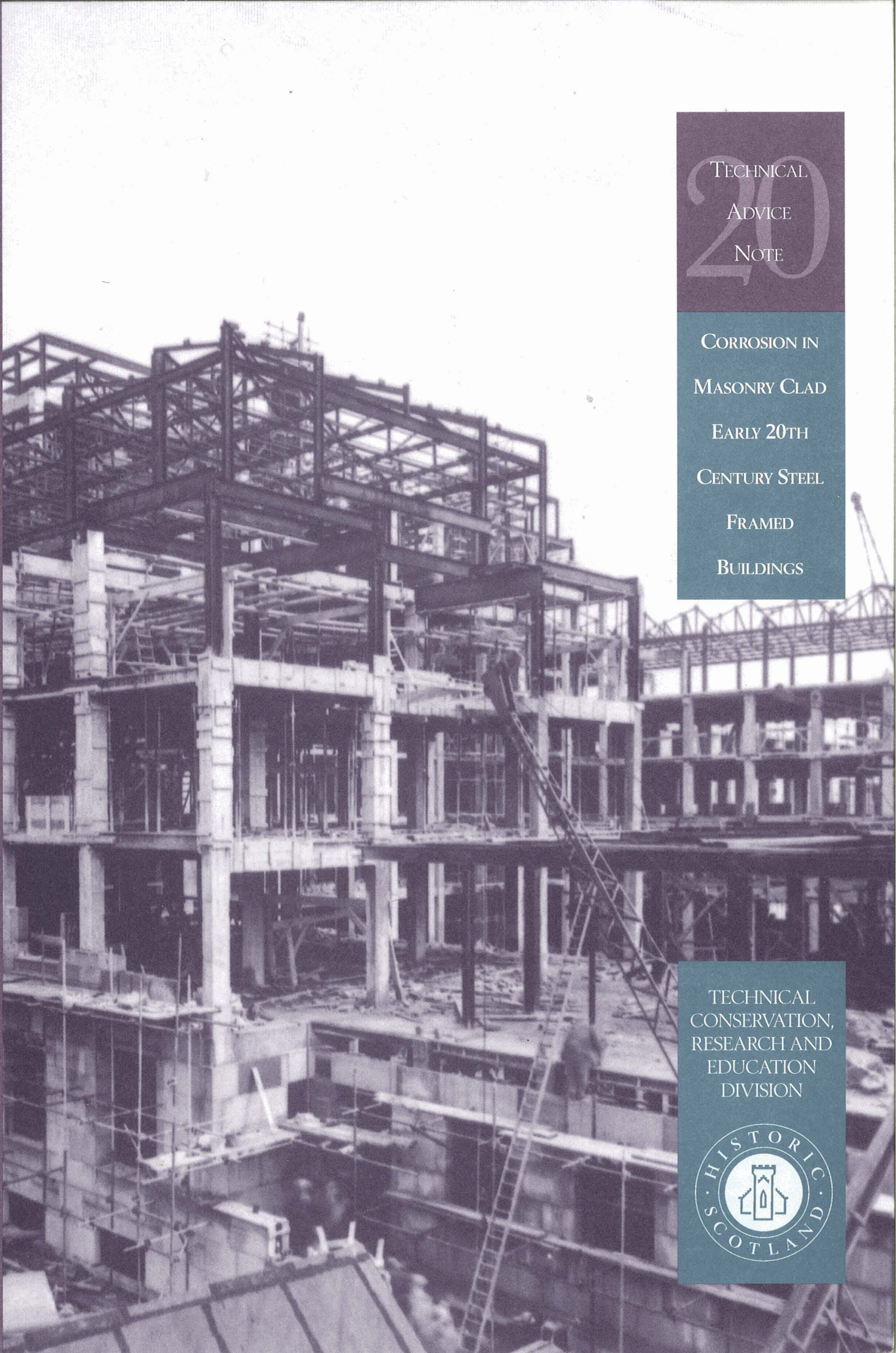
TAN 20

Corrosion in Masonry Clad Early 20th Century Steel Framed Buildings



Technical Advice Note 20

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Technical Advice Note

Corrosion in Masonry Clad Early 20th Century Steel Framed Buildings

by

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Figure 13 : Adapted from Abb2.8, "Dritter Bericht über Schäden an Gebäuden"; Bundesministerium für Raumordnung, Bauwesen und Städtebau, Bonn; 1996.
Figures 54-58: Warland; "Modern Practical Masonry".

PREFACE

This Technical Advice Note is part of an on-going series of notes on practical and technical issues which arise in the care and conservation of historic buildings. They provide guidance on the principles involved in a particular issue and are not intended to be used as prescriptive documents or used as specifications on site.

Rather than model specifications, the intention has been to provide an introduction to the subject of corrosion in masonry clad steel framed buildings (excluding housing) constructed in Scotland, England and Wales during the first half of this century. This was a particularly important era marking the departure from traditional load bearing structural masonry designs to now commonly used skeleton frame and curtain wall cladding constructions.

This note draws together existing information on current methodologies used in the repair of corrosion, it also presents information on newer technologies and more appropriate methodologies for the repair of historic buildings. The principles described are generally applicable to all types of cladding materials. This document should assist those involved in the repair of traditional buildings to draw up appropriate specifications and implement appropriate working practices for the particular situations with which they have to deal.

Professional advice and supervision of the type of work described within this document should be sought from material suppliers, Structural and Civil Engineers, no matter how comprehensive the specification and repair strategy. They should have a sound working knowledge of corrosion in masonry clad steel framed buildings and should also be aware of the principles of building conservation.

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Technical Conservation, Research and Education
June 2000

ILLUSTRATIONS

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1. EXECUTIVE SUMMARY

The cracking, displacement and spalling of stone and masonry due to the corrosion of steelwork is becoming increasingly common in steel-framed buildings constructed during the first half of the 20th Century. This is a serious condition that not only results in significant deterioration and loss of the original façade, but also necessitates both costly and disruptive methods of treatment.

It is currently typical to find between 2–10 mm of corrosion product on structural steel members and greater levels of corrosion are not uncommon. As 'rust' often occupies a volume greater than seven times that of the consumed steel these levels of corrosion do not usually represent a structural problem. The expansive nature of the 'rust' production, however, results in the creation of large stresses that cause cracking, displacement, or even spalling of the external façade, (Figures 1 and 2). In exceptional circumstances greater levels of corrosion can occur and structural problems have been found to exist. In these cases specialist strengthening and/or steel replacement is required in addition to general corrosion protection and façade repair.

Many buildings of this era are now listed, or are located within conservation areas. Their repair necessitates careful and sympathetic consideration of both the engineering and conservation requirements of the building. This TAN therefore describes the causes, problems and consequences of corrosion in some detail and sets the foundations for effective but sensitive methods of repair. Importantly, avoidable corrosion problems are presented and the need for carefully planned preventative maintenance is discussed in some detail.

As they develop behind the façade, corrosion related defects can remain undetected by the untrained eye, and even experienced surveyors may fail to appreciate and recognise the early stages of corrosion. This report therefore aims to provide generic information on typical defects related to steel frame deterioration and set the foundations for survey and inspection. Additional information is also provided on current methods of maintenance and repair that can be applied to halt or significantly retard the early stages of corrosion and prevent the development of further problems.

Figure 1. Cracking and stonework displacement due to corrosion of the underlying steel column.

Figure 2. Large stone spall due to corrosion of the steel column. Cases such as these are clearly a potential safety problem and detailed investigations and remedial actions are required to prevent reoccurrence.

Although primarily aimed at listed buildings, or buildings within conservation areas, the standard information and philosophies of repair and preventative maintenance equally apply to non-listed buildings. However, it is important to recognise that this TAN is only intended for use as a guide in conjunction with appropriate expertise since building-specific differences can occur from a number of non-quantifiable factors. Typical factors that can significantly change the general guidance may include past repair history, unrecorded or non-quantifiable external influences such as bomb blasts, the addition of air conditioning or insulation, and many more.

Many types of masonry facings were used in the construction of early 20th Century steel framed buildings, and include:

- Stone
- Brick
- Glazed brick
- Terracotta
- Faience
- Glass and vitrolite

Despite all the above types of facing materials similar methods of construction were employed in early designs and most building details are in general accordance with E.G. Warland's book 'Modern Practical Masonry' published in 1929. This reference text must be considered an essential tool for any practitioner in the field of steel framed building repair. However, it is always important to recognise that with any large building, small differences or problems may become evident due to the quality of the design, supervision and work force at the time of construction.

The bibliography at Annex C provides sources of particular guidance and advice that compliment the presented discussion of corrosion.

2. HISTORICAL BACKGROUND

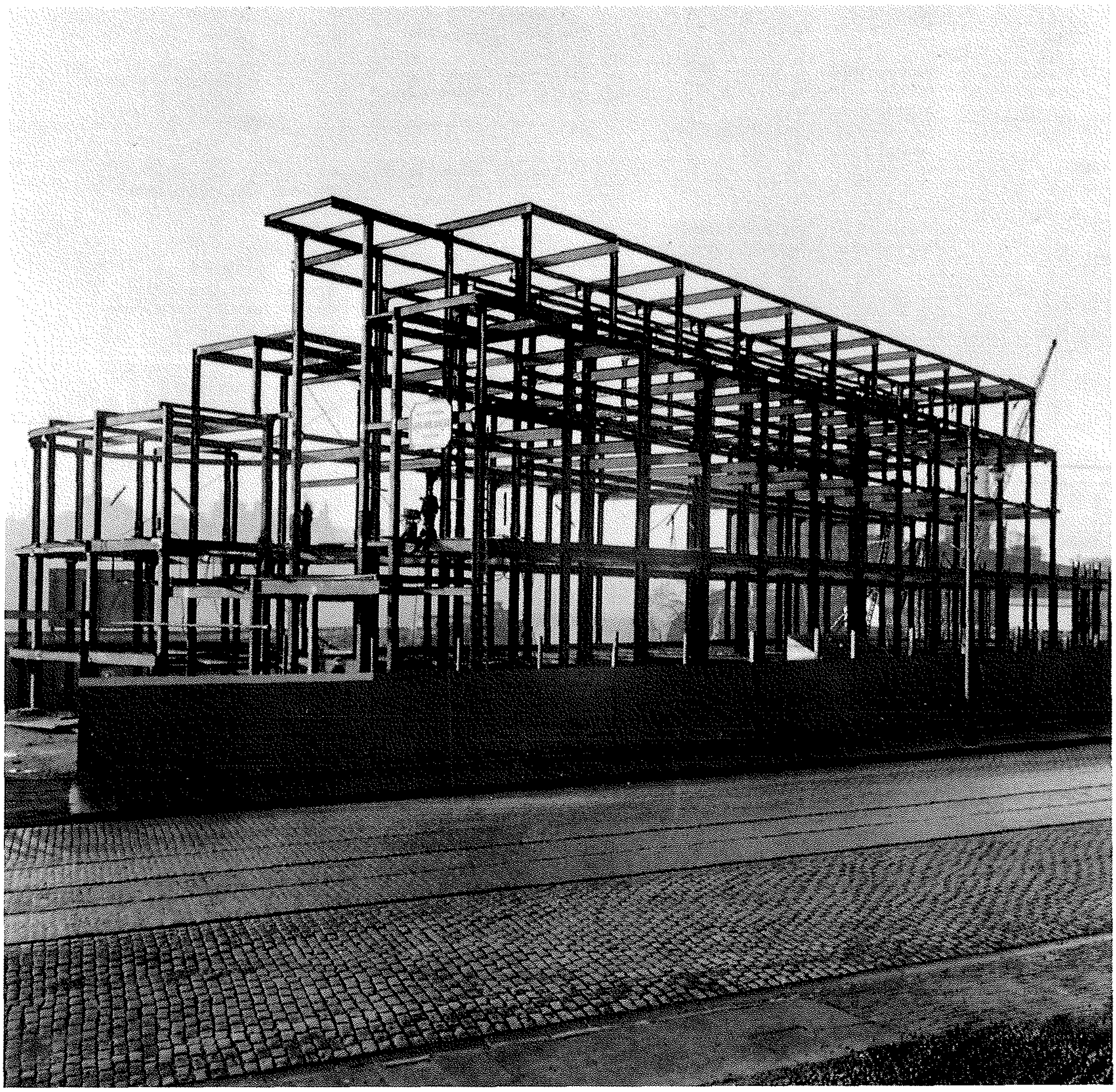


Figure 3. The structural steel skeleton frame typical of buildings constructed between 1909 and 1939.

2.1 Introduction

The exploitation of ironwork in bridge designs began in the latter half of the 18th Century and its suitability for the rapid construction of large structures soon became recognised, (Table 1). Cast iron technology quickly established itself in the UK and its inevitable integration into building design occurred in the mills of the late 18th Century, where columns and beams were utilised to support floor loads. Iron and steel technology steadily developed during the 19th Century and between the late 19th and early 20th Century the first steel skeleton framed buildings evolved, Figure 3. This was a major event in building technology and the steel skeleton frame marked the end of traditional self-supporting masonry designs for medium and high rise buildings. With the load of the stone or masonry carried by the structural steelwork the many obvious advantages of thinner and lighter masonry were quickly exploited. The numerous advantages that the

Table 1: The development of Iron and Steel in UK Construction

Date	Cast Iron	Wrought Iron	Steel
1753	Bonawe Iron Furnace, Argyll		
1776	First cast iron bridge over the Severn at Coalbrookdale		
1792	William Strutt's Mill, Derby uses CI columns.		
1796	Beams used by Charles Bage Ditherington Flax mill at Shrewsbury.		
1808	Broadford Linen Works, Aberdeen (Oldest surviving iron frame surviving in Scotland).		
1849		First rolled 'I' beams prod. in France	
1850	Becomes popular in commercial buildings in USA based on UK and French technology	Plated beams become popular in commercial buildings in USA	
1851	Crystal Palace constructed with a composite CI and WI frame.		
1857		First rolled 'I' sections in USA	
1856			Bessemer Steel making process invented (acidic)
1858	Four storey Boat Store by G.T.Greene, Sheerness first skeleton framed building.		
1868			Siemens Open Hearth steel making process invented (Basic)
1877			Board of Trade Regulations allow steel for bridge building
1882			First steel beams rolled in Scotland by Redpath Brown & Co.
1882			Forth Bridge first all steel structure in UK
1883	Wylie and Lockhead Building, Glasgow cast iron column and wrought iron beam construction in Scotland.		
1884	Home Insurance Building Chicago considered as the first true skeleton framed building. Frame consists of cast-iron (CI) columns and wrought iron (WI) beams, and Bessemer steel above the sixth floor.		
1886			First steel beams rolled in England by Dorman Long & Co.
1889			Both Dorman, Long & Co. and Redpath Brown & Co. open specialist construction departments and produce reliable information
1890			Chamber of Commerce Building, Chicago, USA considered first true steel framed building.
1893		Wrought iron increasingly replaced by steel	
1895			Jenners, Edinburgh first building in Scotland using steel beams and built-up angle section columns.
1899	End of non-framed construction in USA. USA Archive Building last major building in New York with load bearing masonry walls		Royal Insurance Building, Liverpool first steel framed building in Britain.
1903			Steel beams standardised in BS4
1904	End of cast in iron skeleton frames in USA with the collapse of the Darlington Apartments, USA, during construction.		Scotsman Building, Edinburgh, first Scottish building using rolled steel columns
1905			First Steel framed building in London (load bearing walls). Ritz Hotel, London
1906			First substantial steel framed building in Scotland. Forsyth's, Edinburgh
1908			Selfridges, London marks the move towards a fully load bearing frame in Britain
1908			Northern Assurance Building first steel framed building in Glasgow
1909	First early composite (CI and WI) skeleton frame buildings demolished and inspected e.g. Tower Building, New York, USA Reports indicate corrosion of frame due to moisture ingress		LCC building Acts first regulations in UK to recognise steel frame construction methods Acts changed due to pressure from the construction of Selfridges Department Store, London.
1920s			Steel frame construction methods widely accepted throughout UK.
1930			LCC Acts change regarding steel frame construction and height restriction removed.
1939			WWII and end of steel frame construction boom
1945-1970s			Steel frame methods are increasingly replaced in favour of concrete frames.
1970s			Steel frames become increasingly popular with thin stone cladding.

steel frames offer over self-supporting masonry are still exploited today and include taller buildings, rapid construction and greater architectural freedom, such as the creation of large openings.

2.2 The Development of Skeleton Frames

The construction of the Home Insurance Building, Chicago, by William le Baron Jenney in 1884-5 marked the development of steel frame construction techniques and the modern era of multi-storey buildings. Regarded as the first skeleton framed building, the top six of its ten storeys utilised a Bessemer steel cage with the lower frame adopting cast iron columns in combination with wrought iron beams. However, the full load bearing potential of the frame was not exploited in this early design and the skeleton frame was independent of its load bearing masonry walls. Construction of the Chamber of Commerce Building, Chicago in 1889 marked the next major step towards modern steel frame designs. The structural frame now carried all loads without the need for structural masonry.

As steel frame construction methods developed in the UK, British engineers, architects and publicists looked to the development of skyscrapers in America, where more often than not, the frames were of hybrid construction consisting of wrought iron, or steel, beams spanning cast iron columns. Steel framing in France and Germany on the other hand had evolved as a natural progression from cast iron and wrought iron framing (e.g. Menier Factory, Noiseul, 1872-4) and British engineers and architects also looked to the continent for comparison with American technology.

2.3 Cast Iron

The use of metal-framed construction methods in multi-storey buildings was not new to the UK. Cast iron construction methods were first developed in Britain with the construction of the Ditherington flax mill, Shrewsbury, in 1796 with cast iron columns and beams. The technology also developed rapidly in Scotland where the oldest surviving example is now the Broadford Linen Works in Aberdeen, 1808. The walls of these textile mills were load bearing, but as mills became deeper, the degree of load applied to external walls gradually diminished. Cast-iron façades and frames developed from the early mill designs and were first adopted in Glasgow commercial buildings in 1855-72, reaching an apogee at James Watt Dock, Greenock in 1885.

2.4 Wrought Iron

The progression of combining wrought iron beams and cast iron columns began in the United Kingdom in the 1850s. However, the technology did not accelerate to any appreciable level in commercial buildings such as department stores and hotels until the 1880s, e.g. Wylie and Lochead's (Frasers), Glasgow in 1883.

2.5 Steel

The invention of the Bessemer steel making process in 1856 had little impact on the British construction industry because it did not suit British phosphoric ores, although small quantities of steel were imported and used from the continent. Price also limited the use of early steel produced with the Basic Open-Hearth processes suitable for British ores in 1868 with the first steels generally retained for the rail and shipping industries. It was not until 1879 that the first mild steel beams were rolled in Scotland by Redpath and Brown and Company and later in England by Dorman Long and Company in 1886. Shortly after production of the first rolled beams construction on the world's first major steel structure, the Forth Bridge, began in 1882 by the Glasgow contractors, William Arrol and Company.

The first buildings containing structural steel in Scotland included Coat's and Clark's thread mills in Paisley of 1886-9, and most distillery malt barns of the 1890s. These buildings still utilised cast iron columns, but rolled steel girders replaced the use of wrought iron beams. Jenners in Edinburgh, 1893, was probably the first building in Scotland to completely use steelwork with rolled floor beams connected to cruciform stanchions built up of angle sections. This was later followed in Edinburgh by The Scotsman building, designed by Dunn and Finlay in 1898 (built 1899-1902) and was the first Scottish building to have continuous steel stanchions to which the steel girders and joists were riveted. However, the frame of The Scotsman building had load bearing external walls and it was not until 1906 with the construction of Forsyth's (now Burton's) in Edinburgh designed by J.J. Burnett that the first substantial steel-framed multi-storey building in Scotland had steel stanchions present in the external walls. In Glasgow similar developments took place with the first full steel frame building being the Northern Assurance Building 84-94 St Vincent Street, in 1908-9.

Outside of Scotland other key buildings that introduced the steel frame to Britain were: the Royal Insurance Building, Liverpool by Norman Shaw and J Francis

Doyle, designed in 1895-6, occupied in 1900 and completed in 1903; and furniture warehouses for Mathias Robinson in Hartlepool and Stockton on Tees, variously dated at 1896, 1898 and 1901, built by Redpath and Brown of Edinburgh. The Westinghouse Works at Trafford Park, Manchester and the Singer Factory in Clydebank were also pioneers of steel framing with continuous steel stanchions.

There was therefore a pedigree to the commonly noted Ritz Hotel (1904-5) and Selfridges (1908-9) buildings in London which led to the acceptance of the London Building Act of 1909, the first document of importance that covered steel frames and non-load bearing walls.

2.6 The Steel Frame Era

Between 1909 and 1939 steel frame construction methods became highly popular, and numerous buildings were constructed in all major cities and towns of the United Kingdom. A wide ranging variety of cladding was used in these early buildings which included stone, bricks, terracotta, faience and their various combinations. However, despite the large variety of cladding the general methods of design and construction were largely similar.

2.7 Steel and Corrosion

Unfortunately, during the development of steel framed buildings British engineers and architects of the period did not fully appreciate the destructive nature and risks of corrosion in steel framed buildings. At that time, it was often assumed that the cladding surrounding the steelwork (often exceeding 150 mm in thickness) would prevent moisture ingress and avoid corrosion problems. Even in America, the problems of corrosion were not fully understood, publicised or addressed, although problems had become evident in the late 1800s. George Post, an early American designer of steel cage buildings had even questioned the design life of a steel structure embedded in masonry as early as 1894. Post was particularly concerned with the move towards thinner cladding which offered a minimal cover of only four inches as from experience he had found it necessary to remove corroded beams from brickwork encasement. However, despite these early concerns American building codes, such as the 1892 New York Building Code, allowed the thickness of cladding systems to reduce to four inches. Even later forensic investigations of pioneering American buildings failed to fully highlight the potential for corrosion related problems. For example, a 1914 demolition study of the Tower Building, New York, constructed in 1888 noted severe corrosion but dismissed it as being due to a defective flashing. Unfortunately, the causes of steel frame corrosion are not as clear cut as mentioned in these early reports. Moisture penetrates the structure from a wide variety of sources that include the porosity of the cladding, cracked joints due to a lack of expansion joints, condensation, etc.

3. CONSTRUCTION OF STONE-CLAD STEEL FRAME BUILDINGS PRIOR TO 1940

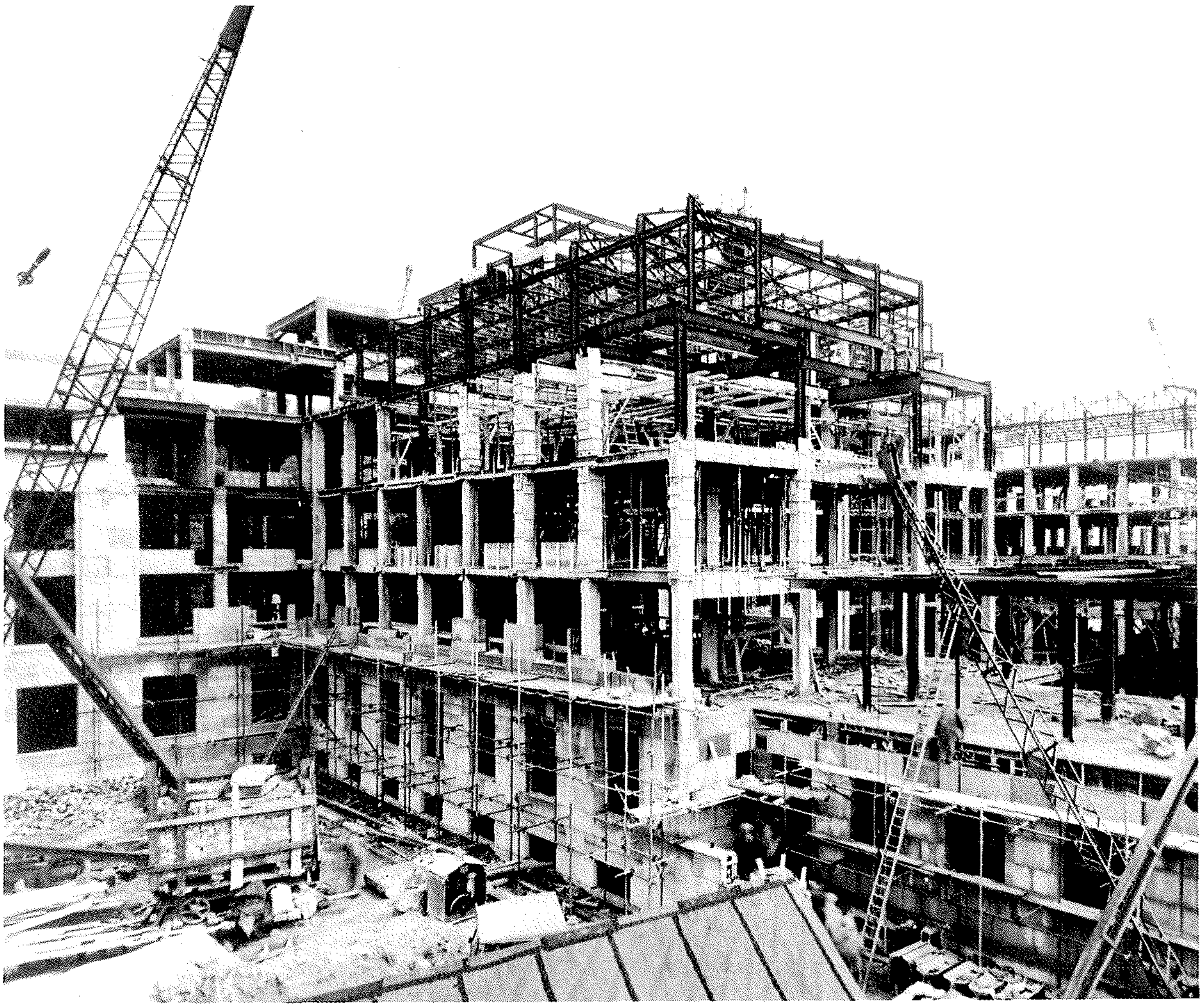


Figure 4. The construction of St Andrews House, Edinburgh. The steel frame, concrete encasement of the steelwork and the addition of stonework can be identified as construction progresses.

3.1 Introduction

The use of traditional masonry, where stones, blocks or bricks were laid in courses or in random fashion to take all loading from floors, walls and roofing had been around for centuries. The first departure took place in UK commercial buildings in the late 19th Century with the introduction of iron and steel frames to take the loads, with masonry or other in-fill material providing the aesthetic weatherproof envelope.

As the two different technologies were integrated it was common to find the first buildings constrained by conservatism and concern and the early steel frames were in-filled with fully supporting structural masonry. It was only after 1909 that full use of the structural steel frame was used to carry all service and environmental loads and the walls became cladding supported by the frame, Figure 4.

3.2 General Construction

The buildings covered in this TAN represent the transition between structural masonry and modern curtain wall designs utilising thin stone cladding. In

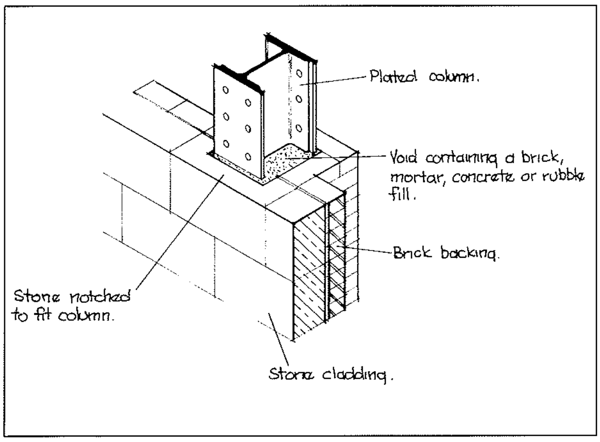


Figure 5. External cladding notched around steel frame column.

these buildings the relatively thick external cladding was notched to fit around the structural steel frame and held in place using a low grade mortar as indicated in Figure 5.

Physical fixings to hold the external cladding to the steel frame and inner brick lining were not widely used in pre-1939 steel framed buildings and are often only found where they were thought to be absolutely necessary, such as on projecting cornice features etc. The mortar in-fill was therefore intended as an adhesive material (but also for fire protection) to physically bond the outer and inner leaf of the building together.

3.2.1 Mortar In-fill

The quality, type and application of mortar in-fill between the steel and external facing material varies greatly both between buildings, and within a single building. However, despite the variability it is found that in-fills were generally composed of a wet mix containing varying quantities of cement, sand and brick rubble fill.

As the stonework was notched to fit around the steelwork either prior to delivery, or on-site using hand tools, cracks were inevitably initiated in the stonework. Such cracks, introduced during construction can act as stress raisers, and as corrosion progresses lead to unusual failures. These cracks are not always in an easily explainable orientation but lie simply on a plane of weakness of the incipient crack.

On fitting notched masonry around the steel frame the stone mason would pour the wet mix into the resultant cavity. Little or no compaction was carried out prior to proceeding with the construction process, resulting in a large percentage of voids. It can also be found that where a cavity was difficult to fill (such as on stones notched around window head beams) in-filling is often incomplete, or inconsistent.

At the time of construction the in-fill grout and mortar would have provided some degree of corrosion protection to the steel members. This occurred through passivation of the steel surface as a result of the natural alkalinity of the mortar. However, due to the often porous nature of the mortar and inconsistencies in filling the steel/masonry cavity, corrosion could occur in these voids from an early stage, Figure 6.

There are two mechanisms which allow widespread corrosion of the steel frame due to moisture ingress through the in-fill mortar:

- expansive corrosion products forming in the in-fill voids which result in jacking away of any protective mortar from its original contact with the steel, leading to further corrosion;
- carbonation of the in-fill after a relatively short time following construction. This leads to a loss of the mortar's alkalinity which itself leads to a loss in corrosion protection.

3.2.2 Brick In-fill

The use of integral brick piers for fire protection of beams and columns was commonplace in the USA in the 1930s. Since there was active technology transfer between the USA and United Kingdom many pre and certainly post 1930s buildings show this style of fire protection. However, even as early as the 1890s it was known that this construction could result in corrosion problems. For example E.G. Warland stated: "Once water penetrates, the brick piers can hold it in direct contact with the structural steel such that layers of rust are eventually formed on the surface of the metal. The serious fractures in the stonework of pinnacles etc., which is stated to be due to decay, is often entirely due to the use of iron vanes or dowels."

3.2.3 Concrete Encasement

Concrete encasement of structural members was an alternative method to brickwork fire protection used in the 1930s. This method is also more favourable in terms of corrosion resistance. Although still able to trap moisture, the concrete encasement, due to its high alkalinity, protects the steel beam from corrosion by forming a natural passive layer on the steel surface. However, the natural protective qualities of the concrete encasement can deteriorate with time in certain conditions due to the chemical reaction between carbon dioxide, moisture and the cement termed 'carbonation'. The time period for carbonation and corrosion initiation in encased columns varies greatly between buildings and depends on factors such as concrete quality, depth of cover and the presence of barriers which halt the diffusion of Carbon Dioxide etc.

Figure 6. Mortar infilling and notched stonework around steel columns and beams. Note the large void at the plated connection due to difficulty in in-filling at the time of construction.

3.2.4 Clinker Concrete

Light weight concretes manufactured with coke breeze aggregates were commonly used in floor construction with the concrete either partially or fully encasing steel beams. The problems of rapid corrosion in these materials were understood as far back as 1937 and references of the time state the incompatibility of clinker or coal residue with steel (e.g. Bylander, Steelwork in Buildings, The Structural Engineer, Jan. 1937). However this technique was common before and even after 1937 and special considerations should be made where these materials are used.

Corrosion problems can occur in clinker concretes from the date of initial construction due to the acidic nature of some aggregates and the porosity of the concrete, (Figure 7). The rate at which corrosion occurs is directly related to the water content of the concrete, with moist concrete surrounding beams giving relatively high rates of corrosion. However, it is important to note that due to the very high porosity and low strength of the concrete a high level of expansive corrosion can be accommodated by the concrete before stresses are transferred to external masonry. Therefore, where clinker concretes are utilised, substantial levels of corrosion may have occurred leading to structural problems without any outward signs of deterioration.

Figure 7. Severe corrosion of this double 'I' section encased in clinker concrete resulted in internal spalling of the concrete and plaster.

3.2.5 Cavity Construction

In later buildings, and certainly in modern steel frames, a cavity is generally maintained between the stone and the frame. Fixings are used to support the cladding and a clear ventilation cavity is maintained to allow the drying out of any ingressing moisture. However, even here caution is advised as ventilation may not be adequate if large amounts of water are present. Also there are many locations, particularly at floor levels where the cavity may be bridged by major stone and brickwork supports, by insulation or by materials designed to inhibit the spread of fire and smoke between floors.

3.2.6 Waterproofing and Water Management

Waterproofing materials, including lead and asphalt applied to external surfaces such as the tops of cornices, can provide protection against ingress of falling rain or ponded water. But age and weathering causes degradation and delamination of such materials, allowing water to access the inner structure. Because such features can be difficult to inspect and are not directly in view they usually receive insufficient attention until damage has already occurred. Similarly, failure to ensure that gutters or downpipes run clear can cause water ingress by the overtopping of upstands or flashings. Where downpipes are constructed within the structure problems can be caused due to internal (and therefore unseen) damage sustained by building movements or by corrosion of the downpipe itself.

Corrosion can occur on all external wall beams and columns. However, the extent of corrosion will be dependent upon a large variety of factors which include the following:

- type and porosity of cladding;
- exposure of building face i.e. north, south, east, west, high or low level;
- microclimatic effects, e.g. weather shielding from other buildings;
- building details and design;
- thoroughness of maintenance and repair strategies;
- location of degraded services (rainwater goods etc.)

3.3 Porosity of Stone

The fallacy that stone cladding is impermeable to water has allowed damage to occur due to neglect or ignorance. In fact some stones particularly sandstones and limestones can act almost like a sponge in absorbing rainwater, and allow saturation.

In general, the more common cladding materials can be ranked approximately as below:

Material	Porosity(%)
limestone	17-23
sandstone	10-24
brick	2-10
marble	<5
terracotta	~1
faience	<1
glazed brick	(depends upon glaze quality)

Although higher porosity materials may be expected to allow the rapid ingress of water it must be remembered that low porosity or relatively impervious materials will trap water which is allowed to make contact with the steel frame. In the case of these materials however, water usually enters the structure through design faults and open or cracked mortar joints.

Mortar or lime putty bedding if incomplete or damaged by freeze thaw action etc. can allow water penetration. Where either of these is allied to severe exposure conditions, the results can be catastrophic. It is true that the stone/mortar combination must allow any moisture penetration to be lost by evaporation when external conditions allow. However, the balance between ingress and egress can be upset by inappropriate replacements or repairs such as cases where lime mortar pointing has been replaced by a cement mortar. Pointing should always be softer than the stone and the use of hard cement mortars generally have the effect of increasing rather than decreasing the risks of water penetration.

In the case of certain stone materials, especially sandstone, it is often found that a bitumescent paint may have been applied to the sides and back of individual stones to prevent staining from the internal brickwork wall. Where the sides and back of the stonework have been treated in this manner the following problems may occur:

- although the stone may appear to be porous, moisture can become entrapped in the in-fill mortar behind the water proofing paint system. As a result, moisture is held in contact with the steel frame for prolonged periods creating favourable conditions for corrosion;
- a poor bond exists between the pointing mortar and masonry resulting in a joint prone to failure and water ingress;
- water becomes entrapped within the mortar joint leading to rapid freeze thaw deterioration of the joint mortar;

- water is rapidly directed towards the steel frame in the resultant waterproof conduit as water is not absorbed by the surrounding stonework.

Intricate stone detailing and flat surfaces such as parapet copings can allow the collection of moisture, and the subsequent entry to the fabric due to stone being constantly wet; particularly on north-facing façades, or unprotected and exposed features.

Large cornices are often sloped inwards to the building, to avoid causing 'waterfalls' of rainwater onto the pavement beneath. While any waterproofing measures, such as asphalt and rainwater management systems (downpipes and gutters) are in good condition, the situation is contained. However, failure or cracking in asphalt due to weathering or building/thermal movements or vibration, can allow water to penetrate into the fabric of the building either directly through porous stone or open joints and reach the steel frame.

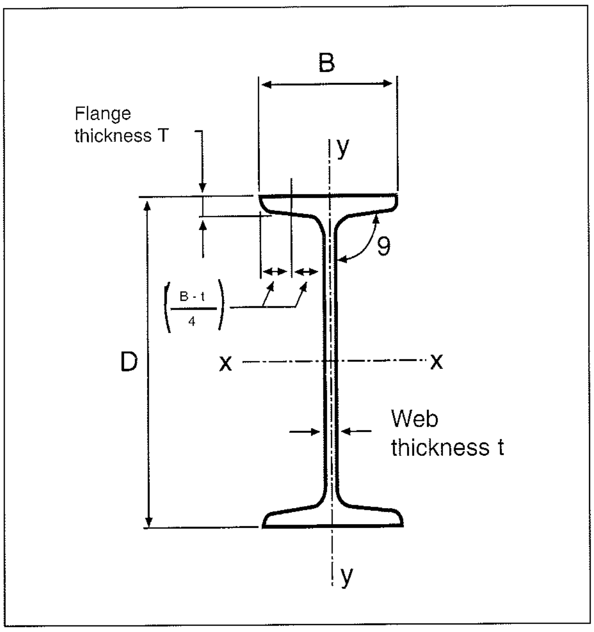


Figure 8. The standard BS4 section.

3.4 Steel Frames

3.4.1 Steelwork

Mild steel section sizes were first published in the Dorman Long handbook of 1887, and shortly after in the Redpath and Brown handbook of 1892. However, section sizes were not standardised until 1903 with the introduction of BS4, Figure 8 and Table 2. BS4 was later revised in 1921 and 1932.

As the majority of steel frame buildings were constructed after 1903, BS4 generally applies to the majority of steelwork in UK buildings. Therefore, if the date of construction is known BS4 can be used to calculate losses in beam section due to corrosion. However, it is important to recognise that non-standard beams were imported which do not conform to the standard. This is particular the case with broad flange beams rolled in the continent of Europe.

The strength of early mild steel was measured by its ultimate tensile strength (UTS), rather than the yield strength used for modern steels, and was specified as 28 to 32 ton/in^2 (435 to 494 N/mm^2). A safety factor of four was usually applied to the UTS value in design calculations to obtain the permissible stress. The UTS of steel is approximately twice that of its yield strength used in modern calculations. Therefore, by current standards a safety factor of two was used in these early design calculations. Although early steel frame buildings were generally over–designed, this factor should always be appreciated when carrying out corrosion and structural assessments.

The earliest steel frames were erected with riveted or bolted connections. Bolted connections were generally favoured for connecting steelwork sections, with rivets

Ref No.	Size D x B	Approximate Mass/Ft	Thickness Web	Thickness Flange
	Ins	lbs	Ins	
BSB1	3 x 1.50	4.0	0.16	0.25
BSB2	3 x 3	8.5	0.20	0.33
BSB3	4 x 1.75	5.0	0.17	0.24
BSB4	4 x 3	9.5	0.22	0.34
BSB5	4.75 x 1.75	6.5	0.18	0.33
BSB6	5 x 3	11.0	0.22	0.38
BSB7	5 x 4.50	18.0	0.29	0.45
BSB8	6 x 3	12.0	0.26	0.35
BSB9	6 x 4.50	20.0	0.37	0.43
BSB10	6 x 5	25.0	0.41	0.52
BSB11	7 x 4	16.0	0.25	0.39
BSB12	8 x 4	18.0	0.28	0.40
BSB13	8 x 5	28.0	0.35	0.58
BSB14	8 x 6	35.0	0.44	0.60
BSB15	9 x 4	21.0	0.30	0.46
BSB16	9 x 7	58.0	0.55	0.92
BSB17	10 x 5	30.0	0.36	0.55
BSB18	10 x 6	42.0	0.40	0.74
BSB19	10 x 8	70.0	0.60	0.97
BSB20	12 x 5	32.0	0.35	0.55
BSB21	12 x 6	44.0	0.40	0.72
BSB22	12 x 6	54.0	0.50	0.88
BSB23	14 x 6	46.0	0.40	0.70
BSB24	14 x 6	57.0	0.50	0.87
BSB25	15 x 5	42.0	0.42	0.65
BSB26	15 x 6	59.0	0.50	0.88
BSB27	16 x 6	62.0	0.55	0.85
BSB28	18 x 7	75.0	0.55	0.93
BSB29	20 x 7.50	89.0	0.60	1.01
BSB30	24 x 7.50	100.0	0.60	1.07

Table 2. BS4 Standard Beam Sizes.

Figure 9. 'Red Lead' paint systems as shown are generally rare in steel framed buildings. However, where used some corrosion protection is provided, especially in locations with voidage. In cases where a mortar connection exists between the frame and cladding corrosion protection is minimal and many such buildings now suffer corrosion problems.

being used for the production of plated and built-up column sections. Where riveted joints and sections are utilised the rivet diameter is generally 60% of the cuphead diameter and their shear strength is 5 tonf/in^2 (78N/mm^2) as specified in BS449.

Full structural welds were not used prior to 1940 due to the early problems in welding mild steel with gas fusion processes. As bolted and riveted connections were used, the skeleton frame can therefore be regard as a semi-rigid construction, especially as additional diagonal wind bracing was not utilised in early UK buildings. However, it is important to recognise that although small movements can occur in semi-rigid frames, for example through excessive wind loading, these are limited in UK buildings. Movement is significantly reduced in UK buildings due to their restricted height and the additional stiffness provided by thick tightly notched masonry cladding. Cracks and open joints observed in early buildings may be due to general building movements, or due to corrosion of the underlying frame.

Where fixings are used to hold stonework directly to the steel frame ordinary mild steel or iron was uncommon. Fixings were often made from bronze or hot dip galvanised steel (or iron) to provide corrosion resistance in stone joints, which at the time were known to be problematic areas.

Although these fixings were rarely isolated from the steel frame to prevent galvanic corrosion, widespread problems are not known to exist from this practice to date.

3.4.2 Corrosion protection

Steel Framed buildings built up to World War II, were largely constructed with common design features but with a variety of cladding materials. At that time the potential problems of steel frame corrosion damage were generally unknown or unconsidered, although it was known that embedded fixings close to external surfaces and in joint locations could cause corrosion problems. It was generally considered that the

Figure 10. Bituminous paint systems such as these are rare in steel framed buildings and provide little corrosion protection.

thickness of the external cladding would provide sufficient protection against the ingress of moisture and prevent corrosion problems. As a result, inadequate precautions against corrosion were taken during the design stage.

Although now seen to be inadequate, some protective measures against corrosion were advocated in legislation on early steel framed buildings. The LCC London Building Act 1930, generally adopted throughout the UK, required one of the following steel treatments:

- all structural metalwork comprised in the skeleton framework of a building shall be cleaned of all scale, dust and loose rust and be thoroughly coated with one coat of boiled oil, tar, or paint before erection;
- after erection of the frame one additional coat of boiled oil tar or paint should be applied;
- where metalwork is embedded or encased in brickwork, terracotta, stone, tiles or other incombustible material one coat of Portland cement wash of adequate consistency may be applied in lieu of coats of oil, tar, or paint.

Recent investigations into a number of buildings have shown the last treatment to be the most commonly applied. Although a Portland cement wash would have provided some initial corrosion protection to the steel frame, the effectiveness of the treatment was relatively short-lived.

The use of cement mortars and grouts assisted to some small extent in inhibiting corrosion due to the alkaline environment occasioned by the cement itself. However, because such mixes, particularly where a rubble/mortar combination was used, were generally not adhered to the steel members there is often a crevice between the in-fill and the steel allowing any moisture to penetrate and to collect. Additionally the in-fill was neither fully compacted nor consolidated. This practice allowed moisture paths to form through the body of the in-fill itself. After long periods any passivation effects were lost and corrosion took its course.

There are examples of buildings where a red lead, (Figure 9), or bituminous coating, (Figure 10), had been applied during construction. However, such examples are not common or typical of the genre as often stated.

The use of oil or tar treatments appeared to have been rare, possibly due to the additional expense involved in application. However, although this treatment could be expected to provide some additional corrosion protection, in one case it is known that serious structural deterioration of the frame occurred. The problem with oil tar treatments may be attributable to poor steel surface preparation and quality control in application. Additionally moisture and oxygen can penetrate poorly applied tar leading to corrosion.

3.5 Movement Joints

It was not until the 1950s that skeleton framed buildings contained movement joints in their outer cladding to accommodate thermal and moisture induced movement. Buildings constructed prior to 1950 are therefore more prone to movement induced defects such as the opening and cracking of mortar joints, or cracking of the cladding material. As these cracks and open joints act as ideal conduits for water transport, the inevitable problems of corrosion are thus directly attributable to the initial lack of movement joints. Movement problems are most commonly found on partly restrained details such as parapet walls and cornice features. In these locations joint deterioration occurs through a variety of simple in plane and complex out of plane movements leading to temporarily or permanently open joints. As these features suffer the greatest exposure to rainfall, the first indications of problems associated with corrosion of the underlying steelwork are usually seen in these locations.

Failure to include movement joints in early buildings resulted from a lack of awareness of the different requirements of structural masonry walling and load bearing steelwork with non-structural masonry. Early load bearing masonry was subject to lower levels of thermal movement (compared to steel framed masonry) due to the greater wall thickness, which generally exceeded 22.5in (570mm) for buildings 70ft (21.5m) in height. Additionally, small movements in traditional masonry walling were accommodated by the lime mortars used in their construction.

Although the cladding of early steel framed buildings often exceeded a thickness of 300mm, thermal stresses and movements are larger than might be anticipated. Recent tests in Edinburgh during the summer months have shown thermal gradient temperatures in excess of 45°C in sandstone buildings. These temperature rises were relatively rapid and reached depths in excess of 150mm within 1h of the surface temperature rise. Combined with the subzero temperatures in winter months seasonal temperature changes are therefore expected to exceed 50°C. The movement associated with a 50°C temperature change for stone materials represents approximately 0.5mm per linear metre of sandstone and 0.25mm per linear metre of limestone. Therefore, assuming a single ashlar joint 5mm in width, a movement of between 5 and 10% can be expected. As this level of movement is greater than a mortar can withstand, especially ordinary Portland cement (OPC) mortars, opening of the jointing is often inevitable.

In addition to thermal movements, certain materials are subject to movements associated with water absorption. This is particularly the case with materials produced from fired clay, such as terracotta and brick, which suffer permanent expansion due to water absorption after manufacture. Terracotta in particular shows a large number of problems due to its brittle nature and greater expansion due to water absorption movement. As this expansion was not accommodated through expansion joints, compression cracks are a common feature in this material which allow the penetration of water. Combined with the low porosity of the surface layer, which prevents moisture entering cracks from escaping, corrosion problems have been exacerbated.

The lack of horizontal compression joints also results in problems as the stone or masonry carry structural loads for which they were not designed. This effect, known as 'stacking', results from the frame load increasing with the height of the building during construction. As construction proceeded, the steelwork loads increased giving the intended beam deflections. However, due to the lack of compression joints, the beams deflected until they came to rest upon the masonry of the lower wall. On reaching this condition, the loads were partially transferred to the cladding. As each successive storey of the building exerted a load on the level below, an increasing load was carried by the external wall at progressively lower levels. As the external walls were not designed to withstand the resultant structural loads, compression cracking often occurred at lower levels, particularly at the base of large columns, resulting in moisture ingress and corrosion problems.

4. CORROSION

4.1 Introduction

Relatively low levels of steel corrosion result in the significant deterioration of stone or masonry façades due to the volumetric expansion of the corrosion products. Expansion is generally 7 to 12 times the original volume of the consumed steel, which results in the rapid stressing of stonework tightly notched and often directly in contact with the steel through a mortar connection. Consequently, corrosion damage occurs which manifests itself as either cracking, or the jacking away, of large stone blocks. Once damaged the façade can allow the penetration of significant levels of water resulting in accelerating corrosion rates.

The corrosion of steel is an electrochemical process in which the metal reacts with its environment to form an oxide or other compound analogous to the ore from which it was extracted. The electrochemical cell causing corrosion consists of an anodic area where the metal is corroded, the corrosive electrolyte such as damp stone or concrete, and a cathodic area which is not consumed but acts as a driving force for the corrosion process. The cathode may be a second or more noble metal in contact with the corroding metal, or it can be another area on the same metal surface. Anodes and cathodes are formed on a steel surface by a variety of mechanisms including: slight changes in steel composition, variations in temperature or the environment, or the connection of a dissimilar metal. These anodic and cathodic (positive and negative) areas are often unpredictable and can also shift and change as the corrosion reactions proceed and the environment changes.

For the corrosion reactions to take place it is essential that both oxygen and moisture are present simultaneously. In the absence of either corrosion will not occur. The corrosion rate is therefore dependent upon the levels and availability of oxygen and moisture and the extent will vary considerably with the site of exposure.

In general, the following main types of corrosion affect masonry clad steel framed buildings:

- uniform attack which appears as a general even rust layer on the surface of the steelwork. This is the most common form of corrosion found in the perimeter steelwork of masonry clad steel framed buildings and is due to a lack of steel protection or carbonation of the mortar or concrete encasement;
- pitting corrosion which is a localised form of attack and can lead to significant localised loss of steel section. This is generally uncommon in masonry clad steel framed buildings. However, it may be found on buildings in coastal regions and at ground levels where wind borne salt and de-icing salts may have penetrated the masonry cladding. In these cases chloride ions released by the salt cause rapid attack of the steel and can cause corrosion problems even when the steel is encased in good quality alkaline mortar or concrete.

4.2 Steel in Concrete and Mortar

In an alkaline environment the steel surface remains passive due to the formation of a stable oxide film and the steel will not corrode. Hydrated cement provides such an environment with the normal pH value often exceeding 12.5. However, moisture and carbon dioxide diffusing through the concrete, or mortar, results in a reduction in alkalinity through a process called carbonation.

Carbonation occurs due to the formation of carbonic acid in the cement pore solution which neutralises the alkaline calcium hydroxide present converting it to calcium carbonate. Initially the carbon dioxide is unable to penetrate deeply into the concrete/mortar surface because of its reaction with the calcium hydroxide in the surface layers. As the outermost layer becomes carbonated the depth of penetration of the carbon dioxide increases. This results in the reduction of the pH in a zone extending from the surface of the concrete/mortar, known as the carbonated zone. Eventually, the carbonation front reaches the steel surface, resulting in a loss of passivity and the initiation of corrosion.

The time scale for carbonation is variable and is a function of a number of factors. The major factors effecting the time to carbonation and hence on-set of corrosion in masonry clad steel framed building are the mortar (or concrete) quality, the masonry type

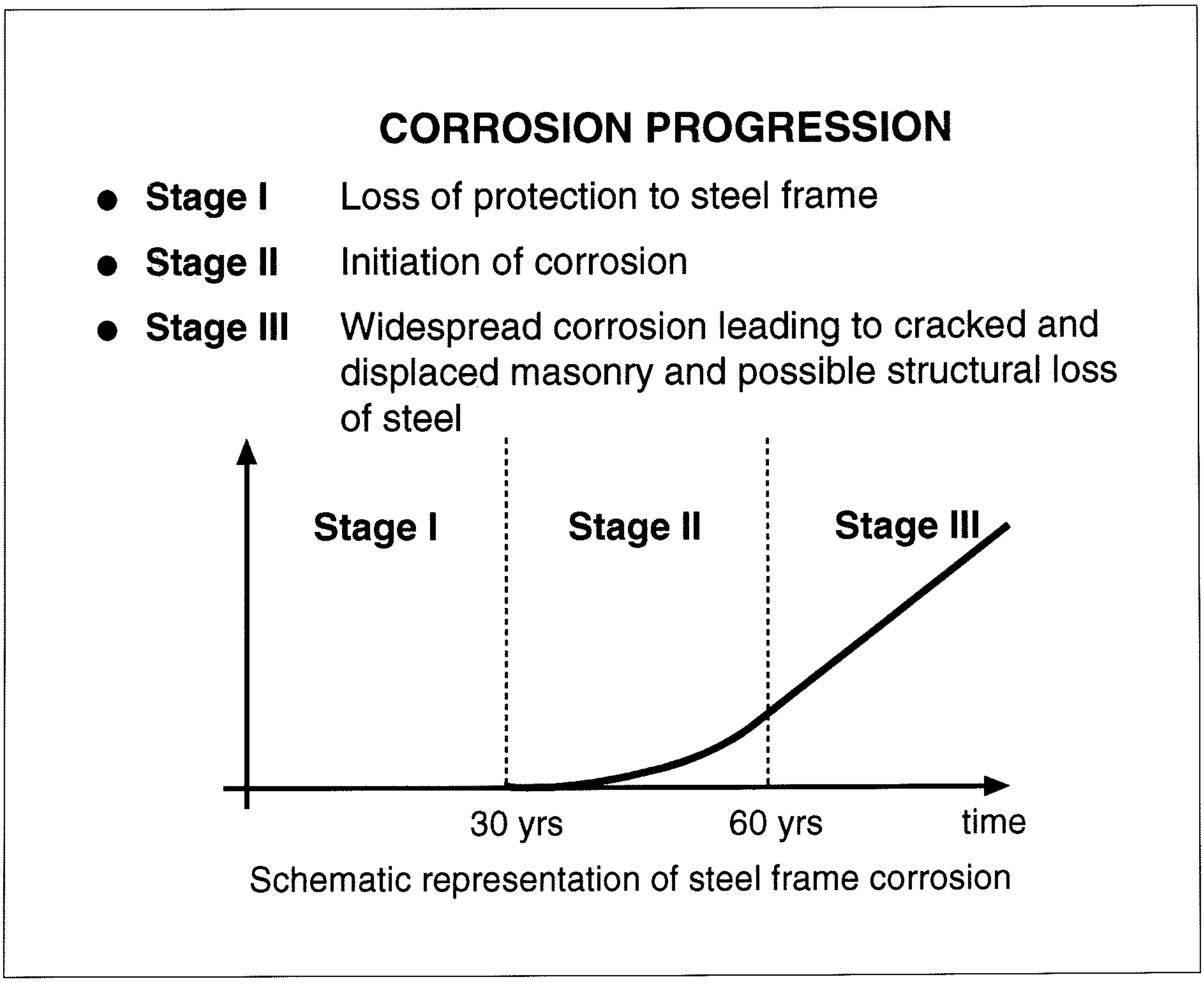


Figure 11. Time to corrosion.

(controlling the diffusion of carbon dioxide into the mortar in-fill), and the depth of mortar cover. It is important to recognise that due to the often porous and inconsistent nature of the mortar in-fill and the relatively low cover of mortar (often less that 25mm on the beam flanges) it is unlikely that the steel frame remains protected for more than a few decades. From a number of surveys of steel framed buildings it is reasonable to assume the time to corrosion as shown in the diagrammatic representation of Figure 11.

As described above, steel will not usually corrode in uncarbonated mortar and concrete. However, in the presence of aggressive ion species, especially chloride ions, the passive film is broken down locally leading to localised pitting corrosion. This occurs significantly when the chloride content of the in-fill mortar exceeds a level of 0.4% by weight of cement. In the case of carbonated mortar it is also important to recognise that the rate of corrosion is also significantly increased by presence of chloride ions. The most common sources of chloride contamination in masonry clad steel framed buildings are from:

- wind–borne salt in coastal regions,
- de-icing salts at pavement level.

As chloride ions can significantly change the rate of corrosion, it is important that the levels of chloride contamination are checked when addressing any steel frame corrosion problems. Failure to address the issue of chloride ion contamination where considered to be a potential problem could result in the selection of inappropriate repair methodologies or failure to predict the likely developments of future corrosion problems. Chemical analyses of chloride ion concentrations can be obtained at any specialist laboratory involved in construction technology and testing.

4.3 Steel in Stone and other Masonry Types

The corrosion rate of steelwork embedded in porous masonry is determined by the resistivity of the material in contact with the steel. This applies since corrosion is an electrochemical reaction where the rate of corrosion is directly proportional to the current flowing in the

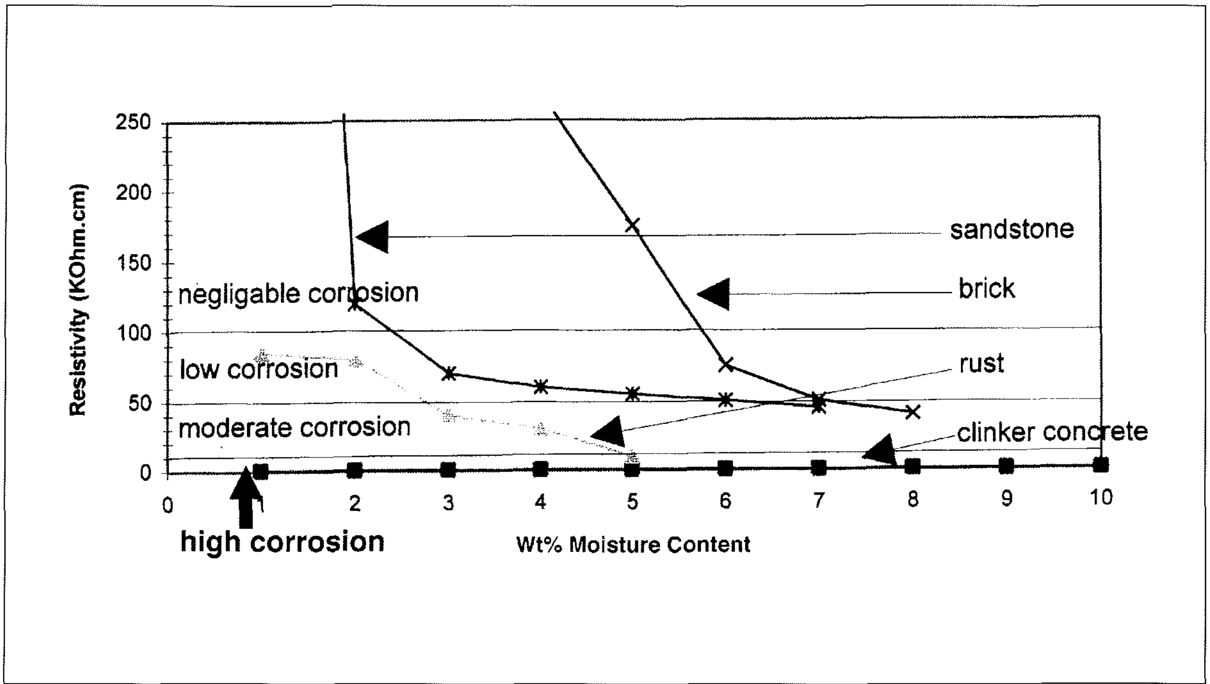


Figure 12. Graph of resistivity vs moisture content for common materials.

material between anodic (corroding) and cathodic (non-corroding) regions of the steel surface. For fully carbonated concrete structures which are analogous to porous stone and other masonry structures it is known that the corrosion rate of the steel reinforcement is approximately related to resistivity as follows:

Resistivity (KΩ.cm)	Icorr ($\mu A/cm^2$)	Corrosion Rate	Approx Metal loss per year (μm)
>100	< 0.1	negligible	1.0
50-100	0.1-0.5	low	1 - 6.0
10-50	0.5-1.0	moderate	6.0 - 12.0
<10	>1.0	high	12 - 50

It is reasonable to assume that the above holds true for porous masonry due to the direct similarity between carbonated concrete. When moisture becomes entrapped within porous masonry low resistivity solutions are formed in the pore structure which lowers the overall resistivity of the material. Therefore, as the level of moisture increases so the overall resistivity of the material falls as shown in figure 12.

The moisture content of a material in contact with steelwork is rarely below 2% by weight. Even in very dry conditions this applies where for example, measurements in Bahrain have shown that concrete does not dry to below 2% moisture by weight. The above data therefore suggests that a stone/masonry structure in the UK will have a moisture content above the 2% level and hence a resistivity which equates to a moderate corrosion rate (6-12μm/yr) in the most favourable of conditions. However, the important factor that is not analogous to reinforced concrete is the layer of corrosion product that can be accommodated in masonry structures before damage occurs. Once formed, any corrosion product layer will dominate the corrosion rate due to its low resistivity in comparison to the surrounding masonry. This corrosion product layer therefore results in moderate to high corrosion rates even at low moisture contents. This is highly important since resistivity/moisture data indicate that once established corrosion cannot be controlled by water proofing techniques, such as the application of flashings as it is unlikely that the moisture content can be reduced below 2%. Consequently, where reasonable levels of corrosion products exist more permanent methods of repair will be required than waterproofing alone.

4.4 Interior Steelwork

The time of wetness of interior steelwork is so short, or the moisture content of concrete encasement (if carbonated) so low, that corrosion of interior steelwork is usually insignificant for the majority of buildings. Most components usually exhibit only superficial rusting on internal members and the only exceptions are in areas prone to high humidities and condensation (such as inappropriately vented cooking areas).

4.5 Perimeter Steelwork

The condition of perimeter sections in old buildings can be variable and depends upon their position in relation to the exterior leaf, the relative humidity of the building interior, and problems such as condensation on the external wall. Steelwork in direct abutment with the outer leaf with good quality sealed joints and low porosity stone, or other masonry usually exhibits low corrosion rates. Conversely steelwork in abutment with a discontinuous joint in the outer leaf can be susceptible to high localised corrosion rates. However, with porous masonry corrosion rates are often found to be moderate even with good quality joints. In this case, corroded steelwork is often indicated by cracking or displacement of external stone and other masonry types due to the volume occupied by the expansive corrosion products.

Where there is separation from the outer leaf by a continuous air gap of at least 40mm corrosion is usually superficial. However, where discontinuous, or random, cavities exist as commonly found in early 20th Century buildings, condensation collects and often leads to relatively high corrosion rates.

5. RECORDS AND DATA COLLECTION

Prior to initiating programmes of corrosion repair or prevention it is essential that data and records are collected on the building, its history, the structure and its constituents. Failure to acquire appropriate records can result in poor planning and result in unnecessary work where for example repairs are initiated on previously treated or non-problematic areas of the façade.

Examples of appropriate records include:

- Original construction details and sketches showing details of the stone or masonry connections with the steel frame, general method of construction, and steelwork details etc.
- Original construction records and notes including bills of quantities etc.
- Photographs showing the construction process and giving details of original finishes etc.
- Press cuttings
- Past remedial treatments
- Survey reports
- Consultants' reports
- Bomb damage and WWII bomb maps
- Maintenance records
- Past and recent repair history
- Records relating to the repair of similar and related buildings
- Records and photographs monitoring and describing deterioration
- Details of any opening-up activities providing new information as to the construction detail and extent of corrosion

The sourcing of appropriate records can be a time consuming process if not carefully planned. A systematic staged approach of research is therefore required which must be reviewed regularly and the relative merits and gains of the research activities assessed. The following is given as an example of a typical information search:

Stage I - Internal Search

Searches of the building owner's or tenant's records are often the most productive sources of information. It is therefore recommended that at least the following avenues are explored.

- Key personnel responsible for operation of the building are approached
- Original construction records are sought. These are often available in the form of a building log book kept by the building owner's maintenance department. In the case of government department buildings, or companies owning large stocks of property records may be held centrally by past or current maintenance divisions and departments. Checks should always be made to ensure that all avenues are explored when dealing with large organisations
- Maintenance departments are approached
- The files of the previous or current building tenant are examined, especially if maintenance is the responsibility of the tenant
- The files of any property management company involved with the building from the date of construction are seen
- the records and reports of any past or present consultants and surveyors are obtained

Stage II - Primary External Sources of Information

The following information sources should be contacted in the following order:

- The architectural practice responsible for the building design. Where the practice is no longer in business checks should be made to determine if the company records and business were taken over by another practice
- The building contractor/mason
- The engineering practice responsible for the steel frame design
- Past consulting engineers
- Local planning authorities
- City and county archives including Dean and Guild Records in Scotland
- Public Record Office
- National Archive of Scotland

- National Monuments Record of Scotland, National Monuments Record Centre or the National Monuments Record for Wales
- The Royal Incorporation of Architects in Scotland or The Royal Institute of British Architects
- Historic Scotland, English Heritage, Heritage Services Environment Northern Ireland or Cadw
- Local museums (photographs)

Stage III - Literature Searches

Literature searches may provide additional information. It is recommended that literature searches start with the following organisations, requesting information on both the building and its architect:

- The British library / National Library of Scotland
- Library of RIBA or RIAS
- Local libraries
- Newspapers contained in libraries (national and local)

Whether historic records exist or not, it is useful to catalogue and record the existing situation and the avenues explored in obtaining information. An information system should then be adopted to record problems as they occur together with the solutions and remedial measures adopted. It is vital that any information relating to the sources of replacement materials for appropriate repairs or refurbishment are always recorded.

Once a data storage system has been set in place all new information relating to the condition of the building should be recorded. New information relating to the condition of the cladding should be carried out in a regular and systematic fashion and this should include information that relates to cracking or displacement, repair and maintenance activities, and specialist investigations. Details of regular inspection work that should be carried out and recorded includes:

- Regular inspection of the façade for the development of corrosion related cracking and stone displacement
- Observing the building in a variety of weather conditions
- Measurement of crack growth and enlargement
- Measuring the movement of displaced stonework
- Recording any areas of spalled masonry and stonework
- Long-term checking of repairs for any continued deterioration

Computer spreadsheets, databases and other packages are useful tools in the logging of information due to the simplicity of data retrieval. As such, these packages can play a major part in the co-ordination of maintenance and repair activities.

6. PROBLEMATIC BUILDING DETAILS

6.1 Introduction

Corrosion rates in steel framed buildings are governed by the levels of moisture entering the structure (except in the case of chloride contamination). As such, it is commonly found that building details exposed to the greatest quantities of rainwater and driving rain are those most prone to corrosion problems. Alternatively, details associated with rainwater removals such as gutters, drains and cornices are also prone to deterioration if poorly maintained or designed. As a general guide, the schematic below indicates the most common problematic areas, (Figure 13).

This sections briefly examines the typical defects likely to be encountered during a corrosion review. However, it should always be remembered that many variations may be encountered to the common examples shown.

6.2 Roofing Failure

Roofing failure is a common problem in steel framed masonry clad buildings. The numbers and types of roofing failure are numerous due to the variety of materials and roofing designs employed in steel framed buildings. As a result, all of the specific faults and repair technologies cannot be discussed in this report. However, the two common generic types of failure are indicated below.

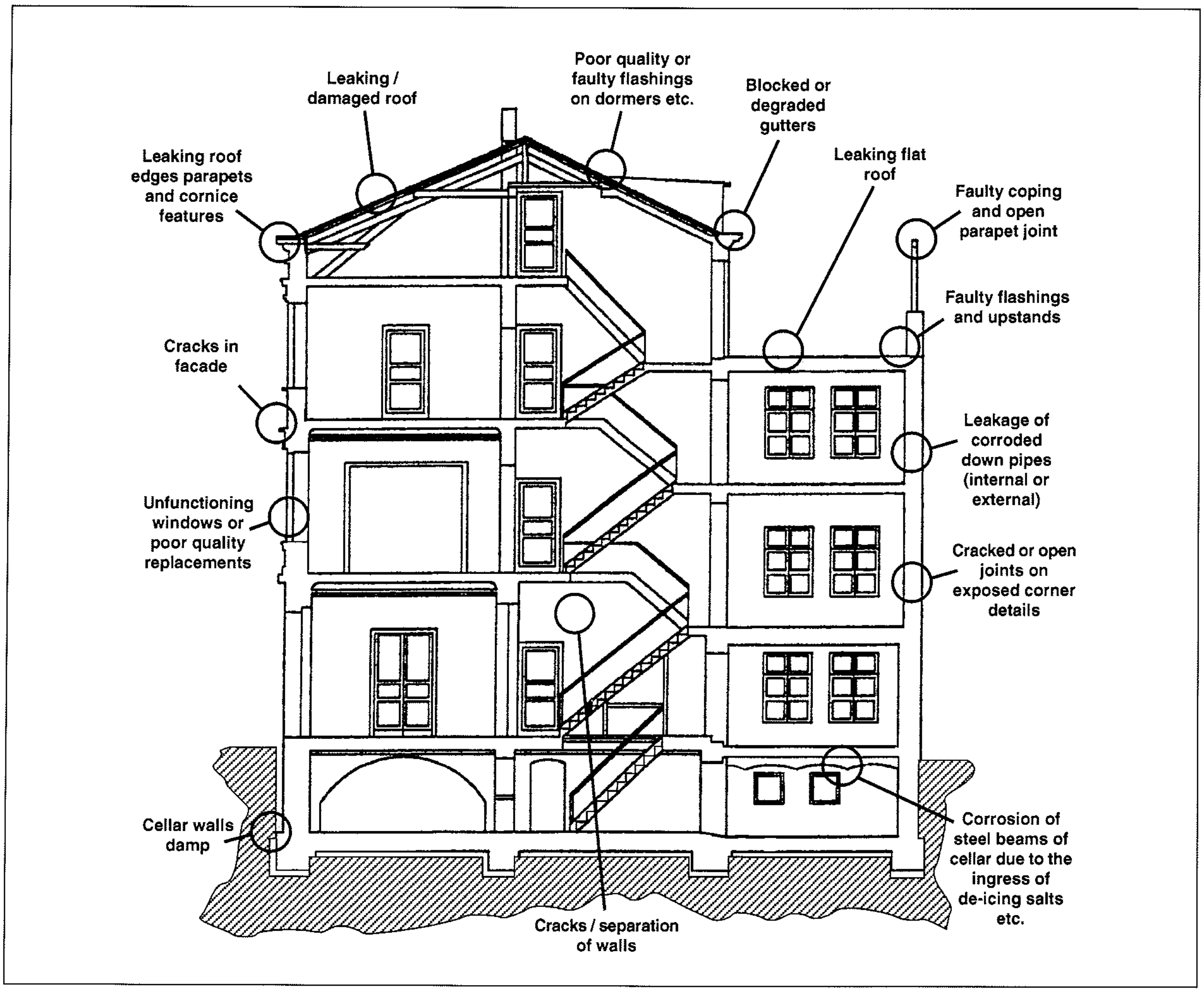


Figure 13. Typical areas of a building where faults lead to the initiation of corrosion. (Adapted from Abb2.8, "Dritter Bericht über Schäden an Gebäuden"; Bundesministerium für Raumordnung, Bauwesen undStädtebau, Bonn; 1996).

Figure 14. Severe corrosion jacking above a glazed brick window head due to water penetration through a faulty flat roof.

6.2.1 Flat roofing faults

The failure of flat roofing in masonry clad steel framed building is of particular importance since steel beams run close to the fabric of the roofing material. Failure therefore allows rapid moisture penetration resulting in an early onset of corrosion damage, Figure 14. It is important to recognise and understand the significance of even small areas of failure since these can allow sufficient quantity of moisture for corrosion to occur.

When assessing flat roofing it is often assumed that the outer faces of the perimeter beams are concrete encased. As a general rule full concrete encasement of perimeter beams should not be assumed. More often than not it is found that concrete encasement does not extend to the external faces of perimeter beams.

Meticulous inspection of flat roofing in masonry clad steel framed buildings should therefore be carried out covering all of the standard problematic details, such as:

- Cracked or torn roofing material,
- Distorted or warped roof coverings,
- Poor jointing of roofing material and the condition of upstands, (Figure 15).

Figure 15. Failed upstand and cracked asphalt on flat roof.

Figure 16. Cracked and displaced masonry due to corrosion resulting from poorly maintained roof.

6.2.2 Slate roofing

Slates or tiles are the most common form of roofing found in masonry clad steel framed buildings. Due to the age of these buildings (usually greater than 60 years) and an often general lack of regular maintenance, displaced or lost slates are a common cause of moisture penetration and corrosion initiation, (Figure 16). Careful attention should be paid to all common slating and tiling faults when inspecting the building.

Care must be taken in the selection of replacement materials. All replacement slates and tiles should match the size, shape, colour and materials of the original.

6.3 Moisture Penetration Through Balustrades and Parapets

Parapets and balustrades are common locations for moisture ingress due to the high degree of exposure to the elements on both faces and the coping. Moisture ingress can occur through degraded coping stones, ashlar joints degraded through thermal cycling, and moisture absorption directly through the parapet stonework/masonry, (Figures 17, 19 and 20). Significant levels of moisture can be absorbed by the stone which are transferred to the mortar in contact with the steel frame, thus promoting significant rates of corrosion, (Figure 18). The rate of moisture transfer is

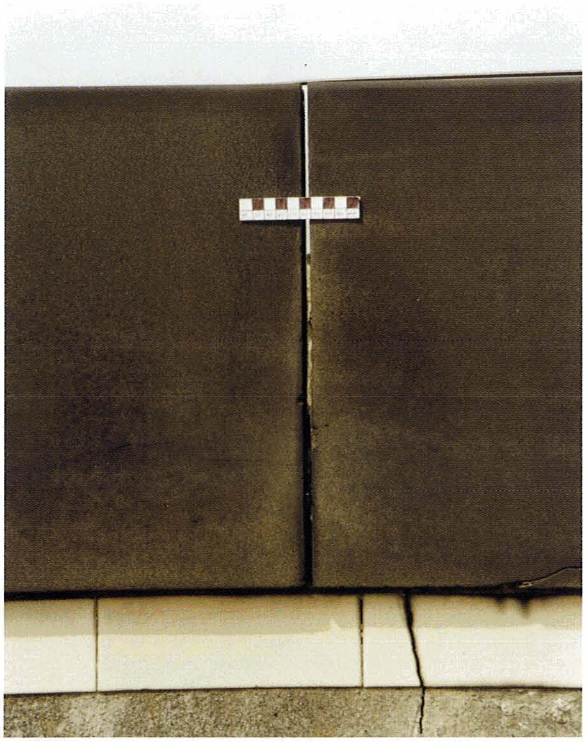


Figure 17. Open joint and cracking in an ashlar sandstone parapet due to thermal cycling. Complete mortar loss has occurred following opening of the joint to twice its original width (each square = 10mm on scale).

Figure 18. Opening up of a column reveals corrosion problems due to moisture ingress through cracked ashlar jointing. Note the additional corrosion product at the joint locations.

Figure 19. Moisture diffusion through the parapet stone work results in corrosion of steel work. In this case corrosion has resulted in enlargement of the joint adjacent to the lower flange.

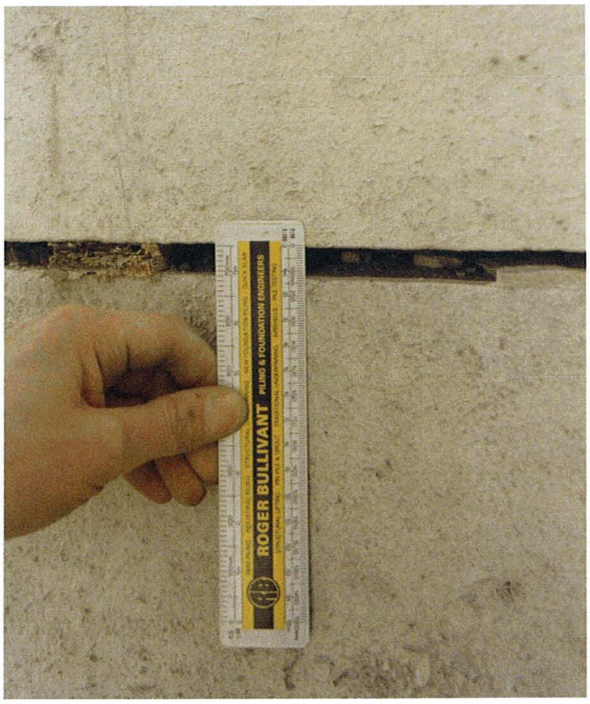


Figure 20. Closer inspection of the parapet stone work of Figure 19 shows corrosion of the lower flange has resulted in opening of the joint from 5mm to 12mm. Problems such as these are typical in corroding steel frame buildings.

dependent upon a number of macro and micro environmental effects. For example in the hot summer months moisture is often driven towards the structural steelwork, due to the higher pressure created on the hotter masonry surface.

Balustrades and parapets experience large and rapid changes in temperature due to their location and high degree of environmental exposure. Consequently, cyclic stresses are induced in mortar joints through thermal expansion and contraction of the masonry. These joints are also unprotected against weathering and failure of the pointing eventually occurs. As a result a direct path for moisture ingress to the steel frame is often created on these exposed locations.

Moisture penetration directly through the masonry material is also a common problem in balustrades and parapets. These areas are often protected by a slightly angled weathering surface that is inadequate for shedding of water and preventing moisture saturation of the stone.

Where water has previously penetrated a parapet the capping of copings is a common early remedial treatment which appears to solve major problems of water penetration through both cracked ashlar joints and the masonry material, (Figure 21). However masonry in contact with the underlying steelwork can not always be kept fully dry to prevent corrosion.

Where cappings are to be utilised careful consideration should always be given to the appearance and the conservation requirements of the building, in addition to the benefits of corrosion protection. It is important that consent is always sought in such cases and the reasons for additions are carefully justified.

Figure 21. The early addition of a capping to a parapet wall coping in a sandstone clad building to prevent water penetration into the building.

6.4 Asphalt Deterioration

The waterproofing properties of bitumen and bituminous mixes were recognised in ancient times. The civilisations of Egypt, Babylon, Assyria and the Indus Valley all used the naturally occurring surface seepage of asphalt for waterproofing. The oldest known example being a water tank in the Indus Valley which dated to 3000BC. However, it was not until the end of the 19th Century that the present uses of asphalt were developed in UK.

The deterioration problems with asphalt waterproofing layers relate both to the material itself and to the conditions under which it has to perform its function of barring the ingress of water. Asphalt and other bituminous products have three main factors which affect its durability, all of which relate to hardening and embrittlement. The main concern is one of oxidative hardening, where finely structured voids interconnect allowing oxidation through the depth of the material. This leads to brittle failure which can be induced by building or thermal movements.

Evaporative hardening is caused where the material can exude an oily fraction into any stone in contact, particularly where no separating membrane has been used, leaving the surface hardened and the stonework soiled.

Cracking can be caused by fatiguing or fretting movements of the substrate; by thermal movements exceeding the strain capacity of the material (perhaps even before any oxidative hardening); by imposed or shock loads or by reflective cracking from below.

Deterioration of vertical asphalt upstands leads to slumping or cracking resulting in lack of adhesion to the wall. This failure of asphalt upstands will allow water to penetrate, (Figure 15 & 28). If the asphalt is not tucked into the parapet or wall masonry the junction should be covered by a flashing to protect it from direct contact with rain or run-off water. Cracking can also occur at the bottom of an upstand due to relative movements between the roof and the wall. Such failure can often be recognised by the appearance of dampness at the junction between the ceiling and the wall in top storey rooms. However the exact location of the defect in the roof can be more difficult to locate due to the 'searching' and flowing nature of water through small crevices.

Frequently only close and detailed inspection can locate defects in the asphalt and such inspections should be undertaken routinely rather than only when a problem of water ingress has been identified.

6.5 Blocked or Deteriorated Guttering

Blocked or deteriorated guttering is probably the most common and avoidable cause of water ingress and corrosion initiation in steel framed buildings, (Figures 22 to 24).

Due to access problems, guttering is rarely cleared or maintained. This, allied with the fact that guttering was often poorly designed with no consideration of the consequences of blockage, can lead to serious problems of inundation. Litter and other matter can rapidly block the gutter outlet allowing the gutter to over–flow, saturating the surrounding masonry. A single outlet from a gutter protected against blockage by a wire mesh is a common guttering design for steel framed building. However, this design is vulnerable to blockage and wherever possible arrangements should be made for a fail safe outlet or for an overflow system.

Once blocked the overflowing gutter allows water to penetrate the façade leading to corrosion of steel members at roof level and cracking and jacking of the masonry, which in turn allows further moisture penetration. With time the process progresses down the façade creating problems at the lower levels.

6.6 Cornice Problems

Ornate projecting cornices are a distinctive architectural feature of early 20th Century steel frame building design. The type and style of cornices are numerous with their design depending upon their position, function and visual requirements. Architects of the time often understood potential problems of moisture penetration through cornices and some preventative measures were taken to combat the problem. However, investigations have revealed that corrosive failure of steel framed buildings is often linked to a lack of understanding of the building behaviour in-service and the lack of measures taken to prevent moisture penetration through cornice designs.

Despite general poor detailing of cornice features, corrosion problems are also associated with a lack of maintenance. Due to their inherent locations cornice features are difficult to examine and often remain neglected during periodic programmes of maintenance. Consequently, obvious paths for direct moisture ingress through either open joints or damaged asphalt coverings remain untreated, eventually leading to corrosion problems.

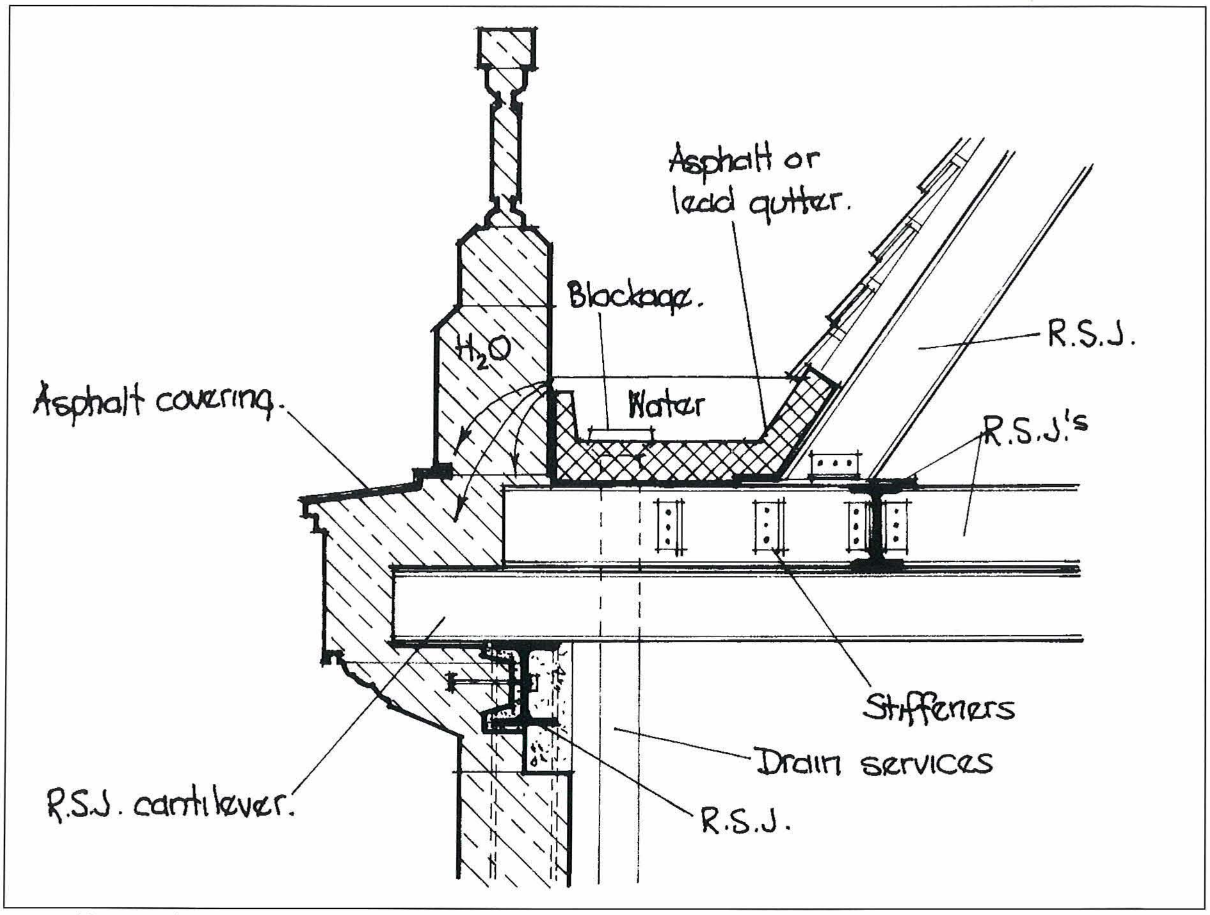


Figure 22. Typical construction of guttering and the associated problem of down-pipe blockage.

Figure 23. Staining of cornice cover flashing due to water overflow as a result of blocked guttering.

Figure 24. Blockage of rainwater outlet pipe in gutter.

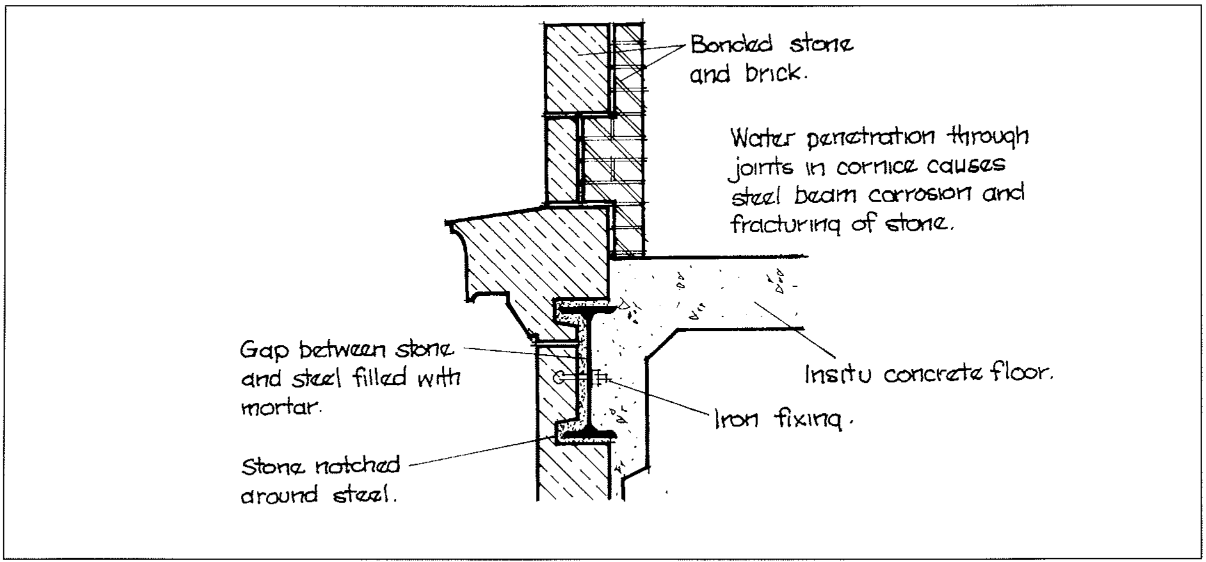


Figure 25. Typical stone/brick masonry design. Water penetration causes steel beam corrosion and fracturing of the stone/masonry.

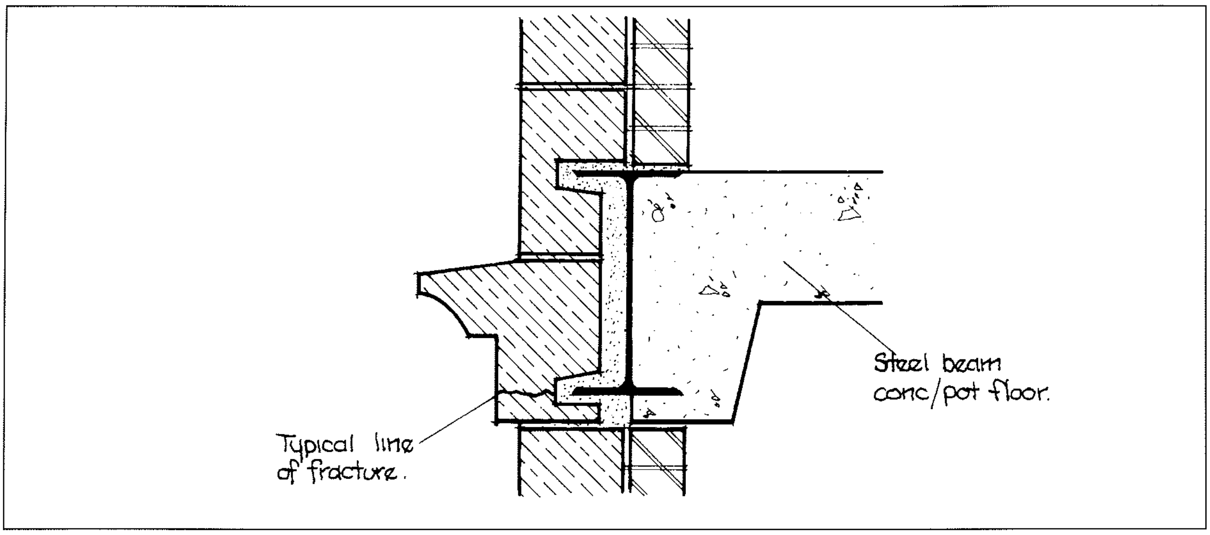


Figure 26. Typical terracotta/faience design. Water penetrates the terracotta through open or degraded joints. Due to the impervious nature of the firing skin or glazing, the moisture becomes entrapped resulting in corrosion of the underlying steel frame and cracking of the terracotta.

6.6.1 Small cornice features and stepped details

Small cornice designs and step features were generally not protected against moisture penetration, although the stone and terracotta units were often shaped to control the movement of water away from the building, (Figures 25 and 26). In addition to the general absorption of water the problems of differential movement between the steel frame and the masonry façade were generally not allowed for, resulting in the progressive opening of masonry joints allowing a path for moisture ingress. Similarly, degradation of the masonry due to long term erosion and environmental attack was not allowed for in the design. Such attack can result in the formation of pits and damage to the top surface of the cornice in which rainwater collects, penetrating the structure with time.

Cornice features were nearly always supported by unprotected steel beams. Consequently, moisture penetrating through the joints, or by diffusion rapidly caused corrosion of the unprotected steel resulting in the formation of expansive corrosion products. With time these corrosion products exert enough pressure on the stone or masonry cladding to cause failure through cracking or displacement, allowing yet further moisture ingress and suitable conditions for accelerated corrosion.

6.6.2 Large cornice features

The top surface of large cornice stones were often sloped inwards with the surface covered with a waterproofing asphalt. Water was then removed from

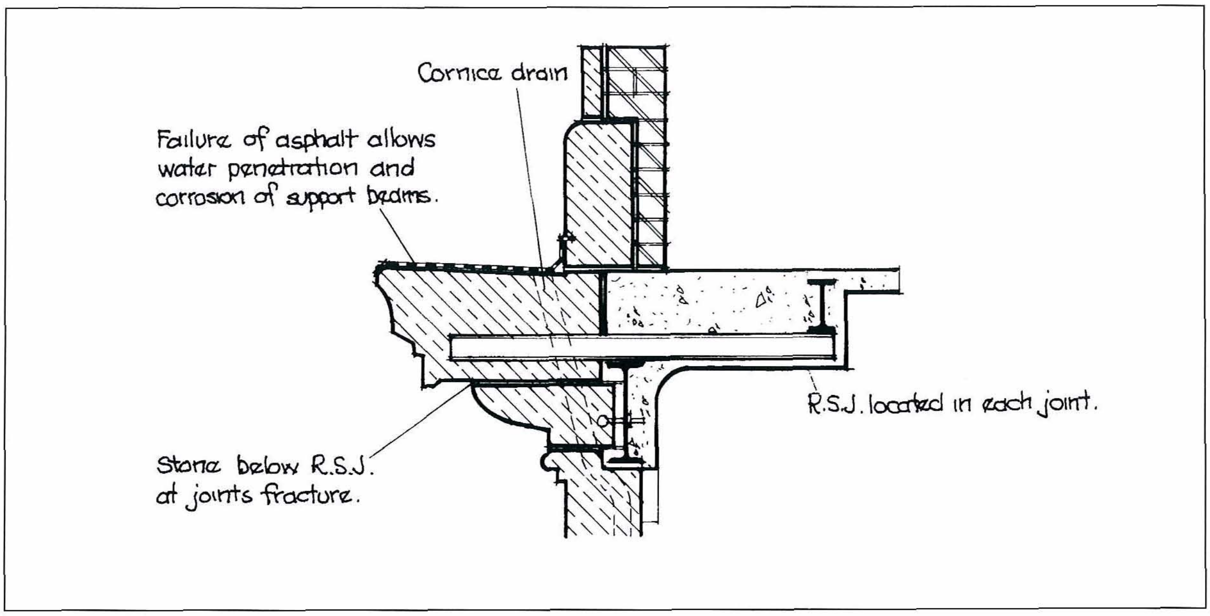


Figure 27. Construction of a large projecting cornice.

Figure 28. Detached asphalt on upstands and cracking due to thermal movements in the underlying stone allows the direct penetration of rainwater.

the cornice via a drainage system, usually concealed behind the masonry façade, (Figure 27).

Due to differential thermal movement characteristics between the masonry and asphalt covering, combined with weathering of the asphalt, cracks are eventually formed allowing water to enter the masonry and cause corrosion of the supporting steel members. It is usually found that dentil courses and the carved features on the undersides of the cornice stones show the first indication of corrosion problems.

6.7 Cracked Rain Water Goods

Cast iron and lead rain water downpipes were commonly hidden behind the masonry façade, (Figures 29 and 30). Pipe work was generally fixed to steel stanchions using cast iron fixings and packed into the structure with brick and mortar which provides further support, as shown below.

Any failure of gutter and pipework itself results in soaking of the steel stanchion supporting the drain pipe thus leading to rapid corrosion of the steel frame. Failure of drain pipes can occur in two modes:

- splitting of the pipe itself due to corrosion,
- failure of pipe work fixings, resulting in cracking or dislocation of the pipe work connections.

Such failures are inherently difficult to spot as they occur behind the masonry façade. As such, severe corrosion damage may have occurred before there is any externally visible evidence. This problem highlights the need for regular inspection and maintenance to give the best chance of early identification of problems.

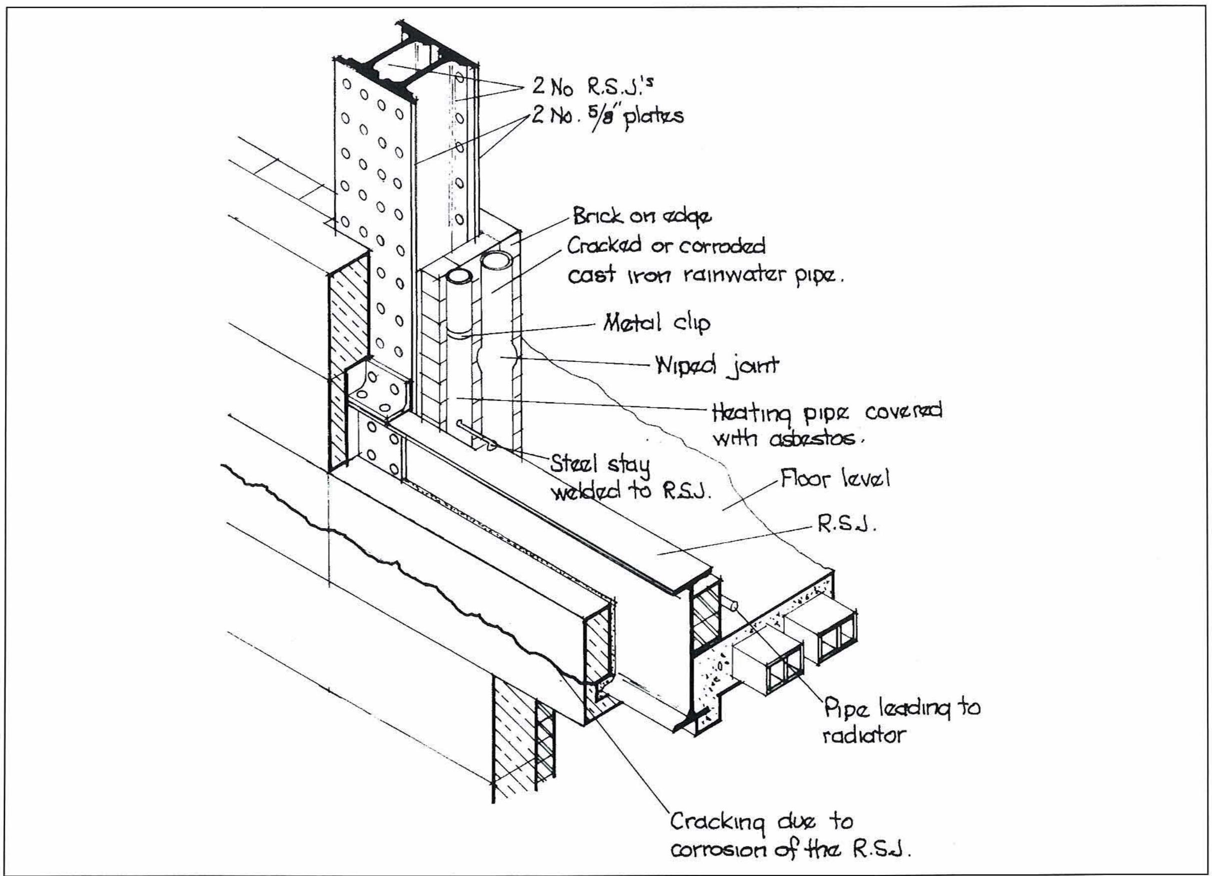


Figure 29. Cracked and corroded rainwater pipes allow saturation of the surrounding masonry and corrosion of the RSJ causing cracking of the stonework along the weakest points, i.e. at flange locations.

Figure 30. Failure of the glazed brick was attributable to corrosion of the steel frame resulting from leakage of the exiting rainwater pipe from within the wall.

The symptoms of corrosion damage, such as 'stone jacking' or masonry cracking due to downpipe failure cannot be distinguished from other forms of corrosion damage. The only tell-tale signs of pipework failure are the presence of large scale water staining originating from behind the façade, or a series of failures following the position of downpipes not evident on similar columns. Water staining may also be accompanied with biological growth depending on the age and severity of pipe failure.

CCTV methods of investigation provide the only accurate method of locating downpipe failure. These methods of investigation are relatively low cost items and early detection and repair easily justifies any expenditure.

As with hidden downpipes, surface water staining and biological growth are also good indicators of failure in external downpipes, (Figure 31). This is particularly useful as cast iron pipes can often appear in satisfactory condition when inspected from a distance due to the corrosion mechanism of cast iron. Failures often occur at seams or on the surface closest to the building which is inaccessible for painting or other maintenance.

Figure 31. Biological growth around cracked rain water pipe indicating failure.

Figure 32. Bituminous waterproofing paint added to a cornice detail.

Figure 33. Closer inspection reveals failure of the bituminous waterproofing layer at ashlar joint locations due to thermal movements of the underlying masonry.

6.8 Lead Work and Flashings

The failure of lead work and flashing is a common and well understood mechanism of roofing failure. The main failures which should be investigated in steel framed buildings are:

- erosion of lead flashing and copings resulting in loss of section;
- cracked flashings;
- poor joints and insufficient overlapping;
- detached flashings;
- poor tuck details.

Although the weathering surfaces of small cornice details were rarely protected against water ingress in original building designs, it is commonly found that bituminous paints or flashings have been added at some stage. However, despite the immediate benefits of waterproofing, it is often found that the effects of such remedial installations were not considered.

Examples of problems caused by poor waterproofing techniques can include:

- irreversible contamination of the stone by bituminous paints;
- water erosion of carved details and other features below the cornice as a result of the displaced water;
- excessive weathering caused by increased water flow below the cornice resulting in discolouration of the stonework e.g. blackening of sandstone and whitening of Portland stone;
- failed waterproofing paints direct water to open joints which act as ideal conduits to the underlying steelwork.

It is important to ensure that condensation does not form on the underside of leadwork as this can cause significant corrosion of the metal by conversion to lead carbonate and other compounds.

Figure 34. Poor raggling of a parapet flashing. Faults such as these can result in the rapid penetration of moisture and corrosion of the underlying steelwork due to water penetration behind the flashing.

Remedial treatments to lead flashings and copings include:

- replacement of deteriorated lead with appropriate weight material,
- repair of failed or faulty joints,
- refixing of detached leadwork.

When specifying lead for replacement on historic buildings the thicker codes are usually specified although in some cases sand cast lead sheet may be required to replace the original. Small quantities of this are made by specialist suppliers although there is no British Standard for the material.

Factors which should be taken into account when determining the weight of lead to be used include consideration of thermal movement, exposure to wind-lift, possible mechanical wear due to foot traffic and on ornate features the need for bossing or dressing into deep profiles.

While most building repair work using lead does not expose workers to major risk of lead poisoning, the Control of Lead at Work Regulations should be followed as well as the requirements of the Construction (Design & Management) 1994 Regulations, known generally as CONDAM or CDM Regulations.

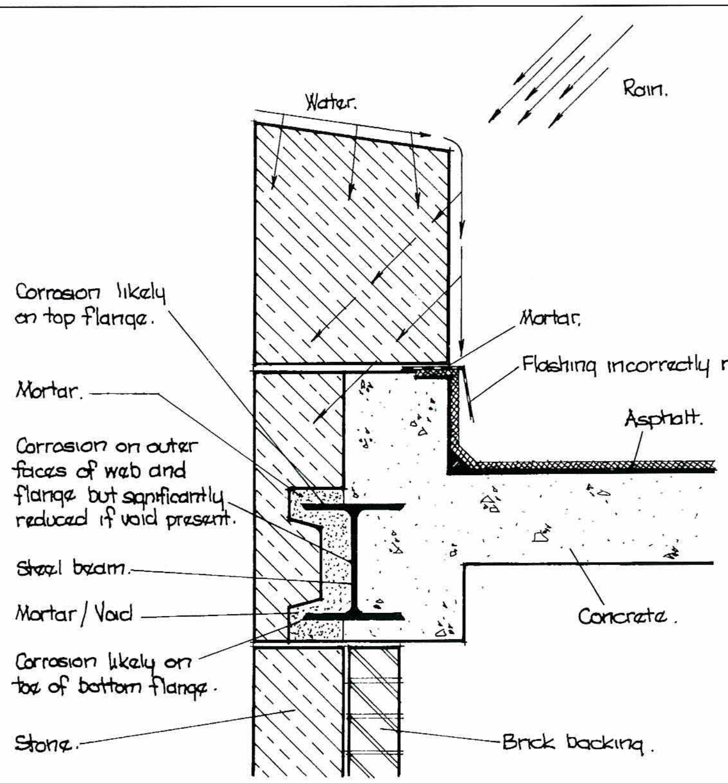


Figure 35. Sketch illustrating water penetration due to the faulty raggling of lead flashing. Note: water will also penetrate through porous stone and masonry in addition to other sources of entry such as cracked asphalt roofing.

Figure 36. Poor quality window replacement can result in the penetration of water. Note - the corrosion of underlying steel work with insufficient concrete cover.

6.9 Windows and Door Openings

As a general rule, original doors and windows should be retained on a listed building. Extensive repairs may be required in certain circumstances. However, repairs are often cheaper and a more historically correct solution than replacement. Only where repairs are clearly out of the question should replacement be accepted and in these cases replacements should always match the originals in every respect.

During the renovation or replacement of windows and doors particular attention should be made to weather tightness in steel framed buildings, Figure 36. Failure to make an adequate seal between the external masonry and window allows the rapid penetration of rainwater which in turn can result in the rapid corrosion of underlying steel members.

If sealant materials are required to achieve suitably weather tight seals then careful materials selection is required to prevent damage to the stonework through the absorption of agents contained within the sealant.

Buildings fitted with secondary or double glazing can suffer a greater degree of window head beam corrosion. It is considered that, prior to the installation of secondary or double glazing, heat escaping from the original windows reduces the moisture content of the masonry/steel interface in this location and hence reduces the corrosion rate. However, it is important to recognise that the corrosion rate will depend on a number of other factors and their interactions such as building type, use, heating system, and exposure (i.e. sheltered or exposed to driving rain etc.). In practice little can realistically be carried out to prevent this effect.

6.10 Fixings

The corrosion and movement of fixings whether embedded internally within the masonry or externally attached can result in damage to the external façade which in turn can allow the direct penetration of moisture resulting in steel frame corrosion problems, (Figures 37 and 38).

Internal ferrous metal fixings were generally avoided in early steel frame construction methods as the problems of corroding fixings were generally understood. Internal fixings have generally only presented problems where iron and steel cramps and pins have

Figure 37. Photograph showing cracking of brick masonry due to corrosion of the fire escape fixing.

been used in poor quality repairs, as original fixings are usually bronze or heavily galvanised steel.

Externally mounted fittings usually present the major problems in early steel framed buildings. Despite the general levels of damage that can be directly attributed to the corrosion of fixings, problems can occur in the underlying steel frame. Typically the most problematic areas are:

- displacement of stone and other cladding materials leading to open joints etc. through the poor design of flagpole fixing and restraint systems that allow the direct penetration of rainwater at high levels;
- corrosion of fire escape fixings resulting in cracking of the façade, (Figure 37);
- corrosion of safety hand rails etc which are often mounted in slots cut into the copings of parapet walls;
- corrosion of iron and steel flag poles, decoration holders and other fixings attached to the masonry.

The severity of corrosion problems induced from external fittings depend upon the fitting location. Fixings located on exposed areas, near problematic areas such as cornice and parapet details usually result in greater risk to the underlying steel frame.

Fixings and reinforcement bars are often added to masonry repairs. It is essential that where any additional fixings are employed within the repair, that stable materials such as bronze or stainless steel are used to prevent later damage through corrosion of the fixing. Failure to use suitable materials will result in later failure or in some circumstances a dangerous condition resulting in spalling of the repair, (Figure 39).

Figure 38. Damage caused by the corrosion of iron and steel fixings has been known for many years. This figure shows damage caused by the corrosion of a small iron fixing. In steel framed buildings the corrosion of any iron or steel fixings results in a similar problem. However, cracks and damage to the façade allows the direct penetration of moisture and corrosion of the steel frame.

Figure 39. Spalling of a high level cornice repair due to corrosion of the mild steel fixing.

7. IDENTIFICATION OF CORROSION PROBLEMS

7.1 Introduction

Visual inspection of the façade for corrosion damage requires close and detailed inspection by an experienced surveyor if all corrosion problems and potential problems are to be identified. Inexperienced surveyors may often miss or completely overlook potentially serious problems and sites of severe corrosion. It is is often found that cracking has been attributed to building movements and as a result inappropriate repairs have been specified.

The generic problems identified in this section will act as a guide to surveying work. It is important to note that the causes of corrosion may not be immediately obvious. Corrosion problems can be pinpointed with greater accuracy if all defects, however minor, are indicated on detailed drawings of the building façade and then related to the building design and component layout (frame, cladding and fixings). Examples of minor details which can lead to the identification of problems can include:

- blocked gutters and drains;
- missing or cracked roofing tiles;
- cracked glass in window frames (indicating building movement);
- cracked mortar joints;
- loose pointing;
- repetitive observations or patterns of cracking, displacement or waterstaining.

Plotting of all such faults on detailed drawings of the façade not only indicates possible linkage between causes and effects of corrosion but may also indicate the extent of corrosion progression. This is particularly advantageous when repairing listed structures where only minimal disturbance to the fabric of the building can be tolerated.

Visual inspections of masonry clad steel framed buildings can either be carried out at close quarters or from a distance using binoculars etc. However, close inspection is always recommended rather than binocular inspections from a distance which have the following problems:

- small hairline cracks are often not seen, (Figures 40 and 41);
- large cracks and displaced masonry may not be visible from certain angles (especially in the case of light coloured stones such as Portland), (Figures 42 and 43);
- failed flashing details and asphalt coverings often remain unseen;

Figure 40. Photograph showing crack in a sandstone parapet. Fine cracks such as these are easily missed in binocular surveys or inspections from a distance.

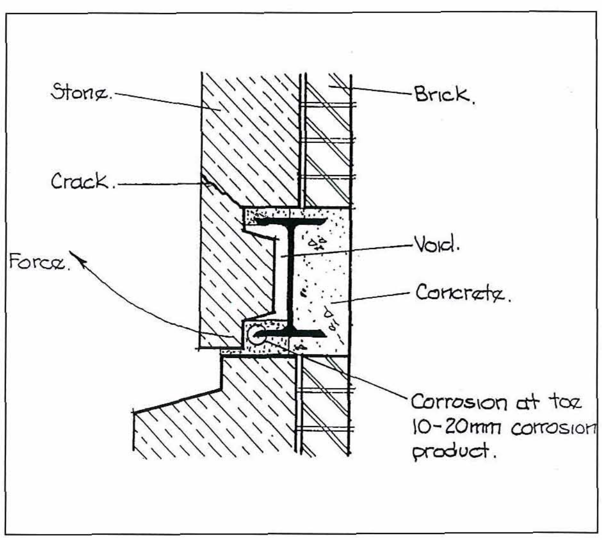


Figure 41. Sketch illustrating the initiation of cracking of Figure 40, due to expansive corrosion products on the beam flanges.

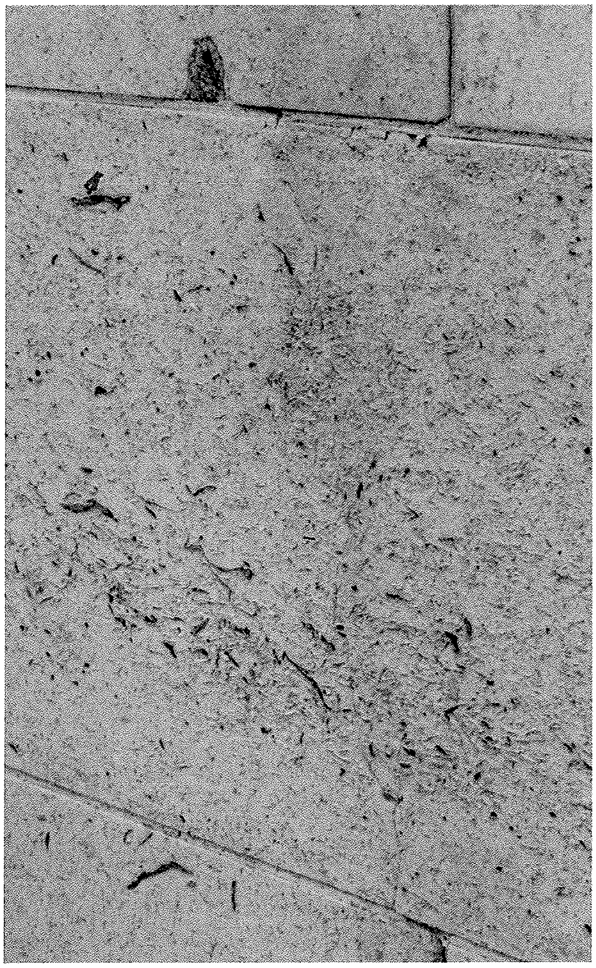


Figure 42. Viewing from a north easterly direction in this Portland stone building, the corrosion induced cracking is easily missed.

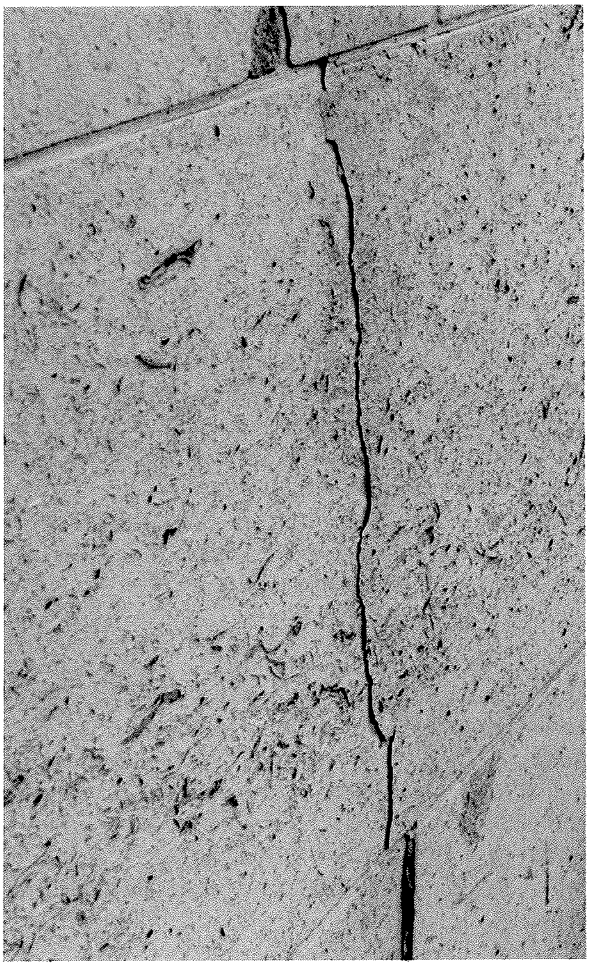


Figure 43. Viewing from the south easterly direction reveals the significant level of cracking due to corrosion of the underlying steel column.(see Figure 44)

- open mortar joints are difficult to detect;
- masonry jacked apart at mortar joints is difficult to identify;
- surfaces hidden behind features such as downpipes and statues remain unseen.

Visual surveys should always be planned in a systematic fashion initially investigating high level regions and known problematic areas as described in Section 6. A typical corrosion investigation survey would include the following items:

1. Overall visual inspection of the main façades noting obvious problems on elevation drawings.

2. Inspection of parapet walls, balconies and roofing details.

3. Inspection of projecting surfaces such as stepped details, small cornice features and main cornice details.

4. Examination of exposed corners.

5. Tracking the location of hidden drainage pipes and examining surrounding masonry.

6. Systematic inspection from top to bottom.

Depending upon the outcome of the survey a detailed building specific survey could be developed and a checklist prepared for future monitoring and maintenance programs.

7.2 Non-Destructive Testing (NDT)

As previously discussed very different distinct types of construction have been employed in 20th Century steel framed building design. Since the differing forms of construction have a large impact on the type and methods of NDT that may be used the engineers should be fully aware of the impact of the construction techniques adopted in the building under investigation and allowances made as required.

Figure 44. Removal of cracked and associated stones confirms corrosion of the column flange as the cause of cracking as shown in Figures 42 and 43.

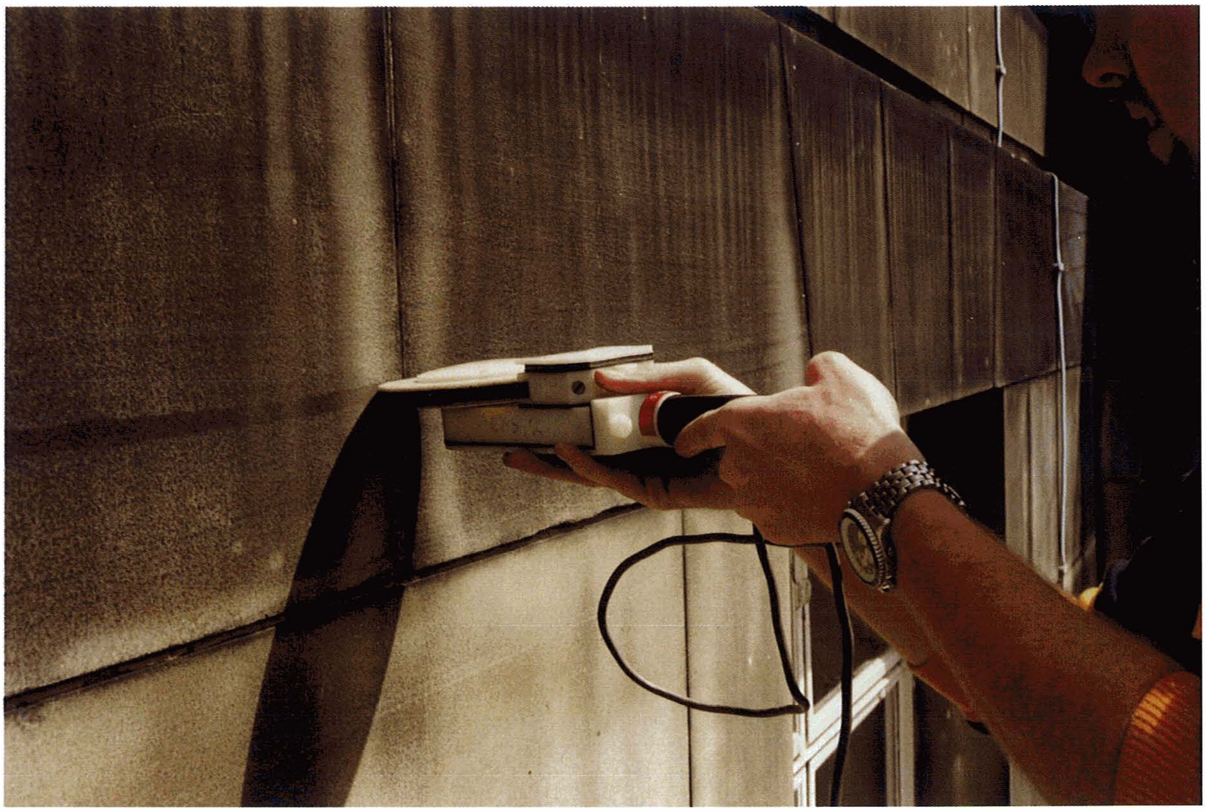


Figure 45. Potential mapping.

In addition to visual observations, these buildings are also potentially suited to a wide variety of non-destructive test methods (NDT). Suitability for NDT is attributable to the mortar in-fill through which a variety of wave forms and electrical signals can be directly transmitted to the underlying steelwork. However, limitations to the effectiveness of NDT can arise in these buildings due to inconsistent or incomplete mortar filling between the steelwork and masonry.

Generally, the consistency and quality of mortar filling varies considerably throughout a building, with certain sections of the building containing air gaps between the steel and masonry. Cavities typically exist on lintel and voussoir stones situated above window heads due to the difficulty of mortar filling during construction. In particular, key stones are rarely notched around the steelwork sections, but bridge the webs of the steel beam section, thus creating a cavity which is difficult to fill.

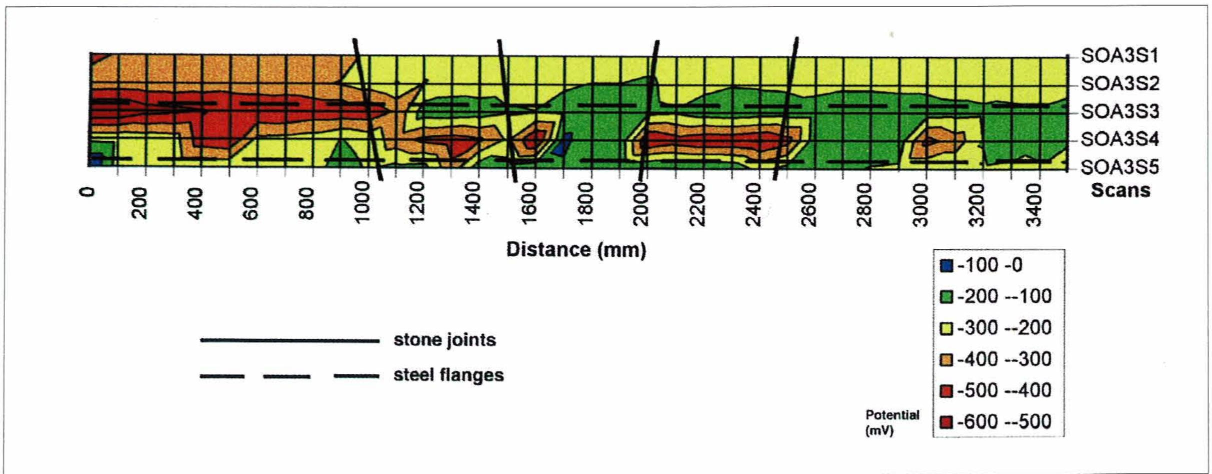


Figure 46. Potential map of figure 45. Solid lines represent stone joints and broken lines give the location of the steel beam. For the Silver/Silver Chloride (Ag/AgCl) half cell probe used in the above testing programme orange and red areas indicate a high probability of corrosion.

Between the late 1930s and the early 1970s steel frame construction became less common due to the development and use of concrete frames. However, the early 1970s saw steel frame construction methods regain popularity, with steel frames becoming the favoured frame option during the building boom of the 1980s.

Buildings constructed from the early 1970s usually included a 25-75mm cavity between the steel frame and external cladding. These buildings are therefore unsuited to non-destructive tests which require a solid contact between the steel frame and masonry cladding. However, these buildings are suited to optical techniques which enable visual inspections of the steelwork through the insertion of fibre optic cables into the building cavity.

From the early 1980s cavity walls became larger, being increasingly filled with insulation to improve the thermal characteristics of the building. The type of insulation filling in these buildings also varies, ranging from partial insulation filling of the cavity, to complete filling of the cavity. In such cases, non-destructive testing and internal visual inspections may prove difficult due to the presence of insulation.

In summary, the following types of construction detail may be encountered in masonry clad steel framed buildings:

- mortar filled cavity between the external masonry and steel frame;
- partially mortar filled cavity;
- 25-50mm cavity between external masonry and steel frame;
- steelwork fully encased in concrete;
- cavity with an insulating layer on the inner wall of the cavity;
- 100mm cavity completely filled with insulation.

7.2.1 *Potential wheel/half-cell survey*

The half-cell – potential wheel provides information on electrochemical reactions taking place on the steel surface through the measurement of electrical potentials. Assessment is achieved through the systematic mapping of corrosion potentials by placing a standard half-cell on the masonry surface in contact with the steel, which in turn is connected to the steel frame via a high impedance voltmeter. The results are used to generate a 'potential map' with iso-potential lines at suitable intervals which provides information on the probability of corrosion risk, (Figures 45 and 46).

A requirement of this method is that the steel frame is connected to the external masonry through a suitable electrolyte such as damp mortar. This method is therefore only suited to buildings constructed prior to the late 1930s. Buildings constructed after then are generally unsuited to potential mapping as the steel frame is separated from the external masonry through a cavity or insulating barrier.

Half–cell methods may also be of limited use in early constructions where the steel frame has corroded to such an extent that excessive rusting has resulted in large scale debonding of the in-fill mortar. A further limitation to this method occurs in buildings where the masonry cladding is electrically insulating, for example terracotta or glazed brick. In these cases potential measurements may be possible through the conductive mortar joints. However, the interpretation of such data are currently unknown.

The measured value of potential difference provides an estimate of the likelihood of corrosion but cannot reliably indicate corrosion rates or identify amounts of corrosion products present on the steel surface. Generally accepted values representing corroding and non-corroding conditions for steel in concrete are given in the American Testing Standard ASTM 876, but care must be exercised when using this standard as the applicability to masonry structures is uncertain. Indications on the locations of corroding steel are more reliably obtained through comparisons of potential changes on the potential map.

Potential wheel/half-cell methods have been applied successfully to several masonry structures and further investigations may confirm potential mapping as an essential tool for the investigation of corrosion in masonry clad steel framed buildings.

7.2.2 *Polarisation resistance*

This technique has been developed over recent years to measure corrosion rates in reinforced concrete structures. As such, this technique may be suited to buildings constructed with a mortar in-fill between the steel and external masonry, which are analogous to reinforced concrete.

To date polarisation resistance techniques for measuring corrosion rates have not been fully investigated on masonry clad steel framed buildings. However, like potential mapping, polarisation resistance is only suitable for buildings constructed with a porous masonry in-fill in contact with the steel frame. Polarisation resistance measurements of corrosion rates are unsuited to buildings constructed with air or insulation filled cavities between the steel and external masonry. These measurements are also unsuited to measurements through very high resistance masonry such as glazed brick, terracotta or faience.

7.2.3 Resistivity measurements and hygrometers

Corrosion rates are related to the moisture content and resistivity of the medium in contact with the steel. Therefore, direct measurement of resistivity and moisture content can provide an indication of likely corrosion rates (see section 4.3).

Resistivity measurements are only suited to buildings constructed with a mortar in-fill between the steel frame and external masonry. These buildings corrode due to electrochemical processes induced by the presence of moisture entrapped in the carbonated mortar in-fill in contact with the steel. The probability of corrosion risk is therefore related to the amount of water present within the mortar in-fill. Since the resistivity of wet and dry mortar varies considerably, measurements of resistivity can provide an indication of corrosion risk.

The full benefits of resistivity measurements in porous masonry are not fully known, but recent tests have shown this method to be promising. A known limitation of the technique occurs during long hot dry spells when a significant proportion of a porous masonry surface dries out. In these instances the surface resistivity of the masonry can be so high that internal measurements of resistance are not possible due the large surface effects. In these instances it is found that the masonry is identified as having a high resistance indicating a dry condition, when this often is not the case for the material in contact with the steel.

A various assortment of moisture meters and indicators with proven track records are readily available for building inspections. These devices are based on the measurement of various material properties affected by water, such as dielectric changes, microwave transmission, infra-red absorption, ionic conduction etc. However, these instruments usually measure moisture content at the measuring surface only, with little or no penetration into the material. These instruments are therefore of limited use on thick masonry cladding, where the moisture content of the external masonry surface bares no resemblance to the surface in contact with the steel frame.

Commercially available equipment developed for the measurement of moisture in flat roofing etc. may prove a suitable technique for monitoring long term moisture content changes in masonry clad steel framed buildings. These systems use small, relatively cheap electrodes that can be unobtrusively embedded within a structure. Strategically placed probes, embedded in

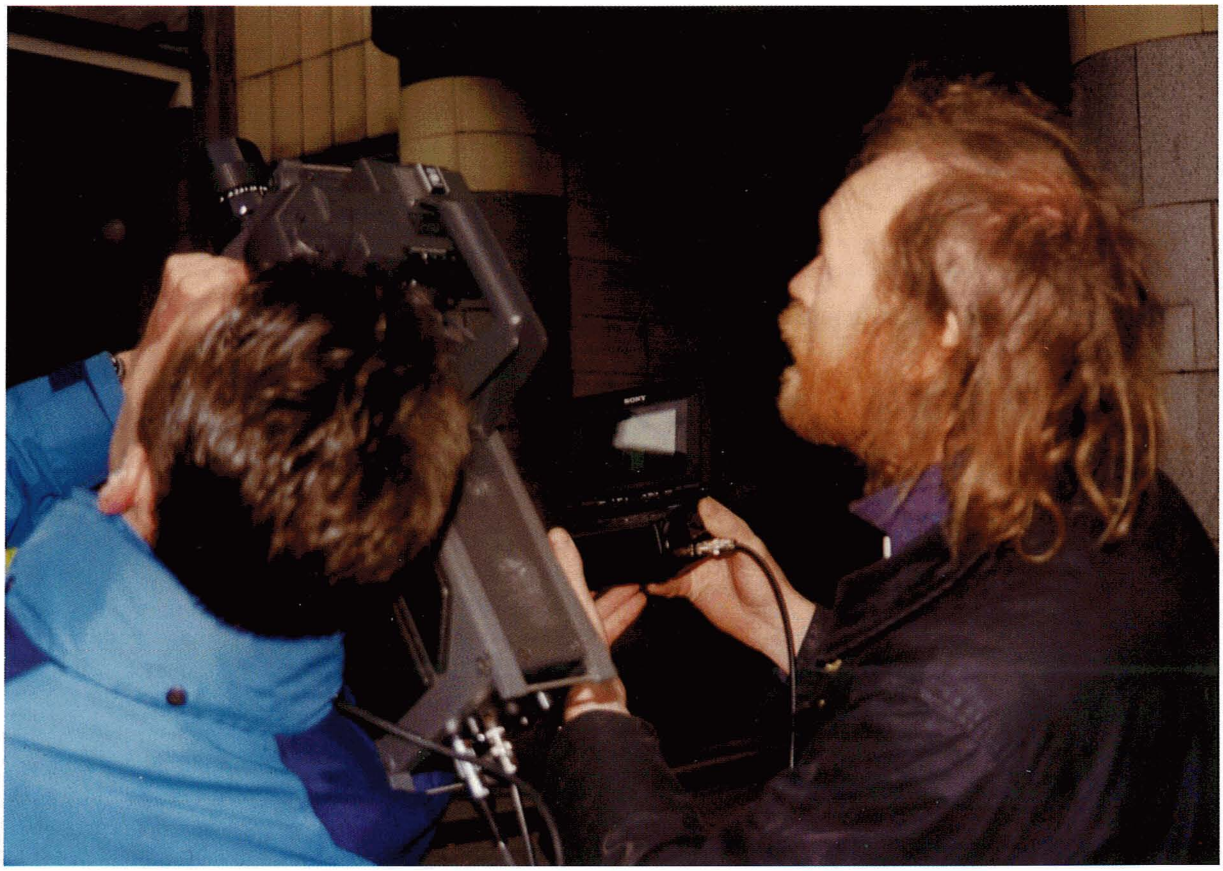


Figure 47. Infra-red thermography measurements.

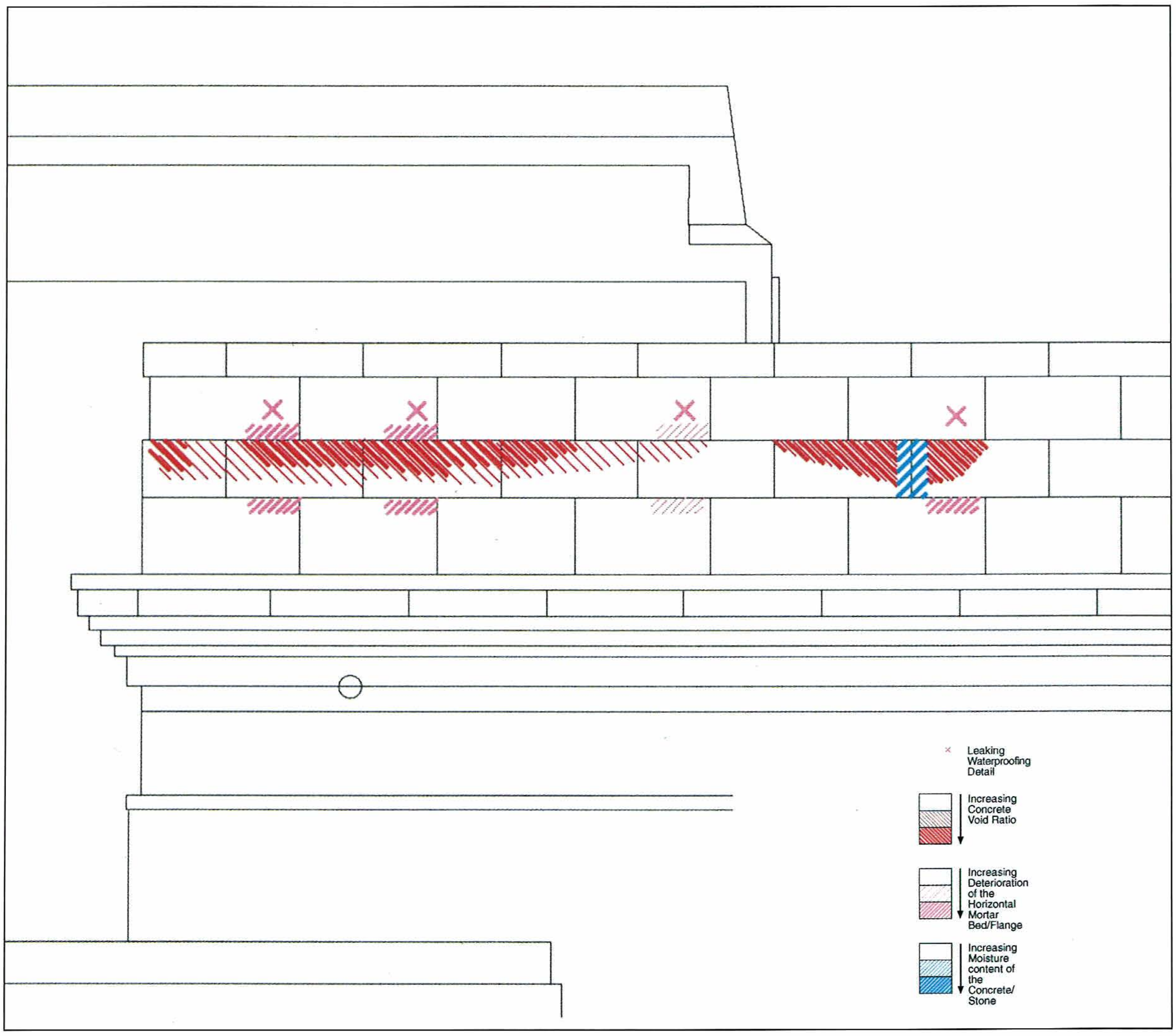


Figure 48. Impulse radar data showing the locations of voids behind a section of Portland stone parapet wall. The darker shading indicates a greater level of voidage behind the Portland stone façade and the crosses indicate a leaking roof detail.

regions of the structure at risk from moisture penetration could therefore provide a system of monitoring and early warning. For example, strategically embedded probes could identify leaking gutters and drains, water ingress through parapets and cornice features, and measure the influence of driving rain etc.

7.2.4 Infrared thermography

Infra Red Thermography (IRT) measurements have shown that the technique is relatively redundant for the direct inspection of corrosion problems. However, this technique was found to be particularly useful for detecting cracks in the external masonry where the heat loss is exaggerated, (Figure 47).

7.2.5 Ultrasonic techniques

Ultrasonic pulse techniques are potentially suited to examining defects and material thickness in early buildings.

Ultrasonic inspections are totally non-destructive and allow detailed inspections of flaws and material thickness to be carried out on small areas of the structure. The principle of operation relies on the successful transmission of short duration (a few microseconds) high frequency wide bandwidth (50 KHz-100 MHz) pulses of sound into the structure. Material boundaries/interfaces and flaws such as voids and cracks reflect a proportion of the transmitted pulse back towards the transmitting device. Reflected pulses are detected by the receiver, or back through the transmitter transducer (transceiver), and processed by electronic timing circuitry. By measuring the time separation between the received echoes, together with knowledge of the velocity of sound in the various material components of the structure, the depth of flaws and thickness of various constitutive components can be calculated.

To date, ultrasonic measurements have not been fully tested on steel framed buildings, although in theory ultrasonic testing would appear a promising technique. Experience of ultrasonic testing on complex concrete structures has revealed the following possible limitations for masonry:

- measurements may be affected by large particles of aggregate in the mortar or inclusions in stone masonry (for example shells in Portland Stone);
- data processing is time consuming;
- the technique is limited to small areas;
- specialised knowledge of the construction practice is required for analysis.

7.2.6 *Displacement measurements*

Careful instrumentation and measurements of displacement changes provide important information on general building movements, thermal and moisture induced movements, excessive steel beam deflections, and the growth of cracks and the displacement of masonry due to the formation of expansive corrosion products. Long term measurements of displacement also provide information on general building behaviour that can lead to possible failure of the cladding, together with information on the causes, extent and rate of corrosion damage. Long term monitoring also provides an indication on the urgency of a repair program, with excessive rates of damage requiring more immediate treatment. In summary, the following potential information can be obtained:

- opening of masonry joints due to thermal and hydrolytic affects, providing important information required for effective repair strategies;
- growth of cracks and the displacement of masonry due to corrosion, providing an indication on the rate of corrosion and urgency of repair;
- excessive deflection of steel beams resulting in masonry failure. This may be due to either load shedding from severely corroded neighbouring steelwork, or through general movement due to insufficient frame stiffness.

Various types of displacement transducers, markers and dial gauges etc. are suitable for use, and proven, on masonry buildings, for example;

- linear voltage displacement transducers (LVDT's);
- linear potentiometers;
- vibrating wire gauges;
- strain gauges;
- tilt gauges;
- tell tales;
- demec gauges.

Displacement measurements are only of maximum benefit when examining changes over relatively long periods of time. The stability of the measurement device is therefore fundamental to achieving reliable performance data.

Displacement measurement techniques are particularly applicable to measuring crack growths and masonry displacements in pre-late 1930s buildings. These buildings are particularly suited as corrosion product formation is directly related to crack growth and masonry displacement. Therefore, information obtained from displacement monitoring is likely to be directly related to the corrosion rate occurring at the monitoring site.

7.2.7 *Impulse Radar*

Impulse radar measurements have been found suitable for investigating the presence of voids and the location of steel work in steel framed buildings, (Figure 48). This information is particularly useful in the absence of detailed design records and when the construction detail is unknown. However, impulse radar cannot

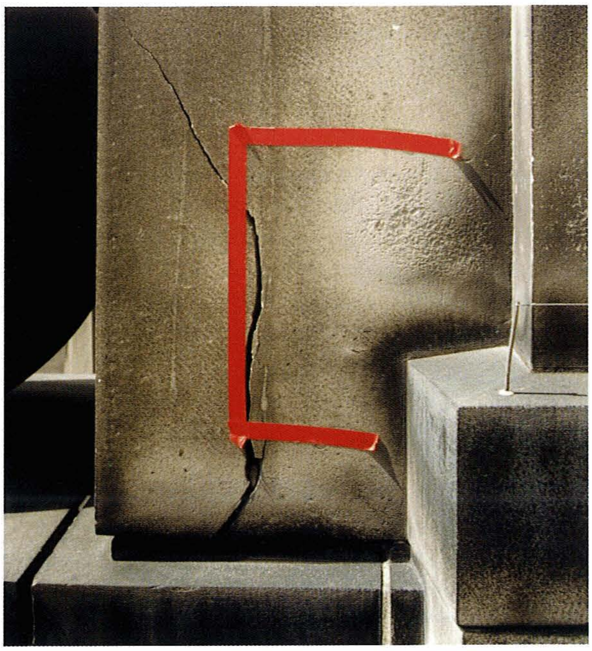


Figure 49. The location of a corroding steel section is identified with a magnetometer and marked with red tape. Its position in relation to the cracking indicates corrosion related damage.

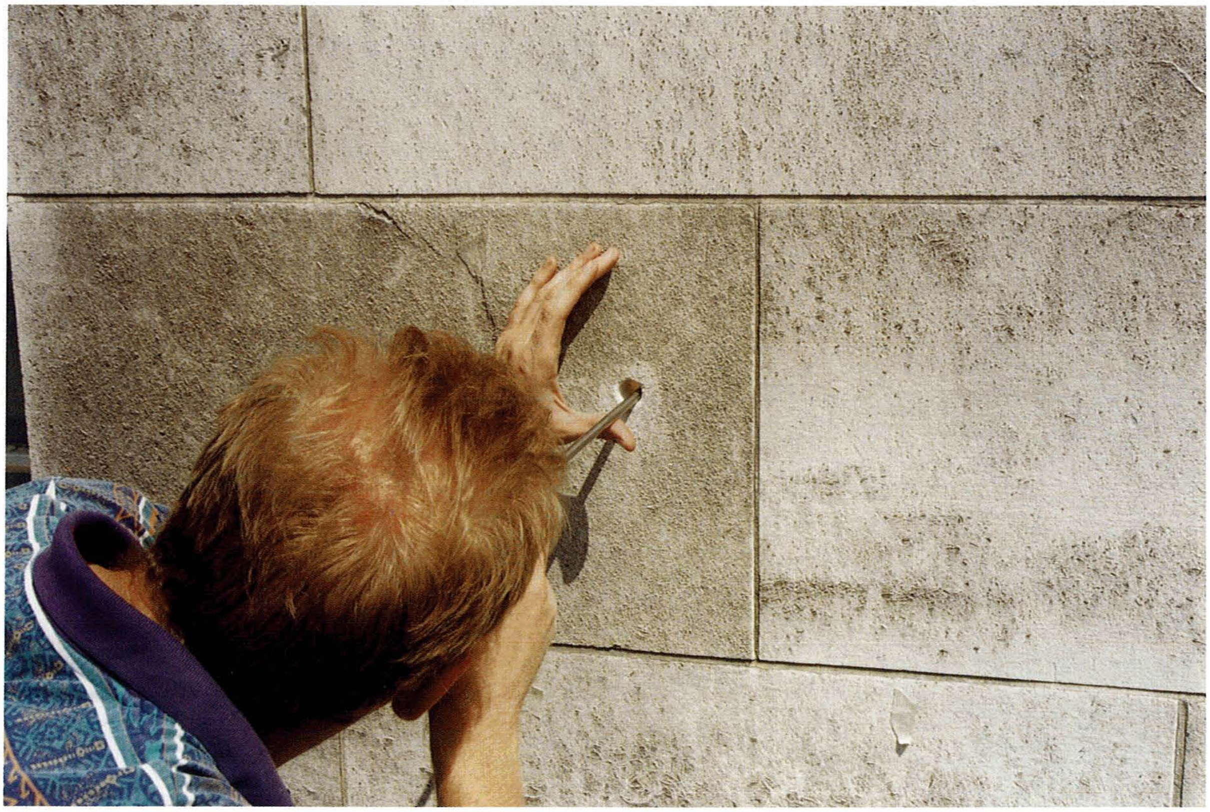


Figure 50. Endoscope in use.

distinguish between the steel frame and corrosion product layer.

Impulse radar operates on the principle of measuring electromagnetic waves reflected from various material boundaries and interfaces, whilst transmitting high frequency (50MHz-5GHz), short duration pulses of electromagnetic radiation into a structure. With careful selection of the waveform frequency, probing radar can be tuned to achieve the most appropriate penetration and the most suitable resolution for the detection of defects and embedded objects such as metal cramps etc.

Due to the depth of penetration and the ability to detect a variety of defects, impulse radar is probably the most potentially useful technique for the surveying of masonry clad steel framed buildings. Measurements can also be carried out in a relatively quick period, covering areas of a few m^2 at a walking pace. Skilled technicians with knowledge of construction practice and the most likely defects to be encountered, can analyse results, which are presented in pictorial form, in a relatively short period. However, as with many other NDT techniques, confirmatory measurements are required using either other NDT methods, or more reliably through destructive testing and opening up works.

The relative advantages and disadvantages are detailed below:

Advantages

1. Relatively quick surveying of structure.
2. Ability to penetrate structure.
3. Possible method for the assessment of all steel frame masonry clad construction types.
4. Non-destructive and safe.

Disadvantages

1. Skilled personnel for interpretation of data.
2. Performance dependent on the complexity of the structure.
3. Accuracy in locating delaminations between 80-91%.
4. Difficulty in detecting small delaminations less than 0.3mm wide.

7.2.8 Magnetometer survey

The detection of embedded metal fixings and steelwork is important when considering repair methodologies for steel framed buildings, (Figure 49). Importantly, all embedded fixings must be detected

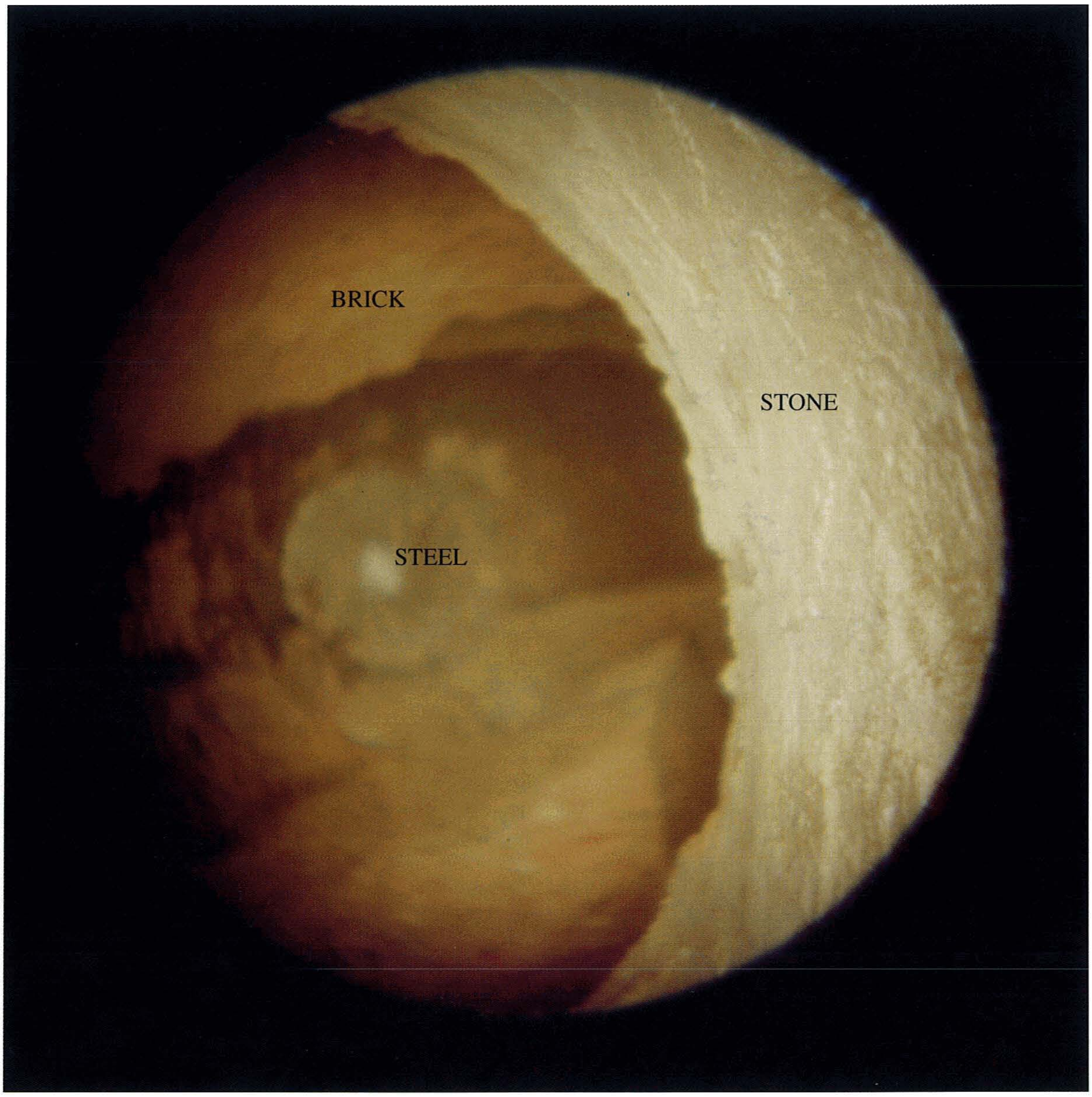


Figure 51. Photograph taken using an endoscope showing the corroding steel, Portland stone, brick in-fill and small cavity between the brick in-fill and steel beam.

when impressed current cathodic protection (ICCP) systems are being considered. Failure to allow for electrical continuity between the steel frame and embedded fixings during the ICCP system design and installation can lead to corrosion problems through stray current corrosion.

Magnetic induction techniques have a proven track record in the location of metal cramps, ties and fixings embedded in masonry, ranging from the use of simple cover meters through to high-tech military mine detection equipment. However, some additional work is required to establish the suitability of the technique for detecting fixings directly in front of steel beams.

In addition to the location of metal fixings, powerful covermeters are potentially useful for determining the location of steel members and their relation to cracks etc.

Although steelwork and fixings can be detected with accuracy, at present commercial equipment is not available for measuring the loss of steel section on corroded beams located behind masonry walls.

7.3 Limited Damage Techniques

7.3.1 Endoscopic examinations

Visual inspections of cavity walls can be achieved with the use of endoscopes. Endoscopes consist of a fibre-optic cable which provides both a source of illumination and a method of viewing. Due to the small size of the fibre optic cable, light source and lens arrangement (between 2 and 15 mm diameter), the endoscope can be inserted through a small hole drilled through the external masonry. During the internal survey a permanent record of the inspection can be obtained through connection to either photographic or video equipment, (Figures 50 and 51).

In addition to the inspection of cavity walls, endoscopes are potentially useful for examining corrosion product formation on traditional buildings constructed with a mortar in-fill between the steel frame and external masonry. In these cases, the extent of corrosion product formation is observed whilst passing the endoscope through a small hole drilled through the masonry, mortar, rust layer and steel surface.

CCTV systems are essential for examining the condition of rainwater downpipes located behind masonry cladding. This is an important area of inspection since it is often found that failed rainwater services often give rise to major corrosion problems.

7.3.2 Drilling and coring

Limited drilling and coring techniques prove invaluable for the provision of dust and core samples for laboratory analysis, (Figure 52). In addition, these techniques also provide access into the structure for visual examination and further site tests. However, approvals for coring and drilling must always be obtained when dealing with a Listed Building.

Examples of suitable laboratory measurements may include:

- analysis of through thickness moisture contents;
- analysis of mortar;
- chloride content analysis (especially useful at ground floor level where de-icing salts may have been used);
- weight of corrosion product providing an indication of corrosion rates.

Examples of potential on-site evaluation may include:

- phenolphthalein carbonation test to examine the possibility of protection provided by alkalinity in concrete and mortar surrounding steelwork;
- access for the insertion of endoscopes for visual internal examinations;
- direct visual examination;
- access to the steel frame where electrical connections are required for electrical surveying techniques, such as potential wheel/half–cell, mapping pad;
- corrosion rate monitoring;
- insertion of resistivity probes or moisture/humidity sensors.

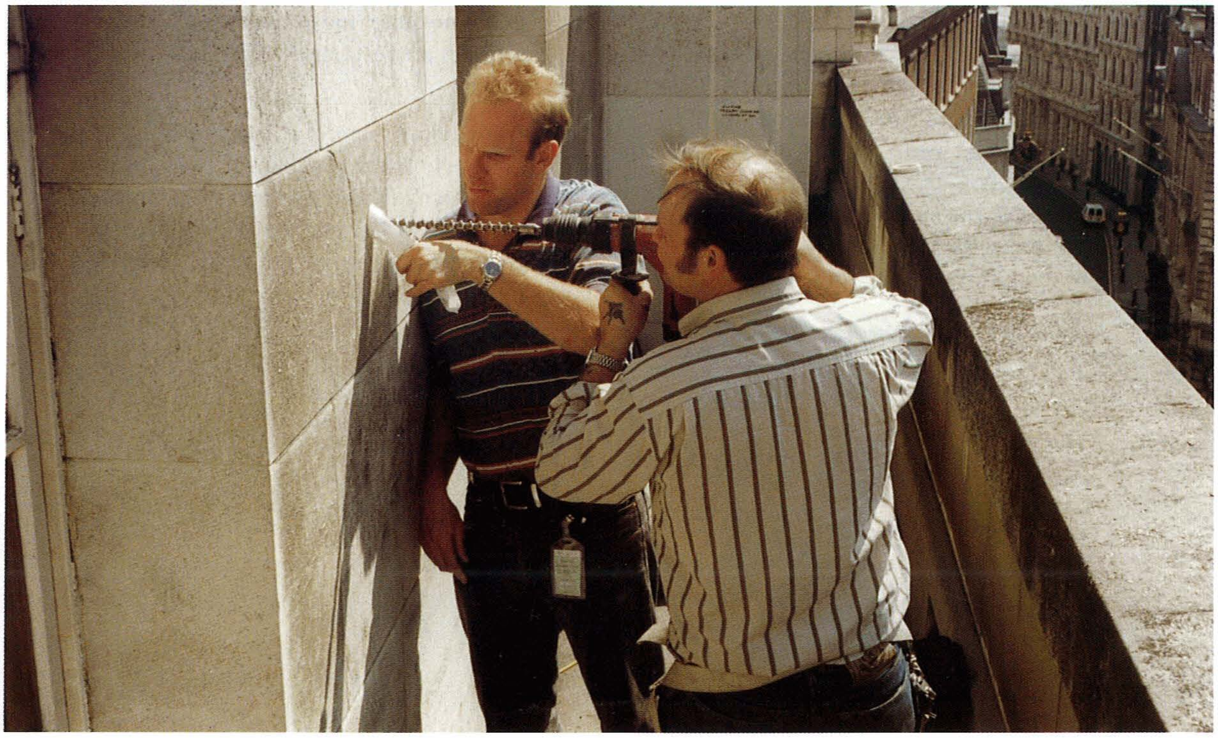


Figure 52. Collection of dust samples for laboratory analyses of moisture content, chloride level and composition. Note: Permission will be required for the drilling holes in Listed Buildings for dust sampling etc.

7.3.3 Removal of exterior masonry

In certain circumstances, it may be necessary to remove selected areas of the exterior facing for visual examination of the steelwork. Cases necessitating the removal of masonry may include confirmation of NDT methods, examination of regions suffering high distress, and the inspection of areas unsuitable for NDT evaluation. However, in these cases it is of importance not to cause excessive damage to the adjacent facings. Care should always be taken to retain as much of the original facing cladding as possible.

When removing facings it is important to recognise that the mortar in-fill can result in removal problems. In general it is found that the mortar is friable and detached from the steelwork which aids stonework and masonry removal. However, it must be remembered that the mortar in-fill was intended as an adhesive to bond the facing cladding to the steel frame and brick wall backing. Therefore, good quality, hard, dense, and well bonded mortar is often found which can result in damage to the facing being removed. Since it is often more difficult to remove the first stone in a large area it is always worth exploring a number of stones, finding the easiest to remove. Following removal of the initial stone, access is available to the bonded faces of adjacent stones, thus allowing the partial removal of good quality in-fill mortar and reducing the possibility of stone damage.

7.3.4 Removal of interior walls

Examination of the steel frame may be possible from the limited removal of internal walls. This is particularly advantageous when dealing with listed buildings, or buildings with highly ornate façades. However, it is important that the steel surface in contact with the exterior masonry is always examined together with the exposed face. Therefore, various mirrors and endoscopes etc. are required for a reasonable assessment of the steelwork. In the case of older buildings containing a mortar in-fill between the steel frame and exterior cladding, it may be possible to reveal the steel frame by the careful excavation of the in-fill mortar. However, it is probable that only limited success can be achieved in such cases.

In addition to the inspection of corrosion, internal inspections allow examination of the construction detail when drawings do not exist, This is often essential for the development of repair specifications.

7.3.5 Overcoring/stress relief coring

Internal stresses in masonry cladding can be calculated using specialist strain gauge and coring techniques developed for concrete bridge structures. An array of strain gauges are bonded onto the inspection area to enable measurement of the two-dimensional strains present in the surface of the cladding material. Following cure of the strain gauge mounting adhesive, the cladding material is cored around the strain gauge array, with the strain gauge array central with respect to the core. Following the coring operation, the amount of distortion in the core sample is measured from the strain gauge array. If the elastic properties of the cladding material are known, or measured from the core sample, the residual stress in the cladding can be calculated from elastic theory.

Overcoring is particularly advantageous when it is unknown whether building movement, thermal expansion, moisture movement or changes in load transfer routes are responsible for cracking as opposed to corrosion.

Prior to any coring, approval must be sought from the client/architect/planning authority. Wherever possible cores should only be taken in non-visual locations. All cores should also be retained after testing to enable replacement and repair of the cored stone at a later date.

8. CONTROL OF CORROSION

There are four basic methods for preventing or controlling corrosion.

8.1 Treating the Environment

In certain situations altering the environment provides a means for reducing rates of corrosion. Typical changes used are lowering the temperature, removing oxygen or oxidisers, changing the concentration of contaminants, and altering the chemistry of the environment. In many cases these changes can significantly reduce corrosion, the effects of which will depend upon the particular system.

In the case of steel framed buildings it is not usually possible to economically change the environment to reduce corrosion. However, in saying this it is relatively easy to alter the internal environment which can influence corrosion rates. Therefore, through an awareness of the factors affecting corrosion, problems can be avoided or a situation reversed. Typical environmental changes that could affect the rate of corrosion include:

- the addition of thermal insulation to the external walls of a building interior;
- the addition of air-conditioning;
- change of internal use. i.e. commercial to residential which results in the formation of condensation etc. on external walls;
- switching off heating in a vacant building or vacant building sections;
- changing the chemistry of the environment, for example by the removal of chloride ions or the addition of corrosion inhibitors.

Items 1 to 4 above all result in changes to the natural propagation of moisture into and out of the external façade which is of paramount importance due to the location of the steelwork. However, fully understanding the flow of moisture through the façade is a complex area of building technology requiring detailed computer modelling. Moisture flow is dependent upon the properties of the materials, partial pressures, external conditions, the internal building environment and their relative interactions As such, it is only possible to generalise about methods of corrosion control, due to the number of building types and building uses.

Moisture will tend to advance from warmer surfaces to cooler surfaces. The addition of insulation, air conditioning or switching off heating can either result in a general advancement of moisture towards the steel frame, or slow the rate at which moisture is driven away from the steelwork, thus initiating a greater number of corrosion problems, (Figure 53).

In practice when exposing corroded steel work in office buildings continually occupied since construction it is usually found that corrosion is significant on the outer facing webs and flanges, with internally facing flanges and webs displaying superficial corrosion only. These observations highlight the importance of moisture content and environment on corrosion, with the warm surface being kept dry and hence with a lower degree of corrosion.

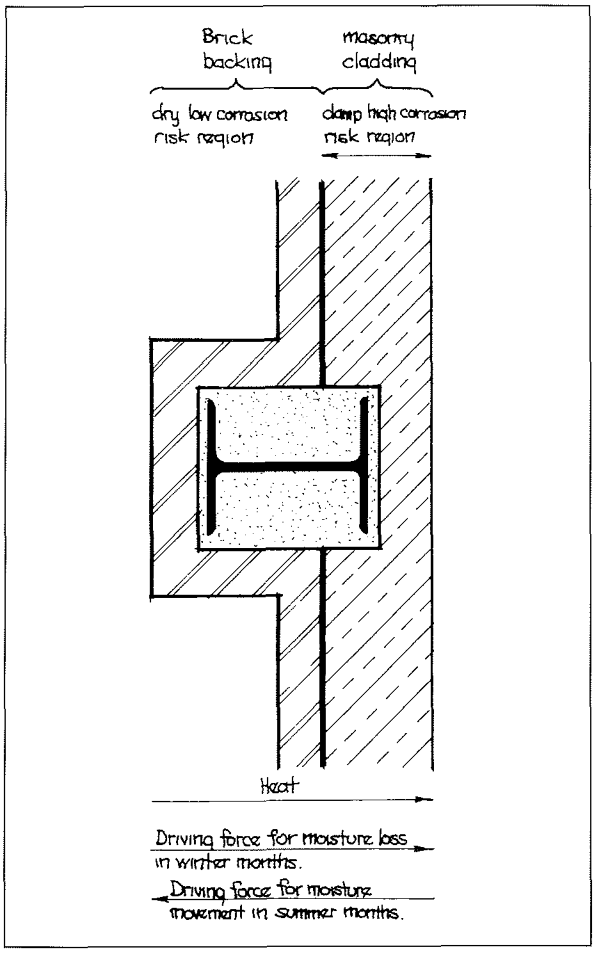


Figure 53. Driving force for moisture movement diagram.

In addition to the movement of moisture, the chemistry of the environment can significantly affect corrosion. If aggressive ions such as chlorides are introduced into the façade from de-icing operations or by natural processes then significant increases in corrosion can occur. However, once chlorides ions reach the steelwork, treatment is only possible by removing and replacing the contaminated environment, unless cathodic protection systems can be developed. A possible method of treating steel frame corrosion in the future may be by chemically changing the environment through the applications of chemicals know as 'inhibitors' into mortar surrounding the steel frame.

To date there is no proven track record of the suitability of inhibitors for steel framed buildings. As such, their suitability and track record are unknown and their use is not recommended for Listed Buildings. In particular careful consideration should be given to the following points:

- corrosion inhibitors may accelerate the corrosion of some non-ferrous metals. Particular attention should be given to buildings containing lead flashings, galvanised or sherodized fixings, bronze cramps and fixings, aluminium window frames, galvanised window frames;
- corrosion inhibitors may attack some plastics and organic materials such as UPVC or bitumen;
- the effect of the corrosion inhibitor on corrosion monitoring devices should be understood.

8.2 Protective Coatings

The application of a protective coating to the steel which is either organic or cementitious, is the most common method for preventing corrosion and is used for the greatest variety of applications.

The choice of protective coating system for steelwork will be dependent upon several factors which include the environment at the site of exposure, the size and shape of the structural members, the site conditions, difficulties of maintenance etc. These factors have to be considered before making a decision on the type of coating to be used, the number of coats and thickness of each coat, the method of surface preparation and method of application.

The refurbishment of steel framed buildings by painting initially involves cleaning and preparation of the steel frame to accept the paint system. Providing the steel can be cleaned to a suitable bright metal finish then proven zinc rich paint systems can be utilised. However, if the surface preparation cannot be guaranteed as is often the case due to access problems etc. then surface tolerant paint systems should be selected for repair. A typical remedial paint system would involve a three coat system with a dry film thickness of 100-120mm per coat. The manufacturer's estimated lifetime of the coating system would be up to 10 years. However, in practice a significantly higher life expectancy could be achieved.

A high standard of surface preparation prior to the application of a cementitious coating is not necessary to achieve corrosion protection. Further advantages of using a cementitious coating include its ability to repassivate the steel and provide a dense highly alkaline protective coating, enhanced chemical resistance and ease of application. At present the life time of a cementitious coating is unknown. However it is expected that protection could match or exceed those obtained with organic coating systems. It should be noted however that some cementitious coatings may not be suitable in environments subject to chloride ion ingress.

8.3 Impressed Current Cathodic Protection

Impressed Current Cathodic Protection (ICCP) is a system in which an electric current is applied from an external source to oppose the natural flow of electric current that gives rise to electrochemical corrosion. This can be done by either the sacrificial anode method which is unsuited to steel framed buildings or using an impressed current method.

In the impressed current system the current is applied from an external DC source through specially designed anode materials. These anodes are usually small precious metal coated titanium materials which remain unaffected under anodic conditions and last for many years. This technique is a new method of repair in respect to steel framed structures and has a number of advantages when compared to traditional repair options.

ICCP systems can not reverse damage caused by corrosion but they significantly retard corrosion to such a level that the problems of corrosion are effectively halted. As such they can be used to stop further damage and prevent damage in undamaged regions. The particular advantage of cathodic protection over traditional repairs is that it is not necessary to remove large quantities of stonework or other masonry to treat the corrosion. This method of repair is therefore more conservation friendly as replacement units are not required for materials that would normally be irretrievably damaged during removal and repair.

When considering Cathodic Protection the points set out in Annex C must be considered.

8.4 Attention to Design

To minimise corrosion damage, design details should avoid water traps, produce good drainage, promote air circulation, provide access for cleaning and maintenance and address problems associated with inappropriate materials specifications and uses.

Where practical, cavities should be introduced around existing perimeter sections and the risk of water ingress should be considered at the redesign stage. Water should be drained away from the base of the steel columns or other areas such as hangers, brackets and fixings where moisture may remain in the cavity wall.

Remedial building of the outer leaf around the steelwork should include either, or a combination of the following options:

- introduction of a clear air gap between the steel work and external face. Where the cavity is of reduced width between the steel and outer wall, water and rot resistant membranes or impermeable insulation materials may be installed to prevent moisture reaching the steel surface. Where such a vapour or moisture barrier is introduced, care must be taken to ensure that problems of condensation are not exacerbated;
- protective coatings should always be applied to the steel surface before the rebuilding of the outer leaf especially where abutment is unavoidable;
- if possible, encasing the structural steelwork in suitably selected concrete with sufficient cover prior to reinstatement of the façade to provide a suitable level of corrosion protection to the steel frame;
- the application of anti carbonation coatings to exposed concrete encasement.

8.5 Understanding the site conditions

Whilst considering these issues, there is a need to gain a fuller understanding of the actual prevailing site conditions so as to aid the decision making process. Much can be achieved through actual site based analysis and this can be assisted through reference to earlier building construction text books. In particular, Warland's "Modern Practical Masonry" published first in 1929, contains many detailed illustration in explicit isometric projection.

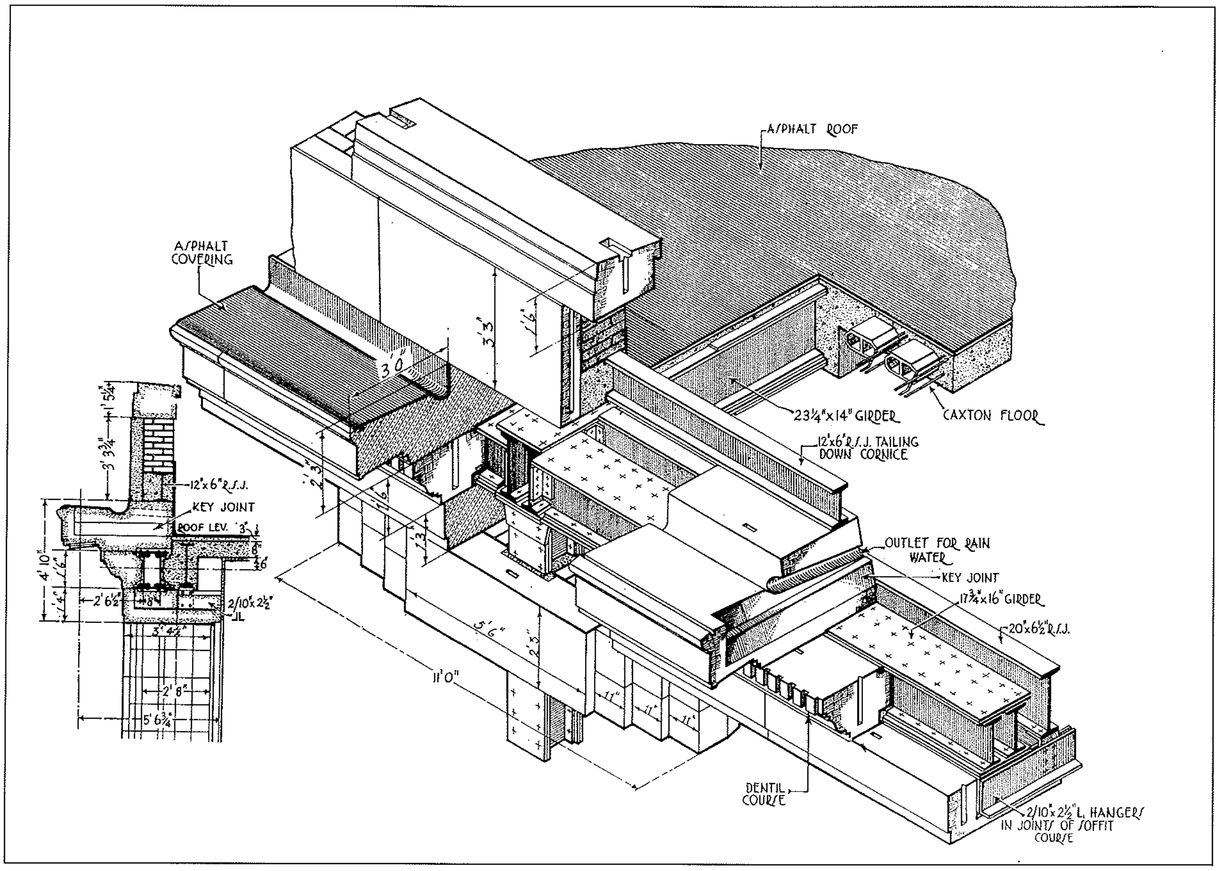


Figure 54. The construction of a Cornice. (Warland; "Modern Practical Masonry")

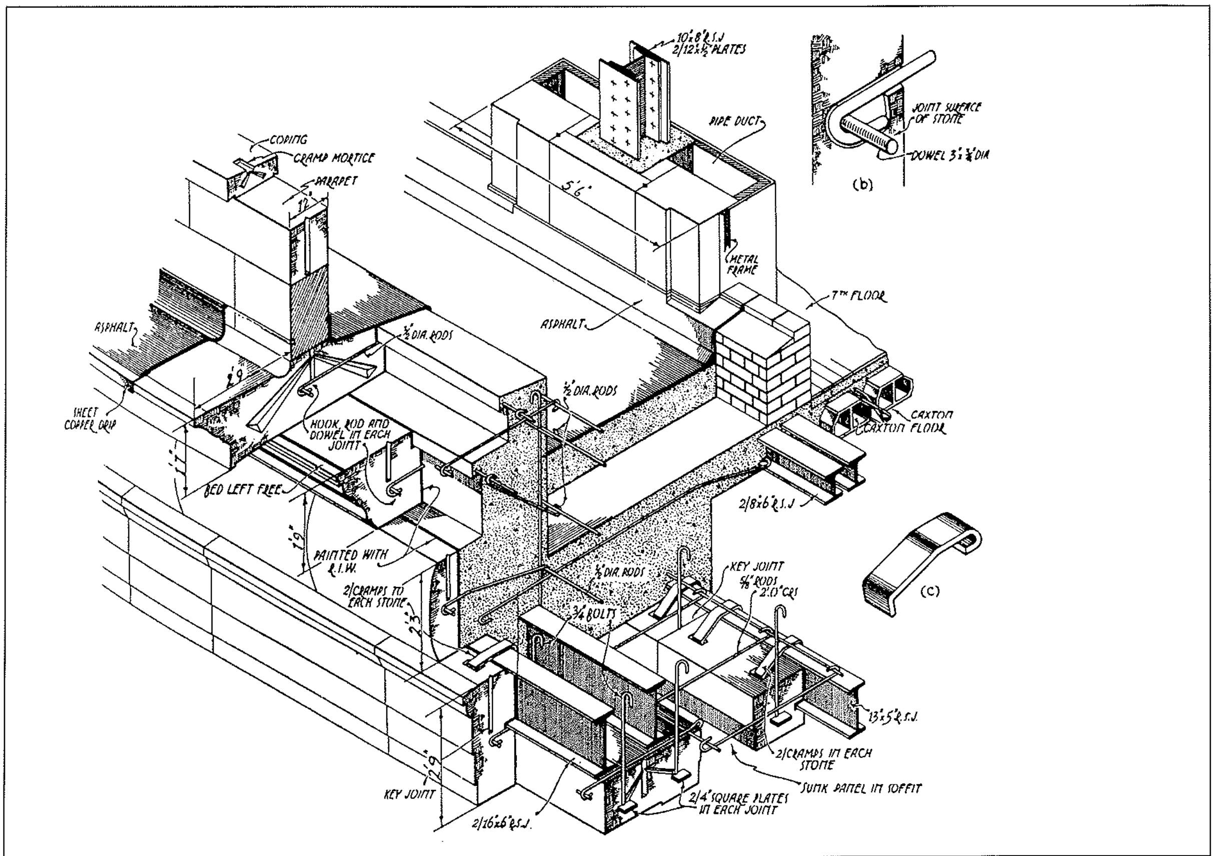


Figure 55. The construction of a Entablature. (Warland; "Modern Practical Masonry")

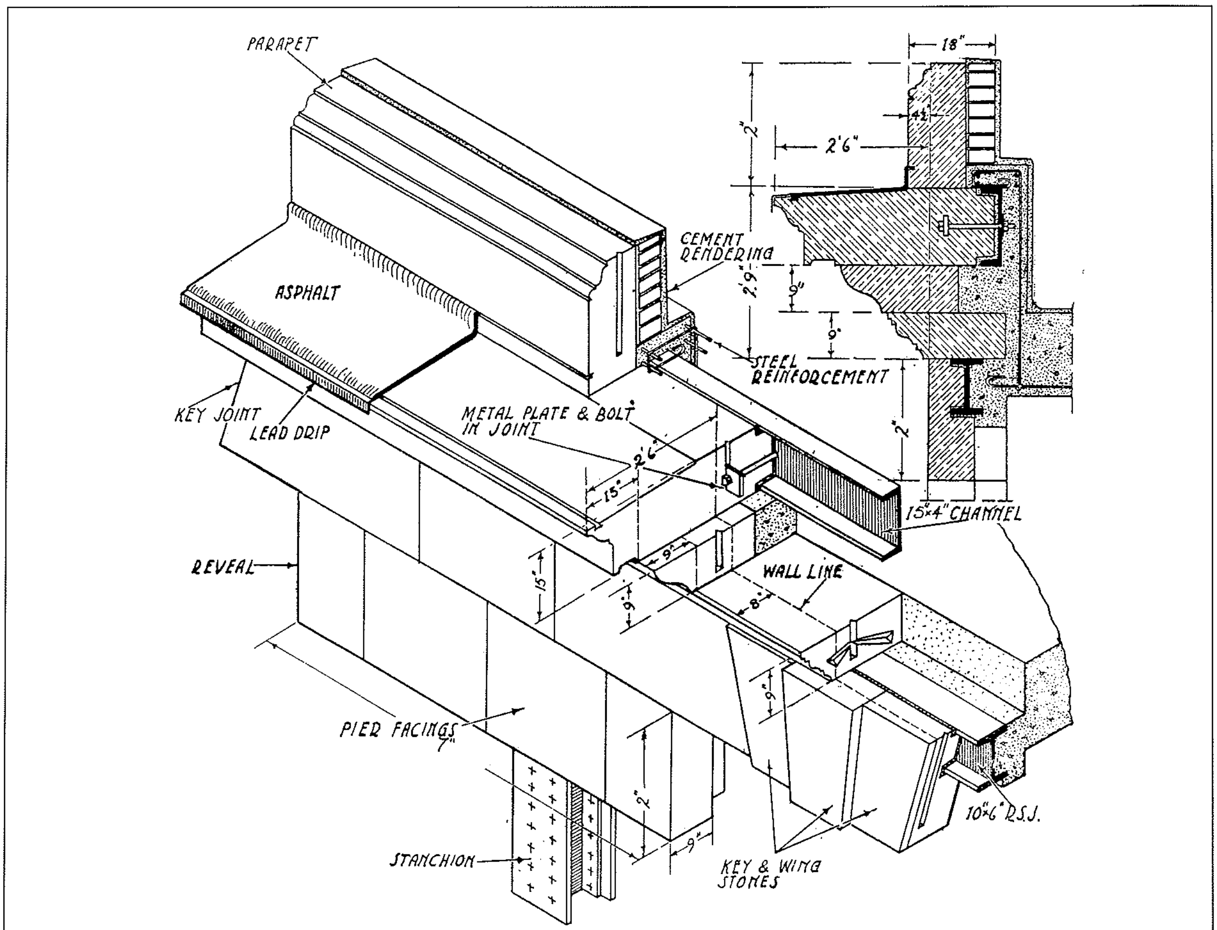


Figure 56. The construction of a Main Cornice. (Warland; "Modern Practical Masonry")

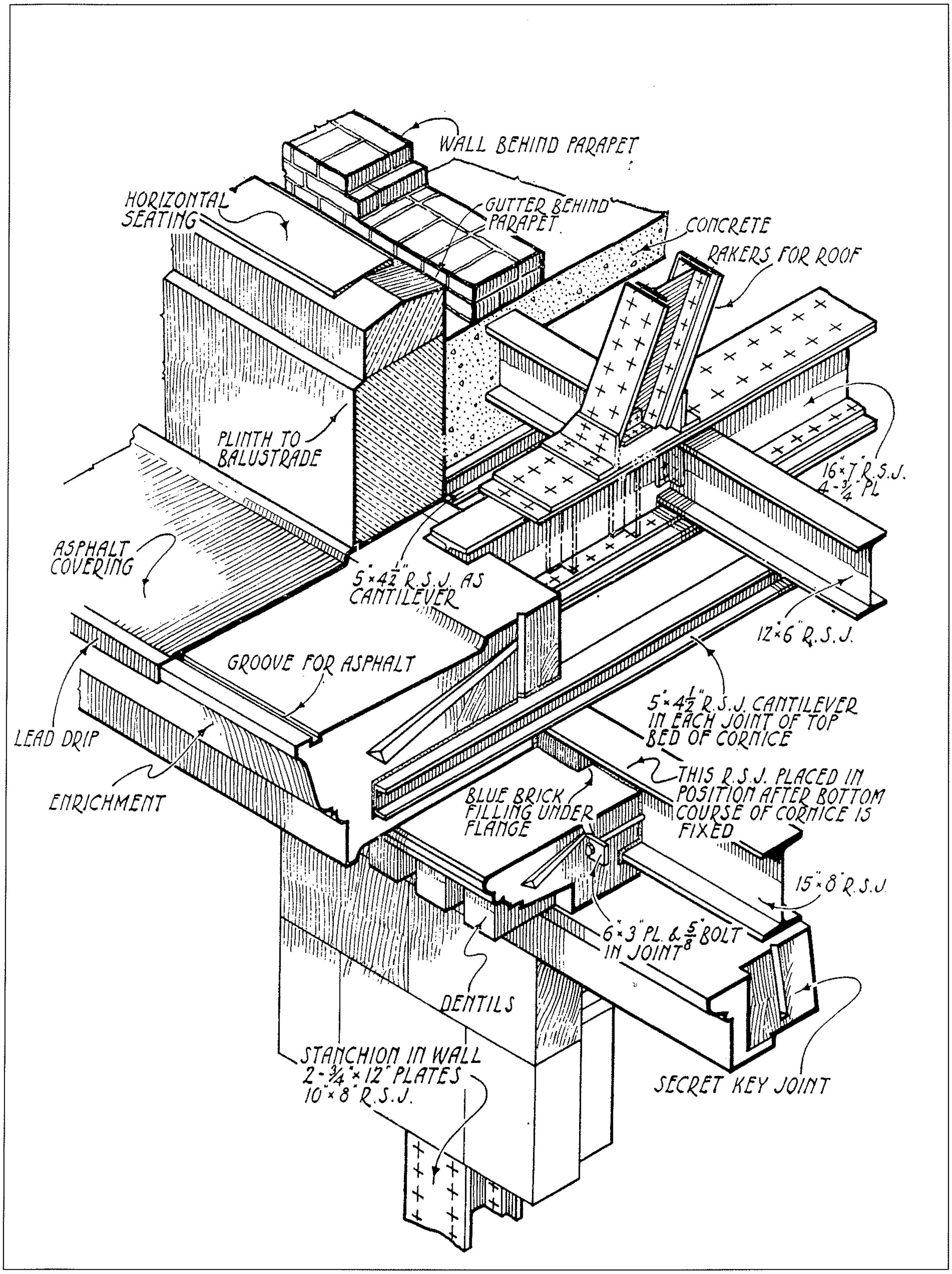


Figure 57. The construction of a Main Cornice. (Warland; "Modern Practical Masonry")

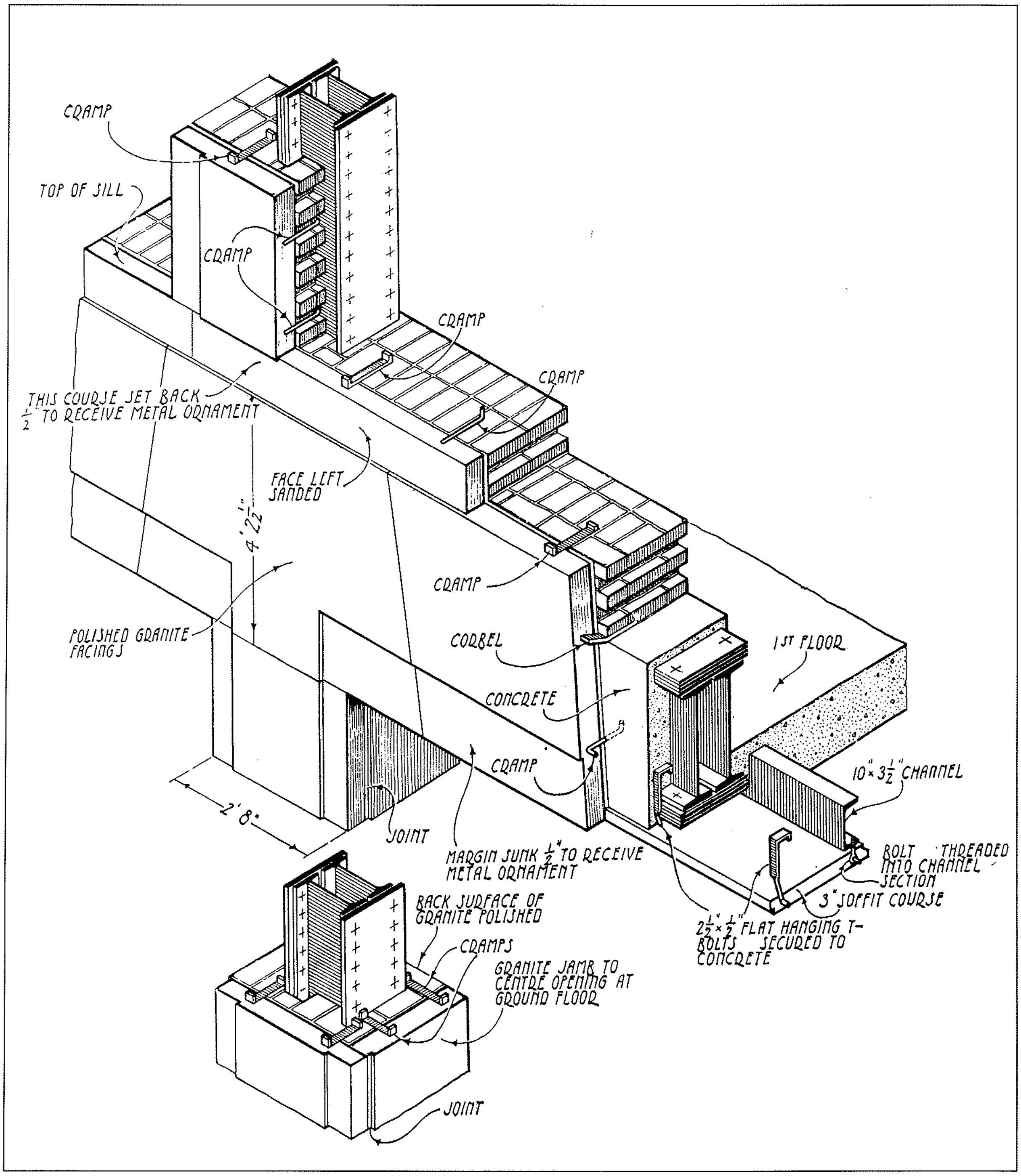


Figure 58. Slab facings of a external wall. (Warland; "Modern Practical Masonry")

9. REPAIR

9.1 General

Various measures might be considered to stop or reduce the rate of corrosion in masonry clad steel framed buildings. However, all traditional methods of prevention and repair involve the destructive removal of displaced or damaged masonry and the removal of corrosion products, followed by the application of a suitable coating prior to reinstatement of the masonry. Due to the highly disruptive nature and costs of traditional repair techniques, regions not showing corrosion related problems usually remain untreated. As such, unprotected sites exist throughout traditionally repaired buildings providing potential areas for further corrosion related damage.

It is unlikely that alternative solutions to masonry removal, corrosion treatment and masonry replacement can be found for treating highly displaced and damaged masonry. However, treatments other than painting may be used to protect the steel against corrosion. Alternative protective treatments could include concrete encasement, cementitious coatings, and the use inhibitor / polymer impregnated tapes that can be applied in lieu of a paint treatment.

Slightly damaged or undamaged regions can be protected from corrosion by other techniques which do not involve the removal of masonry and are more conservation friendly. Alternative methods of repair in these cases may include the following which are discussed in more detail in this section:

- impressed current cathodic protection;
- moisture repellent treatments for the masonry;
- addition of flashings;
- treatment with corrosion inhibitors;
- addition of DPC's to prevent moisture reaching the steel frame;
- inclusion of sealant materials into ashlar stone joints to prevent moisture ingress following mortar failure.

The scale and details of the remedial treatment governing the expected design life of repairs are often dictated by costs which can vary greatly between buildings. Other factors which govern the type and method of repair can include:

- influence from planning authorities;
- role of national strategy agencies when repairs concern listed buildings;
- the speciality and knowledge of the contractor;
- length of remaining leases for which the tenant has responsibility for repairs;
- level of disturbance that can be imposed upon building occupants and the surrounding area.

9.2 Removal of Masonry

Ashlar masonry surrounding the site of corrosion damage should only be removed to a sufficient level to ensure successful treatment of corrosion. Care should always be taken with listed structures to ensure that minimal damage is caused to masonry outside the general area of severe corrosion.

9.3 Traditional Repair and Paint Treatments

The traditional methods of treating corrosion damage involve:

- grit blasting the corroded steel to a bright metal finish as described by the Swedish Standard S1S 05 59 00 Sa2½ finish;
- application of a corrosion inhibiting paint/coating system, e.g. a zinc rich two part epoxy;
- where appropriate the addition of DPC's, particularly if a cavity can not be achieved between the steel and external ashlar masonry;
- replacement of the masonry leaving a cavity between the steel frame and external cladding providing this is not visually evident.

This treatment provides an adequate repair with a design-life expectancy dependent upon the preparation of the steelwork and the choice of paint system. Treatments can last well beyond the paint manufacturers' guaranteed lifetime, assuming good preparation prior to painting, due to the presence of the air gap that replaces the gap previously occupied by mortar.

The creation of an air gap is an important feature which extends the lifetime of the repair by:

- preventing damage to the paint system through movement of the façade;
- removing damp masonry from direct contact with the steel frame;
- allowing a gap for the formation of corrosion products preventing jacking and masonry cracking;
- shielding the paint from the external environment.

9.3.1 Fixings for Traditional Repairs

During reinstatement of the removed cladding, fixings are often required where previously none existed. Fixings are often required due to the removal of the natural compressive forces and backing mortars originally holding the stonework in place and the incorporation of cavities. Failure to include fixings in certain details could result in a dangerous condition if not carefully examined during development of the traditional repair methodology.

Typical fixing details commonly used in the repair of steel framed buildings are shown in Figures 59 to 66. However, it should be noted that various designs will be required in a single refurbishment project and specialist advice is always required in their use.

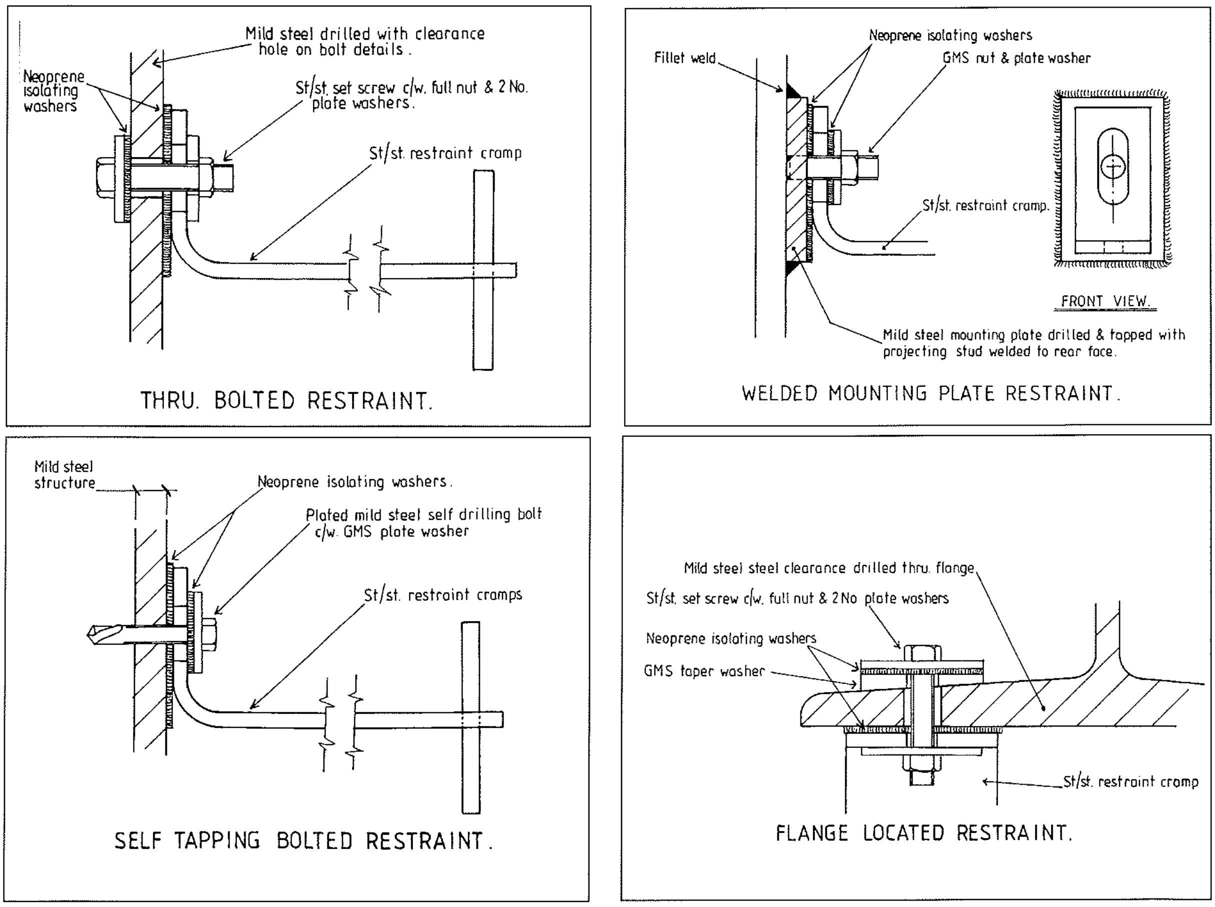
When installing fixings in any refurbishment project it is important to ensure the use of stable non-corrosive materials such as grade 316 stainless steel. When any dissimilar metal is used incontact with the steel frame it is essential to electricaly isolate the fixing to prevent galvanic corrosion.

However, if ICCP systems are to be developed for the repair region the opposite holds true and fixings should be continuous with the steel frame and the isolators shown in Figures to 59-66 omitted. In the case of ICCP repair systems the steel frame should be painted 200mm either side of the fixing to prevent bimetallic corrosion prior to commissioning the the ICCP system and to allow for periods in which it may be shut down.

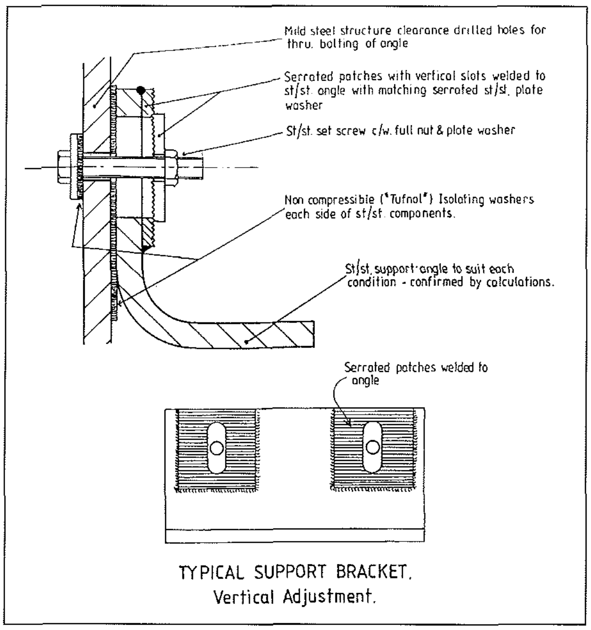
In addition to metallic fixings some non-metallic composite materials are beginning to appear. These may be especially useful for pinning and doweling. Non-metallic fixings are of interest especially when ICCP type systems are being considered or isolation of the fixing may be difficult.

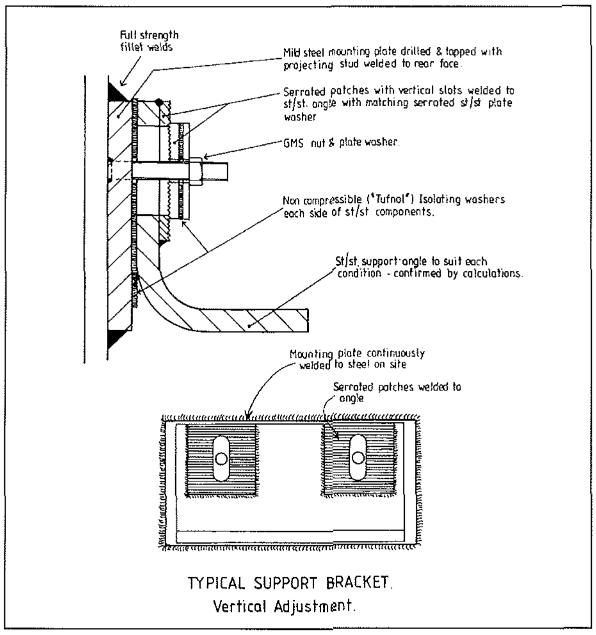
9.3.2 Suitable Coating Treatments

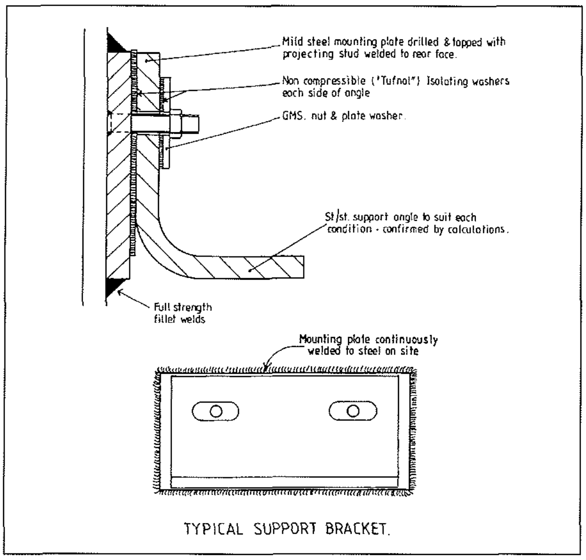
In the selection of a suitable protective coating it is important to recognise the following:

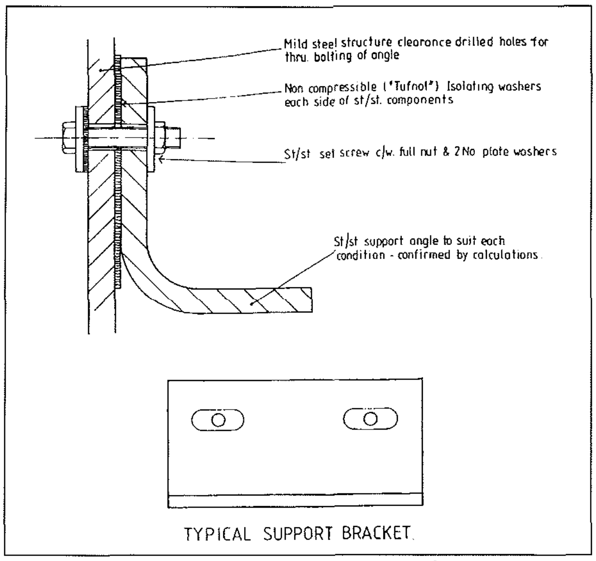


Figures 59 to 62. Suggested bolted restraint methods used for reinstatement of repaired masonry. It is of importance that the stainless steel is isolated from the steelwork using the isolators shown to prevent galvanic corrosion at the bimetallic contact.









Figures 63 to 66. Typical stainless steel support brackets used for reinstatement of repaired masonry. It is of importance that the stainless steel is isolated from the steelwork using the isolators shown to prevent galvanic corrosion at the bimetallic contact.

- a definitive exposure category rating is not identifiable. The steel frame will not be directly exposed to atmospheric conditions and may be subjected to continual wetting and drying.
- manufacturers coating performance data are often related to exposure of the steel under defined atmospheric corrosion conditions.
- where surface preparation cannot be guaranteed, a surface tolerant system is the preferred repair option e.g. surface tolerant aluminium based epoxy systems, or cementitious coatings.
- zinc rich epoxies should only be considered if a high standard of surface preparation can be achieved i.e. Swedish Standard S1S 05 59 00 Sa2½ gritblast finish.
- an air space should always be provided (where possible) prior to replacement of the masonry. The reinstatement of the mortar is a potential cause of corrosion and coating failure;
- additional protection will be achieved by the application of a bitumen or Micaceous Iron Oxide (MIO) coating over the aluminium primer systems;
- in general the guaranteed lifetime of the coating system is expected to be between 5 and 10 years. However, performance will significantly exceed the guarantee period with good surface preparation and good working practices;
- cementitious coatings can provide 10 years guaranteed protection of steel work with minimal surface preparation.

9.3.2.1 Environment

With the refurbishment of steel framed buildings, the environment cannot be clearly identified (e.g. it falls between the exterior and interior exposure regimes categorised in BS 5493). In general there are two potential environments in which the paint system must perform:

- painted steel in contact with mortar in-fill;
- painted steel in purposely formed cavity.

Corrosion of the steel and deterioration of the paint film will not occur unless water and oxygen are both present on the surface of the protected steel. As a mortar contact is likely to place the steel in a permanent moist contact condition this situation should be avoided in reinstatement.

If a cavity is purposely created between the steel and outer cladding during reinstatement the exposure conditions are not clearly defined. Cavities created around the steel as a result of omitting the mortar in-fill are likely to have similar properties to those found in modern cavity walls, where for example humidity levels of less than 70% are found. In general it should be assumed that any steelwork within the cavity is subject to a process of continual wetting and drying which will be more detrimental than direct exposure. As most steel framed buildings within the UK are located within major cities and towns it is also reasonable to assume that the painted steelwork is exposed to pollutants found in industrial atmospheres.

Once repaired the steel is not located in an accessible position and maintenance of the coating system is not an option. Additionally it should always be noted that even with the best working practice mortar droppings can bridge any cavity and alter the environment. These factors should always be considered when specifying a repair coating and the building owner provided with a durable coating system to minimise any risk of future repairs.

During repair it should be remembered that complete treatment of the steel is not always necessary or carried out for budgetary reasons. Where cavities have been introduced during traditional painting repairs it should always be remembered that condensation and water collection may occur within the newly formed cavities. This may result in wetting of the mortar in contact with the steel in untreated adjacent areas causing accelerating corrosion. Water movement should always be managed away from untreated regions. This can be achieved by the insertion of DPC's etc. Failure to install a DPC between treated and untreated areas will result in accelerated corrosion in the untreated region.

9.3.2.2 Organic Paint Systems

There are two organic paint systems that are most suited to the repair of traditional steel framed buildings: aluminium epoxy or zinc rich epoxy (or polyurethane). It is generally accepted that both systems provide excellent corrosion protection. However, differing levels of surface preparation may be tolerated.

Zinc rich primer systems provide sacrificial galvanic protection to the steel and require good electrical contact. With zinc systems a high standard of surface preparation is required by shot blasting to a quality of at least Sa 2½ as described in the Swedish Standard SIS 05 5900.

Aluminium epoxy systems offer good corrosion protection and can be obtained as surface tolerant systems. These surface tolerant systems do not require the same high surface finish specification as zinc rich systems (although preparation to an Sa 2½ finish is always recommended where possible).

The paint system selected should reflect the achievable level of surface preparation. Since a high standard of surface preparation cannot often be guaranteed due to access and noise and dust restrictions, steel preparation is often restricted to manual cleaning. Where limited cleaning operations (e.g. wire brushing) are specified it is unlikely that a suitable surface can be obtained for zinc rich primer systems. In these circumstances surface tolerant aluminium filled epoxy systems are recommended. In both cases typical paint systems would involve a two to three coat paint system with a dry film thickness (dft) of 100 - 120 microns (μm) per coat. The estimated lifetime of the coating system would be up to 10 years.

Additional protection can be gained for either system by the subsequent application of a bitumen or Micaceous Iron Oxide (MIO) based coating.

9.3.2.3 Cementitious Coatings

As with the application of organic coatings, accessibility to the steel work sections may present certain difficulties as far as surface preparation is concerned. However, unlike conventional organic coating systems, surface preparation prior to a cementitious coating application does not have to be to a high standard in order to achieve corrosion protection.

Various cementitious coating systems have been developed to allow high build along pipelines for example by brush or spray application. Also, the addition of a water based epoxy resin to various formulations has produced coatings for use where the surface remains damp on coating application and minimal surface preparation is possible i.e. 'I' section beams in sewers and external surfaces of water pipes.

Further advantages of a cementitious coating system include:

- the ability to passivate the steel and provide a dense highly alkaline protective coating.
- good abrasion and high resistance to freeze thaw cycles and de-icing salts.
- very high resistance to water permeability and diffusion to carbon dioxide.
- enhanced chemical resistance.
- ease of application by either brush or spray normally in two coats of 1mm thickness.

A factor which should be considered with cementitious coatings is the application conditions. Normal winter concreting conditions often apply and work should not be conducted when the temperature is below 5°C.

9.3.2.4 Summary of Representative Coating Systems

The following table is not intended to provide a definitive list of materials suppliers and systems. The table is only intended as a guide to typical currently available systems at the time of writing.

Supplier	Material	Remarks
Liquid Plastics Ltd (Flexcrete) PO Box 7 London Road Preston Lancashire, PR1 4AJ	CEMPROTEC 941 CEMPROTEC E942	Cementitious coatings with up to 10 year guarantee. Thixotropic properties enable ease of application by brush or spray. Can be applied to damp or wet surfaces.
SBD Dickens House Maulden Road Flitwick Bedford, MK45 5BY	Cementitious products SBD Brushcoat Mulsicoat Smooth (anti-carbonation coating)	With the anti-carbonation coating, system should provide a 10 year life to first maintenance Can be applied to St 2½ prepared surface Thickness to 300µm. (Vol of 11 litres10-20 m² in 2 coats. 4-8 m² per litre in 2 coats.
Sigma Coatings Ltd Tingewick Road Buckingham MK18 1ED	Sigmacover Aluprimer	Recommended dry film thickness: 75-125µm
International Paint Ltd Stoneygate Lane Felling Tyne and Wear NE10 0JY	Interplus 256	Two pack high build epoxy Contains aluminium pigments. Apply two coats at 120µm per coat.
Johnstones Paints PLC Unit 4 Oldfield Lane North Greenford, Middlesex UB6 8QE	Aluminium Epoxy ST211	Two coats at 75µm per coat Coverage rate @ 8.7 m² /litre
Sika Ltd Watchmead Welwyn Garden City Herts. AL7 1BQ	ICOSIT primer : followed by ICOSIT POXICOLOUR	1 coat at 80-100µm. Consumption 350g/m² Two component high build epoxy coating for steel. Two coat application at 100µm per coat. Consumption 300g/m²
W & J Leigh's & Co. 155 Commercial St London E1 6BL	EPIGRIP M902 Winterfast EPIGRIP M903 Brush Micareous Iron Oxide	Two pack epoxy aluminium primer. Wire brush surface. Two coats at 125µm per coat by brush. If considered necessary, one coat application of Micareous Iron Oxide to guard against moisture ingress. (125µm per coat)
Permarock Products Ltd. Jubilee Drive Loughborough, Leicestershire LE11 0XS	DISBOXID 483 DISBOXID 441	High build/Al rich epoxy primer 50µm dry film thickness High build epoxy top coat 50µm dry film thickness

Table 3. Summary of Representative Coating Systems

Despite the expected life costs of each of the above systems it is important to evaluate the costs of each of the above systems against total repair cost. The cost of the paint system is usually a minor element in the repair program and the consequences of an earlier failure will have large future implications for the building owner. This is especially important where a tenant is responsible for maintenance and repair and there is a conflict between short term tenant requirements and the longer term owner and conservation requirements.

During traditional repairs a cavity is created between the steel and external masonry. However, it is not common practice to include DPC's between repaired cavity zones and untreated regions. Failure to introduce a DPC between these areas will result in accelerated corrosion of the untreated region since the cavity will act as an ideal conduit to the untreated region for moisture entering the structure or forming due to condensation. It is therefore fundamental to ensure that DPC's are added between repaired and untreated regions to prevent future corrosion problems in the untreated areas at the time of repair.

9.4 Cathodic Protection

The term cathodic protection describes a general area of technology covering two basic forms of electrochemical corrosion prevention, namely sacrificial (or galvanic) cathodic protection or impressed current cathodic protection. Galvanic CP is the oldest form of electrochemical corrosion prevention and consists of connecting a more corrosive metal such as zinc or magnesium to the steel that corrodes in preference to the steel and generates a protective current that prevents corrosion of the steel in contact with the sacrificial anode material. This form of protection is well documented and understood and is commonly used to protect iron and steel structures in aqueous environments and wet soils. This form of CP is only suitable in situations in which the electrolyte (soil or water) is suitably conductive and allows the current generated by corrosion of the sacrificial anode to pass to the corroding steel. Impressed current cathodic protection (ICCP) differs from Sacrifical CP in that an inert non corrosive anode material is placed in the structure or soil and the protective current is forced on to the steel surface through a power supply. The important benefits of ICCP are that:

- the cathodic protection current can be pushed through higher resistivity elecholyles (concrete, stone, mortar etc) by the higher drive voltages available from power supply;
- inert catalytic anodes are not consumed and as a consequence they have high design lifes in comparison to sacrifical anodes.

Impressed current cathodic protection (ICCP) may provide an effective method of preventing corrosion damage in early 20th Century buildings constructed with an in-fill between the steel frame and external cladding. However in considering ICCP careful consideration should be given to the items raised in Annex B. It should be noted that ICCP cannot be applied to buildings without a suitable electrolyte, such as damp mortar, in contact with the steel frame. Cathodic protection is therefore not suitable for protecting steelwork in buildings constructed with large cavities or insulation between the steel and external masonry cladding. Early buildings are suitable for ICCP and those with large voids or inconsistent in-filling can be modified by grouting techniques to make ICCP technology viable.

Impressed current cathodic protection systems operate on the principle of preventing corrosion by passing a current from an externally placed anode material, through a connecting electrolyte (facing and mortar), to the corroding steelwork (cathode). As a result, electrochemical reactions are prevented at the steel surface through the prevention of ferrous ion (cation) formation on the steel surface and the removal of reactive negatively charged ions (anions). Great care must be taken in the design process to ensure adequate protection and the prevention of damage to the structure. Examples of important design considerations for masonry clad steel framed buildings will include:

- careful choice and placement of anode systems to ensure full protection to the steel frame, whilst being sympathetic with the façade and conservation requirements;
- continuity of electrical contact between the steel frame and ties, cramps, fixings etc. to prevent their accelerated deterioration through stray current corrosion;
- prevention of overprotection currents which may result in hydrogen embrittlement or hydrogen blistering of the structural steelwork;
- careful control of currents to ensure suitable protection when resistivity changes occur in the masonry through wetting and drying cycles.

9.4.1 Introduction to CP

The corrosion of steel in cement based materials is an electrochemical process. Dissolution of steel (oxidation reaction) liberates electrons and forms anodic sites.

$$Fe \longrightarrow Fe^{2+} + 2e^{-} \qquad (1)$$

In order to maintain charge neutrality, a reduction reaction occurs at an adjacent area called the cathode:

$${}^{1}/_{2}O_2 + H_2O + 2e^{-} \longrightarrow 2OH^{-}$$

The oxidation reaction (1) is the first step in the process of forming rust. It is initiated where acidic conditions on the steel surface (often resulting due to carbonation of the mortar in-fill) are sustained within the incipient anodic sites and result in localised lowering the steel potential. This causes an electrical potential difference between the incipient anodes and the adjacent cathodic areas and results in current flow between them. Subsequently, corrosion of steel proceeds when the following conditions are maintained:

- acidity or lower pH within the pits;
- lower potential within the pits;
- electrical potential difference between the anodic and cathodic areas.

Both oxidation and reduction reactions occur simultaneously and the corrosion rate is reduced and/or stopped when one of these reactions is controlled and/or ceased. As the conditions are mostly ideal for both oxidation and reduction reactions external control is required.

To stop the corrosion process, the anodic reaction (1) must be suppressed. ICCP arrests the corrosion process by the following methods:

- lowering the steel potential in the negative direction sufficiently where oxidation reaction can not recur;
- lowering the electrical potential difference between the anodic and cathodic areas;
- generating alkalinity at the steel surface as a result of reduction reactions;
- removing aggressive ions, such as chloride from the steel surface.

In impressed current cathodic protection (ICCP) of reinforcing steel in concrete, it is normal to apply an external anode, and to apply a current from an external anode to the steel. The potential is then depressed to a value at or below the lowest anode potential before ICCP was applied.

Another way of viewing ICCP is that when steel corrodes, a positive ionic current flows away from the steel surface into the concrete. ICCP effectively reverses the direction of current flow, by forcing an ionic current to flow from the external anode to the steel.

9.4.2 Feasibility of ICCP for steel framed buildings

There are several important factors which must be assessed before concluding that ICCP is a viable option for a steel framed building:

- continuity of the steel frame, fixings and other metallic items;
- contact between steel and mortar;
- current distribution (controlled by mortar and stone resistivity);
- location of anodes (joint details and steel work detailing);
- aesthetic constraints (installation details).

9.4.2.1 Continuity

Early 20th Century steel frame buildings contain a large variety of metallic elements in their construction. Typical details often include at least two of the following items and often more:

- steel beams and columns;
- fixings that are either bronze, iron, steel or galvanised steel;
- iron, steel, galvanised steel or bronze cramps between stone elements;
- steel reinforcement bars hooked over the top flanges of spandrel beams in concrete floor construction;
- small steel reinforcement wires connected to the top and bottom flanges of beams to form a cage for the concrete encasement of the inner faces of steel beams;
- chicken wire meshes to aid in internal works such as concreting and plastering;
- cast iron rain water downpipes and copper water pipes.

Failure to ensure the electrical continuity of all metallic elements in a steel framed building can result in stray current interactions between the various elements of the structure, resulting in accelerated corrosion of discontinuous items. The importance of electrical continuity is well established in concrete ICCP and early investigations and site trials have shown the importance of electrical continuity in steel framed buildings.

Ensuring electrical continuity of the steel frame, stonework and masonry fixings and any reinforcement bars etc. present in flooring systems is an essential element to the application of cathodic protection systems for steel framed buildings. Designers and engineers involved with the development of ICCP systems for steel framed buildings should therefore be fully acquainted with:

- all common design details;
- historical methods of building construction;
- testing and inspection methods for the identification of discontinuous metallic items.

In addition to the above, the CP designer should also be familiar with any repair activities taking place on the building where stainless steel dowels and cramps are to be used in the repair and stabilisation of damaged stone or other facing materials. Where it is known that discontinuous metal fixings are proposed, consideration should be given to their stray current interactions. Potentially problematic fixings should be either connected to the steel cathode or be substituted with appropriate non-metallic materials such as GRP dowels.

9.4.3 Electrolyte

Corrosion prevention in historic steel framed buildings is possible by cathodic protection techniques since the protective current can be passed through the stonework or masonry via a mortar or concrete connection with the steel frame. However, although details often exist of the steel and masonry layout, knowledge of the mortar or concrete connection between the two elements is not always known. It is often found that the quality and consistency of the mortar in-fill between the steel frame and masonry façade is highly variable. The mortar in-fill often contains large voids and in certain circumstances is completely absent. This is particularly true for regions of the façade that would have been difficult to fill during construction, such as behind the stonework of window heads etc. As the mortar in-fill is essential for ensuring the passage of the protective current to the steel beam it is therefore vitally important to ensure adequate consideration for voidage in any CP design.

Knowledge of historic building construction methods is essential when establishing the possibility of voidage. Expert knowledge of steel frame construction enables a rapid risk assessment of voidage to be carried out and enables areas requiring further inspection to be pinpointed. Following risk assessments and inspection it is often reasonable to make one of the following choices:

- a large consistent void exists (greater than 25mm) in which corrosion rates are minimal and protection is not required;
- a large void exists in which corrosion is occurring at a significant rate and treatment is required. The voided cavity must therefore be grouted to ensure protection;
- small voids exist (less than 10mm) in which corrosion has occurred. However, due to the

Figure 67. Installation of a mesh ribbon anode into the beds of ashlar stonework.

restricted size of the voids protection is not required. This applies since an installed ICCP system will stop corrosion when the void becomes filled with corrosion products that act as an electrolyte.

9.4.4 Resistivity

The resistivities of most masonry materials are in a suitable range for the application of cathodic protection when containing more than 2% moisture by weight. However, as with any porous material it is important to understand the behaviour of moisture content on resistivity. Most masonry materials have resistivities that exceed 1 M.ohm.cm when moisture contents fall below 2%. As the outer surfaces of the cladding material will tend to be in a dryer state than the internal areas, the placement of anodes and the rating of power supply output voltage must be correctly chosen to ensure adequate protection of the steelwork.

Particular care is required when designing ICCP systems for use in materials such as terracotta, faience, and glazed bricks. In these materials, the glazing or fire skin layer will effectively act as an insulator making it impossible to throw protective currents to the steel surface. Protection is possible however if the anode materials are made to contact with the underlying porous material beyond the surface layer. To ensure effective contact, anode materials must either be laid directly within the main body of the masonry blockwork, or in joints in which the insulating surface has been removed. However it is important to note that in the case of listed buildings it is essential that damage to the façade does not occur during the installation of anode materials and the outward appearance remains unaltered.

In general, ICCP systems should operate on a constant current basis. As the resistivities of masonry materials are generally higher than concrete materials the constant current source should be capable of providing a sufficient drive voltage. Experience to date suggests that the voltage outputs of masonry ICCP systems should be capable of providing a maximum drive voltage of between 20 and 30V.

9.4.5 Anodes

A number of anode types are applicable in the protection of steel framed buildings. However, the two most suitable types are:

- expanded Mixed Metal Oxide activated (MMO) titanium mesh ribbon anodes approximately 1mm in thickness and up to 25mm in width;
- discrete rod anodes (ceramics or carbonatious backfilled Mixed Metal Oxide (MMO) coated titanium rods).

Figure 68. The entrance colonnade to the Royal College of Science, Dublin (1991), the first full scale cathodic protection system for the protection of corroding steel 'I' sections.

Expanded mesh ribbon anodes are particularly useful for insertion into fine ashlar jointing of stonework and the mortar joints of brickwork, (Figure 67). Ashlar stone joints are typically 5mm in width and brick joints approximately 10mm in width making it possible to insert the mesh ribbon. Ribbon anodes are generally installed using standard masonry pointing techniques with a suitable soft mortar for the masonry in repair. It is particularly important with this class of anode to use a correctly graded mortar that is not too hard for the masonry in repair.

The particular advantages of expanded MMO titanium mesh ribbon anodes are:

- the anodes are not visible;
- anodes can be installed using standard masonry pointing techniques at the time of external repairs;
- anodes are usually situated parallel to beam and columns;
- minimal internal disturbance.

It is often not possible to install discrete rod anodes externally due to their size and the resultant disturbance to the façade (although in the case of brickwork the larger joints may be suitable for certain anode types). However, discrete rod anodes can be inserted internally and require no external access.

In the case of discrete anode systems however, great care should be given to the generation of acids on the anode surface as a result of the anodic reactions. Currents should always be kept to a minimum level and should not exceed $100mA/m^2$ on the anode surface. Where the discrete anode is not embedded within an alkaline material, great care is required in the decision to utilise these anode types and their operating conditions.

9.4.6 Track Record

The first Cathodic protection system for the prevention of steel beam corrosion in a masonry structure was designed and completed in 1991, (Figure 68). The CP system provides protection for the entrance colonnade to the Royal College of Science, Dublin, a limestone structure containing two parallel structural 'I' beam members. Since its completion in 1991 regular remote monitoring via embedded (Ag/AgCl.KCl) reference electrodes has shown the system to be performing adequately through 24 hour depolarisation measurements. Further visual inspections carried out annually have also confirmed the findings of the electrochemical monitoring and no corrosion problems have been identified.

Since the development of this first CP system for masonry, further systems were designed and installed for masonry buildings in the early 1990s. Typical systems have included the protection of iron cramps in the grade I listed Inigo Jones Gateway of Chiswick House, London, and the corrosion prevention of iron staircase supports embedded in brickwork at the grade I listed Kenwood House, Hampstead.

The first full scale CP installations for the protection of complete steel frame façades have been designed and installed over the last two years. These systems include the faience façade of Gloucester Road Underground Station protected with a discrete rod anode system, and the Joshua Hoyle Building, Manchester Piccadilly, a brickwork and faience façade protected with a expanded titanium mesh ribbon anodes inserted in the mortar jointing. These systems have shown the practicality of protecting full building façades and the versatility of CP systems for listed buildings. In the case of the Joshua Hoyle CP system protection of two five storey façades was found to have a cost saving in excess of 50% in comparison to traditional approaches of repair involving the removal of masonry and steel painting.

During the development of this advice note it is known that CP systems are now being designed and installed to protect steel work elements on a number of steel framed structures. It is also known that the latest revision of BS 6270 on the cleaning and surface repair of buildings will include CP as a repair option.

9.4.7 Life Expectancy

The life of an ICCP system will depend on the performance of individual component parts. With the exception of the anodes and monitoring electrodes embedded within the structure all component parts can be maintained and replaced as required.

An ICCP system would be expected to provide a minimum operational life in excess of 20 years. With appropriate maintenance and replacement of the electronic circuitry the CP system should provide a life in excess of 50 years. The estimated life of the various major components would be as shown in Table 4 and the system should be designed to allow for the replacement of components with a limited life span.

9.4.8 Sacrificial Cathodic Protection

The low electrical conductivity (high resistivity) of most common stone and masonry prevents the use of sacrificial cathodic protection. Sacrificial cathodic protection is unsuitable since the driving voltage that occurs by connecting a dissimilar metal anode such as

Table 4. Summary of Components and Typical Estimated Life

Component	Estimated Life (years)	Comments
Electronics and Control Systems	20 years +	Life of electronic components varies and design should allow for their replacement. With maintenance, life of system determined by the availability of electronic components.
Mixed Metal Oxide activated (MMO) titanium anode ribbon at normal design current density of $100mA/m^2$	50 years +	Anode life expected to significantly exceed 50 years. Calculations predict life times greater than 200 years
Carbon backfilled anodes at $100mA/m^2$	20 years +	High current densities significantly above 100mA/m2 may reduce life.
Ceramic anodes in cementious backfill	20+	Also here too High Anode Current densities should be avoided to prevent acidification damage in carbonate stonework.
Ag/AgCl reference	up to 20 years	Failures can occur, however, accurate detailed monitoring is only required for first 10 years of operation. Monitoring design should incorporate graphite electrodes for long-life monitoring.
Graphite reference electrodes	50 years +	Life expected to significantly exceed 100 years.
Cables	20 years+	Cable Life as per all normal cabling requirements

zinc or magnesium is insufficient to drive the necessary levels of protective current through the masonry to the steel surface.

The unsuitability of sacrificial CP has been shown through a large number of opening-up investigations on 1920s and 1930s buildings that incorporate galvanised fixings in contact with the steel frame. In all cases seen to date it has been found that corrosion of the steel frame occurs within 50mm of the galvanised fixing indicationg negligible sacrificial protection.

9.5 Masonry Water Repellent Treatments

Penetrative silane, siloxane, siliconate and some fluorinated polymer systems may provide a water repellent barrier for certain types of masonry. These systems provide protection against water ingress through deep penetration and the lining of internal micro-pores, reducing the wetability of the masonry surface. As the internal pore structure remains open the ability of the masonry to 'breathe' remains unaffected. Consequently, pore lining polymer treatments should not increase the risks of surface deterioration as found with pore blocking penetrative sealing resins.

Although masonry repellent treatments offer an attractive repair option, the following important uncertainties may prevent their use:

- uncontrollable darkening of certain masonry surfaces may occur following application;
- service life is unknown;
- water, as a consequence, may be shed towards deteriorated features (e.g. cracked joints) and into the internal structure;
- water repellent resins may not be suited to certain masonry types;
- weathering;
- condition of the stonework;
- salt movement issues;
- climatic effects.

It is recommended that small trial areas are always carried out before considering this option.

9.6 Flashings

The addition of lead flashings (and other materials) to highly exposed features such as cornice and stepped features can prevent a significant level of moisture penetration, particularly through degraded joints. However, careful attention must be given to the following points:

- the potential for staining problems caused by water run off;
- water erosion and freeze thaw damage caused by water running on to projecting features such as ornate carvings;

- visual impact of the flashing;
- careful attention to the correct mounting of the flashing and that it is appropriately tucked into the structure;
- ensuring that driving rain does not penetrate beneath the flashing;
- moisture is controlled to a sufficient level;
- care in the application of a flashing should be exercised.

9.7 Corrosion Inhibitors

Corrosion could possibly be arrested in mortar filled cavity buildings through the in-situ addition of corrosion inhibitors to the mortar in-fill. Inhibitors can possibly be placed into the in-fill by either the injection of a controlled viscosity slurry; the placement of pellets designed to controllably diffuse inhibitors into the mortar in-fill; or through the application of vapour phase inhibitors to the masonry surface.

The life-time of repairs using inhibitor systems in this type of situation is unknown. Inhibitors added to porous mortars after their cure may not provide adequate corrosion protection due to inadequate diffusion of the inhibitor, or due to leaching away of inhibitors following application.

At present the risks associated with inhibitor systems when applied to historic structures are unknown. However they are expected to include:

- possible corrosion of some non ferous metals;
- deterioration of some plastics or organic materials;
- unknown long term effects on stone and other masonry;

Care should always be exercised when considering these novel repair systems for listed and historically important buildings and the potential for long term problems addressed. Due to the unknown performance and lack of performance data it is not possible to recommend this treatment and research should always be carried out prior to consideration.

9.8 Damp Proof Courses

Specific design faults, and/or age related deterioration can result in failure of the external cladding, resulting in the ingress of water and subsequent corrosion damage. For example, where small beam deflections may transfer stresses to the masonry cladding resulting in cracking and subsequent water ingress. Repair methods therefore need to address these design faults and problems before concentrating on the treatment of corrosion damage.

In certain cases, it may be impractical or too costly to address the design fault issue during repair, especially where access is restricted. As such, further corrosion related damage may occur following treatment. Cases such as these could possibly be solved by the insertion of damp proofing membranes. The strategic placement of damp proof membranes and weepholes into the structure will provide protection to steelwork by controlling the ingress of water and preventing further corrosion. As the ingress of water is controlled, the cladding can be reinstated, knowing that despite the subsequent ingress of moisture due to cracking of the stone, steel work is protected from further corrosion problems.

During the design and installation of DPC's it is important that attention is given to the following details:

- ends of the DPC;
- position of weepholes;
- the effect of water run off on the stonework i.e. staining and erosion of stone below the DPC;
- avoiding the introduction of slip planes;
- condensation and its effect;
- changes in water flow.

The injection of chemical DPC's (or resins to encapsulate steel work) is not recommended for listed buildings. These systems usually involve the drilling of unsightly holes in conspicuous locations which are considered unacceptable on ashlar stonework. In addition, it is unlikely that sufficient injection control of a chemical DPC can be achieved to adequately prevent moisture from reaching the steel frame.

It should also be mentioned that the addition of a DPC may require listed building consent.

9.9 Mortars

Failed pointing and open joints are a major cause of moisture ingress into the fabric of steel framed buildings. Consequently, an assessment of the state of mortar pointing and level of maintenance should always be made when assessing a steel framed building.

Mortars should never exceed the strength of the surrounding masonry and specialist advice should be sought on appropriate mixes, (Figure 69).

Lime mortars often achieve the best balance between workability and the heritage requirements of a building. The specification of appropriate materials and techniques for the use of lime mortars in the repair and conservation of historic buildings will always

Figure 69. Poor quality repairs to ashlar jointing. Note the poor workmanship, inappropriate materials and failure to treat the cracked horizontal joint. Repairs such as these are not acceptable on a Listed Building and they may cause later problems to the façade.

require an assessment of site conditions as well as of the materials to be used. Due to the complexity of issues regarding the use of lime mortars, specialist advice should always be sought. A general summary on the importance of lime mortars and their application can be found in Historic Scotland's Technical Advice Note 1 "Preparation and Use of Lime Mortars".

9.10 Insertion of Sealant Materials

Masonry clad steel framed buildings constructed during the first half of the century rarely contained movement joints. Due to the lack of these joints, movement from thermal and hydrolytic expansion and contraction effects has resulted in the opening up of the mortar joints of masonry cladding. Consequently, water enters opened joints, reaching the steel frame and causing corrosion damage.

Sealant materials may provide effective repair and preventative measures through:

- addition of movement joints into the structure to prevent the opening of mortar joints;
- repair of opened joints, preventing the ingress of water;
- placing a sealant material into mortar joints (this may be left or recessed prior to pointing to prevent water ingress in the event of mortar failure).

However, it may be found that such repair strategies are not possible due to practical or conservation issues.

Examples of practical issues concerning the addition of sealant materials include:

Figure 70. Sealant staining due to inappropriate materials selection on the coping stones of a sandstone parapet wall.

- sealant materials may stain masonry, (Figure 70);
- sealants result in an impermeable barrier at stone joints leading to a high masonry water content at the joint which may lead to accelerated erosion of the stone;
- unsuitability of primers;
- true expansion joints cannot be cut into a Listed façade;
- sealant materials can prevent the escape of moisture from behind the façade in low porosity cladding materials such as terracotta and faience.

Examples of conservation issues concerning the addition of sealant materials include:

- wide movement joints can not be included into the structure due to appearance changes. Therefore all movement joints must follow the line of existing ashlar jointing using original or failed joint widths;
- sealant materials in mortar joints may change the appearance of the façade;
- damage could be caused to the façade if the sealant is incorrectly installed.

Polymer impregnated pre-compressed foam sealant tapes avoid many of the practical and conservation issues regarding traditional gun applied sealant materials. These materials are easily placed into open joints larger then the pre-compressed tape width. After installation the pre-compressed tape expands to fill the joint thus forming the sealant joint, (Figure 71). Sealant tapes offer many advantages over conventional gun applied sealants which include:

Figure 71. The installation of a precompressed tape sealant to a parapet joint.

- waterproof but breathable joint;,
- simple application;
- easy removal;
- primers are not required;
- joints as small as 2mm can be repaired.

At present the minor limitations in the use of pre-compressed tape sealant are their range of available colours. Due to the foam types used to manufacture these sealants the most common colours available tend to be grey or black. However, these colours are suited to some types of masonry such as weathered sandstones etc. Recent tests have shown that tape sealants can be inserted and over-pointed to form a waterproof joint matched with the surrounding mortar. However, it must be noted that the intention in these cases is not to form a movement joint. In these cases the aim is to form a waterproof joint where it is known that a traditional lime mortar joint will fail due to excessive movements which relate to the general lack of movement joints in the original building design.

Recent accelerated weathering and diffusion tests on a range of tape sealants have indicated that it is unlikely that any long-term staining will occur to sandstone masonry as a result of either Ultra Violet (UV) degradation or thermal diffusion. However, it essential to always check the compatibility of any sealant material with its substrate material and where data does not exist accelerated long-term tests should be carried out prior to specification and installation.

Steel framed masonry clad buildings constructed during the later half of the 20th Century increasingly included sealant joint materials to accommodate thermal movements etc. These polymeric sealant joint materials only have a limited effective life time, and as such need replacing following failure. However, the repair and replacement of degraded sealant materials needs careful consideration, together with specialist advice and knowledge. Failure to repair and replace degraded sealant materials can result in water ingress and corrosion of the structural frame.

9.11 Stone Repair

Cracked stones can be repaired in certain circumstances by the use of, or a combination of, adhesive bonding, pinning, resin injection and mortar patching. These repair methods may be of use in locations where stones are difficult to replace. Difficulties may be encountered with replacing stone

Figure 72. Repairs carried out on a Portland stone façade using stainless steel pinning. The tape marks the flanges of the underlying steel and the mason points to the pin locations.

especially if a replacement results in disturbance to a significantly weathered façade, or replacement stone is unavailable due to the closure of the original quarry etc.

Prior to tackling any stone repair it is important that underlying corrosion problems are treated prior to renovation. Failure to address the root cause of damage will in the first instance result in repeated failure, eventually leading to a worsening condition due to failures around fixing pins and cramps.

The treatment of corrosion requires removal of the cracked stone for accessing the steel surface, except where ICCP systems are being employed. Care must therefore be taken to avoid excessive damage to the stone during removal. Particular attention should always be made in preventing damage to the arises of cracks during stone removal which could result in the creation of obvious bond-lines following jointing of the stone and repair.

A typical repair to a simple tensile crack is shown in Figure 72. Repair consists of drilling both sides of the bond-line and the insertion and bonding of stainless steel fixing pins to provide additional strength to the repaired stone. An approved thixotropic stone adhesive should always be used to bond the broken stone observing the manufacturer's recommended

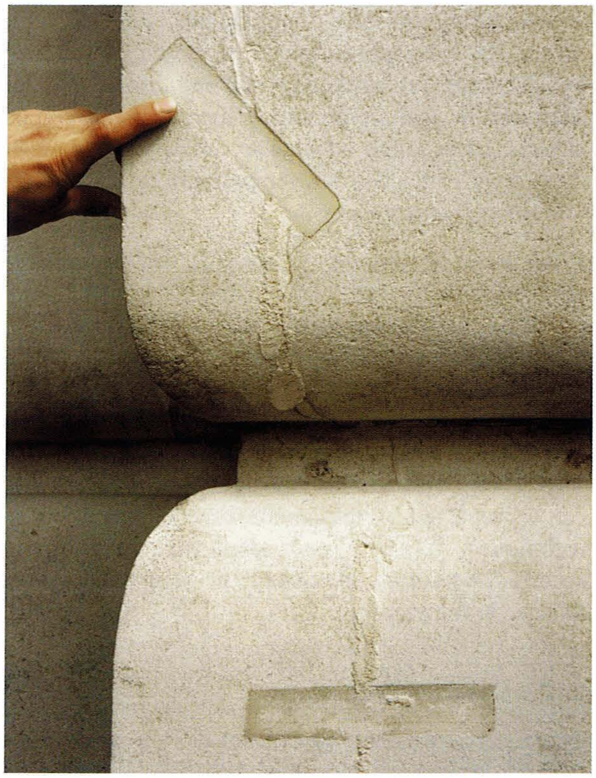


Figure 73. 'Dog cramps' on a Portland stone building.

temperature cure time to ensure adequate strength in the reformed stone.

Epoxy resins are common adhesive materials for masonry repair. Epoxy resins allow stress transfer and with appropriate formulation they have the following attributes:

- cure shrinkage is minimal after hardening;
- a wide range of pot lives and cure rates can be provided, with allowance for different application temperatures;
- excellent adhesion can be obtained and maintained in wet conditions and on alkaline surfaces;
- a high modulus can be obtained for efficient stress transfer;
- both low viscosity crack injection resins and thixotropic resins and adhesives are readily available.

The main limitation of most epoxy resins for this type of work however is the limited ability to cure at low temperatures (usually below 5°C). In addition, solvents should never be added to epoxy resins (or any other type of resin) to assist penetration as detrimental shrinkage, poor resin cure and poor adhesion are likely to occur.

Polyester and (meth) acrylate resins are also employed for resin injection and bonding, but in general these materials are not recommended without a full understanding of their requirements and specialist advice. For most applications these systems are limited by shrinkage on hardening and are prone to poor adhesion in wet conditions. However, for certain circumstances some advantages can be obtained as they can provide good low temperature cure and lower viscosities than epoxy resins.

If the cause of corrosion is treatable to an acceptable level without the removal of stone, or a temporary repair is required then broken stones can be stabilized by the application of 'dog cramps', (Figure 73). This is a standard method of stone repair which is beyond the scope of this report. However, it is important to ensure that cracked stone is made weather-tight to prevent the ingress of moisture. Weather-tightness in these cases can be achieved by the careful use of resin injection techniques. As with any resin injection activity specialist advice should always be sought to prevent damage to the masonry.

9.12 Concrete Encasement

The concrete encasement of steel work provides long term protection against corrosion (greater than 60 years), providing suitable cover is given to the steel (greater than 40mm) and a suitable concrete is chosen, (Figure 74). The effectiveness of this repair option is dependent upon the carbonation rate of concrete in contact with the steel and levels of aggressive ion species in the concrete, for example chloride ions.

In addition to the protective qualities of concrete, concrete encasement can also be used to strengthen severely corroded steelwork through the incorporation of suitable levels and arrangements of reinforcement. Where reinforcement is required, a minimum cover of 75mm should be allowed for to provide room for the reinforcement and its cover and to create room for the concrete pour.

Concrete encasement methods have been used with success in the past, with the most prominent building to date being Sunlight House, Quay Street, Manchester, designed by Joseph Sunlight and completed in 1933. This method of repair was chosen due to the severity of corrosion damage and a design life requirement for the repair in excess of 60 years. In this case, the concrete provided both structural support and corrosion protection to the remaining steel frame.

Limitations to concrete encasement may exist when repairing listed structures. It may be found that achieving adequate concrete cover to the steelwork requires that the masonry is moved forward creating an additional feature in the façade. This problem was encountered with the Grade II Listed Sunlight House building. In this case permission was granted to move the external cladding forward around steel columns as concrete encasement was the only repair method available for treatment of the severe corrosion damage. However in general this should be regarded as a last resort only.

9.13 Protective Tapes

Tape systems impregnated with polymers and inhibitors can provide an effective alternative repair method to paint systems for corroded steelwork. These repair systems have a successful track record and may offer various advantages over paint treatments. The various advantages and disadvantages are shown below.

Advantages

- surface tolerant requiring only minor surface preparation such as wire brushing;
- no curing period;
- low probability of damage during reinstatement of the masonry;
- ease of application.

Disadvantages

- adhesion of tape system dependent on careful application;

Figure 74. Preparation for the concrete encasement of a steel 'I' section.

- small possibility of masonry staining;
- unknown lifetime of repair system.

9.14 Realkalisation

Realkalisation is an electrochemical technique developed for the prevention of reinforcement corrosion in carbonated concrete. At the fundamental level realkalisation consists of applying a relatively high current to the reinforcement steel from an anode temporarily fixed to the external surface of the structure. Corrosion protection is achieved through the production of hydroxyl ions on the steel surface which restores alkalinity generating a corrosion resistant oxide layer on the steel reinforcement.

During the process a buffer solution (e.g. sodium carbonate) is held in contact with the outer surface and becomes transported into the concrete surface. The sodium carbonate solution is an important requirement of realkalisation and fulfils the following roles:

- protection against the acidic conditions generated at the anode (surface of the structure);
- providing a buffer against future carbonation and long-term loss of corrosion protection.

Although the corrosion of steelwork in masonry clad steel framed buildings is similar to that of carbonated concrete, realkalisation has not been tested on these structures. However, realkalisation is unlikely to form a suitable repair option for masonry clad steel framed buildings and would not be recommended for the following reasons:

- the effects of depositing buffer solutions to the pores of stone and other masonry types could result in long term deterioration problems in the masonry;
- a risk of damage to the masonry surface exists due to the aggressive nature of the anode reactions;
- the mortar contact with the steel contains large voids in which corrosion may continue after realkalisation;
- most stone and other masonry materials have a significantly higher porosity than concrete (eg limestone 17-23%). The effect of high porosity on the life of a realkalisation treatment is currently unknown, but it is likely to significantly reduce the effectiveness of the treatment;
- Gases are generated at the anode and cathode surfaces which could result in damage to the façade.

9.15 Iron and Steel Repairs

Repairs, strengthening and joining of members having iron as their main element, depend generally on the particular iron material used. The three main such iron-based materials encountered in building structures built prior to 1930 are Cast Iron, Wrought Iron and Steel.

Cast iron was used in Britain as a building material from the late 18th to mid 20th Century. Even in 1948, BS 1452 lists seven grades of cast iron. Cast iron continued to be the most common material for vertical supports until just before the First World War, and is known to have been used subsequently. Cast iron beams were used to a lesser extent, their parabolic form evolving from inverted T to I-section. Malleable or wrought-iron sections and angles, riveted together for strength, began to displace cast iron in certain situations for beams and bressumers from the 1850s to the 1880s, when mild steel became available in sufficient quantity to be used structurally. Often more than one material is used in the same building according to its particular properties: cast iron in compression, wrought-iron in tension. Steel might be used in either situation, interchangeable with wrought-iron, and could still incorporate cast iron elements, such as the shoes transferring vertical column loads.

Cast iron contains higher amounts of carbon and is not forgeable, or weldable; but may be brazed in some cases. Cracks may also be repaired by cold stitching methods. Two propietary systems for stitching are available at present namely 'Metalock' and 'Metal Stitching'. Both these systems are similar and involve drilling a series of holes in line across the crack and inserting a connector which effectively stitches the broken halves in position. The'stitch' is repeated at regular intervals across the crack and following the repair the joint is cleaned, filled and painted to restore the damaged section profile.

Wrought-Iron is low in carbon and is nearly pure iron. It is malleable and can be forged and bent to shape, and in certain cases can be welded, although problems may be experienced. Welding electrodes must be compatible with the iron or steel, having the highest carbon content, in the repair. Structural welded joints in wrought-iron should be of the 'butt type' and fillet welds should only be used for lightweight non-structural attachments, and not for repairs, as there is a risk of delamination. In fact welding of wrought-iron members must always be treated with caution as elongated slag intrusions generally exist in the metal's structure and top layers of metal can become delaminated when welding is attempted.

Figure 75. Severe corrosion of a structural steel column. Corrosion in this case was attributed to alteration of the building environment that resulted in wetting of the steel column.

Old structural members may contain rivets and layers of plating, especially on flanges, to enhance or adjust the section properties. Care must be taken when making repairs with fixings onto the surface of a plate, as it in turn depends upon its fixing to other plate layers for its integrity.

Steel members may be repaired by welding, amongst other methods but may need to be preheated to ensure a sound welding repair. The 'carbon equivalent' values of the particular metal must be assessed from laboratory tests unless there is detailed mill information available, and advice should be sought on detailed requirements before welding is attempted.

Adhesive repairs are now permitted as a structural repair; but this type of repair or strengthening work must be cleared with the regulating authorities, before the remedial design is commenced. Where adhesive may be affected by fire, adhesive repairs should not to be used. Where adhesive repairs are used they depend critically upon careful preparation and cleaning of the metal surfaces to be fixed. Adhesives for the stronger repairs are at present of the epoxy-resin types, and manufacturers should be consulted regarding their successful application and use. Some adhesives are susceptible to 'creep' under load and so details of the duty required must inform the selection process. Members subjected to moisture or dampness must be provided with selected compatible repair materials.

Flat surfaces of members may be strengthened by the use of plate-bonding techniques where plates of strip steel or carbon-fibre reinforcement are applied with selected adhesives.

Strengthening and repair work may be achieved by bolting if access is available and the member sizes permit these methods. Alternatively drilling and tapping into all plates from one side and using 'set-screws' and plating, to carry the forces involved, may offer a suitable repair. Allowances must be made for the loss of the existing material from the drilled holes. Steel packing pieces should be provided to clear the heads of existing rivets, bolts, or welds, and so provide a smooth surface for any new steel plate. Grades of bolts and plates should be selected depending on the duty required. As such, repairs may require Listed Building consent and it is advisable to consult the relevant planning authority well in advance.

In any load carrying composite repair the respective values of the Elastic Moduli and the other physical properties, of the materials should be taken into consideration, in the assessment of the design stresses.

Generally, all types of iron and steel members, after repairs, need painting and compatible fire protection.

The risk of setting fire to adjacent materials and structures must always be assessed when welding and brazing works are contemplated. Too many historic buildings have been damaged or totally destroyed by inattention to such risks.

Similarly there may be hazards due to members containing rivets suddenly releasing their energy due to impact, heating or overstressing and therefore, repair work must be 'risk assessed' carefully.

9.16 Embedded Rainwater Downpipes

Where embedded rainwater downpipes are known to be leaking repairs are required to prevent continued corrosion. As it is often too costly and disruptive to replace embedded pipework the following repair options exist:

- installation of new pipework located within the building interior and by-passing of the original pipework.
- repairing the original pipework with addition of plastic liners.

The addition of pipework to the building exterior is not recommended due to the significant alterations in appearance. Where exterior pipework is the only practical repair solution planning consent is required in the case of Listed Buildings.

10. ISSUES REGARDING THE MAINTENANCE OF LISTED BUILDINGS

10.1 Categories of Listed Buildings

The processes for the Listing of Buildings in Scotland, England and Wales differ in their detail but have the same intention:- to protect buildings of special architectural or historic interest. The term 'building' is used to include any structure and any part of a building and also any object or structure which is fixed to a building or which falls within the curtilage of the building and, although not attached to the building has formed part of the land since before 1948. The curtilage is the area attached to the building within its boundary and may include for example a front or rear garden, mews buildings or stables. The categories of listing are graded according to the importance of the building in terms of historic or architectural interest.

In Scotland the categories are:

Category A:	buildings of national or international importance, either architectural or historic, or fine little-altered examples of some particular period, style or building type.
Category B:	buildings of regional or more than local importance, or major examples of some period, style or building type which may have been somewhat altered.
Category C(S):	buildings of local importance, lesser examples of a period, style or type whether as constructed or as altered; simple well-proportioned traditional buildings often forming part of a planned group or grouping well in association with buildings in a higher category.

Groups of buildings often have their group value stressed by inclusion within A or B Groups. These Group categories do not alter the individual category but emphasise that the value of individual buildings is enhanced by their association with others in the group.

In England and Wales Listed Buildings are classified into three grades according to their importance:

Grade I:	buildings defined as being of exceptional interest
Grade II*:	buildings of 'more than special interest'
Grade II:	buildings of special interest (the bulk of the list)

The definition of 'special architectural or historic interest' is wide ranging and includes buildings that are old and have survived without too much alteration and are, therefore, good examples of a certain period of architecture. Other buildings may be deemed to be important because of their historic associations, detailed features, unusual construction or because they form part of an interesting group of buildings such as part of a terrace or square.

The reason for listing buildings is to protect part of the nation's heritage from unconsidered alteration or demolition.

When a building becomes Listed it is the whole of that building which is protected including its internal as well as its external features and although the list may contain no detailed interior description nonetheless Listed Building consent may be needed before any alteration or replacement can be undertaken. For example such consent may be required before any alterations to, or removal of, items that are structural, such as columns or beams or decorative plaster work or painted ceilings, chimney pieces or panelling. Listed building consent must be sought whenever an owner proposes internal or external alterations or extensions to a Listed Building which would affect its character. If the planning authorities consider that the work would not have an effect on the character they may indicate to an applicant that Listed Building consent is not needed. However, it is important to note that what may be seen as an improvement in appearance by, for example, cleaning of stone, the risk that irreversible damage may be caused means that a proposal to clean a Listed Building requires Listed Building consent.

10.2 Maintenance Strategies

For owners and users of clad steel-frame buildings, it is vitally important to have strategies and procedures in place for dealing with maintenance issues; a framework of inspection and reporting procedures which will ensure timely identification and location of developing problems, backed by procedures to ensure follow-up action where necessary. The foundation for such systems should rest initially in a risk assessment of the property against the likelihood of various maintenance or damage scenarios. Necessary immediate actions can then be prioritised and the frequency of future inspections for particular problems can be set.

Similarly, potential problems can be classified as 'maintainable', 'repairable' or 'replaceable' to allow appropriate and timely arrangements to be made. For example gutters and downpipes are generally maintainable; regular inspection and cleaning and painting can be carried out. However, at some point in their life they may reach a state such that they need repair rather than maintenance perhaps due to movement, cracking or corrosion and at yet later stages may need replacement.

The maintenance regime must allow for all these eventualities by the development of a knowledge and understanding of the durability and life of individual building components and systems and by monitoring to ensure that preventative measures are taken in good time or that items needing repair are spotted and dealt with early.

The starting point for any such regime must be to ascertain the current situation and state of all the various elements and the possible causes of problems; with attention focused by the risk analysis. Certainly the major causes of problems in steel frame, stone clad buildings relate to penetration from outside rather than inside sources (although the potential for leaks in plumbing and heating systems must not be ignored). Rainwater ingress is the most likely source of problems and its entry routes can be many and various including:

- entry through cracks in the structure;
- directly through porous stone;
- through mortar joints;
- bypassing flashings and upstands;
- forced entry through small crevices by wind pressure or thermal pumping.

It is therefore vital that data and records are collected on what is known about the building, its history, the structure and its constituents. From that base of information records must be maintained and updated and any future repairs or replacements confirmed as appropriate and that they will not place the structure at further risk of deterioration. For example repairs to pointing must be done using materials which ensure the mortar is softer than the stone as well as ensuring that the appearance of replacement mortar will not impair the appearance of the façade.

10.3 Records and Data Collection

With any property asset it is important that the maximum amount of information should be available. This may take the form of scaled drawings (ideally); photographs or sketches (even paintings which may show original detail which has been obscured or removed) and any written notes or descriptions of the building and its surroundings. In addition to these historic records it is useful to catalogue and record the existing situation, perhaps at the time the building passes into your hands and to then collect information as to the problems occurring, the solutions and remedial measures adopted and any information which relates to the sources of replacement materials for appropriate repairs or refurbishment.

Such information should be updated regularly as programmed (or unplanned) inspections and repairs are undertaken. Where repairs are of such a magnitude or consequence that they require Listed Building and/or other planning approvals the information will be demanded for the application itself and handy records can be crucial in the preparation of the applications.

Computer spreadsheets, databases and other packages are useful tools in the logging of information due to the simplicity of data retrieval. As such, these packages can play a major part in the co-ordination of maintenance and repair activities.

10.4 Replacement materials

Where older and Listed Buildings are concerned the principle guiding repair or refurbishment activities should be, wherever possible, to repair rather than replace those original or period items. Where later and inappropriate repairs or replacements have been incorporated the principle should be that wherever feasible such items should be replaced using materials which are exact replacements or, at least, are in keeping with the original style of the building. For example, quarries used for the original construction have often long-since been closed and replacements have to be the closest achievable match. Remember also that even if the original quarry is still open (or can be re-opened) stone from different faces or areas of a quarry can differ significantly.

Such principles must also be addressed in situations such as those where faience terracotta façades have eroded or otherwise degraded and some of the detail has been lost. Here the balance must be maintained between a natural desire to achieve or recapture the original detail and the significant visual impairment where replacement stone becomes obtrusive and detracts from the appearance. Similarly it must be realised that replacements may perhaps be of slightly different composition from the original and may cause accelerated weathering or deterioration of the adjacent original material.

Other such problems occur with repointing, which, if poorly executed or incorporating inappropriate materials (or mortar mix) can cause physical damage to the fabric of the building. It can also radically alter the appearance of the building and diminish its character. It is therefore important that great care be taken to ensure that the materials and standards of workmanship are appropriately specified and monitored. If possible a concealed area should be used as both a trial panel and to provide and set the standard for all the work.

10.5 Maintenance

There is no specific duty on owners to keep their buildings in a good state of repair but local authorities have powers to take action where a historic building has deteriorated to the extent that preservation may be at risk. These powers relate to urgent or emergency repairs and to the issue of repair notices if the authorities consider that a Listed Building is not being properly maintained.

These powers are limited in what they can require, but it is prudent for owners of Listed Buildings not to allow situations to develop where exercise of such powers is considered. Far better, by regular inspection and planned preventative maintenance, to keep both the fabric and function of the building in a good state of repair and to plan for timely replacement of items before they reach their durability limit or the end of their design (or useful) life.

The fundamental cause of corrosion is the presence of moisture which enables electrochemical reactions to take place on the metal surface. Removal of surface moisture therefore prevents electrochemical processes from occurring and prevents corrosion. Corrosion damage in masonry clad steel framed structures can therefore be avoided by preventing moisture from reaching the surface of the structural frame.

Lack of regular maintenance is the major cause of water reaching the steel frame and initiating severe corrosion damage. Water reaches the steel frame through defects in the external cladding material, or through saturation of the external masonry due to blocked and overflowing gutters and damaged drains etc. The regular inspection and maintenance of features likely to cause moisture ingress can therefore prevent excessive corrosion and damage to the fabric of the building. Although it is beyond the scope of this report section to discuss typical defects and causes of corrosion damage that require maintenance a brief summary of desirable maintenance is given below:

- clearing of blocked gutters and drains to prevent overflow and water saturation of the masonry;
- repair of damaged flashings and asphalt coverings;
- replacement of lost or damaged roofing tiles;
- repair and maintenance to flat roofing;
- repair of damaged drains and water pipes;
- Repointing of cracked mortar joints, especially at parapets, balustrades and cornice features;
- inspection and repair of sealed joints.

The installation of moisture probes at locations prone to moisture ingress can provide an early warning of potential corrosion problems if excessive wetting occurs. The installation of moisture sensors linked to real time alarms could therefore aid maintenance programs and reduce the need for expensive remedial treatments following corrosion related failures.

Maintenance must be considered an integral part of occupancy of the building and must not be compromised. The maintenance and inspection of the whole building fabric must be organised into a coherent strategy. All maintenance must be properly planned and if temporary access is to be provided for a specific reason then full advantage should be taken to inspect as much of the fabric as possible. This will give an early opportunity to check for any deterioration, and establish whether a full inspection programme is required.

A full maintenance log must be maintained by those responsible for maintenance. This log must contain basic information as to the materials used, when the work was carried out and by whom. Any guarantees should be recorded so that any resulting defect can be checked to see if it is still within warranty. All too often repairs are carried out by the owner which are still under warranty, partially due to incomplete records being kept.

The CDM Regulations Safety File contains much of the information required by the Maintenance Log and this could easily be adapted to include the relevant information. Unfortunately most of this existing information may well only cover the M&E services which are likely to have been replaced in historic buildings and would be documented as part of the regulations. It is unlikely to cover the fabric in general.

The maintenance checklist in Annex A is a guide only to issues which may present themselves in individual buildings, but the intent is to assist in the organised collection and use of available data to inform decisions on present and future maintenance requirements and to provide a framework for a coherent maintenance strategy.

10.6 Cleaning

The effect of cleaning processes on corrosion are not fully understood and require further investigation. However on limestone buildings cleaning processes that involve the spraying of water onto the façade for long periods of time may result in significant increases in corrosion for reasonable periods of time due to the high absorption of water. This is particularly true where water sprays are left running for many hours or even days.

The importance of continual wetting requires further investigation. However it is likely that the moisture levels at the steel surface will increase significantly and remain high for a number of months after cleaning. Without further information the following is recommended as good practice:

- the time of wetting is controlled and minimised;
- cleaning is carried out in the dryer summer and autumn seasons to enable faster drying cycles;
- cleaning is only carried out after the repair of cracks and obvious sources of water ingress.

ANNEX A. MAINTENANCE INSPECTION CHECKLIST

Item	Typical problem	Inspection cycle
ROOF: PITCH		
Natural slate	Slipped, broken or missing	Inspection autumn and spring
Reconstituted slate	Poor quality slates, coloured slates subject to efflorescence, poor aesthetics, can distort.	Can be dislodged in high winds, inspect regularly after periods of windy weather.
Concrete tiles	Check for tile displacement	Inspect yearly
Clay tiles	Check for tile displacement	Inspect yearly
Copper	Check laps and joints, interfaces	Inspect yearly
Zinc	Check laps and joints, interfaces	Inspect yearly
Lead	Check laps and joints, interfaces	Inspect yearly
Stainless steel sheet	Check for signs of lifting at seams, interfaces.	Inspect yearly
ROOF: FLAT		
Exposed asphalt	Inadequate falls, ponding, poor termination details, blisters, water ingress.	Yearly inspections, check condition of any solar reflective paint treatment. Check terminations, check for distress in the surface, due to movement. Blisters indicate moisture present.
Inverted single ply roof	Prone to mechanical and chemical damage.	Keep strict control on chemicals used as part of remedial work. Especially diesel for generators. Inspect ceilings monthly for first signs of moisture.
Built up felt system	Inadequate falls, ponding, poor termination details, blisters, water ingress.	Yearly inspections, check for signs of distress. Debonded laps and termination details. Consider use of solar reflective paints.
Mechanical plant	Can cause damage to all types of roofing membranes. Remember access across roofs required to install replacements. Pop rivets left on the roof can damage membranes.	Adequate supervision when installing and during routine maintenance of items of plant. Keep working place tidy. Remove all offcuts. Provide dedicated walkways with protection to the membrane.

Item	Typical problem	Inspection cycle
Service penetrations	Tenants fit out left unsupervised. Poor waterproofing details can result.	Plan the location of the penetrations, ensure they can be waterproofed adequately. Check condition during routine roof inspections.
Maintenance routes	Provide dedicated walkways for access to items of plant to minimise damage to the roof as a whole.	During routine maintenance checks, which are usually undertaken every three months, check for signs of any damage caused to the roofing system.
ROOF DRAINAGE		
Gullies	Get blocked easily in autumn with leaves	Remove any build up of debris during yearly inspections. If, during this period they are found to be blocked, reduce period between inspections to six months and review.
Down pipes	Split, joints/seals break, blockage	Blocked down-pipes can cause splitting of the pipe and cause the seals to fracture. Essential to keep the roof free from debris.
Roof parapets	Water penetration through parapets due to defective DPC's or defective mortar joints.	Ensure that all joints in the parapet walls are satisfactory. Repoint as required. Inspect as part of a planned maintenance programme.
Flashing details	Defective termination details due to thermal movement or from incorrect fixing.	Inspect all flashing details during routine yearly inspections.
Copings	Water ingress through perpends.	Carry out check as part of the planned yearly inspection.
ATRIUM		
Glazing	Glass breakages, leaking seals	Carry out check as part of the planned yearly inspection.

Item	Typical problem	Inspection cycle
WALLS		
Natural stone	Damp through joints, moisture through face of stone, movement of the stone due to deterioration of embedded metal, discolouration.	Inspect when access is available during planned maintenance. Inspect every four years.
Terracotta and faience	Moisture ingress through joints. Cracking of terracotta and mortar joints.	Inspect when access is available during planned maintenance. Inspect every four years.
Reconstituted stone	Damp through joints, moisture through face of stone, movement of the stone due to deterioration of embedded metal, detachment due to loading from brickwork above.	Inspect when access is available during planned maintenance. Inspect every four years.
Facing brick	Damp patches, movement of the brickwork due to deterioration of embedded metal, cracks.	Inspect when access is available during planned maintenance. Inspect every four years.
Cornices	Leaks through asphalt water proofing, open mortar joints leading to moisture ingress.	Inspect when access is available during planned maintenance. Inspect every 2-4 years.
RENDER		
Sand/cement	Loss of adhesion, movement of the substrate.	Inspect for signs of cracks, seal to prevent moisture ingress, investigate the cause. Inspect every four years.
WINDOWS		
Timber	Distortion, deterioration of stains or varnishes.	Check for signs of structural movement, this will generally occur in more than one element, check condition of paintwork; maintain stained surfaces every four years, varnish every two years.
Aluminium	Distortion, leaking, deterioration of finish.	Check for signs of structural movement, this will generally occur in more than one element. Check surfaces for pitting and fading. check every four years.
Sealant	Defective joint sealant due to sag, splitting, or becomes detached leading to moisture ingress.	Carry out yearly inspections if access is available. Ensure the correct sealant is used to cater for joint geometry and movement and determine the cause of premature failure. If no access is available, inspect during planned maintenance, every four years.

ANNEX B.
IMPRESSED CURRENT CATHODIC PROTECTION: INSTALLATION CHECKLIST

The application of impressed current cathodic protection requires careful consideration of the following parameters.

1.0 Application

1.1 An assessment of the alternative traditional methods of repair should be carried out on a life cycle cost basis. ICCP will not necessarily be the cheapest option at installation and may only provide savings in the medium to long term.

1.2 The condition, location and type of steel to be protected must be researched.

1.3 The condition of the stonework, the layout of the joints and the size of the joints will have a major bearing on the effectiveness of the installation if installed from the building exterior.

1.4 Careful planning will be required for internal cable routing and the location and accessibility of all the electronic CP hardware.

2.0 Design

2.1 ICCP will not be effective in areas of voids; protection can not be transferred across a gap.

2.2 Other metal components such as fixings, flashings and reinforcement may be effected by the presence of the ICCP. Stray current corrosion is an important factor that requires careful assessment.

2.3 The condition and type of stone will have a bearing on the design and cost of the installation. Potential for staining from particular types of anodes should be adequately researched.

2.4 All designers should be able to demonstrate suitable levels of experience and either be members of the Corrosion Prevention Association and the Institution of Corrosion, or members of the National Association of Corrosion Engineers, or demonstrate other suitable qualifications.

2.5 The design should be durable and standby reference electrodes included if a design life of greater than 20 years is required. Adequate local rectifier units should be included to allow a comprehensive monitoring regime to be set up for the system.

3.0 Procurement

3.1 The assessment of specialist ICCP contractors should be undertaken. Interviews and the visiting of projects is essential.

3.2 The type of contract should be carefully considered.

3.3 The costs of the installation should be kept under review. Due to the nature of the work adequate contingencies must be included for both design and implementation.

3.4 Inspection of the installation including routine measurements for continuity and initial energising tests should be carried out.

3.5 A detailed survey of the condition of the stone work should be carried out before the work commences and after the completion of the installation.

3.6 The appointment of a suitably qualified auditor should be considered if the design team does not posess the necessary qualifications.

4.0 Maintenance and Monitoring

4.1 Detailed records of the installation are vital. The location of all the anodes and other equipment should always be recorded.

4.2 Maintenance and monitoring agreements should be built into the contract to ensure that any immediate repairs and modifications in the short term are covered.

4.3 Monitoring equipment is required to record the performance of the system. Specially designed software should be used in conjunction with a database. Monitoring should continue on an annual basis and necessary adjustments to the ICCP system settings made as appropriate.

ANNEX C
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