coefficient between the iron and the surrounding masonry material and mechanical action applied on the element. Even externally situated bracing frames made of steel may prove to be a significant source of deterioration in masonry. Fractures in stones found in structures or statues can be caused by iron clamping members. Star cracking can be caused by perpendicularly inserted iron bars and nails. Bursting can be caused by corroded or deformed iron dowels, and is a very common failure in ancient monuments, especially those restored using poorly protected steel elements. It can also cause the opening of vertical joints. Finally, staining deposits of orange to dark red colour can form on surfaces where iron oxides are driven by rainwater from overlying corroded iron members and around their anchoring areas. This deterioration may be caused by both structural and non-structural elements, ties and gratings accordingly being two possible sources [80].

Historical timber members are commonly connected and reinforced with or braced by iron. Partially embedded iron fastenings can aggravate alkaline and acid attack on moist timber, resulting in loss of strength and hardness [79]. The moisture content in timber is a source of corrosion. Iron insertions, such as nails and straps, can cause cracking in timber with wide moisture content fluctuation. Iron connecting plates may trap moisture in the plate-timber interface, resulting in localized timber deterioration in sensitive locations, such as joints and supports [71].

Reinforced concrete deterioration, especially in the earliest applications, is strongly linked to rebar deterioration. Historical reinforced concrete buildings suffer from the effects of incomplete understanding of the composite material and poor design and execution (insufficient cover, buckling of compressed rebars etc.). Corrosion of the reinforcement has led up to its virtual disappearance in some cases and practically always to cracking of the surrounding concrete. These flaws severely reduce the longevity of historical reinforced concrete buildings.

7. INSPECTION

7.1 General

Information on a historical iron structure is drawn from a series of complementary procedures and approaches. The objective is to establish the desired level of knowledge regarding the history, function and condition of a structure as a whole and of its individual parts.

7.2 Historical Data

Sources of historical information, as in all types of historical structures, include: construction documents, material and construction/execution standards and construction contracts.

These are usually easily accessible to some degree in the case of iron structures and members due to various reasons:

- The high price of iron in antiquity and up to the technical revolution demanded that the production and supply of the material for any purpose, especially structural, had to be closely regulated and supervised. Historical studies have unearthed contracts on the production, delivery and cost of iron for building projects thousands of years old.
- The advent of all-iron structures coincides, as was illustrated before, with a rationalized approach to building engineering, necessitating the production of detailed drafts and construction details, and of building codes. Construction drafts, either those of the original structure or any possible interventions, might not be readily available, but building codes should be generally accessible. In any case, however, built reality may be quite different and should always be verified by in-situ measurements.
- Iron production was a highly specialized chemical procedure, the details of which are well documented; material properties are bound to fall within more clearly defined boundaries, compared to masonry materials, for a particular era. Information on the production processes employed by the suppliers of the material for a particular structure might be available. Additionally, material standards from a particular era might be obtainable without much effort.

Historical data alone cannot offer in-depth knowledge on specific issues, such as material properties and developing deterioration mechanisms. However, historical research in the investigation of historical data may yield important additional information, potentially more abundant and accurate than in the case of other historical structures for the reasons previously given, offering an important complement to any other investigation procedures to be undertaken.

7.3 Non-Destructive Investigation

7.3.1 General

Non-destructive investigation is an invaluable tool in estimating the condition and properties of an iron structure. The practically null invasion on the structure's integrity and historical fabric fall well within the approaches adopted and suggested by all contemporary charters on historical heritage conservation. The possibility of in-situ application and minimal necessity for result processing are major factors to be considered in the investigation process.

Most non-destructive methods are not suited to offering qualitative results. However, they constitute a necessary investigative step. Many of the following examples were derived historically not from concrete knowledge of the mechanical and strength properties of the material but from practical and observational experience, later solidified by scientific considerations and rationalized instrumentation methods. The same is true of many of the destructive testing methods to be presented in the following segment.

7.3.2 Visual Inspection

By use of simple and inexpensive instruments, such as a magnifying glass, a borescope and weld gauges, gross defects such as general member deterioration, excessive sagging or buckling, construction defects, cracking, corrosion and surface degradation can be easily and rapidly detected and documented. While it cannot detect internal defects, it is always the first investigation step on a historical structure, useful for a general structural condition assessment. Macro-etching, meaning the rudimentary preparation and polishing of the test surface, is required.

Visual inspection constitutes, in all probability, the earliest iron investigation method and, therefore, the most historically significant.

7.3.3 Percussion Test

Drawing from their influence from their familiarity with timber structures, as was presented earlier, engineers inspected early iron structures by striking members with small hammers, judging the soundness of the material and the integrity of joints by the produced sound and the feel under the hammer. Clearly, no qualitative results can be obtained by this method, but it is an oft applied supplement to visual investigation for the spotting of weak subsurface areas.

7.3.4 Spark Test

As indicated previously, the spark test can help identify the type of iron alloy used in the construction of a member. It's main function, however, is to estimate the carbon content, the parameter on which most of the alloy's strength and mechanical properties depend. With proper application, this method can estimate the carbon content with an accuracy of 0.1%.It is an investigation method of some historical significance but of declining popularity [78].

7.3.5 Microstructure Investigation

Microscopic investigation can be performed in-situ, with the only interference to the structure being micro-etching, meaning the polishing of a small surface with a very fine grit. The properties assessed, such as grain size, flaws and chemical composition can provide information on the strength and ductility capabilities of the alloy [46].

7.3.6 Acoustic and Ultrasonic Testing

By the emission and reception of ultrasonic waves (0.1÷25MHz) propagating through an iron mass, internal discontinuities can be detected. Internal voids, changes in density, lameral tearing, porosity, composition changes, inclusions etc reflect the waves or reduce their velocity through the medium, offering a qualitative condition overview of an iron member. The results can be quantified when compared to similar test results from an available database in order to estimate strength and hardness. The half-century of application experience in this area can provide invaluable assistance in that regard. It is inexpensive, fast, can provide in-depth readings but is difficult to perform on complex shapes or members with rough surfaces and the accuracy of the results is linked to the precision of the execution [76].

By the use of the acoustic tomography method, internal discontinuities can be more accurately mapped within the iron mass in terms of position and size. It is similar in principle to the ultrasonic emission method, but requires a large number of repetitions to be practically useful [71].

7.3.7 Radiography

The method works by emitting X-rays or γ-rays through an iron member with the purpose of detecting internal voids, undercutting, incomplete penetration in welds, changes in structure and other similar defects. It can also be useful for detecting the presence of iron members placed within masonry, concrete or timber structures [50]. It is a reliable testing method but the drawbacks include the potential health risks from the radiation, the high cost, the need to access two sides of the structure (one for emission and one for capturing the radiation) and the influence of the defect orientation on the detection process [71].

Iron members, such as ties and connections, can be inspected by the X-ray radiography method in an effort to reveal the morphology and depth of the corrosion of their surface, corroded iron masses being far more penetrable by the emitted radiation and clearly visible on the X-ray film [77].

7.3.8 Magnetic Particle Investigation

The magnetic particle method functions by measuring the magnetic susceptibility of an iron mass; defects disrupt the magnetic field of a ferromagnetic material by increasing magnetic resistance of the surrounding material. The magnetic particles are forced to follow longer routes than those dictated by the magnetic field lines to which the member is subjected. The method is easy and fast in its application and can provide qualitative results. However, a single reading may not detect all defects, depending on their orientation relative to that of the applied magnetic field, and its penetration depth is small [71].

7.3.9 Liquid Penetrant Method

A special liquid penetrant is applied on a specially prepared surface and enters any cracks through capillary action. The surface is subsequently wiped, leaving only the liquid that has penetrated in any possible cracks. The penetrant becomes visible when covered by a developing solution and shone on with black light. By this method any superficial defects, such as cracks, porosity and incomplete weld fusion are highlighted. It is usually applied as a complement to the magnetic particle method [71].

An early form of the liquid penetrant method was employed by railway workshops from the 1850s to the 1940s. In this method, a heavy oil commonly available in railway workshops was diluted with kerosene in large tanks so that locomotive parts such as wheels could be submerged. After removal and careful cleaning, the surface was then coated with a fine suspension of chalk in alcohol so that a white surface layer was formed once the alcohol had evaporated. The object was then vibrated by being struck with a hammer, causing the residual oil in any surface cracks to seep out and stain the white coating. This method was in use until the magnetic particle method was introduced and found to be more sensitive for ferromagnetic iron and steels.

7.3.10 Eddy Current Testing

An Eddy current (electron flow) is produced in and around a conductor when alternating current is applied to it and is induced to any other proximate conductor. The current is disrupted when discontinuities are present in the second conductor; the iron sample investigated. A detector coil is used to pick up any perturbations in the magnetic field. Higher frequencies of at most 8Hz are used for near-surface investigation and lower of at least 50Hz for more in-depth readings. It is a simple method of moderate cost, which may not, however, locate discontinuities of a certain orientation relative to the field [71].

7.3.11 Thermal Methods

These methods, infrared thermography being the most common, are not used to assess the condition of iron members, but rather as a means of locating iron members, like dowels or reinforcement bars in masonry assemblages and reinforced concrete members [71].

7.3.12 Electromagnetic Methods

The covermeter, which works by measuring the influence of rebars on a magnetic field, serves to locate the position and continuity/integrity of the reinforcement in concrete and masonry structures. Radar and GPS investigation can also be used for the same purpose, but also for measuring the chloride concentration in iron structures [71].

7.3.13 X-Ray Diffraction

XRD investigation can prove to be a use a useful tool for the characterization of historical iron. Requiring only minute quantities of material, too small for the extraction to prove structurally or artistically detrimental, both iron members and the iron ores from which they were created may be investigated in order to determine their chemical composition [71].

7.4 Destructive Investigation

7.4.1 General

The purpose of destructive testing is to offer, for the most part, qualitative direct results on the condition of iron structures, the obvious drawback being the interference with the fabric and, possibly, the safety of the structure. A further issue is the number and location of the tests performed; samples can only be extracted from selected area and are not necessarily representative of the entire structure. Historical iron structures, however, exhibit far greater homogeneity than, for example, masonry structures. There is also the additional issue of iron structures, especially wrought iron and steel bridges, that were dismantled, moved or strengthened with materials of unknown properties; destructive testing will not be indicative of the overall condition and behaviour of the material.

7.4.2 Hardness Testing

Hardness is the ability of the material to resist plastic deformation, such as the one caused by penetration. It can used to indirectly estimate the tensile strength of an iron alloy, an important parameter for the material. It is advantageous to express results in the Brinell scale, proposed in 1900, which is more closely related to strength characteristics, especially for steel. It can also assist in estimating the alloy’s ductility characteristics and homogeneity and to correlate the different members’ properties with one another in case of mixed alloy systems.

The test is portable, requiring simple hand-held equipment, and can be performed in-situ.

7.4.3 Chemical Testing

Chemical procedures are fairly common tests that are widely used for determining the exact chemical composition of iron alloys. Samples are obtained by drilling. Properties that can be assessed through this method are weldability (useful for intervention design), corrosion resistance and ductility, the last one being the property with the wider fluctuation in historical iron structures, and of particular importance in most modern structural design approaches. Chemical analysis is also a useful tool in the investigation of the composition and condition of old paint layers as well as the identification of the corrosion products in iron surfaces [46].

Modern portable spectrographs allow for this test to be performed in-situ.

7.4.4 Bend Testing

The test is performed by subjecting an extracted bar-shaped specimen to bend through a specified U-shaped arc. This test locates the direction of the grain in the specimen and also estimates its ductility. The results obtained from the bend test are not easily quantifiable and, given the wide dispersion of ductility in historical iron, cannot be generalized to the entire structure without considerable possibility for error.

7.4.5 Tension Testing

Tension testing constitutes the most common destructive test for the investigation of metals. Samples are extracted by flame cutting, machined in order to assume the desired shape and subjected to uni-axial tension. The parameters measured include the load-elongation curve, strength and percentile cross-section reduction (necking).

The variety of the strength characteristics obtained by this method includes the yield and ultimate strength as well as the ductile behaviour of the sampled material. Specialized laboratory equipment is required for the execution of the test.

Tension testing has a long history of application and has served engineers in the investigation of iron structures since 1824, when the first tensile testing machine was built. Further contributions to the equipment and material science made testing or iron a standard practice.

7.4.6 Impact Testing

Through impact testing, the toughness of an iron alloy can be estimated and, in turn, its resistance against brittle failure. The sample preparation is similar to that for the bending test (notched bar) but the deformation is applied rapidly by a heavy swinging pendulum, forcing it to bend and fracture at a high rate.

Instrumented impact testing with a swinging pendulum has existed since 1898. The concept, however, of impact testing has existed, in various forms, since 1824 as a means of determining the capacity of iron to withstand dynamic and impulsive loads. Initially, it was applied only on brittle materials, such as cast iron, in which crack initiation is easier, thus leading to fracture rather than bending of the specimen, which was usually a full member. Until 1895, which saw the advent of national standards for this type of test, impact testing was of a qualitative and comparative nature [66].

7.4.7 Residual Stress Testing

The residual stress test is a means of measuring the stresses present in an unloaded member. These stresses occur as a result of the manufacturing and assembly processes, such as casting, welding, machining, moulding or heat treatment. The importance of measuring these stresses lies in the fact that they are commonly associated with fatigue failures. The test is performed by drilling a hole in the investigated member on which's surface a set of three strain gauges have been properly arranged. The gauges measure the strains due to the relief of the stresses around the hole. From these strains, the principal stresses on the surface can be extracted [71].

8. REPAIR AND MAINTENANCE OF HISTORICAL IRON

8.1 General

The nature of the deterioration mechanisms of historical iron in structures is such that it requires constant maintenance and control. This is especially true of iron structures which are still part of a county's infrastructure, such as bridges. Since the investigation and maintenance of an existing structure is generally more economical than the design and construction of a new one, preservation and strengthening projects on iron structures are of considerable financial importance. Finally, the restoration of secondary iron elements, such as clamps, dowels and ties, in structures aims at the maintenance of structural safety as well as the preservation of historical fabric and authenticity of structural function.

8.2 Historical Repair and Maintenance

Before the technical revolution, the repair of iron members in structures mainly involved their removal and replacement, and then only of members that were accessible, meaning that embedded clamps and dowels were practically never restored unless in the case of structural collapse. Their secondary importance, from both a structural and, especially, architectural perspective, did not warrant a different approach. Tie rods and rings were not strengthened due to lack of technical capability, but rather were replaced by or supplemented with additional members in case of damage or if any evidence of structural inadequacy of the existing members arose.

Iron members were strengthened with cold repair methods, including straps, threaded studs screwed on both sides, dowels and pins, were a fairly common practice, especially since welding had not yet evolved into a practical solution. The compatibility of the old with the new material was not always sought in a rationalized way, resulting in significant chemical composition discrepancies in the alloys that may be found in a single restored structure or even alloys of different types, such as steel used in a wrought iron structure or wrought iron girders strengthening cast iron beams. Functional problems often arose due to the chemical and mechanical incompatibility of the materials used. For instance, cast iron discontinuities were sometimes repaired by pouring concrete. Shrinkage of the concrete leaves openings that, when filled with penetrating water, cause further corrosion [68].

The corrosion of ferrous alloys was always perceived as a serious problem. Four different methods of protection were traditionally used for the most part: painting, electroplating, the Bower-Barff method and cathodic protection. Exposed iron was covered by a coat of paint to protect it from corrosion and sources of chemical decay. Repair of defects in the coating was, and still is, standard practice in maintenance of iron members. Even so, most decisions on the type of paint to be applied were made on an aesthetic basis, except for critical structural components. Electroplating, involved the application of an alloy containing coating, usually copper or bronze, which formed a protective patina and was developed in the 1830s, although it was not available commercially until the 1870s. The Bower-Barff method involved the heating of members to bright red in contact with air and admitting a heated steam. This formed a protective layer of magnetite, which prevented further corrosion. The method was published in 1877. Finally, cathodic protection was first conceived and attempted in 1824, but iron was used as the sacrificial anode to protect copper in ships. While initially rejected by naval engineers, this application later found its way into the building industry as standard practice [67].

8.3 Modern Repair and Maintenance

8.3.1 Structural Maintenance

Modern structural restoration methods on historical iron structures focus more on repair and consolidation of existing members rather than replacement. Additional material is used to strengthen, prop, reinforce, tie and support the existing structure, necessitating only a very small degree of alteration to the original structural system. Reinforcing iron members of small size, such as clamps and dowels usually cannot be restored in this manner, requiring replacement by new members of the same material or a material compatible with the structure in question. The extraction of a large number of corroded or otherwise damaged clamps and dowels can provide a wealth of information on the material properties and its production methods, thus possibly revealing a more suitable restoration or protection approach, not requiring the radical dismantling of large structural assemblages. In any case, traditional materials and application techniques should be sought to be applied. Examples of possible materials include stainless steel, phosphor bronze or titanium, since corrosion is often the main deterioration factor.

Wrought iron members are normally restored using mild steel, since charcoal iron is no longer produced, making it scarce and usually not possessing the necessary properties. Welding may not be always feasible, since the high temperatures developed can lead to iron recrystallization. However, most wrought iron can be welded satisfactorily. Cold repair methods should be possible to be applied in most cases, regardless of the type of alloy, and they constitute standard practice when repairing sampled areas in an investigation project.

Figure 8.1: Cold repair of sampled bridge beam web with riveted plate [70].

Cast iron structures suffering from damaged, missing or corroded castings are usually repaired by recasting the same, or another compatible, material. Additionally, large cast iron members cannot be welded on site. Major cracks in cast iron members may be repaired by welding with nickelalloy welding rods [75].

Steel can be more easily repaired, since it is suitable to welding to a variety of other materials, such as stainless steel, and it is comparatively easy to find compatible restoration materials.

8.3.2 Chemical Protection

Modern methods of chemical protection of iron usually involve the application of a protective coating as a shield against corrosive agents in the environment. For the application of a coating the removal of older paint layers, deposits of soluble salts (ferrous sulphate and chloride) and surface corrosion is a necessary first step [74]. Flame treatment or hot air blowers are appropriate for wrought iron, since they only remove loose mill scale, while cast iron may be cleaned by more abrasive, mechanical methods like sandblasting, the high hardness of the material allowing such treatment. Chemical removal of the corrosion may also be employed, using acids or alkaline products, but is not recommended. The sacrificial layer usually contains iron oxide, zinc oxide and zinc phosphate as the inhibiting pigments in all coats, binders and the primer to be applied. It should be noted that the substances removed from iron surfaces and those used to coat them often constitute environmental and health hazards, a fact that should be taken into account when applying these methods [67].

Cathodic protection of iron works by attaching sacrificial anodes, such as zinc or aluminium, to iron members or by applying an electrical current. Cathodic protection is usually employed to complement the application of protective coatings, especially since a highly polluted atmosphere containing SO_2

may lead to rapid de-passivation of the zinc coating. As a general note, the aforementioned chemical protection methods are rather short-lived, lasting no more than 10 years, depending on the environmental conditions [50].

Figure 8.2: Aluminum anode on steel member.

9. CASE STUDY – THE PARTHENON

9.1 General Description of the Monument

9.1.1 General Layout

The Parthenon is composed of an architectural arrangement, the work of Iktinos and Kallikrates, unlike any other in Greek territory; an octostyle, peripteral Doric temple with Ionic architectural features. The maximum dimensions are (L×W×H): 72.32×33.69×19.80 and the structure were built between 447 and 438, with the sculptures being completed under Fedias' supervision in 432.

The temple is founded on the rigid rock of the Acropolis, a fact that contributed to the integrity of the building while in its complete form and to the survival of the standing superstructure in later times, after the undisrupted form was compromised.

The stone members were built exclusively of Pentelic marble and laid dry, relying on skilful joint construction, precise placement, a high friction coefficient and various iron connecting elements to ensure structural continuity.

9.1.2 Brief Historical Overview

According to historians, explorers and other observers from various eras, the Parthenon had withstood the passing of time with very little sign of alteration in its form and structural integrity. Apart from residual deformations due to earthquakes, all major alterations and damages to the monument were from man-induced actions which left it vulnerable to further deterioration.

The first major damage incident was the burning of the interior of the temple during a Heruli raid in 267AD. Apart from the damage caused to the connections themselves from the fore, damage to the stones and joints from heat fractures and cracking may have exposed a number of iron elements to atmospheric action, which was further aggravated by the fact that the roof had also been destroyed. Apart from the roof, several coffer slabs were destroyed, resulting in the loss of the structure's roof diaphragms and the loss of much of its monolithic structural character. The second, and most severe, damage incident was the setting off of the gunpowder stock kept in the monument from a cannonball fired on the structure during the siege of the Acropolis in 1687. The explosion caused major collapses and fracture of marble members in most parts of the building and caused the rupture, extruding, exposure and loss of a large number of connections. Damages to and weakening of the mortises were equally extensive.

Soon after the founding of the independent Greek state, the first restoration projects in the Parthenon commence (1834). Iron first became prominent in the restoration projects between 1898 and 1902, and remained as such until 1928. Galvanized steel was imported in large quantities from Switzerland and N. Balanos became the undisputable head of the structural restoration, even gaining independent initiative in all technical subjects from 1911 onwards. In between structural restoration projects, preservation and further documentation of the monument continue.

Earthquake damage was first effectively documented in the 1981 Athens earthquake, which caused significant movement of the marble members. These damages acted as an incentive to conclude documentation of the monument and compile the current architectural and structural restoration studies being implemented.

9.2 Description of Connecting Elements

9.2.1 Types and Geometry

Horizontal and vertical tensile connection was done by double-Ts, vertical shear connection with rectangular dowels and horizontal prestressed buttressing was done with inclined dowels. All types were lead protected except for the inclined dowels, which were of a temporary nature and not a strengthening measure to rely on in the long run.

Double-Ts' cross sections average between $3 \cdot 30mm^2$ and $5 \cdot 50mm^2$ at the web, an anchoring length of 0.12÷0.25m, flange width of 0.1m, flange thickness of 0.02m and are anchored at about 0.04÷0.06m of depth from the upper surface of the block. Dowels had a cross section of about $10 \cdot 50mm^2$ and a height of 0.12m. While dowels have more steady dimensions throughout the structure, double-T sizes tend to decrease in the upper courses of the structure, the larger ones being placed at the orthostate (lowest stretcher course of the walls) [51].

Figure 9.1: Clamp and dowel [57].

One additional type of horizontal connection was recently discovered in parts of the walls which consisted of a regular double-T member with its flange inclined towards the web like a pair of hooks. This provides a slight alteration of the normal anchoring method, by inducing a small degree of prestress to the element to augment anchoring, but not to the extent were fracture of the marble should occur before rupture of the iron [54].

Comparing the size of the mortises to that of, for example, the tensile reinforcement elements, it is observed that the iron was encased in lead of at least 10÷15 times greater volume. In the case of dowels this ratio is similar [51].

9.2.2 Layout and Placement

Connections, being delivered ready from the manufacturing facility under specified provisions, were very much of standard dimensions and arrayed in a mostly standardized fashion, especially in the walls, which are of a more repetitive structure. This standardization of the elements and their mortises, in terms of size, position and number per stone block, has proven to be a valuable instrument in the identification of the original position of displaced blocks. In fact, of the 10 quantifiable parameters for stone identification in the walls having to do with measured dimensions, 6 have to do with connections and mortises. Additionally, the placement procedure was also largely standardized allowing for rapid execution [51].

Tensile connections were generally positioned along the length of structural elements, especially those with sufficient interlocking and small slenderness of the stones, and not as a transversal bridging reinforcement. This layout is retained until the height of the architraves, which are composed of three independent segments and secured by a large number of transversal tensile connections. These connections bridge the gap between segments and despite this discontinuity in confinement in a mortise lead covers the entire clamp. Finally, diagonal connections were placed in the interlocking point of the orthostates, due to insufficient interlocking between the two parts. Dowels were arrayed so as to be stiff and resistant in the longitudinal direction. Exceptions to this general rule are the corner stones of the walls, which included dowels oriented in both directions to compensate for the lack of interlocking [51].

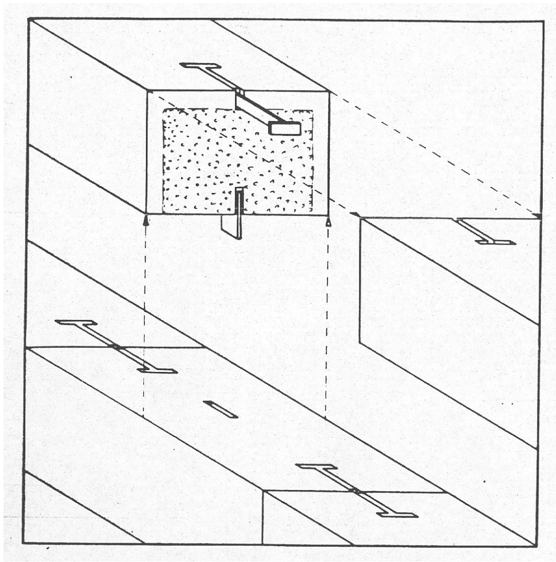


Figure 9.2: General arrangement of connections in a block [55].

Some marble structural components were placed without connections or dowels or neither. The drums in the columns contained no dowels between them or their foundation. The crepida contained connections at the four corners, unlike standard construction practice of the era, because of insufficient cover provided by the overlying stones; builders preferred not to place iron at all than to leave it exposed. The long walls were not connected by dowels to the underlying structure, which has resulted in the shift of a large portion of the North wall due to earthquake action and the explosion. The beams and coffer slabs over the East and West wings are unconnected and undoweled. The intention was to structurally separate the colonnade from the cella walls as much as possible, since giving a monolithic character to the entire structure was deemed impossible.

In the general case, connections were anchored in areas situated sufficiently away from the edges of the stone block so that when loaded with an excessive load the failure surface developed in the stone would be uninterrupted. For example, double-Ts under direct tension form a half conic frustum failure surface originating from the flange and developing towards the face of the stone, with an area around 200 times greater than the area of the connection's web. Elements with larger cross section also are of greater length and placed further from the edges of the stone to increase the area of the stone failure surface accordingly. It is evident that ancient builders sought to ensure that failure of the marble does not supersede that of the iron element. Assuming a 45^0 angle of the failure surface, connections should be at a distance of at least half their length from the edge.

In case any local discontinuities or weaknesses were discovered in a stone block, the mortise position was shifted somewhat in order for the failure surface to be developed in areas away from that weakness.

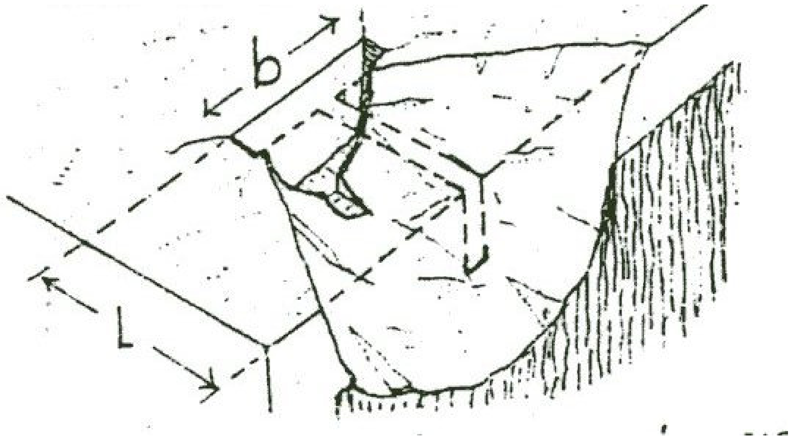


Figure 9.3: Tensile connection anchoring and stone failure surface.

Stone member joints were painstakingly carved, being the main source of shear resistance, a fact understood by ancient builders. Apart from providing high friction between stones, the quality of the workmanship ensured that the joints were sealed to such a degree that water, and sometimes even air, could not penetrate and aggravate the corrosion of the iron.

9.2.3 Investigation of Iron Elements

Documentation of the in-situ segments, past interventions and knowledge of the original form of the structure assist in determining whether any in-place iron element belongs to the original structure or is part of a later restoration effort. In the former case, it may be decided that further investigation of the element is warranted to verify its origin and to shed more light on the nature of the material.

When the existence or position of an iron element in a particular member needs to be verified, γ-radiation can be used to locate it, while at the same time assisting in spotting internal cracks and fracture lines in the marble. This method has been applied in locating previous restoration iron elements, whose position is not always known due to insufficient technical documentation of the projects.

The investigation procedure of an iron specimen usually consists of a number of standard steps and approaches. Initially, a small part of the element is immersed in resin to stabilize the loose corrosion products on the surface. Then, the immersed part is removed by cutting and polished and chemically treated to reveal the microstructure for microscopic investigation. Scanning electron microscopy is used to determine the exact type and depth of the corrosion products, which are then removed and analysed using X-ray diffraction. The chemical composition of the alloy is determined using mass spectrography methods, while the same sample can then be subjected to hardness testing. Finally, the microstructure may be investigated with optical or scanning electron microscopy [58].

9.2.4 Material Properties

The latest restoration project required the dismantling of a large number of stone members for proper reconstruction. This provided the restorers with a large number of connections (ancient and modern) for study. This made it possible for the mechanical properties of the material to be investigated and related to the direct iron production techniques of the era.

The structure of the original iron in clamps and dowels in the monument consists of layers of soft iron and hard steel of relatively high carbon content welded by forging in high temperatures, resulting in a highly non-homogeneous final material. The interior structure of the elements was discovered by sectioning them along their length and observing them macroscopically, revealing a single sheet of iron between two sheets of steel or visa versa.

Chemical analysis of the specimens revealed exceptionally small percentages of sulphur content, the highest measured value being 0.004%. This may have contributed to the very high corrosion resistance exhibited by these elements, which survived with very little sign corrosion even when exposed to atmospheric action after being extruded from their mortises and their protective lead coating. Interestingly, the Iron Pillar of Delhi contains less than 0.006% sulphur and has resisted corrosion in a very similar manner. Another significant chemical contaminant is phosphorus with 0.16% inclusion, a value very high for most Greek irons. This corroborates the theory that although probably processed in Laurium, the raw material was mined and imported from elsewhere. Laconia has been proposed as a possible source for the material. Finally, carbon content tends to fluctuate, even in the same element, around 0.7%, as do the results of hardness testing, which are directly linked to the carbon content [64].

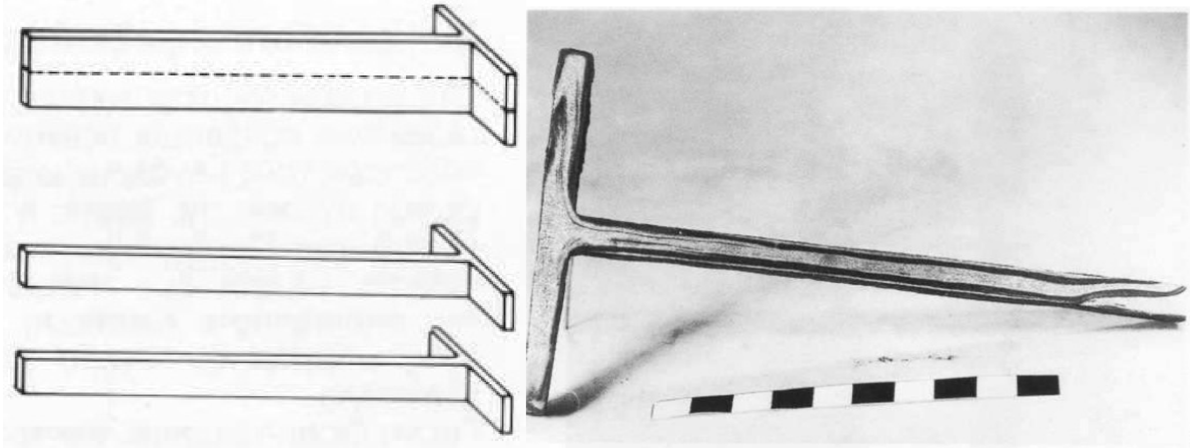


Figure 9.4: Section of ancient clamp; black strips are iron and white are steel [64].

9.2.5 Mechanical Properties

Connection specimens have been subjected to tensile testing. 7 samples were extracted and shaped as close as possible to the specifications of the ASTM E8-69 standard, yielding 2 test subjects per extracted connection. The results are given in the following table:

Table 9.1: Mechanical properties of connections' iron [52].

Mean Yield Strength	f_{sym}	265MPa (218÷356MPa)
Mean Ultimate Strength	f_{stm}	428MPa (335÷538MPa)
Characteristic Yield Strength	f_{syk}	200MPa
Characteristic Ultimate Strength	f_{stk}	360MPa
Mean Modulus of Elasticity	E_{sm}	220GPa
Ultimate Strain	ε_{um}	3.5÷22.5%

Yield and ultimate strength values had significant dispersion, but not so much as those for the ultimate strain. This wide variation of the properties is determined by the iron/steel sheet ratio and arrangement, the quality of the welding between plates, percentage of slag inclusions and deterioration state of the specimen. The ductility was governed mainly by microcracking of brittle areas of the specimens in the plastic region. It was observed that following the gradual rupture of the steel strips, elongation and necking of the iron parts took place.

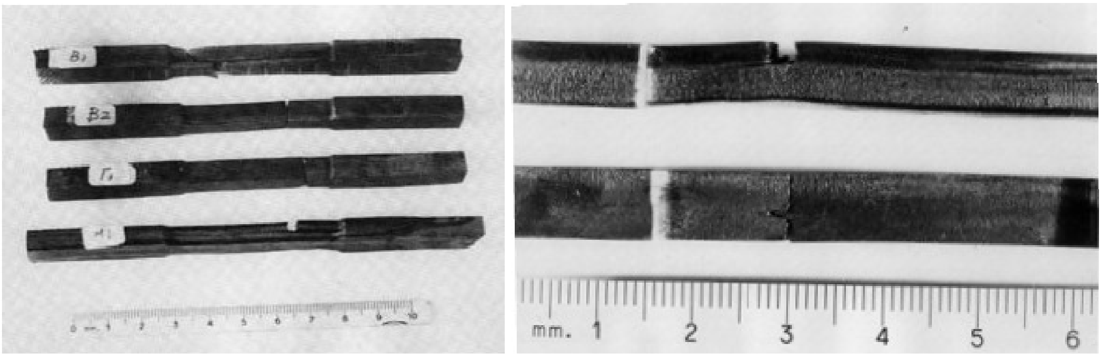


Figure 9.5: Iron members after tensile tests [59].

9.2.6 Structural Function and Importance of Connecting Elements

Iron connections were originally conceived as a supplement to the shear resistance of the joints provided by friction and would only come into effect after the friction bond was overtaken by an external load. Their role at that point would be to prevent small movement, something to which the marble blocks were also vulnerable in the incomplete state of the monument. The solid rock foundation prohibited differential settlement to a large degree, thus sparing the connections from a further source of mechanical strain in the steady state.

Although intended and shaped to function primarily in tension, double-Ts can and do carry significant shear forces. Indeed, in-situ findings, investigation of failed mortises and connections and numerical analyses have indicated towards a mostly shear function of the tensile connections. Dowels may also carry a small amount of tensile load (for example in case of uplift or rocking of the overlying member) assuming that they are sufficiently anchored by friction to the mortise by means of the lead protective coat.

Concerning the effect of the connections on structural performance during an earthquake incident, what was described in the previous chapter applies fully to the Parthenon; most of the test and analysis setups are based on the geometry of the Parthenon in the first place. In the monument's intact state, the thorough interlocking of the stones would have allowed for very little relative movement, thus reducing the amount of mechanical strain on and structural contribution of the connecting elements to the overall response. A matter still awaiting resolution is the contribution of connecting elements to the seismic resisting characteristics of wall structures with discontinuities: wedge shaped cut-offs, loss of bed joints, missing stones etc. This matter is of particular importance for the in-situ portions which will not be restored with new stone to fill in incomplete members.

As a final note on the perceived strength capabilities of iron in ancient monument architecture, when builders used clamps to bridge imperfections in members that were eventually deemed fit for use, they used a very large number of elements of significant size. The result is a reinforcement disproportionate to the loads it might be required to bear. When compared to the very small amount of iron used to secure stones in other structural elements, the contribution expected by builders of ordinary clamps and dowels to structural performance becomes uncertain.

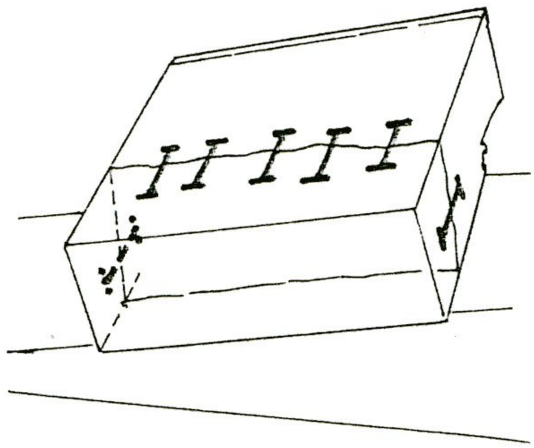


Figure 9.6: Bridging of discontinuity with iron clamps by ancient builders [51].

9.3 Pathology of Connecting Elements

9.3.1 Corrosion

Iron corrosion is a problem that affects both ancient and restoration iron, the later being the most vulnerable group. Ancient iron has exhibited substantial resistance to corrosion, even when exposed to environmental action for centuries; iron findings exposed for centuries were discovered to have a corrosion product thickness of 500μm to 2mm in a total member thickness of 6÷8mm and having a macroscopically good appearance. A significant part of this corrosion may be attributed to the very recent aggravation of atmospheric conditions in Athens due to pollution, meaning that ancient iron still protected in mortises should be in very good shape. However, corrosion remains a significant problem for iron and should be addressed as a continuous and developing phenomenon.

Restoration iron exhibited far worse corrosion behaviour, being of unsuitable chemical composition and poorly protected, despite being of superior strength and ductility. It is considered that 100% of restoration iron has corroded in all applications: new connections, bracing members and reinforcement bars in concrete.

Figure 9.7: Superficial corrosion of ancient iron clamp [58] and extensive corrosion of recent restoration iron clamps.

9.3.2 Forced Removal

A large number of connection elements was violently extruded from their mortises and subsequently lost in the explosion of 1687. Following the explosion and until the 1830s, iron members were systematically removed from their mortises (revealed by detonated gunpowder charges) for the iron itself, but mostly for the lead for ammunition casting, since the Acropolis still functioned as a fort. This has led in loss or fracture of elements and the carving of the mortises to the point where they no longer can function as originally intended, especially in the segments that did not collapse. This is a failure type exclusively associated with historical members.

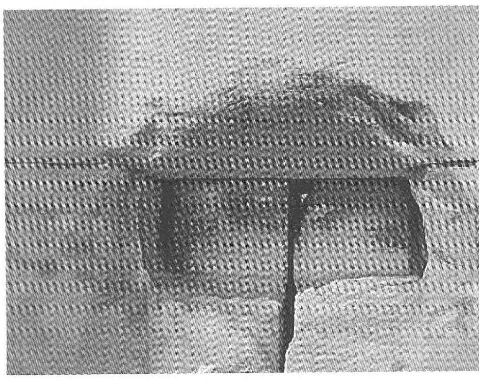


Figure 9.8: Carved dowel mortise for extraction of iron and lead.

9.3.3 Mechanical Failure

Rupture of connecting elements clearly renders them structurally inactive and requiring replacement. Many ruptures of clamps and dowels were caused by the 1687 explosion, during which the surrounding stone was not particularly affected. It affected historical iron and is a possible hazard for both original and new connections in case of future strong seismic events. Uneven loading due to changes in geometry, such as missing segments, may lead to yielding and rupture.

9.3.4 Stone Pathology due to Connecting Elements

The theory postulated concerning the dimensioning of the ancient connections so that failures do not happen in the mortise seems to agree to a large extent with the documented damage from the 1687 explosion; double-Ts ruptured in tension, dowels were sheared or extruded and the mortises survived with only a small degree of exfoliation of the surrounding marble. Damage to the surrounding stone has been mainly attributed to corrosion expansion. However, while largely true for clamps in tension, this explanation may not be adequate to interpret all damages.

Anchoring area damage accounts for the majority of stone pathology due to iron in the monument (more than 90% of total documented damage). Additionally, documentation of anchoring area damage has indicated failures in 41% of dowel anchoring areas and 28% in clamp anchoring areas (both in shear). Damages are of a similar repetitive nature for all blocks, thus excluding direct human involvement in the deterioration. Furthermore, the corrosion level of most ancient connections is very low. Finally, corrosion expansion usually causes exfoliation on one side of the stone, rather than two, as has been the case with most such damages in the Parthenon [61].

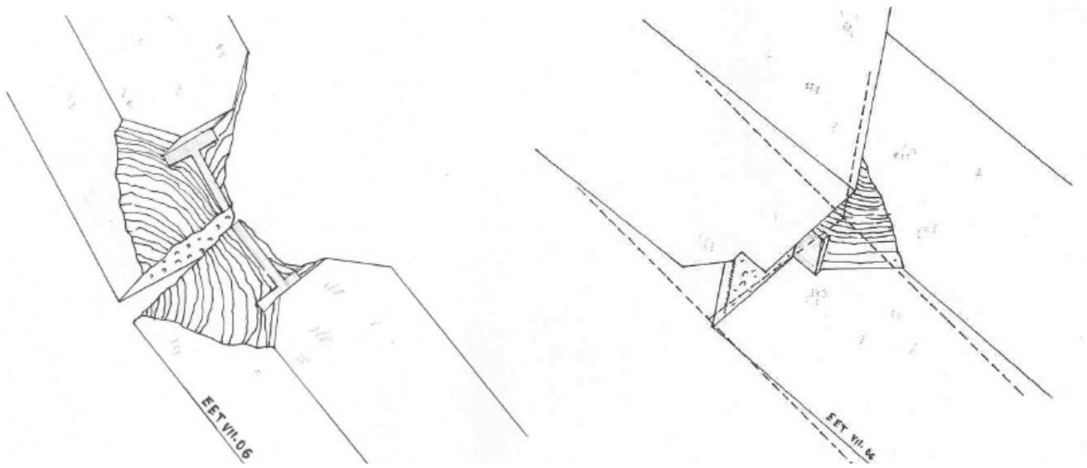


Figure 9.9: Typical detachment failures due to shear action of clamps and dowels [61].

The above statements indicate towards a detrimental effect of connections subjected to shear on the surrounding stone. The structural movements necessary for such failures may have been allowed following the loss of the roof diaphragms and the subsequent loss of monolithicity under seismic action. Dowels seem to be the most prominent source of deterioration, especially since numerical analysis has shown that stones in the same course tend to move in groups under seismic loads, as opposed to stones in consecutive courses, where relative displacements are greater. In any case, corrosion expansion may not be a necessary condition for failure.

Finally, corroded rebars in reinforced concrete members and stone completion parts have resulted in damage to the concrete itself and the exposure of the reinforcement but also to the damage of nearby marble. This is especially true of completions whose rebars were inserted in original marble for anchoring, causing in both internal damage and surface deterioration. The exposed rebars have also caused rust coloration of nearby stone, an alteration associated with newer iron connections of all types as well.

9.4 Restoration of Iron Elements

9.4.1 Historical Restorations

The first restoration of the iron elements was done 100 years after the Heruli raid by the Byzantine emperor Julian. Archaeological findings indicate that the mortises and lead casting channels were hastily carved and the reconstruction was executed according to the economical and technical conditions of the era, which were rather unfavourable when compared to the ancient approach. Iron from that restoration has not survived for study [54].

19th and early 20th century restorations attempted to fully restore those connecting elements that could be replaced. The new connections were in part attempts at adopting ancient methods or new solutions. The ancient adopted methods consisted of the placement of Π-shaped clamps or double-Ts completely or partially covered with cement mortar or, more rarely, cast lead in original repaired or sound mortises or in new mortises carved in the vicinity of the old. This application was considered entirely faithful to the original construction practices and the character of the monument, despite being different in several key points: the cross-sections were significantly larger (the lead/iron ratio was nowhere near the ancient ratio presented above), placement was often poor and the stone joints were not as shut as in the original arrangement [42].

9.4.2 Modern Restorations

The restoration of the connecting elements is no longer executed with iron, but with titanium protected by Portland cement mortar with silica sand. The steps of the current restoration efforts involving connections are the removal of corroded restoration iron, abrasive cleaning of the mortise, chemical removal of rust stains from the surrounding stone, dismantling, repositioning and placement of the new connections. Original mortises are utilized as much as possible, with the carving of new ones being avoided as much as possible; if the mortise is damaged Π-shaped clamps of circular cross section are used which are anchored by means of the drilling of two holes for that purpose. This anchoring method is sometimes also used in double-Ts if one edge of the mortise is intact and one is damaged [56].

The Ultimate State Design method was adopted for the design of the new connections. Unacceptable failures linked to the connections are the rupture of the marble at the anchoring area and large relative displacements resulting in an unstable state. In case of a severe earthquake, acceptable failures concerning the connections are the opening of joints without connection rupture and small relative displacements of stone members. These criteria were compiled considering the architectural and artistic features of the monument as being of greater importance than the preservation of the connections, whose artistic value is null, and also by documenting damages that have proven to be structurally acceptable (non-threatening to the structure's character and safety) [56].

The above conditions are met by appropriate design of the clamps in tension, of which the length is given and the rest of the dimensions are derived from calculation based on the anchoring area size. The loads assumed for every member are known, being confined to the self weight of the overlying stones to be placed according to the restoration plan. The head of the clamp is strengthened and the web is weakened, so that yielding and deformation occurs in the body and not in the anchorage area of the element. These clamps have exhibited significant capacity for plastic deformation, thus ensuring structural function after opening of the joint. For the design of clamps and dowels in shear, the element size is derived from the anchoring area size and deformability is offered by a relieving gap in the mortise, which is not filled with mortar. However, shear connections tend to fail by brittle marble fracture in the majority, if not all, of the cases [52].

The behaviour of the connections as specified in the proposed design criteria was verified in experimental investigation. These experiments revealed the plastic capabilities of titanium in the case of the opening of joints (failure elongation is greater than any documented vertical joint opening), the adequacy of the design approach (connections fail before marble), the null influence of the mortise filling material (cement or lead) on the structural behaviour of the connection and the brittle failure of the marble when the connections are loaded in shear [52].

Figure 9.10: Titanium restoration clamps (photo A. Drougas).

Replacement of the titanium connections in case of failure or possible incompatibility is a simple process, relatively harmless to the surrounding stone. Therefore, practically full reversibility is an advantage of this sort of restoration, in compliance with modern restoration theory.

9.5 Restorations Using Iron

9.5.1 Historical Restorations

One of the first restoration efforts involving iron was the completion of stone members damaged in the Heruli raid with lime mortar secured on the in-situ part with iron bars. By most accounts it was a hasty and ill-executed restoration, of which very little remains [54].

The restorations of the 19^{th} and early 20^{th} century made heavy use of iron for the connection of fragmented members with embedded rods and anchored clamps and in reinforced concrete for incomplete stone member completion. Π-shaped and double-T clamps in new mortises externally bonded with no or very little lead protection at the insertion points alone were very widely used. These clamps were of large cross section and length, often visible and rather unsubtle compared to ancient practice.

Mechanical pinning of exfoliated parts, mostly of a decorative rather than a structural nature, using small iron pins were used throughout the restoration history of the monument.

Figure 9.11: Recent restorations with external clamps and reinforced concrete (photos A. Drougas).

9.5.2 Modern Restorations

Iron and steel are no longer used for any structural elements in the restoration projects of the Parthenon. In fact, a significant part of the current restoration project is to remove iron and halt the deterioration processes related to them. They have been replaced by the more expensive but also far more compatible titanium for all applications. Stainless steel could had been an alternative and was proposed as such, but the area's marine environmental conditions, containing Cl^-, does not allow its use, since it corrodes 30 times faster than titanium in these conditions and tends to fail in a brittle manner due to stress corrosion. Additionally, steel protected by cast lead was also not used because, although very similar to the ancient practice, the lead would lose its passivation layer under the effects of acid rain freely pouring through the roofless structure [50].

10. CONCLUSIONS

10.1 General Conclusions on Construction

Iron in historical construction from antiquity to the technical revolution has always been associated with innovation and experimentation, either as a complementary reinforcement means or as a primary structural component. It is associated with the rapid surpassing of all structural milestones in terms of span or height

Due to the character of iron pathology, mainly its rapid corrosion, the longevity and robustness of structures incorporating iron as an original part is directly influenced by the a few key factors: application experience in similar typologies and the rationalization of the approach adopted during the design and execution phase. This applies to ancient practices and modern methods alike.

The historical iron typologies that still survive and offer evidence of their existence and structural function are, as a rule, those that where the result of a lengthy development process, through trial and error and study of the shortcomings of the material. For example, clamping and doweling in ancient Greek monuments was applied in such a way that corrosion was not a particularly major issue, making iron a near universal part of major buildings. Similarly, historical iron architecture and elements of inadequate design and faulty execution due to poor understanding have not survived or are in need of constant maintenance, unlike the experience and workmanship that created, for example, the Iron Pillar of Delhi.

When in later times, such as late Middle Age Europe, iron production saw a rise in output, designers were quick to incorporate it in major architectural works. However, enthusiasm in the material was never greater than immediately following the onset of the Industrial Revolution; confidence in conjunction with lack of application experience and knowledge of the material (practical knowledge actually acquired in, but not passed down from, antiquity) sometimes led to impressive but ultimately flawed achievements, such as the Paris Pantheon. In any case, the advances in construction engineering associated with or spurred on by the demands involved with iron structures were eventually of great benefit to all facets of civil engineering works which were slower to incorporate progress in design, analysis and execution; traditional rules and methods were still employed for the design of masonry, for example, until its substitution by reinforced concrete.

Finally, general knowledge of the development of iron use in construction is a necessary requirement for restoration projects, since it provides an understanding of the successful applications and the pathology of the unsuccessful ones.

10.2 General Conclusions or Restoration

Depending on the purpose of the structure and the typology of the iron implements employed in it, different restoration approaches are necessary. In any case,

Ancient monuments and buildings incorporating iron as a reinforcement means require a comprehensive approach in order to fully understand their structural role in the fabric, which is not always completely known, especially since the intended purpose and the actual effect of iron do not always coincide. Extracted specimens, which are quite common due to the attempts to halt the detrimental process of corrosion, can provide a wealth of insight in the properties of the material and its production methods and should be approached first and foremost through chemical material identification methods. Since their reintroduction to the fabric is usually not an option, and since their artistic value is often quite limited, chemical investigation can reveal the most appropriate and compatible material for their replacement; titanium and FRP are currently the most usual choices, since practical experience has yet to reveal any compatibility problems they may be responsible for.

Industrial and infrastructure heritage structures built in iron warrant a maintenance approach based on capacity and viability assessment to verify their compliance with ever increasing demands. Material identification may be necessary, especially in case undocumented interventions have been performed in the past. Sampling to verify ductility primarily and strength secondarily is often necessary, while cold repair methods to undo the damage from sampling and to provide the necessary strengthening constitute an acceptable interference with the structure's fabric. Many of the necessary parameters can be obtained by in-situ inspection methods, which can be of great benefit in terms of cost and time, corroborating the notion that repair strengthening of infrastructure is generally more economical than complete substitution.

10.3 Recommendations on the Restoration of the Parthenon Connections

Critical errors in restorations of ancient monuments incorporating iron have been committed until quite recently, the restorations on the Athens Parthenon of the 19th and early 20th century being a prime example of compromised artistic value due to improper use of the material, going against ancient practices apparent in the structure itself. The compatibility issues of unprotected iron with ancient stone masonry were successfully diagnosed. The same cannot be said, however, of the structural intricacies and the effect of the connections on the structural behaviour of the structure.

Despite the fact that contemporary designers are equipped with extensive knowledge of material science and structural analysis techniques as well as the modern theoretical guidelines to apply them to restoration practice to full effect, the current reconstruction project on the Parthenon suffers from a number of deficits as far the restoration of iron elements is concerned. The design approach generally adopted is that of Ultimate State design with a list of acceptable and unacceptable failures compiled but without prior safety level assessment for the structure. Given the probabilistic nature of modern earthquake design of structures, earthquake being the main structural hazard in the area, it poses as a candidate issue for reconsideration. The intervention proposal (replacement of all accessible connections) took into account qualitative criteria for the cause and effect of documented failures, largely bypassing the quantitative assessment step before the design step. Additionally, owing to computational difficulties at the time when the interventions were proposed, the effect of the connections was studied on a local level rather than on the structure as a whole; calculating their behaviour as it affects individual members but not on the dynamic response of the structure. In essence, the structural necessity of the connections for the structure to withstand earthquake action was not verified, unlike the case of the Barcelona Cathedral for example. Despite having acquired in the meantime the computational tools necessary for the job and furthering the understanding of the structural behaviour of the connections, sometimes disproving the adequacy of the design criteria adopted for the new members, the restoration projects continue largely unaltered.

As far as structural authenticity is concerned, it has been proposed that replacement of the damaged connections with new ones in the monument's ruinous state contributes to the partial restoration of the monolithic character of the structure. However, the behaviour of the structure in its intact state and in its present condition are radically different; the connecting elements are responsible for many of the structural damages suffered by the damage following the explosion of 1687, when structural integrity was compromised, therefore making the goal of restoring their originally intended structural purpose, as perceived by restorers, by their replacement not realistic. In fact, it may serve to perpetuate those deterioration mechanisms it aims to remedy. Furthermore, loss of the connecting elements does not necessarily constitute loss of architectural fabric, since they were intended by ancient builders to be invisible to observers. This was not taken into account in a reconstruction approach otherwise heavily involved in restoring the original form to the highest attainable degree.

In conclusion, although addressing compatibility issues raised by previous restorations with the choice of a new material (the lessons of faulty previous applications have been thoroughly studied and titanium is a sensible choice both in compatibility terms and mechanical terms since it is much more ductile than FRP), the structural design approach for the connecting elements suffers both on a local level as well as on the structure as a whole; marble still fails before the connection in shear (the main, if not only, structural deformation according to experimental and numerical investigation) and the beneficial effects for earthquake resistance in the structure's current state have yet to be verified for all member and assembly typologies. Therefore, the monument is under danger of further irreversible structural deterioration by an intervention of unproven efficiency. A rethinking of the design approach in terms of philosophy, intended goals, calculation and execution is necessary, possibly leading to the modification of the restoration method concerning connecting elements. This may require the postponing of the project until a new design approach is compiled based on the latest pieces of technical information on the subject and the result may range from the use of even smaller connecting elements, thus reducing their already minor structural contribution to an even lower level, to the abandonment of their replacement altogether in some structural assemblages, such as walls. Alterations in the reconstruction practice developed over a significant amount of time with much dedication and that has been in effect for several years is bound to face several difficulties and obstacles, but scientific evidence indicates that it is a matter that warrants special attention.

As far as the iron (ancient and recent) already present in the structure, the project has assumed a very effective approach. Restoration of the form of the structure by dismantling erroneously placed stones makes corroded intervention iron accessible for removal, thus halting the deterioration process in those locations. As far as newer iron located in correctly placed stones, which are not scheduled to be dismantled, it is highly recommended to regularly inspect the stone for any sign of cracking. Ancient iron has largely resisted corrosion, making its removal unnecessary, especially since it is usually located in the lower courses of stone assemblies where shear deformation is limited and the hazard of stone failure because of it smaller. Therefore, not dismantling original in-situ portions appears to be an appropriate choice.

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