ADVANCED MASTERS IN STRUCTURAL ANALYSIS
OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

Master's Thesis

Hui-Yin Lee

INVESTIGATION ON THE USE OF IRON AND STEEL FOR RESTORATION PURPOSES DURING 19TH AND 20TH CENTURY

UNIVERSITAT POLITÈCNICA
DE CATALUNYA

University of Minho

Education and Culture

Erasmus Mundus

ADVANCED MASTERS IN STRUCTURAL ANALYSIS
OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

Master's Thesis

Hui-Yin Lee

INVESTIGATION ON THE USE OF IRON AND STEEL FOR RESTORATION PURPOSES DURING 19TH AND 20TH CENTURY

Spain | 2008

DECLARATION

Name:	Hui-Yin Lee
Email:	huiyinlee0202@hotmail.com
ID nº:	214274530

Title of the Msc Dissertation:	INVESTIGATION ON THE USE OF IRON AND STEEL FOR RESTORATION PURPOSES DURING 19TH AND 20TH CENTURY
Supervisor(s):	Pere Roca I Fabregat
Year:	2008

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

University:	Technical University of Catalonia (UPC)
Date:	17h July 2008
Signature:	

Acknowledgement

I am deeply indebted to my supervisor Prof. Pere Roca I Fabregat, who is always positive and helpful for his students.

I would like to express my gratitude to all those who gave me the possibility to complete this thesis. I want to thank the Erasmus Mundus Programmr for giving me this opportunity to particiapte in this Master and financial support.

Especially, I would like to give my special thanks my family for their support all the way. I am thankful to all my family members for their thoughtfulness and encouragement. "

At last but not least, I would like to thanks all of the friends who I made in Europe for all the good time we shared.

Hui-Yin Lee

Abstract

   Since the earliest times, wrought iron cramps and dowels were used in the traditional masonry structures to secure stones which might be prone to movement or displacement.

   In the period between the late 19th century and the early 20th century, masonry-clad buildings are exploded to use. However, due to the porous nature of the mortar and the inconsistent fill around the steel members, the protective oxide film is lost over time, resulting in corrosion of the steel framing and other embedded metals.

The metals which are used for historical construction are cast iron, steel and wrought iron. The causes of metal deterioration are corrosion, mechanical breakdown, weathering and connection failure. The traditional restorations are repair, replacement and jointing method. And new, a new method, cathodic protection, is also applied on historical building restoration. New materials began to be used for replacing the original materials, The most common have been aluminum, epoxies, reinforced polyester, glass fiber-reinforced concrete and titanium.

   The first cathodic protection system for stone clad steel framing was installed in 1991. Cathodic protection (CP) prevents corrosion by converting all of the anodic sites on the metal surface to cathodic sites by supplying electrical current from an alternate source. Different from the traditional way, CP method does not to remove the masonry and install new masonry back.

   According to Roberto Pane, the extreme variety of cases and the need for safeguarding a large amount of monuments shows that restoration can not be constrained within stiff limits .As a conclusion of this studying, due to the former experience, the Barcelona Cathedral's façade can be considered to use the CP method for restoration blend with the old with regard to size, scale and appearance.

Table of contents

List of Figures

List of Tables

1. Introduction

Since the earliest times, wrought iron cramps (Figure.1) and dowels were used in the traditional masonry structures to secure stones which might be prone to movement or displacement. They were also used in ordinary ashlar walls, to tie relatively thin stone facings back to the core. Dowels and cramps were also embedded in the facing itself to help maintain its structural integrity(Iain Mccaig, Kevin Davies, David Farrell, 2001).

Figure 1 The metallic cramp

Figure 2 The Brooklyn Museum, a masonry clad steel-framed building, was built in 1897 (NY,USA)

In the period between the late 19th century and the early 20th century, masonry-clad buildings are exploded to use (Figure.2). In early steel frame construction, the relatively thick external cladding was notched to fit around the structural steel and the void filled with a low grade cementitious mortar, which often contained brick and rubble filled. This type of construction enabled moisture to collect within the masonry and mortar fill, which is in contact with the steel surface. Architects and engineers originally thought the mortar used to construct the wall systems would provide some degree of corrosion protection to the steel members due to the natural high alkalinity of the cement. In alkaline environments, steel surfaces will remain

passive due to the formation of a protective oxide film, which provides some degree of corrosion protection. However, due to the porous nature of the mortar and the inconsistent fill around the steel members, the protective oxide film is lost over time, resulting in corrosion of the steel framing and other embedded metals (Steven F. Daily, Steven D., Somerville, P.E.).

Metal structural components used in small residential buildings are usually limited to beams and pipe columns in basements, angles over small masonry openings, and beams over long spans elsewhere in the structure. These components are almost always made of steel, although in buildings erected before 1890 to 1900 they may be of cast or wrought iron. While cast iron is weaker in tension than steel, when found in small buildings it is rarely of insufficient strength unless it is deteriorated or damaged.

Problems with iron and steel structural components usually center on corrosion. Inspect them as follows:

1. Lintels (or keystone) and other embedded metal components in exterior masonry walls can corrode and in time become severely weakened themselves. Rain and snow often contain carbonic, sulfuric, nitric, or hydrochloric acid that lowers the pH of rain water, thereby accelerating corrosion. Check all embedded iron and steel to determine its condition. Make sure lintels have adequate bearing. Corrosion can also displace surrounding masonry.

2. Columns should be checked for adequate connections at their base and top, and for corrosion at their base if they rest at ground level. Eccentric (off-center) loading or noticeable tilting of columns should be remedied.

3. Beams should be checked for bearing, adequate connections to the structure, and deflection. Bearing can be significantly reduced on pilasters, piers, or columns in differentially settled buildings; inspect such conditions carefully. Beams in small residential buildings rarely deflect. If deflection is found, however, the cause should be determined and supplemental supports or plates should be added to correct the problem.

4. Fire damage to iron and steel structural components should be carefully inspected. Iron and steel rapidly lose their load-bearing capacity when exposed to fire and will under-go considerable expansion and distortion. In general, a structural iron or steel member that remains in place with negligible or minor distortions to its web, flanges, or end connections should be considered serviceable. Sagging or bent members or those with a loss in bearing capacity should be replaced or reinforced with supplemental plates.

1.1 Motivations

Due to the deterioration of these metals, corrosion for instance, it can lead to tremendous stresses on the surrounding materials like mortar, stone and masonry, resulting in cracking, spalling and jacking away of large stone blocks. Corrosion damages not only destroy the integrity of the historical heritage, but also cause a serious public hazard. For restoration purposes, this report intends to identify some of the most common deterioration problems of metal heritage members and their traditional repair methods and the modern treatments.

1.2 Objective

The main objectives of this paper are the identification of the varieties of historical use metal and the deteriorations of metal, and the restoration methods.

2. Metal

2.1 The Varieties of metal for historical constructions

The difference among the cast iron, steel and wrought iron is carbon content. The broad range of values for this proportion is given in Table 1(D.K. Doran,1992):

Table 1 Carbon contents of cast iron, steel and wrought iron

Material	Carbon content (%)
Cast iron	2.0-4.5(generally 2.5-4.0)
Steel	0.2-1.5
Wrought iron	0.02-0.05

2.2 Cast iron

Cast iron used in the construction industry could be divided into three main categories:

1. Historic cast iron, that is mainly grey cast iron, as widely used in structures between about 1780 and 1880 but also including some malleable cast iron, made by the heat treatment of white iron castings.

2. Modern grey cast iron, which is virtually the same as the historic grey iron but it is generally of a higher quality and is covered by British Standards. It is mainly used in mechanical engineering rather than in structure.

3. Ductile cast iron, or spheroidal graphite cast iron, which again is little used in construction today but which is covered by British Standards and could have a major future as a structural material. It is a relatively modern material dating from after 1946.

   The most notable characteristics of historical cast iron are its much greater strength in compression than in tension and its non-linear behaviour under tensile load. These features present problems of analysis which are not shared by the other metals normally used for structures.

2.2.1 Varieties of cast iron

The carbon in historic iron occurs either in the form free graphite flakes or in the combined form of iron carbide. The main characteristics of the three types of cast iron available in the 19th century (grey, white or malleable) are summarized in Table 2(D.K. Doran, 1992)

Actually all the cast iron used in major construction was grey cast iron with nearly all the carbon in the form of free graphite.

White cast iron was only useful in construction as a step toward the manufacture of small components of malleable cast iron produced be the prolonged heat treatment of white iron castings. This process was quite widely used for step irons, hinges, locks, catches and for some decorative ironwork of a delicate character which would be subject to accidental damage.

Table 2 Varieties of historical cast iron

Type of cast iron	Nominal composition (% by weight)	Microstructure	Physical properties	Uses	Notes
Grey	C 3.4, Si 1.8, Mn 0.5	Graphite in flake form in an iron matrix. Flakes form discontinuities.	Strong in compression. Relatively weak in tension. Good resistance to corrosion. Easily machined and cut. Very large castings practicable.	Main form of cast iron used in construction, for columns, beams, decorative panels etc., as well as machinery.	Historic cast iron nearly all grey iron. Little used in construction today except for pipes, pipe fittings, manhole covers, etc.
White	C 3.4, Si 0.7, Mn 0.6	No free graphite. Carbon combined with iron as hard carbides. Low equivalent carbons. Low silicon content.	Very hard and very brittle. Machined by grinding only.	Surfaces needing high resistance to abrasion.	Virtually irrelevant to construction industry.
Malleable	C 2.5, Si 1.0, Mn 0.55	Made by prolonged heat treatment of white iron castings. Carbides transformed into graphite in nodular form with few discontinuities in iron matrix.	Very strong in tension as well as compression, with good ductility.	Hinges, catches, step iron and similar castings of limited size. Decorative panels of fragile design.	Likely to be superseded by ductile iron which has similar properties and can be cast in a wide range of section thickness.

2.2.2 Grey cast iron

Silicon is essential to making grey cast iron as opposed to white cast iron. When silicon is alloyed with ferrite and carbon in amounts of about 2 percent, the carbide of iron becomes unstable. Silicon causes the carbon to rapidly come out of solution as graphite, leaving a matrix of relatively pure, soft iron. Weak bonding between planes of graphite leads to a high activation energy for growth in that direction, resulting in thin, round flakes. This structure has several useful properties.

The metal expands slightly on solidifying as the graphite precipitates, resulting in sharp castings. The graphite content also offers good corrosion resistance.

Graphite acts as a lubricant, improving wear resistance. The exceptionally high speed of sound in graphite gives cast iron a much higher thermal conductivity. Since ferrite is so different in this respect (having heavier atoms, bonded much less tightly) phonons tend to scatter at the interface between the two materials. In practical terms, this means that cast iron tends to "damp" mechanical vibrations (including sound), which can help machinery to run more smoothly.

All of the properties listed in the paragraph above ease the machining of grey cast iron. The sharp edges of graphite flakes also tend to concentrate stress, allowing cracks to form much more easily, so that material can be removed much more efficiently.

Easier initiation of cracks can be a drawback once an item is finished, however: grey cast iron has less tensile strength and shock resistance than steel. It is also difficult to weld.

Grey cast iron's high thermal conductivity and specific heat capacity are often exploited to make cast iron cookware and disc brake rotors.

2.2.3 White cast iron

With a lower silicon content and faster cooling, the carbon in white cast iron precipitates out of the melt as the metastable phase cementite, Fe3C, rather than graphite. The cementite which precipitates from the melt forms as relatively large particles, usually in a eutectic mixture where the other phase is austenite (which on cooling might transform to marten site). These eutectic carbides are much too large to provide precipitation hardening (as in some steels, where cementite precipitates might inhibit plastic deformation by impeding the movement of dislocations through the ferrite matrix). Rather, they increase the bulk hardness of the cast iron simply by virtue of their own very high hardness and their substantial volume fraction, such that the bulk hardness can be approximated by a rule of mixtures.

In any case, they offer hardness at the expense of toughness. Since carbide makes up a large fraction of the material, white cast iron could reasonably be classified as a cermet. White iron is too brittle for use in many structural components, but with good hardness and abrasion resistance and relatively low cost, it finds use in such applications as the wear surfaces of slurry pumps, shell liners and lifter bars in ball mills and autogenously grinding mills, balls and rings in coal pulverizes and balls for rolling-element bearings and the teeth of a backhoe's digging bucket. Although the latter two applications would normally use high quality wrought high-carbon martens tic steels and cast medium-carbon martens tic steels respectively.

It is difficult to cool thick castings fast enough to solidify the melt as white cast iron all the way through. However, rapid cooling can be

used to solidify a shell of white cast iron, after which the remainder cools more slowly to form a core of grey cast iron. The resulting casting, called a "chilled casting", has the benefits of a hard surface and a somewhat tougher interior.

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

2.2.4 Malleable

Malleable iron starts as a white iron casting, that is then heat treated at about 900 °C. Graphite separates out much more slowly in this case, so that surface tension has time to form it into spheroidal particles rather than flakes. Due to their lower aspect ratio, spheroids are relatively short and far from one another, and have a lower cross section vis-à-vis a propagating crack or phonon. They also have blunt boundaries, as opposed to flakes, which alleviates the stress concentration problems faced by grey cast iron. In general, the properties of malleable cast iron are more like mild steel. There is a limit to how large a part can be cast in malleable iron, since it is made from white cast iron.

2.2.5 Historical Use

Because cast iron is comparatively brittle, it is not suitable for purposes where a sharp edge or flexibility is required. It is strong under compression, but not under tension. Cast Iron was first invented in China, and poured into molds to make weapons and figurines. Historically, its earliest uses included cannon and shot. In England, the ironmasters of the Weald continued producing these

until the 1760s, and this was the main function of the iron industry there after the Restoration, though probably only a minor part of the industry there earlier.

Cast iron pots were made at many English blast furnaces at that period. In 1707, Abraham Darby patented a method of making pots thinner and hence cheaper than his rivals could. This meant that his Coalbrookdale Furnaces became dominant as suppliers of pots, an activity in which they were joined in the 1720s and 1730s by a small number of other coke-fired blast furnaces.

The development of the steam engine by Thomas Newcomen provided a further market for cast iron, since this was considerably cheaper than the brass of which the engine cylinders were originally made. A great exponent of cast iron was John Wilkinson, who amongst other things cast the cylinders for many of James Watt's improved steam engines until the establishment of the Soho Foundry in 1795.

Cast iron bridges

The major use of cast iron for structural purposes began in the late 1770s when Abraham Darby III built the Iron Bridge, although short beams had been used prior to the bridge, such as in the blast furnaces at Coalbrookdale. This was followed by others, including Thomas Paine, who patented one; cast iron bridges became common as the Industrial Revolution gathered pace. Thomas Telford adopted the material for his bridge upstream at Buildwas, and then for a canal trough aqueduct at Longdon-on-Tern on the Shrewsbury Canal.

It was followed by the spectacular Chirk Aqueduct and the breath-taking Pontcysyllte Aqueduct, both of which remain in use following recent restorations. Cast iron beam bridges were used widely by the early railways, such as the Water street bridge at the Manchester terminus of the Liverpool and Manchester Railway.

However, problems arose when such a bridge collapsed shortly after opening in 1846. The Dee bridge disaster was caused by excessive loading at the centre of the beam by a passing train, and many similar bridges had to be demolished and rebuilt, often in wrought iron. The bridge had been under-designed, being trussed with wrought iron straps, which were wrongly thought to reinforce the structure. Nevertheless, cast iron continued to be used for structural support, until the Tay Rail Bridge disaster of 1879 created a crisis of confidence in the material. Further bridge collapses occurred, however, culminating in the Norwood Junction rail accident of 1891. Thousands of cast iron rail under-bridges were eventually replaced by steel equivalents.

2.2.6 Structural use

Cast iron has been used for centuries, and was used occasionally in architecture in the pre-modern period. It was in eighteenth century Britain that new production methods first allowed cast iron to be produced cheaply enough and in large enough quantities to regularly be used in large building projects. One of the first important projects was The Iron Bridge in Shropshire, a precedent setting structure made almost entirely of cast iron. However, it was grossly over-designed, and the makers (principally Abraham Darby) suffered financially as a result. The quality of the iron used in the bridge is not high, and nearly 80 brittle cracks are visible in the present structure. Later designers and engineers, such as Thomas Telford improved both the design and quality of the material in his bridges (for example, at Buildwas upstream of Coalbrookdale) and aqueducts (such as the world-famous Pontcysyllte Aqueduct in North Wales.

Cast iron has some architectural advantages, and some weaknesses. It is strong in compression and its strength and stiffness deteriorate when subjected to the high heat of a fire. In the early era of the

industrial revolution it became popular to use cast iron in factory construction, in part owing to the misconception that such structures would be "fireproof." Cast iron was strong enough to support the heavy machinery but was vulnerable to the frequent fires that would occur in such factories. William Strutt pioneered this innovation, building a number of industrial buildings using cast iron supports. However, there were numerous building collapses caused by brittle fracture of large cast iron beams, where the bottom side of the beam was in tension, often from defects such as blow holes within the beams. Internal defects like blowholes were common in large beams.

Cast iron was also used widely in bridge construction for the new railway system, sometimes with horrific results, especially when cast iron girders were used instead of arches. The first use was at the Water Street terminus of the Liverpool and Manchester Railway in 1830 to a design by William Fairbairn, a successful design which was demolished about 1900 owing to the widespread concern about cast iron under bridges on the rail network in Britain. To build longer spans, wrought iron trusses were added to strengthen the structure by Robert Stephenson over the river Dee. Such trussed bridges had to be demolished following the Dee bridge disaster of 1847. This led to the use of wrought iron composite beams formed by riveting sheets together, and then steel rolled beams when steel became available in the late 1860s and 1870s. Cast iron continued, however, to be used in railway under bridges, and there were a number of serious failures involving loss of life. The most serious accident occurred in 1879 with the Tay Bridge disaster when the centre part of the bridge collapsed in a storm as an express train was passing over. The whole train was lost with more than 75 passengers and crew. The weakest parts of the bridge were cast iron lugs holding tie bars in place, and cast iron in new bridges was effectively abandoned after the disaster. Most small

cast iron beam structures were demolished and replaced after the Norwood Junction rail accident of 1891.

2.3 Steel

Generally, carbon is the most important commercial steel alloy. Increasing carbon content increases hardness and strength and improves hardenability. But carbon also increases brittleness and reduces weldability because of its tendency to form martensite. This means carbon content can be both a blessing and a curse when it comes to commercial steel.

And while there are steels that have up to 2 % carbon content, they are the exception. Most steel contains less than 0.35 % carbon. To put this in perspective, keep in mind that's 35/100 of 1%.

Now, any steel in the 0.35 to 1.86 % carbon content range can be hardened using a heat-quench-temper cycle. Most commercial steels are classified into one of three groups (Bob Capudean, 2003):

1. Plain carbon steels
2. Low-alloy steels
3. High-alloy steels

Plain Carbon Steels

These steels usually are iron with less than 1 percent carbon, plus small amounts of manganese, phosphorus, sulfur, and silicon. The weldability and other characteristics of these steels are primarily a product of carbon content, although the alloying and residual elements do have a minor influence.

Plain carbon steels are further subdivided into four groups:

1. Low

2. Medium

3. High

4. Very high

Low. Often called mild steels, low-carbon steels have less than 0.30 % carbon and are the most commonly used grades. They machine and weld nicely and are more ductile than higher-carbon steels.

Medium. Medium-carbon steels have from 0.30 to 0.45% carbon. Increased carbon means increased hardness and tensile strength, decreased ductility, and more difficult machining.

High. With 0.45 to 0.75% carbon, these steels can be challenging to weld. Preheating, post heating (to control cooling rate), and sometimes even heating during welding become necessary to produce acceptable welds and to control the mechanical properties of the steel after welding.

Very High. With up to 1.50 % carbon content, very high-carbon steels are used for hard steel products such as metal cutting tools and truck springs. Like high-carbon steels, they require heat treating before, during, and after welding to maintain their mechanical properties.

Low-alloy Steels

When these steels are designed for welded applications, their carbon content is usually below 0.25 % and often below 0.15 %. Typical alloys include nickel, chromium, molybdenum, manganese, and silicon, which add strength at room temperatures and increase low-temperature notch toughness.

These alloys can, in the right combination, improve corrosion resistance and influence the steel's response to heat treatment. But the alloys added can also negatively influence crack susceptibility, so

it's a good idea to use low-hydrogen welding processes with them. Preheating might also prove necessary. This can be determined by using the carbon equivalent formula, which we'll cover in a later issue.

High-alloy Steels

For the most part, we're talking about stainless steel here, the most important commercial high-alloy steel. Stainless steels are at least 12 % chromium and many have high nickel contents. The three basic types of stainless are:

1. Austenitic
2. Ferritic
3. Martens tic

Martens tic stainless steels make up the cutlery grades. They have the least amount of chromium, offer high harden ability, and require both pre- and post heating when welding to prevent cracking in the heat-affected zone (HAZ).

Ferritic stainless steels have 12 to 27 % chromium with small amounts of austenite-forming alloys.

Austenitic stainless steels offer excellent weld ability, but austenite isn't stable at room temperature. Consequently, specific alloys must be added to stabilize austenite. The most important austenite stabilizer is nickel, and others include carbon, manganese, and nitrogen.

2.3.1 Steel Classification Systems

Before we look at a couple of common steel classification systems, let's consider one more high-carbon metal, cast iron. The carbon content of cast iron is 2.1% or more. There are four basic types of cast iron:

1. Gray cast iron, which is relatively soft. It's easily machined and welded, and you'll find it used for engine cylinder blocks, pipe, and machine tool structures.

2. White cast iron, which is hard, brittle, and not weldable. It has a compressive strength of more than 200,000 pounds per square inch (PSI), and when it's annealed, it becomes malleable cast iron.

3. Malleable cast iron, which is annealed white cast iron. It can be welded, machined, is ductile, and offers good strength and shock resistance.

4. Ductile cast iron, which is sometimes called nodular or spheroidal graphite cast iron. It gets this name because its carbon is in the shape of small spheres, not flakes. This makes it both ductile and malleable. It's also weldable.

註解 [N1]: 靠要 放錯段!!

2.3.2 Historical Use

Before the introduction of the Bessemer process and other modern production techniques, steel was expensive and was only used where no cheaper alternative existed, particularly for the cutting edge of knives, razors, swords, and other items where a hard, sharp edge was needed. It was also used for springs, including those used in clocks and watches.

Since 1850, with the advent of faster and more efficient steel production methods, steel has been easier to obtain and much cheaper. It has replaced wrought iron for a multitude of purposes. However, the availability of plastics during the later 20th century allowed these materials to replace steel in many products due to their lower cost and weight.

2.4 Wrought iron

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

Examples of items that used to be produced from wrought iron include: rivets, chains, railway couplings, water and steam pipes, raw material for manufacturing of steel, nuts, bolts, horseshoes, handrails, straps for timber roof trusses, boiler tubes, and ornamental ironwork.

Wrought iron is no longer produced on a commercial scale. Many products described as wrought iron, such as guard rails, are made of mild steel. They retain that description because they were formerly made of wrought iron or have the appearance of wrought iron. True wrought iron is occasionally required for the authentic conservation of historic structures.

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 weld ability. Furthermore, sheet wrought iron cannot bend as much as steel sheet metal. Wrought iron can be cast, 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.

Figure 3 The puddling process of smelting iron ore to make wrought iron from pig iron. *Tiangong Kaiwu* encyclopedia published in 1637, written by Song Yingxing (1587-1666).

Wrought iron is less affected by rust than most other ferrous metals due to its slag inclusions. The slag fibers tend to disperse the corrosion into an even film, thereby resisting pitting. 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.

2.4.1 Historical Use

The structural use of iron dates from the Middle Ages, when bars of wrought iron would be used occasionally to tie masonry arches and domes. The usage continued to increase throughout the Middle Ages, initially for construction and weaponry and, later, in an ornamental fashion on churches and monasteries.

Wrought iron has successfully competed with bronze for prominence since about 4000 BC and it eventually replaced the high quality bronze. It took over bronze in the manufacture of swords, axe

heads, plows and other items of general use.

With the introduction of blast furnaces in the 15th century the availability of wrought iron increased. Craftsmanship reached new heights in the period of Great English Ironwork, which started in 1690.

More skilled use of wrought iron was made in the provision of decorative elements of buildings but the structural century with English Iron-Master Abraham Darby's first Iron Bridge. The bridge was made entirely of iron arches and ribs, cast in a foundry and transported to the building site for assembly. Although this advertised remarkable architectural capabilities of iron, few architects designed buildings constructed entirely of this material.

Smaller items, such as solid or hollow iron columns made of wrought iron, also found widespread application from 1770 onwards. Their use reduced the need for heavy load-bearing internal walls or masonry piers and could be assembled quickly by unskilled labor.

Wrought iron, with its high tensile strength came again to the fore in the Railway Age. Ship building practices of fabricating structures by riveting together rolled wrought iron sections, came into use in buildings, particularly in bridge building for the railways.

By the turn of the 20th century, three inventions, namely coke, the blast furnace and the Bessemer Converter, unlocked the production of steel. 22 kilotons were produced in 1867, 500 in 1870, 1 million in 1880 and 28 million by 1900. Today, worldwide production of steel is around 850 million tons. Due to, increased use of steel (Which could be mass-produced far more cheaply than wrought iron), wrought iron was in decline. However, wrought iron has enjoyed something of a renaissance in more recent years.

3. Causes of Metal Deterioration

3.1 Corrosion

Corrosion means the breaking down of essential properties in a material due to chemical reactions with its surroundings. In the most common use of the word, this means a loss of electrons of metals reacting with water and oxygen. Weakening of iron due to oxidation of the iron atoms is a well-known example of electrochemical corrosion. This is commonly known as rust. This type of damage usually affects metallic materials, and typically produces oxide and/or salt of the original metal. Corrosion is a common problem for metal. Corrosion is the deterioration or breakdown of metal because of a reaction with its environment.

Figure 4 A corroded wrought iron chain.   Figure 5 A corroded steel

Most structural alloys corrode merely from exposure to moisture in the air, but the process can be strongly affected by exposure to certain substances. Corrosion can be concentrated locally to form a pit or crack, or it can extend across a wide area to produce general deterioration. While some efforts to reduce corrosion merely redirect the damage into less visible, less predictable forms, controlled corrosion treatments such as passivation and chromate-conversion will increase a material's corrosion resistance.

3.1.1 Corrosion Process

The corrosion process which is happened in masonry metal buildings is electrochemical reaction in the nature. Corrosion will result in the flow of electrons between anodic and cathodic site on the metal surface. Most metals are thermodynamically unstable and will revert back to their original energy state. For corrosion to occur four basic elements are required:

Anode: Site where corrosion occurs and current flows from.

Cathode: Site where no corrosion occurs and current flows to.

Electrolyte: A medium capable of conducting electric current by ironic current flow (i.e., soil, water or mortar)

Metallic Path: Connection between the anode and cathode, which allows current return and completes the circuit.

3.1.2 Corrosion as an Electrochemical Process

A piece of bare iron left outside where it is exposed to moisture will rust quickly. It will do so even more quickly if the moisture is salt water. The corrosion rate is enhanced by an electrochemical process in which a water droplet becomes a voltaic cell in contact with the metal, oxidizing the iron.
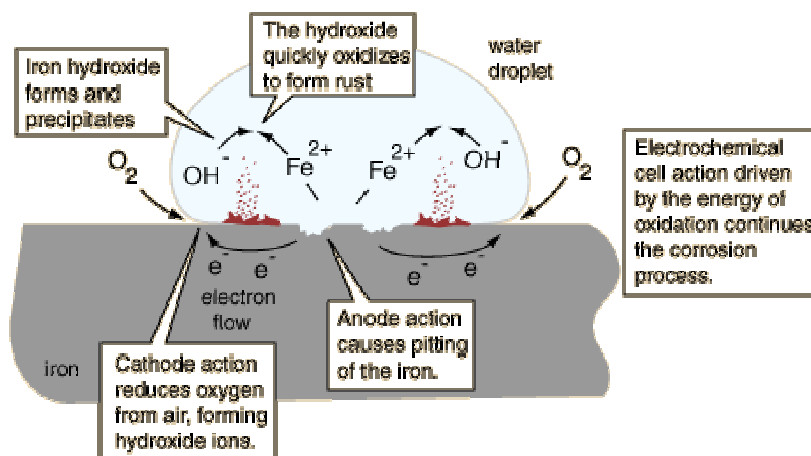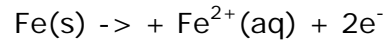

Figure 6   Electrochemical Process (Hill & Kolb, 2001)

Considering the sketch of a water droplet, the oxidizing iron supplies electrons at the edge of the droplet to reduce oxygen from the air. The iron surface inside the droplet acts as the anode for the process(Ebbing,1990)

$$Fe(s) \rightarrow + Fe^{2+}(aq) + 2e^-$$

The electrons can move through the metallic iron to the outside of the droplet where

$$O_2(g) + 2H_2O(l) + 4e^- \rightarrow 4OH^-(aq)$$
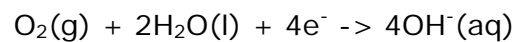
Within the droplet, the hydroxide ions can move inward to react with the iron(II) ions moving from the oxidation region. Iron(II) hydroxide is precipitated.

$$Fe^{2+}(aq) + 2OH^-(aq) \rightarrow Fe(OH)_2(s)$$
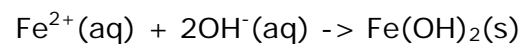
Rust is then quickly produced by the oxidation of the precipitate.

$$4Fe(OH)_2(s) + O_2(g) \rightarrow 2Fe_2O_3 \cdot H_2O(s) + 2H_2O(l)$$
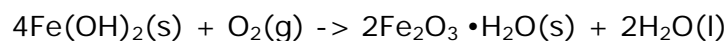
The rusting of unprotected iron in the presence of air and water is then inevitable because it is driven by an electrochemical process.

3.1.3 Types of Corrosion

3.1.3.1 Uniform corrosion

Uniform attack appears as an even layer of rust on the steel surface. This is the most common form of corrosion that is found in perimeter steel of masonry clad steel framed buildings. Uniform corrosion (see Figure 7) is generally due to electrochemical reactions, which occur from the presence of oxygen and moisture. Under certain conditions the water or moisture that is in contact with the steel, may have extremely low values of pH due to acidic pollutants from rainfall. In fact acid rain pH surveys have shown that acid precipitation at a pH of

2 is not uncommon, especially during the initial period of snow or rain. Carbonation, another contributor to corrosion, is a process by which carbon dioxide enters into the masonry and reacts with the steel. Carbon dioxide combines with the pore water in the mortar to form carbonic acid, which reduces the pH of the mortar to approximately 8 or 9. At these levels the protective oxide film is no longer stable and with adequate supply of oxygen and moisture corrosion will start. The penetration of masonry by carbonations is a slow process, the rate of which is determined by the porosity and permeability of the mortar.

3.1.3.2 Pitting corrosion

Pitting corrosion (see Figure 8), or pitting, is a form of extremely localized corrosion that leads to the creation of small holes in the metal. The driving power for pitting corrosion is the lack of oxygen around a small area. This area becomes anodic while the area with excess of oxygen becomes cathodic, leading to very localized galvanic corrosion. The corrosion penetrates the mass of the metal, with limited diffusion of ions, further pronouncing the localized lack of oxygen. The mechanism of pitting corrosion is probably the same as crevice corrosion.

The mechanism of pitting corrosion is supposed by some that gravitation causes downward-oriented concentration gradient of the dissolved ions in the hole caused by the corrosion, as the concentrated solution is denser. This however is unlikely. The more conventional explanation is that the acidity inside the pit is maintained by the spatial separation of the cathodic and anodic half-reactions, which creates a potential gradient and electro migration of aggressive anions into the pit.

This kind of corrosion is extremely insidious, as it causes little loss of material with small effect on its surface, while it damages the deep

structures of the metal. The pits on the surface are often obscured by corrosion products.

Pitting can be initiated by a small surface defect, being a scratch or a local change in composition, or damage to protective coating. Polished surfaces display higher resistance to pitting.

3.1.3.3 Crevice or concentration cell corrosion

The process is similar to pitting corrosion except that it occurs in the very narrow gaps between faying surfaces where the solution concentrates by capillary or other action. Some moisture evaporates and the remaining solution trapped in the crevice becomes stagnant and increasingly corrosive. Crevice corrosion is often brought about by poor sealing/protection practices when applying/rinsing off acid etches cleaning solutions prior to painting.

If dust containing salt is allowed to remain trapped in joints hygroscopic action will eventuate in a corrosion cell. Water staining found between bundled and stored aluminum sheets is a form of crevice corrosion.

3.1.3.4 Galvanic corrosion

Galvanic corrosion (see Figure 9) is an electrochemical process in which one metal corrodes preferentially when in electrical contact with a different type of metal and both metals are immersed in an electrolyte. Conversely, a galvanic reaction is exploited in primary batteries to generate a voltage. A common example is the carbon-zinc cell where the zinc corrodes preferentially to produce a current. The lemon battery is another simple example of how dissimilar metals react to produce an electric current.

When two or more different sorts of metal come into contact in the presence of an electrolyte a galvanic couple is set up as different

metals have different electrode potentials. The electrolyte provides a means for ion migration whereby metallic ions can move from the anode to the cathode. This leads to the anodic metal corroding more quickly than it otherwise would; the corrosion of the cathodic metal is retarded even to the point of stopping. The presence of electrolyte and a conducting path between the metals may cause corrosion where otherwise neither metal alone would have corroded.

Even a single type of metal may corrode galvanic ally if the electrolyte varies in composition, forming a concentration cell.

A common example of galvanic corrosion is the rusting of corrugated iron sheet, which becomes widespread when the protective zinc coating is broken and the underlying steel is attacked. The zinc is attacked preferentially because it is less noble, but when consumed, rusting will occur in earnest. With a tin can, the opposite is true because the tin is nobler than the underlying steel, so when the coating is broken, the steel is attacked preferentially.

A rather more spectacular example occurred in the Statue of Liberty when regular maintenance in the 1990s showed that galvanic corrosion had taken place between the outer copper skin and the wrought iron support structure.

Although the problem had been anticipated when the structure was built by Gustave Eiffel to Frédéric Bartholdi's design in the 1880s, the insulation of shellac between the two metals failed over a period of time and resulted in rusting of the iron supports. The renovation replaced the original insulation with PTFE (Polytetrafluoroethylene).

3.1.3.5 Other corrosion forms

Intergranular corrosion (see Figure 10): attacks the grain

boundaries within the metal structure when the chemical differences between grains and the grain boundaries react with each other in the presence of an electrolytic solution. Usually occurs in areas where end grain is exposed, rivet holes for example. Exfoliation corrosion, where grain layers are lifted away, is an advanced form.

Stress corrosion cracking: occurs when high internal tensile stresses induced in the metal during manufacture are allowed to remain i.e. the metal is not properly stress relieved. A high permanent stress can also be introduced during structure assembly if any of the welding or fastening processes are incorrectly performed. If this residual stress condition or a stress condition introduced during normal operation exists in association with pitting or other corrosion multi-branched internal cracking may occur within the metal.

Filiform corrosion: occurs in high relative humidity conditions under paint coatings such as polyurethane finishes usually because contamination traces were not completely removed from the substrate or a treatment process was not allowed to fully complete before applying the next coating.

Fretting or friction corrosion occurs when vibration or in-flight loads causes oscillatory movement between faying surfaces.

A form of **chemical corrosion** will occur if incompatible surface coatings come in contact; for example methyl ethyl ketone [used as a solvent in a number of fabric cements] will attack zinc chromate metal primers leaving the metal open to corrosion under the fabric.

Also **organic acids** are present in bird and animal wastes so keep mice out of the airframe (and by the way you've no idea the damage that mouse urine can do to electronics); and if you operate from a

cattle paddock clean off any 'meadow mayonnaise' that accumulates.
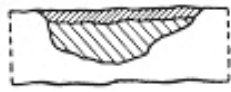
Figure 7 Uniform corrosion

Figure 8 Pitting corrosion
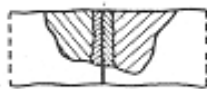
Figure 9 Galvanic corrosion

Figure 10 Intergranular corrosion

3.2 Mechanical breakdown

Metal architectural elements can also fail from purely physical causes such as abrasion or a combination of physical and chemical attack, such as weathering and stress corrosion cracking.

3.2.1 Abrasion

Abrasion is the erosion of the metal caused by the impact of dust, san grit, sleet, rain and hail, or by rubbing with another architectural or human element. Abrasives can encourage corrosion by removing the protective corrosion deposits from the metal surface. Abrasion is a critical problem with metal flashings and valleys used on slate roofs. As the slate deteriorates, particles break off and are washed down the valleys, causing erosion.

3.2.2 Fatigue

Fatigue is failure of a metal by the repeated application of cyclic stresses below the elastic limit-the greatest stress a material can withstand without permanent deformation after removal of the load. It results from a gradual or progressive fracture of the crystals. It has

been estimated that approximately 90% of the structural failure of metal railroad bridges are fatigue failures which develop late in the life of the structure.

3.2.3 Creep

Creep is the continuous flow or plastic deformation of soft metals under sustained stressing, sometimes under relatively high temperatures. It tends to distort the metal, causing thin areas that may failure and a lack of stain hardening. The stressing may be related to thermal expansion and contraction and the weight of the metal.

3.2.4 Fire

Fire can cause unprotected metal framing members to become plastic and fail rapidly. Structural iron or steel that has survived a fire without deformation is usually safe to reuse, but any questionable member should be load tested

3.2.5 Overloading

Overloading is the stressing of a metal member beyond its yield point so that permanent deformation, fracturing, or failure occurs. The member can fail through the application of static loads, dynamic loads, thermal stresses and settlement stresses either singly or combination. Buckling is a form of permanent deformation from overloading which is usually caused by excessive weight but can also be caused by thermal stresses. Members can also be overloaded if their support is removed and loads are redistributed to other members which can become overstressed and deformed.

3.3 Weathering

A metal architectural element subjected to the weather is exposed

to various chemical and physical agents at one time. The result is a kind of synergism where the total effect is greater than the sum of the individual effects. For instance, the rate of corrosion accelerates with increases of temperature, humidity and surface deposits of salts, dirt and pollution.

3.4 Connection Failure

The failure of the connections of metal architectural elements, especially structural members, can also be caused by a combination of physical and/or chemical agents. The most common type of connections used for metal structural elements of historic buildings including bolting, riveting, pinning and welding. These connections can fail through the overloading, fatiguing or corrosion of the connectors. Common examples of this type of failure include the corrosion, usually by the galvanic effects, of nails, bolt heads, rivets and areas covered by fastening plating. The effective cross-sectional area of the connections is often reduced by corrosion, making the connectors more susceptible to stress failure.

4. Methods for repair and rehabilitation of metal

Common problems encountered today with metal construction include badly rusted or missing elements, impact damage, structural failures, broken joints, damage to connections, and loss of anchorage in masonry.

Oxidation, or rusting, occurs rapidly when metal is exposed to moisture and air. The minimum relative humidity necessary to promote rusting is 65%, but this figure can be lower in the presence of corrosive agents, such as sea water, salt air, acids, acid precipitation, soils, and some sulfur compounds present in the atmosphere, which act as catalysts in the oxidation process. Rusting is accelerated in situations where architectural details provide pockets or crevices to trap and hold liquid corrosive agents. Furthermore, once a rust film forms, its porous surface acts as a reservoir for liquids, which in turn causes further corrosion. If this process is not arrested, it will continue until the iron is entirely consumed by corrosion, leaving nothing but rust (Margot Gayle David and John G. Waite, 1998).

When the historical structures need to restore or renovate, the question arises of the whether damaged or broken elements can or should be repaired.

The restoration techniques are directly linked to both the types of material used and the question of whether the intention is to simply to restore the appearance of the structure or to ensure that actual forces can be accommodated. This chapter will indicate the methods that can be considered for use on cast iron, wrought iron and steel. If it is necessary to replace elements attention will be also be paid to the availability of historic types of iron and steel and to when modern materials be used(G.G Nieuwmeijer & G.J. Arends, 2003).

When a structure that has a high value of history is only slightly damaged it is usually possible to return it to its original condition and thus to retain a consistent appearance and to show how it was constructed. However, when the damage is more serious some elements will have to be replaced. Depending on the historic and cultural value and the budget, either the original materials and construction methods will be used or it will be necessary to resort or the use of modern materials and modes of connection. However, the new construction must be blend with the old with regard to size, scale and appearance.

4.1. Repairs

4.1.1 Repair techniques used for cast iron

The most important methods of repair are welding, using dowels, metal stitching and using adhesives. The degree to which forces can be transferred depends on the method used.

4.1.1.1 Welding

Owing to the high carbon content it is different although not impossible to weld cast iron. This method requires great skill. A distinction must be made between hot and cold-welding. With hot welding, the cast iron must be slowly preheated up to 450℃-600℃. An electrode with a cast iron or carbon rich steel core must be used for the welding and to avoid stresses the welded element must be allowed to cool slowly. The bigger the cast iron element, the more difficult it is to weld it. Preferably the preheating must be done in a furnace but it may also be done in situ.

For cold welding the cast iron element is either cold or only slightly preheated. The electrode used must have a different composition from that of the parent material and is usually rich in nickel. The weld

must be able to withstand a relatively high strain during cooling. Overheating must be avoided and the weld must cool slowly.

Hot welding usually provides a stronger connection than cold welding. However, for both methods it is better to consider a welding to be a means of adhesion rather than a connection that can transfer strong forces. It is always wise to access the suitability of the materials for welding in the laboratory before using this method.
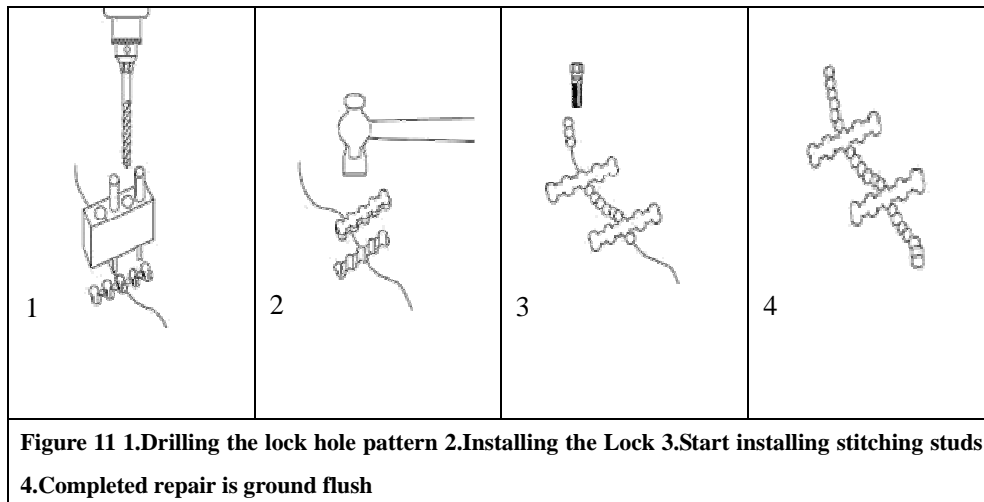
4.1.1.2 Dowels

The repair of parts that do not need to bear any forces, such as decorative elements, can be carried out by simply using dowels. These are glued into holes drilled on each and thus the link is restored. It is also possible to drive tap-bolts into each part and then to weld these to each other, in which case it is easy to determine the strength of the connection.

4.1.1.3 Metal stitching

This is a cold technique that can be used to repair cracks. Locks are inserted at right angles to the crack and the crack itself is closed with studs. For the locks holes are drilled at regular intervals. The material between the holes is cut out so that they are jointed and the locks, which are made of a special alloy, are inserted into these spaces. Threaded holes are then drilled along the crack and into these studs are screwed overlap each other. After this the joint is ground smooth. With this method the original strength can usually be restored. The locks take up the tensile force perpendicular to the crack, while the studs ensure that the crack is closed and the transfer of the shear stress.(see Figure 11)

In places where there is a concentration of stresses, cracks come together or more material has been lost, master locks can be used.

These insertion pieces are made to measure and joined to the parent material in the way described above.

Figure 11 1.Drilling the lock hole pattern 2.Installing the Lock 3.Start installing stitching studs 4.Completed repair is ground flush

4.1.1.4 Adhesives

The "gluing" of metals was developed in the aircraft, space industries and coachwork industries. Under workshop conditions a string and durable connections can be made. An adhesive connection provides a uniform transfer of forces, but considerable skill is required in the application of the adhesive. The use of adhesive is relatively new in civil engineering but could provide an attractive method for repairing broken cast iron elements.

4.1.2 Repair techniques used for wrought iron and steel

When repair or strengthening s necessary, welding, bolted joints and in principle, adhesive methods can be considered. Wrought iron can welded, but during the rolling process contaminants have resulted in the development of a laminar structure. In the direction of rolling a strong connection can be made, however at right angles to the rolling direction and also when the material is loaded by shear forces caution is advised. When part of a rolled profile is seriously corroded the damaged part can be sawn or ground out and new material can be

welded in. A profile can be strengthened by welding on plates or strips. Siemens-Martin steel is usually suitable for welding but with Thomas steel there is a risk of brittle fracture.

When wrought iron or other old type of steel are being welded it is necessary to consider the need to investigate whether the material is suitable for welding. For the analysis the laboratory can usually manage with a few metal shaving. Advice can then be given about the filler rod and the welding process.

4.2 Replacement

If the original material has been seriously damaged by corrosion or when such features are missing or damaged beyond repair or when it requires much strengthening it is necessary to replace profiles or structural elements. Materials such as cast iron, wrought iron and steel and the elements made from these materials must be investigated. Occasionally, a matching replacement can be obtained through the existing catalogs of iron foundries. Small elements can be custom cast in iron at small local foundries, often at a cost comparable to substitute materials. Large elements and complex patterns will usually require the skills and facilities of a large firm that specializes in replication.

4.2.1 Cast iron

Elements made of grey cast iron, such were formerly used, can be easily obtained. Often they can be ordered from catalogues containing cast iron balustrades, lamp posts, window frames and similar elements. Columns beams and other structural elements can be re-cast. Foundries are usually equipped to produce items in series. Products may range from very large series to single items and sometimes foundries place restriction on the size of the items they can cast. When elements have to be replaced it is often possible to use the

original elements to make the new moulds. If greater tensile strength and reduced brittleness are desired modern nodular cast iron can be used. For cast iron widow frames nodular iron replicas are made and this material is certainly to be recommended for beam. For small series of windows or when the budget is limited window modern steel frames may replace frames.

4.2.2 Wrought iron and old types of steel

Wrought iron, which can only be manufactured by puddle process, is now almost unobtainable. At the Blist Hill site of the Ironbridge Gorge Museum, Shropshire, England, a limited amount of wrought iron is produced as one of the activities of this "living museum". In addition it is possible to melt old wrought iron and to roll it again. Old profiles can only be rolled to a limited extent. In Whaley Bridge, Cheshire, England, there is a rolling mill that can make simple mechanical forging the desired profile can be formed from a standard glazing bar.

However, when elements have to be replaced modern steel profiles are usually used; a profile that is as close as possible to the original profile was chosen. Whenever high demands are placed on corrosion resistance, profiles can be galvanized or stainless steel can be used. Bessemer, Thomas and Siemens-Martin steel are no longer produced. The last rolling mill in east Europe that still produced these old types of steel closed in 1990.

4.2.3 Jointing methods

The technique of riveting is still used. As in the case of welding, further investigation the riveting of Thomas steel is necessary, with a view to artificial ageing. For joints that are out of sight in Particular, welding is often used. Structural connections that are visible are also often welded and for the visual effect rivet heads are often welded onto the structures. Sometimes people even go so far as to stick on

plastic imitations.

Welded joints are cheaper, but the appearance of the structure is considerably changed. However this gives an honest indication that the structure has been repaired. Modern nuts and bolts are available in many types in many types and sizes but the square nuts and bolts that were used in early iron structures are only available to a very limited extent.

4.3 Substitute Materials

In recent years, a number of metallic and non-metallic materials have been used as substitutes for cast iron, although they were not used historically with cast iron. The most common have been aluminum, epoxies, reinforced polyester (fiberglass), and glass fiber-reinforced concrete (GFRC).

4.3.1 Cast aluminum

Cast aluminum has been used recently as a substitute for cast iron, particularly for ornately-detailed decorative elements. Aluminum is lighter in weight, more resistant to corrosion, and less brittle than cast iron. However, because it is dissimilar from iron, its placement in contact with or near cast iron may result in galvanic corrosion, and thus should be avoided. Special care must be taken in the application of paint coatings, particularly in the field. It is often difficult to achieve a durable coating after the original finish has failed. Because aluminum is weaker than iron, careful analysis is required whenever aluminum is being considered as a replacement material for structural cast-iron elements.

4.3.2 Epoxies

Figure 12 This lightweight fiberglass column at street level sustained damage from impact within a few years of installation. Photo: Building Conservation Associates.

Epoxies are two-part, thermo-setting, resinous materials which can be molded into virtually any form. When molded, the epoxy is usually mixed with fillers such as sand, glass balloons, or stone chips. Since it is not a metal, galvanic corrosion does not occur. When mixed with sand or stone, it is often termed epoxy concrete or polymer concrete, a misnomer because no cementitious materials are included. Epoxies are particularly effective for replicating small, ornamental sections of cast iron.

Since it is not a metal, galvanic action does not occur. Epoxy elements must have a protective coating to shield them from ultraviolet degradation. They are also flammable and cannot be used as substitutes for structural cast-iron elements.

4.3.3 Reinforced polyester

Reinforced polyester, commonly known as fiberglass, is often used as a lightweight substitute for historic materials, including cast iron, wood, and stone. In its most common form, fiberglass is a thin, rigid, laminate shell formed by pouring a polyester resin into a mold and then adding fiberglass for reinforcement. Like epoxies, fiberglass is non-corrosive, but is susceptible to ultraviolet degradation. Because of its rather flimsy nature, it cannot be used as a substitute for structural elements, cannot be assembled like cast iron and usually requires a separate anchorage system. It is unsuitable for locations where it is susceptible to damage by impact, and is also flammable.

4.3.4 Glass fiber-reinforced concrete

Glass fiber-reinforced concrete, known as **GFRC**, is similar to fiberglass except that a lightweight concrete is substituted for the resin. GFRC elements are generally fabricated as thin shell panels by spraying concrete into forms. Usually a separate framing and anchorage system is required. GFRC elements are lightweight, inexpensive, and weather resistant. Because GFRC has a low shrinkage coefficient, molds can be made directly from historic elements. However, GFRC is very different physically and chemically from iron. If used adjacent to iron, it causes corrosion of the iron and will have a different moisture absorption rate. Also, it is not possible to achieve the crisp detail that is characteristic of cast iron.

4.3.5 Titanium

Titanium may also be connected directly with metals and alloys such as stainless steels which are galvanically compatible when in their passive condition in a specific environment. These alloys may become activated by local corrosion or pitting but the added effect of coupling to titanium is small. The primary consideration must be to ensure that the alloy selected is appropriate for the service environment.

Figure 13 Modern use of titanium to replace steel strengthening

4.4 Cathodic Protection techniques

4.4.1 History

Traditional methods of repair for masonry clad steel framed buildings, which consist of removing the masonry, treating the steel with a protective coating or paint, providing new mortar encasement and installing new masonry might be both an expensive and impractical option. Cathodic protection (CP), a corrosion control method which was presented by Sir Humphrey Davy in 1824 as a series pf papers to the Royal Society describing how CP could be used to prevent the corrosion of copper sheathing in the wooden hulls of British naval vessels. Since then it has been applied to many other areas, including marine application and for the preservation of buried underground structures such as pipelines and tanks. In 1991 the first cathodic protection system for stone clad steel framing was installed by Taywoods Engineering on the entrance colonnade of Dublin's 1019 College pf Science, now the Irish Prime Minister's residence. In 1995, English Heritage applied cathodic protection to corroded ferrous cramps of the Inigo Jones gateway, which stands in the parkland surround Chiswick Housein London, England. Now this same technology is being applied to steel-frame structures in the UK and North America.

4.4.2 Theoretical principles

Cathodic protection prevents corrosion by converting all of the anodic (active) sites on the metal surface to cathodic (passive) sites by supplying electrical current (or free electrons) from an alternate source.
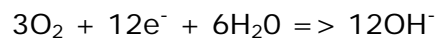
Usually this takes the form of galvanic anodes which are more active

than steel. This practice is also referred to as a sacrificial system, since the galvanic anodes sacrifice themselves to protect the structural steel or pipeline from corrosion.

In the case of aluminum anodes, the reaction at the aluminum surface is:

$4Al => 4AL^{+++} + 12\ e^{-}$ (four aluminum ions plus twelve free electrons)
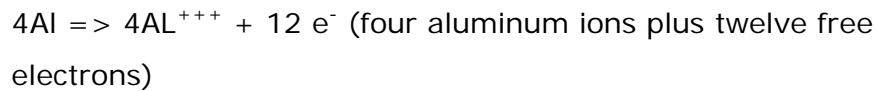
and at the steel surface,

$3O_2 + 12e^{-} + 6H_2O => 12OH^{-}$

(oxygen gas converted to oxygen ions which combine with water to form hydroxyl ions)

As long as the current (free electrons) is arriving at the cathode (steel) faster than oxygen is arriving, no corrosion will occur.

4.4.3 CP system types

Cathodic protection may be achieved by two somewhat different techniques, although the principles described above hold true for both. These are sacrificial anode cathodic protection and impressed current cathodic protection.

Sacrificial Anode Cathodic Protection

Sacrificial anode cathodic protection (SACP) system uses sacrificial anodes (made of zinc, aluminum, magnesium or alloys of these) which corrode preferentially to the metalwork. These are placed in close proximity to the corroding metalwork and are electrically connected to it. As the sacrificial anode corrodes it generates a current that passes through the building material to provide

protection to the embedded metal work. The current is conducted ionically though the building material by means of pore water contained within it.

Impressed Current Cathodic Protection

Impressed current cathodic protection (ICCP) systems are commonly used where there are increased current requirements for corrosion protection, where the driving voltage is greater than what can be obtained with galvanic systems and where there may be a need for detailed control of the system.

ICCP systems are extremely accurate and can be controlled to deliver optimal protective current to the structure. Anodes are connected to a DC power supply to deliver low-voltage electric currents and are controlled by strategically placed reference electrodes. These reference electrodes are connected to a monitoring system that observes and verifies the system performance.

Whether applied to reinforced concrete, steel frame structures or other structures subject to corrosion, CP provides all the products and engineering support needed to design optimal ICCP systems.
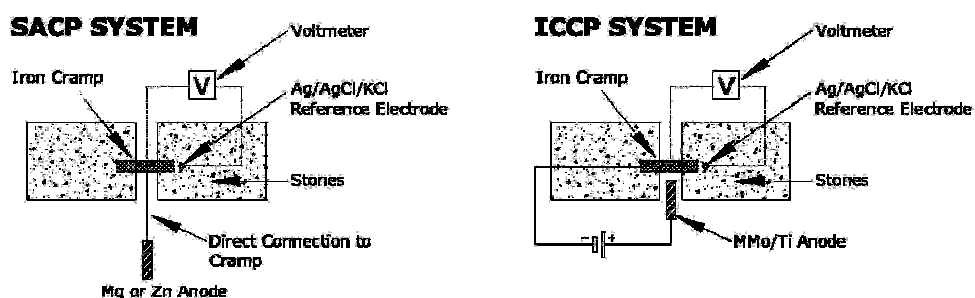

Figure 14 Schematic of SACP and ICCP Systems

As the ICCP systems forces the metal to become cathodic, and therefore protected, the other side of the CP circuit becomes anodic and therefore more corrosive. Materials for these current emitters (or anodes) therefore have to be highly resistance to corrosion. A variety of commercial anodes are available for use with ICCP systems: Carbon-loaded coatings can be used over shout periods although their life is normally restricted to 10 to 15 years. For extended use, embedded titanium anodes, coated with precious metals or conductive ceramic coatings, are normally used.

Conductive coating systems are either based on thermally sprayed zinc or conductive paint. The organic-based conductive paint is generally water-based and loaded with graphite to provide a current pathway. Conductive, connections, surface-applied overlays are also available and these normally contain carbon fibers and/or graphite in sufficient quantities to provide a continuous conductive pathway for current. The resulting coating is lightweight and has mechanical and thermal properties similar to that of concrete. However, coatings and overlays are not normally used on heritage structures due to aesthetic constraints.

For **titanium-based anodes**: titanium on its own is unsuitable as it readily oxidizes in the air and especially when acting as an anode. It builds up an electrically resistive barrier. Platinum, or a conductive ceramic mixed metal oxide (MMO) coating is therefore applied to substrates to give a low resistance layer to emit the current. Platinum is expensive but the MMO coatings are cheaper and those coated anodes are now available as mesh, ribbon or wire. These are suitable for supplying high currents (up to 110mA/m^2) and have a reported lifetime on excess of 75 years. Mesh is typically used to provide

protection to large areas of reinforcement in concrete, whereas ribbon and wire may be used in the joints between stones and bricks to provide protection to horizontal and vertical iron and steel members.

However, this protection may not be provided in the few cases where in very strong reducing acid conditions (e.g. in concentrated sulphuric and hydrochloric acids and hydrofluoric acid) the oxide film on titanium is attacked and cannot be maintained or restored.

Stand-alone (or discrete) anodes, comprising MMO coated titanium rods, are also available. These are also suitable for supplying large currents ($800mA/m^2$) and have an estimated life of 300 years. There are often more expensive than the surface mounted MMO coated anodes. The discrete anodes may be linked together using titanium wire and are commonly used where deeply embedded metalwork is to be protected or where surface-mounted systems are inappropriate. The discrete anodes are placed in pre-drilled holds on either side of the embedded metalwork using either a carbon loaded backfill or cementicious grout to fix them in. The titanium connection wires are hidden in the joints and repointed.

The design of a CP system should also take into account many other factors including:

1. The surface area of iron or steel to be protected.
2. The resistivity of the masonry or stonework.
3. The distance and uniformity of the anodes to the embedded metalwork.
4. The service lifetime of the CP systems.
5. The aesthetic of the building.

5. Case Study

5.1 Buried metal cramp conservation in the Inigo Jones Gateway, Chiswick House grounds,London(Keith Blackney and Bill Martin)

The Inigo Jones Gateway which is in the parkland surrounding Chiswick House, and English Heritage property in London, has been at least three different restoration attempts. This stone gateway was designed by Jones in 1621 and the flanking walls were most probably added in 1738.

Figure 15 The Inigo Jones gateway

By 1990 it was considered to be in such poor condition that action needed to be taken to address the main causes and symptoms of deterioration, something which the previous interventions had

signally failed to achieve. These interventions had only served to compound the decay mechanisms. One of the most serious threats to the stability of structure, in common with so many historic buildings, was the corrosion of metallic cramps embedded in the masonry. The accepted practice of cutting out or dismantling to remove such fixings was not considered appropriate and instead a method of nondestructive electrochemical rehabilitation, ICCP, was explored and developed for use on the structure.

5.1.1 Survey

In 1990 a survey was commission by English Heritage to assess the condition of the gateway and to provide suggestions for remedial treatment. The survey identified three main forms of decay affect the Bath stone structure.

1. The **decayed surface** of the Bath Stone gateway. The build-up of dirt and the deposited material on the wall had resulted in the formation of skins of calcium sulphate, the product of the reaction of the calcium carbonate of the Bath stone with the sulphur dioxide and trioxide in the urban atmosphere.

2. **Erosion of the stones**. Hard repair mortars had been used in areas of previously deteriorated work. Because of the impermeability of these repairs and the difference in density between them and the surrounding stone, the soluble salts present in the stone at the time of treatment, were either entrapped behind the patches, where they acted on the underlying stone to produce zones of deeply-seated erosion, or they acted on the stone surfaces at the edges of the repairs.

3. **Iron cramps rusting.**

Impulse radar (IR) was selected to be the survey method. IR

indicated that not only the location of metal fixing but it would also give a good indication of their condition and effect on surrounding masonry.

The Inigo Jones gateway was divided into horizontal survey lines along joints between ashlar and where possible through the center of each stone.

The results of using of IR were as following:

- precise dimensional relationships of the structure
- a range of fixings, cramps and dowels relationship of core to block formation
- locations and conditions of cramps
- type and orientation of cramps
- cramps depths were also given
- non-metallic fixings and areas of non-metallic wire armature
- Micro-cracks in the masonry
- block depths

5.1.2 Repair strategy

1. ICCP installation

English Heritage considered that in principle it would be possible to cathodically protect wrought iron, the main metallic material for cramps and dowels, and that brick and limestone would carry sufficient moisture to enable the even distribution of protection current. Also a system of keyhole surgery was advised to make the cable-to-iron connection. The criteria for this system were:

- To be electrically can mechanically sound

- To connect a small diameter wire to an embedded cramp at

230mm depth using a working envelope of a 10mm diameter hole.

- To be suitable for use (even if some further development were needed) during a large ICCP installation.

After a site testing, the redesign used information gained from the various site surveys which suggested that cracking and damage to the stonework was localized mainly, not unexpectedly, around the cramps located close to the surface. Five cramps on the south elevation and nine on the north elevation were selected to take the ICCP treatment. Monitoring would be achieved by placing five reference electrodes at selected locations. Two-pieces anodes would be placed on either side of the cramps. The DC negative and positive connections would be in a ring main configuration with cramp and anode connections being insulated with double layer mastic filled heat-shrink sleeving. Individual reference electrode cables were taken back to the monitoring panel on the transformer rectifier, sited in the house.

2. **Repair to deteriorated render and repairs to stone works**.

This part included replacements of a small number of selected stones and rebuilding of the previously collapsed section beneath the pediment and the repointing od the holes and chases resulting from the ICCP installation.

3. **Cleaning, consolidation and sheltercoating of the stone surfaces.** The cleaning of the stone and render surfaces was accomplished using a Microparticle system from Jackson and Cox Ltd. This is a dry air-abrasive method using aluminum oxide particles with a range of 17-20 microns. The blasting media is

expelled from the nozzle at various angles or vortices onto the stone surface. This visual level of cleaning decided upon was a general reduction of the black sulphate layers.

5.1.3 Conclusion

The successful application of the cathodic protection at Chiswick has demanded a multi-disciplinary approach, combining practical expertise in metals and masonry conservation practice with materials science and modern technology transfer skills. The low levels of structural intervention achievable through the use of this keyhole surgery may provide am answer of the thorny problems associated with rusting ferrous metal in historic constructions, be they stone, brick or concrete. Perhaps the greatest challenge in historic masonry structures terms is providing ICCP for iron cramps embedded in lead. Theoretically possible, this area will require further research in order to ascertain both levels of effectiveness and potential preferential corrosion.

5.2 Barcelona Cathedral

Figure 16 Cathedral

5.2.1 The façade

Barcelona Cathedral (Catedral de Santa Eulalia de Barcelona) the Gothic cathedral seat of the Archbishop of Barcelona, Spain The cathedral was constructed throughout the 13th to 15th centuries on top of a former Visigothic church. The Gothic-like façade is from the 19th century.

The Neo-Gothic façade is 40 meters wide, consists of home flanked by two towers with high pinnacles, is adorned with all kinds of elements of Gothic style of vertical lines and with great profusion of images and saints.

The Dome, designed by architect August Font I Carreras has a height of 70 meters and took place between the years 1906 and 1913. The exterior of the dome base crown concludes with the image of St. Helena, mother of Constantine, who was said to rediscover the true Cross, dedicated to the cathedral along with the Santa Eulalia, this

sculpture was done by the artist Eduard Alentorn. In the endings of the peak there were image of winged angels.

5.2.2 Current condition of the façade

By visual inspection, it is easy to see some cracks on the façade and the pinnacles. Since the façade was built in 19th, at time used the metal to build the façade and dome. In the passing of the years, combined with atmospheric changes, has meant the iron has rusted. This has caused the stone to expand, producing cracks and eventually leading to pieces breaking off.

Figure 17 The rust cramp

Figure 18 The rust cramp

Figure 19 The crack on the pinnacle due to the metal corrosion

Figure 20 The corrosion of the metal elements.

Figure 21 The corrosion of the steel components

Figure 22 The support of the dome.

5.2.3 Repair

The repair works have already begun from 2006. Two main purposes are concern:

1. Cleaning: Result of pollution, the build-up of dirt cover the splendor façade. Removing the dirt can probably prevent the reaction between the calcium carbonate of masonry with the sulphur dioxide and trioxide in the urban atmosphere.

2. Replacement: Because the original metal corroded very serious, the rust metal inside the façade are replaced with similar materials.

5.2.4 Recommendation

Replacement is a way for the materials which are in very serious deterioration situation, but base on the conservation principles of heritage structures, we should try to keep more original as much as possible.

Since the cathodic protection method has started to apply on the historical heritage for almost 20 years and got good results, then it may be able to be considered to use on Barcelona Cathedral.

6. Conclusion

As the preservation and reuse of historical buildings increased dramatically in the 1980s and into the last decade of the 20th century, however, some new technologies have become available for treating historic building materials, including metals.

Corrosion is a common problem for metal. Corrosion is the deterioration or breakdown of metal because of a reaction with its environment. The restoration methods of corrosion would be the traditional ways like welding, dowels and metal stitched. A modern method, cathodic protection, is applied on stone clad steel framing in 1991, and now already have more application on the historical heritages.

Repair and replacement are usual methods for metals and now the modern technical treatments, like cathodic protection, are applied to restore the historical metal components also. New materials, like titanium and epoxies, have been instead of the original or similar ones. Traditional and modern methods don't conflict with each other, but need to investigate and evaluate the corrosion problem before the conservation works.

According to Roberto Pane (1950), the extreme variety of cases and the need for safeguarding a large amount of monuments shows that restoration can not be constrained within stiff limits. Depending on the historic and cultural value and the budget, either the original materials and construction methods will be used or it will be necessary to resort or the use of modern materials and modes of connection. However, the new construction must be blend with the old with regard to size, scale and appearance.

Reference

· Bill Martin, The Application of Cathodic Protection to historic Masonry Structures, Building conservation team, 2004

· Bob Capudean, Carbon content, steel classifications, and alloy steels,2003

· Corrosion Control" NAVFAC MO-307 September 1992
D.K. Doran, Construction Materials Reference Book.1992

· David Farrell, Kevin Davies, Practice Aspects of Cathodic Protection for the Conservation of Iron and Steel in Heritage Buildings, Rowan Technologies Ltd.,2001

· Ebbing, Darrell D., General Chemistry, 3rd ed, Houghton Mifflin, 1990
G.G Nieuwmeijer & G.J. Arends ,The maintenance of historic iron and steel structures: repair techniques, 2003

· Hill, John W. and Kolb, Doris K., Chemistry for Changing Times, 9th Ed., Prentice Hall, 2001

·http://hyperphysics.phy-astr.gsu.edu/Hbase/chemical/corrosion.html, May, 2008

· http://www.r-f.com/metal_stitch_repair.asp, June, 2008

· http://www.wrought-iron-crafts.com/techniques-of-restoration.html, July, 2008

· Iain Mccaig, Kevin Davies, David Farrell, Cathodic Protection of Iron and steel,2001

· John G. Waite,   The Maintenance and Repair of Architectural Cast Iron,2001

· Keith Blackney, Bill Martin, The application of Cathodic Protection to historic Buildings., 2001

· Margot Gayle David and John G. Waite, Metals in america's historic buildings,1998

· Recognizing Metals and their Corrosion Products,Bart Ankersmit, Martina Griesser-Stermscheg, Lyndsie Selwyn, and Susanne Sutherland, 2008

· Steven F. Daily, Steven D., Somerville, P.E., Using Cathodic Protection to Control Corrosion of Masonry Clad Steel Framed Buildings, Corrpro Companies, Inc., 2007

· The Ohio Department of Natural Resource Division of Water, Dam Safety: Problems with Metal Materials,2001