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Review of Corrosion Resistance of Metal Components in Masonry Cladding on Buildings

by A.H.P. Maurenbrecher and R.J. Brousseau

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Canada

Preface

The structural elements of a building most likely to deteriorate are those directly or indirectly exposed to the weather. This includes parking garages, balconies and cladding on buildings. The Structures Laboratory has a research program addressing the latter aspect – the structural durability of the building envelope. The emphasis is on how the building geometry and the environment interact to create sites conducive to material damage such as corrosion.

This report* is part of the above program. It presents a review of the durability of metal components in masonry cladding on buildings. Financial support for this review by the Nickel Development Institute is gratefully acknowledged.

* Second printing, June 1993, with minor editorial corrections. The list of ASTM standards on page 64 was also revised to show the latest editions.

Summary

Masonry is a popular cladding for buildings because it provides an aesthetic and durable cladding which normally requires very little maintenance over the life of the building, normally not less than 50 years. In 1991, about 73 million square metres of masonry cladding were built in Canada and the USA. This cladding is usually attached to the building by steel components such as ties and shelf angles. These steel components are usually hidden from view. It is therefore important that they be durable for the life of the cladding. But how durable are they in practice?

This report brings together existing information on the corrosion resistance of metal components in masonry cladding to form a basis for making better decisions on corrosion protection in Canada and the United States. It includes a survey of existing requirements in codes and standards, and a review of factors affecting corrosion resistance. The many factors affecting corrosion make it difficult to predict the life of ties. This explains why some countries require that ties be made from materials, such as stainless steel, which have a high probability of achieving a long life.

In North America, the most commonly used form of corrosion protection is a zinc coating on mild steel (galvanized steel). There have been many reports of corrosion of galvanized steel ties although there have been few cases of failure due solely to corrosion. Nevertheless, failures are likely to occur in future since many buildings contain ties with only a nominal coating of zinc, much less than required by current standards. The possibility of cladding failure also depends on the location and number of ties affected by corrosion, any alternative support the cladding may have, the needed tie strength, and the loads on the cladding.

British experience and preliminary observations in Canada show that current code requirements for galvanized ties in Canada and USA are not adequate to ensure long term durability for such ties exposed to air and moisture for a significant part of their lives. These conditions could occur in cladding on high-rise buildings, and in cladding directly exposed to driving rain.

More extensive investigations of the condition of ties in existing buildings are needed to determine appropriate levels of corrosion protection. The required levels will vary depending on factors such as building details, and the geographical location of the building.

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1. Introduction

1.1 BACKGROUND

Masonry cladding (veneer) attached to the building structure with metal connectors is used extensively in many areas of North America. Masonry has been a popular cladding for wood frame housing since the end of the last century [Ritchie 1967; Borchelt 1988]. It is also used in the form of cavity walls in loadbearing low-rise masonry buildings especially since the 1930s; their use as cladding in high-rise buildings did not start until the 1940s [Plummer 1960]. Masonry cladding is still popular. In 1991 about 7 million square metres were built in Canada, and about 66 million square metres in the USA.

Masonry provides an aesthetic and durable cladding which normally requires very little maintenance over the life of the building. Lateral support to the masonry cladding is usually provided by metal ties, and vertical support is usually provided by steel shelf angles, concrete floor slabs and basement walls. The most common material used for wall ties in North America is galvanized mild steel. The life of galvanized ties, in a situation conducive to corrosion, depends on the thickness of the zinc coating and the thickness of the steel. Specifications for such ties have been very inadequate or have not been enforced. An example was the requirement in Part 9 of the National Building Code of Canada [NRC 1985] which specified that ties be *corrosion resistant* and that corrugated strip ties be at least 0.41 mm thick. No minimum limit on galvanizing is specified and the tie thickness is very small. Such ties have corroded through in less than 10 years. Although initially used for low buildings and housing, they have also been used in high rise buildings where exposure conditions are much more severe, and repairs are much more expensive.

Metal connectors are expected to have a life in excess of 50 years [CSA A370, 1984]. The life of the connectors is largely dependent on the material used and its location (in the building and in the environment). The life is difficult to predict since so many factors influence corrosion. Corrosion resistance requirements have been based on past experience and individual judgment. But the existing requirements may be inadequate especially with the changing design of buildings. The application of masonry cladding to high-rise buildings is a relatively recent phenomenon. The use of insulation in cavities, higher buildings and thinner walls have increased environmental stresses on the wall system. In addition architectural details on many modern buildings have led to increased water penetration of masonry walls. These factors have led to increased problems with building facades including masonry; insurance claims for facades in the USA have increased from 15% of all building claims in 1960 to 33% of the claims in 1980 [Brand 1990].

Corrosion faults take time to show up. When they do, the problem causing it may already have been repeated in many other buildings. A better understanding of durability is needed by architects and engineers so that faults can be avoided at the design stage. Corrosion can lead to horizontal cracking in the mortar joints, rust-staining, spalling and ultimately failure of the cladding. Cases of collapse due to corrosion have been infrequent. Collapses where they have occurred were primarily due to missing ties or poor installation.

Nevertheless, with time corrosion is likely to become a more serious problem. Two surveys of galvanized ties in existing housing, conducted in Britain, found that 23% and 51% respectively of the observed ties had red rust on them [Moore 1981b]. This led to a large increase in the required minimum zinc coat on galvanized ties [BSI 1243, 1981]. In Canada and the United States there have been several papers and reports about corrosion of metal components in cladding. Three of the more comprehensive are Grimm [1985], Warnock-Hersey [1985] and Keller et al [1992]. But these surveys did not determine the extent of corrosion over a building, and only one estimated the rate of corrosion. What is needed is a more systematic survey of tie performance such as the one conducted in Britain. Without such surveys it is difficult to estimate the extent and seriousness of the corrosion problem.

1.2 OBJECTIVES

The objective of this report is to bring together existing information on the corrosion resistance of metal connectors in masonry cladding. This will form the basis for improved performance feedback and information transfer. The following items are covered:

1. *A review and evaluation of existing information.*
   - metal components used in masonry cladding in North America
   - methods of providing corrosion resistance
   - current code requirements
   - work on the durability of wall ties

2. *A review of the performance of wall ties in Canada and USA* (emphasis on Canada)
   - cases of corrosion including those observed by the Institute for Research in Construction are documented. Where available relevant exposure data is included, but a full performance survey is not intended at this stage. Check measurements of the thickness of the zinc coating on ties are included.
   - environments and locations are given where corrosion is likely to occur
   - suggestions are given for laboratory and field studies needed to check the long term durability of steel in masonry cladding.
   - this study was coordinated with the work of the Canadian Standards Association technical committee on masonry connectors to address their concerns on durability.

2. Use of metal components in masonry cladding

2.1 CLADDING USE IN BUILDINGS

Most of the standard size clay and concrete bricks produced in North America are used as cladding on buildings. The amount of cladding currently built in Canada and USA can therefore be estimated using the number of brick manufactured.

2.1.1 Canada

In 1989, a high year, Canada manufactured approximately 700 million clay brick of which 500 million were made in Ontario. In addition about a 100 million were imported from the USA. Ninety percent or more of the bricks were used for cladding on buildings. In 1991, a low year, the number manufactured had dropped to approximately 480 million. Of these, about 85% were used for residential construction, and 15% for industrial, commercial and institutional buildings. In addition to clay bricks, approximately 100 million concrete facing bricks were produced in 1991, most of them in Ontario and Quebec.

The bricks manufactured in 1991, are equivalent to 7 million square metres of cladding, assuming the cladding is the thickness of a brick.

2.1.2 United States

In 1989, a high year, 8 billion clay bricks were produced (based on standard size bricks, 194 x 57 mm). In 1991 this had dropped to 5.5 billion. Of these bricks over 60% were used for cladding on buildings. The number of concrete facing bricks produced in 1991 was 1.5 billion.

The bricks manufactured in 1991, represent about 66 million square metres of cladding, assuming the cladding is the thickness of a brick.

2.2 TIES, ANCHORS AND SUPPORTS

Metal components used in masonry cladding include wire bed joint reinforcement, flat metal and wire ties, lintels, shelf angles and reinforcement bars. The extent of their use is not well documented.

Examples of some common ties used in new buildings are shown in Fig. 1. Ties, anchors and their performance are described by CSA standard A370 [1984], BIA [1987] and CMHC [1991]. The most popular ties are wire ties for high-rise buildings, corrugated strip ties for low-rise housing and dove-tail anchors where the backup to the cladding is concrete.

The number of ties needed to give lateral support to the cladding depends on the lateral loads and the cavity spacing. For cavity widths up to 150 mm and wind loads not exceeding 2.2 kPa, CSA A370 gives maximum spacing for some of the more common ties. For Z wire

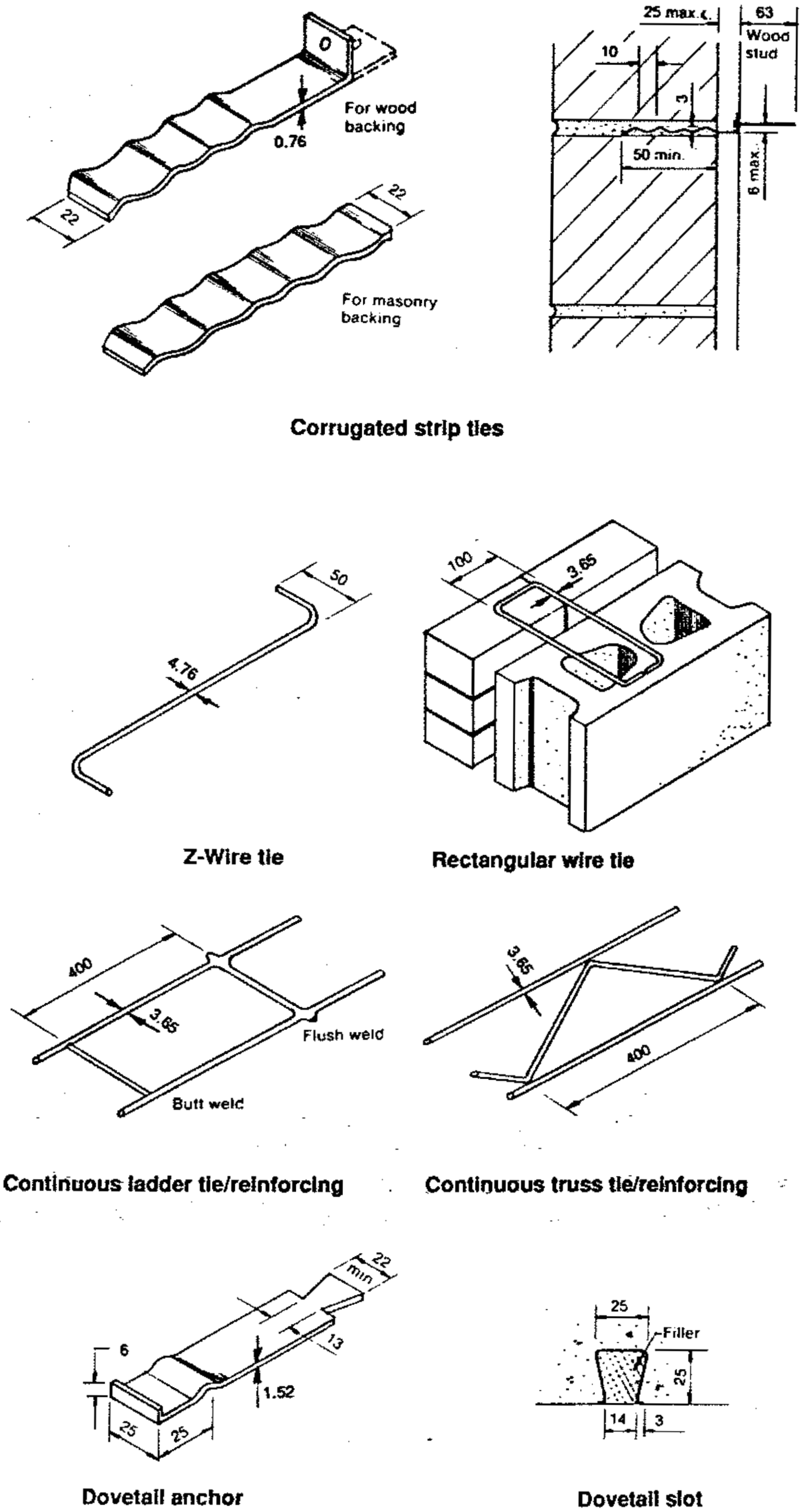

Figure 1 Typical ties for masonry cladding [from CSA A370-84]

ties (cavity ≤ 150 mm), rectangular wire ties (cavity ≤ 125 mm) and dovetail ties (cavity ≤ 40 mm) the maximum spacings are equivalent to 2.8 ties per square metre of brick cladding. Three rectangular wire ties per square metre are needed for cavity widths between 125 and 150 mm. For corrugated strip ties, 4.2 per square metre are needed (cavity ≤ 25 mm; wind pressure ≤ 1.4 kPa). For truss and ladder wire ties, the vertical spacing is 0.6 m for cavity widths up to 125 mm, and 0.4 m for increased widths up to 150 mm.

Shelf angles and lintels are used to support masonry over openings and give vertical support to masonry cladding. Masonry cladding requires non-combustible vertical supports. Where the height exceeds 11 m above the top of the foundation, the supports shall be spaced at vertical intervals no greater than 3.6 m [CSA S304, 1984]. The spacing requirements may be waived if an engineering design justifies the changes.

Ties are all available in galvanized steel and many in austenitic stainless steel (type 304; type 316 available on special order). Some companies can also provide epoxy coated, galvanized steel ties although there is no standard governing them in Canada or USA. Shelf angles and lintels are usually mild steel with a protective paint coating although galvanized steel is becoming more common in some areas. Stainless steel is also available. In Britain most shelf angles are made in stainless steel. Changes in construction methods and the introduction of stricter requirements are gradually leading to an increasing demand for fixings with improved corrosion resistance. A British report predicts an increasing demand for corrosion resistant fixings, with stainless steel the most popular choice [Anon 1987a].

Retrofit ties
BRE Digest 329 [1988] discusses retrofit ties used in Britain and their installation. The most common material for retrofit ties is austenitic stainless steel. Such ties are gradually being introduced into North America. The major tie manufacturers already sell one or two varieties of such ties.

2.3 COSTS

In 1976, the gross annual sales of anchors, ties and fasteners for brick masonry walls in the USA was estimated to be US$15 to US$25 million [Grimm 1976]. In recent years, codes and standards have begun specifying thicker zinc coatings on galvanized ties which in turn has increased costs (roughly doubled). Nevertheless the increase in cost is small in comparison with the total cost of the cladding. Doubling the cost of the connectors in a building is said to be less than 1% of the masonry cladding cost [CSA A370, 1984; Grimm 1976].

2.3.1 Canada

Examples of the approximate cost in 1992 of hot-dip galvanized ties direct from the manufacturer are:

- Wire truss tie (200 mm)	\$1.30 per metre
- Z wire tie (200 mm)	\$240 per 1000
- Rectangular wire tie (100 x 200 mm)	\$420 per 1000
- Corrugated strip tie (32 x 200 mm)	\$100 per 1000

The cost of the above ties per square metre of cladding depends on the lateral loads on the veneer and the size of the cavity. For example, a wire truss tie every second block course would cost \$3.25/m^2 while corrugated strip ties spaced at 400 mm x 600 mm would cost \$0.42/m^2. Over the last two years, the cost of galvanized steel has been dropping more than that of stainless steel thus the relative cost of stainless has increased. Costs are also dependent on how much steel is ordered at a time. As larger quantities of stainless steel are ordered and the number of ties made from it increase, the price will drop. Current relative costs for wire ties vary by a factor of 1.5 to 2.6. The factor may be higher if much welding is required to fabricate the tie. Strip and plate type ties may also cost more unless the manufacturer has a die for making them. A die is expensive and only warranted if there is a large enough demand for the tie. For example, currently a stainless steel strip tie could cost up to 10 times more than a hot-dip galvanized one.

2.3.2 USA

Catani [1985] stated hot-dip galvanized wire joint reinforcement (galvanized after fabrication) is almost double the cost of mill galvanized reinforcement. The increase per square metre of wall is 65 cents. Hot dipping a rectangular wire tie increases the cost per square metre by 27 cents. In a more recent article, Catani [1991] stated stainless steel type 304 costs five times more than 460 g/m^2 hot-dip galvanized steel.

2.3.3 Britain

Most ties in Britain are either stainless steel (approx. 50% of the market) or hot-dip galvanized steel with a minimum coating of 940 g/m^2. The relative costs in 1991 of ties made from these materials are [AJ 1991]:

Cost per m^2 of wall (3 per m^2; 50 mm cavity; tie length approx. 150 mm)

Butterfly (wire):	Galvanized \$ 0.34	Stainless \$ 0.44	Ratio	1.31
Twisted (plate) :	\$ 0.46	\$ 0.90		1.95

A new tie, which appeared recently on the market, made from type 304 stainless steel is said to cost the same as its galvanized equivalent [Cochrane 1990].

2.3.4 Germany

A report assessing the possible use of epoxy coated, galvanized steel shelf angles estimated they would be 22% cheaper than those in stainless steel [Schiebl & Ohler 1989].

3. Current code requirements

This section summarizes the code requirements in different countries. More information is given in Appendix C.

3.1 CANADA

CSA standard on Masonry Connectors, A370 [CSA 1984], gives requirements for minimum corrosion resistance. The standard may be applied to all buildings. All connectors in exterior walls are required to be *corrosion resistant* except anchors in direct contact with cut stone which must be *noncorroding*. *Corrosion resistant* applies to connectors treated or coated to retard harmful oxidation or other corrosive action, e.g. galvanized steel. *Noncorroding* applies to connectors which are corrosion resistant because of their composition, e.g. stainless steel or bronze. The term *noncorroding* is misleading since such ties also corrode but generally at slower rates. It would be better to talk in terms of different levels of corrosion resistance.

Corrosion resistant ties must have a level of resistance equivalent to galvanized steel with the minimum zinc coating specified in the standard. The minimum coating for wire ties is 458 g/m^2. For strip and plate type ties it varies from 305 g/m^2 to 610 g/m^2 on each face depending on the thickness of the tie. The zinc coatings were set according to thicknesses listed in ASTM standards for galvanized steel products, hot-dipped after fabrication. The variable levels of zinc coating mean variable levels of corrosion resistance. In contrast the British standard requires a minimum of 940 g/m^2 for all galvanized ties.

Noncorroding ties must have a level of durability equivalent to type 304 stainless steel.

Part 9 of the National Building Code (NBC) covers small buildings up to a height of three storeys, a maximum area of 600 m^2 and specific occupancies (residential, business and personal services, mercantile, and medium and low hazard industrial). The 1990 edition incorporated the minimum requirements in CSA standard A370. Previous editions specified that the tie be *corrosion resistant* but gave no minimum requirements for corrosion resistance.

3.2 USA

The USA has three building codes which govern construction in different parts of the country (Standard Building Code, Basic Building Code and Uniform Building Code). They all specify galvanized steel with a minimum zinc coating of 458 g/m^2. The ACI/ASCE masonry design standard has the same minimum but lower values are allowed when the tie is completely embedded in mortar or grout. Revisions proposed in 1992 to the ACI/ASCE standard will not allow these lower values.

3.3 EUROPE

A European standard is being developed for wall ties, straps, hangers, brackets and support angles [CEN 1990]. The current draft lists suitable materials and gives their relative corrosion resistance.

Germany and Switzerland require stainless steel ties. Sweden requires galvanized steel or stainless steel ties; stainless steel must be used if the cladding is higher than 6 metres. The Dutch model building code specifies galvanized wire ties as a minimum but local regulations may be stricter. For example, Amsterdam requires copper, bronze or stainless steel.

The British standard for wall ties gives a choice between galvanized steel (coating of 940 g/m^2), austenitic stainless steel, copper, phosphor-bronze and aluminum bronze. In London, the use of galvanized ties in buildings exceeding three storeys in height is prohibited (since 1972). For other metal components in walls different levels of corrosion resistance are specified according to environmental exposure conditions.

France requires a high level of corrosion resistance for buildings designed according to DTU 55.2 [CSTB 1984]. Examples of allowable materials are brass, bronze (not cast) and austenitic stainless steel.

4. Corrosion resistance

4.1 CORROSION PRINCIPLES

More detailed discussions of the points covered in this section are given in Appendix A.

Corrosion is the deterioration of a metal through reaction with the environment. For example, iron when placed in water will corrode and form an iron oxide; or silver placed in a solution containing sulphides will tarnish forming a silver sulphide. Very few metals are stable under nearly all conditions. The only practical exceptions are gold and platinum. [Gellings 1985].

This report only considers corrosion of metals to their oxide form, a process called oxidation (or rusting in the case of iron and steel). It is an electrochemical reaction where an electric current passes through a conducting solution (water) between two parts of the same metal or between different metals (current flows from an anodic area which corrodes to a cathodic area). Both oxygen and water need to be present. Oxidation can occur uniformly over the whole surface of the metal or locally (e.g. pitting corrosion).

When an oxide layer is formed on a metal surface, it can act as a barrier against current flow and therefore inhibit further corrosion provided the layer remains intact (often called passivation). Alkaline environments can encourage the development of passive oxide layers. Dissolved $Ca(OH)_2$ in the pore water of a cement matrix such as mortar provides such an alkaline environment with a pH value approaching 12.6. Under these conditions, a passive oxide layer is formed on steel protecting it from further corrosion. If the pH of the mortar drops below 9.5 the passive layer may be destroyed [Derrien 1990]. Carbonation of mortar is the major reason for a reduction in pH (see section 5.2.1.1).

Corrosion resistance can also be improved by applying protective coatings to mild steel, or by replacing mild steel with materials having a higher corrosion resistance.

4.1.1 Mild steel with protective coatings

Steel can be protected by more resistant coatings. Zinc is the most common coating used for wall ties. It corrodes at a much slower rate than steel; 1/10 to 1/50 in most atmospheric environments [Simm 1983], and provides better protection than most other coatings because of the ability of zinc to act as a sacrificial anode. The steel underneath becomes the cathode and does not corrode (cathodic protection). Because of this action, the steel exposed by scratches in a zinc coating does not usually rust significantly until most of the neighbouring zinc is consumed (the thicker the zinc coating the longer the protection). Scratches up to 6 mm wide are protected [AGA 1990], but for the thinner zinc coatings on ties a width of 3 mm is probably more realistic [CSA A370, 1984]. This beneficial characteristic also offers protection to steel surfaces exposed by cutting galvanized sheet or wire. The life of a zinc coating is determined by the exposure conditions, and is proportional to its thickness [Sereda 1975; Simm 1983]. In addition, the corrosion rate of zinc increases when it acts in a sacrificial mode. In an alkaline cement/lime environment zinc forms a stable film in the pH range 6 to 12.5. Salts and other contaminants may affect this stability [BRE 1986]. Cadmium is an alternative to zinc since it also offers cathodic protection. It is more expensive than zinc, and is also more toxic.

Protection by other pure metallic or organic coatings is generally inferior to that of zinc. Coatings such as plastic, epoxy or copper are effective in resisting corrosion, but because they do not offer cathodic protection to the steel, great care must be taken not to scratch or mar the coating. Puncturing during transport, storage or installation can lead to local pitting and subsequent general corrosion when the coating is forced off by the expanding layer of rust. Bitumen coatings used in the past have not performed well [de Vekey 1984; Fishburn 1943]. Mild steel ties coated with a compatible, durable resin at least 1 mm thick may be better [BRE 1988].

Plastic or epoxy coated galvanized steel is probably a satisfactory alternative but there is insufficient data available to estimate service life [de Vekey 1984]. Preliminary tests using such coatings on galvanized steel shelf angles and wire truss reinforcement indicate they may be suitable [Schiebl & Ohler 1989; Pfeffermann 1987 & 1991].

4.1.2 Materials with high inherent corrosion resistance

Materials with high inherent corrosion resistance such as copper, bronze and stainless steel are alternatives to coated mild steel. Austenitic stainless steel is the most popular. Ties made from it are expected to have a life in excess of 100 years. Type 304 (chrome-nickel steel) is suitable for most situations, but if high levels of chlorides are present then type 316 (chrome-nickel-molybdenum steel) should be used. This type is recommended in areas exposed to high salt contents (e.g. road salts and marine spray) [BRE 1988; de Vekey 1989].

4.2 INTERACTION BETWEEN DIFFERENT METALS

Increased corrosion may occur if dissimilar metals are in electrical contact with one another in the presence of moisture. Type and relative areas of the metals in contact, and the conductivity of the moisture affect the rate of corrosion. Under atmospheric conditions, the corrosion is usually localized near the points of contact. The severity of the corrosion depends on the time the contact remains wet which is dependent on environmental factors and the location of the connector in the wall.

Contact between stainless steel (cathodic) and aluminum, zinc, and mild steel (anodic) may be tolerable (although not recommended) provided that the anodic material has a larger relative area thereby reducing the anodic current density so that any increased corrosion will be less noticeable. Thus it may be acceptable to use stainless steel bolts to fix a galvanized shelf angle, but not the other way round. Maness [1991] found corroded galvanized anchor bolts which had been used with stainless steel shelf angles. This represents the case where the corroding anode is small compared to the cathode. In conditions conducive to corrosion (moisture and oxygen), a high current density in the small anode will lead to a much increased corrosion rate. An example where the area of the more corrodible metal is larger, is a stainless steel screw attached to a steel stud. Since the more corrodible stud has a far greater surface area than the screw, there should be little increase in the rate of corrosion of the stud [Krogstad 1992]. The use of electrical isolators such as plastic washers or neoprene to separate different metals, will greatly reduce the risk of any increased corrosion [Harris & Edgar 1991].

5. Factors affecting corrosion in masonry cladding

5.1 INTRODUCTION

There have been no direct studies of either the detailed environmental conditions in masonry cladding or the corrosion processes of metals under those circumstances. Corrosion occurs where there is oxygen and moisture. In practice corrosion is most likely to occur in locations which are often damp. Corrosion rates will be higher where there is frequent wetting and drying which ensures fresh supplies of oxygen in addition to moisture.

These conditions occur in walls showing efflorescence, walls with frost damage, walls directly exposed to wind driven rain, and particularly in areas with poor details such as masonry below window sills with inadequate drips and flashings. Areas where drying is inhibited are also more susceptible to corrosion: insulated cavity walls, and walls with glazed brick or a coating of paint. Leakage of humid indoor air through inadequate air barriers to the exterior can also be a source of moisture. This is worst near the top of buildings (as is wetting from rain), around window frames and in buildings with high humidity (swimming pools and museums).

Corrosion is most likely to occur in the part of the tie in the mortar joint within the external wythe of the cavity, under mortar droppings on the part of the tie in the cavity, and in wet cavity insulation. In other words in areas likely to retain moisture for longer periods. In wet environments, the part of the same metal component with less exposure to oxygen can act as an anode and corrode first. The alkaline condition of the mortar will initially inhibit corrosion but this protection reduces with time because of acid components in rain water derived from carbon dioxide and pollutants in the air. For most wire and strip ties, corrosion will not be evident except for thicker ties and shelf angles where expansion caused by the corrosion products results in spalling of the brick or horizontal cracking in the mortar joint.

Factors affecting corrosion are:

- Material factors such as material(s) making up the connector, mortar density and composition including additives, masonry units and insulation.

- Environmental factors such as exposure of wall to wetting (frequency and time of wetness), pollutants in the air (SO_2, NO_2) and temperature.
- Construction details such as design details which reduce moisture ingress into the wall, workmanship and location of connectors within the wall.

5.2 MATERIAL FACTORS

Materials making up connectors are discussed in section 4 and Appendix A. Here other material factors are considered.

5.2.1 Mortar

5.2.1.1 CARBONATION

Alkaline conditions in mortar provide some initial protection against corrosion but carbonation reduces this alkalinity. Carbonation is the reaction of atmospheric carbon dioxide, in the presence of moisture, with the alkalis in the mortar and concrete to form carbonates and is typically of the form $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$. During this process the pH of the concrete falls from about 12-13 (alkaline) to 7-8 (neutral) [de Vekey 1982]. Industrial pollutants such as SO_2 normally increase the rate of acidification [de Vekey 1982]. Nevertheless, CO_2 generally has the greatest effect on the reduction in alkalinity because of its much greater levels in the atmosphere.

Indicator tests on samples of mortar from walls show that carbonation of a mortar bed is substantially complete in about 10 years, except perhaps in the mortar-filled frogs of bricks [Moore 1981b]. The more porous the mortar the more rapidly this occurs. For example, in dense concrete the penetration may be no more than 15 mm but in mortars which are more porous because of their much higher water to cement ratios the depth is much larger [Kropp & Hilsdorf 1979]. Higher porosity mortars (higher water/cement ratios and lower cement contents) will carbonate faster, as will mortars adjacent to masonry units having higher porosities. High strength, dense mortars, such as a 1:3 cement:sand mix with a well graded sand, may take much longer to carbonate.

Both oxygen & water must be available for normal rusting to occur. Further the pH needs to be on the low side. Ionic salts, especially chlorides, alter the corrosion process and reduce the pH sensitivity [de Vekey 1989]. Recent laboratory tests on carbonated concrete and mortars have shown the main variable affecting corrosion rates in carbonated specimens was moisture content, determined by the relative humidity of the surroundings [Page 1990]. At RH $\leq$65%, negligible corrosion was recorded but, at RH $\geq$75%, the corrosion rate increased significantly. Variation in cement type had only a modest influence compared with that of the porosity of the cement matrix.

The use of lime in mortar is said to help inhibit corrosion of wall-ties, although there may already be sufficient free lime in cement for this purpose [Thomas 1970]. On the other hand, mortars with higher lime contents are more permeable therefore permitting faster carbonation [de Vekey 1990a]. Plasticizers in mortars can also increase the permeability of the mortar (e.g. masonry cements). Higher strength, dense mortars give longer protection because of slower carbonation rates, but high strength mortars are not recommended for masonry cladding as they are much less able to accommodate movement.

5.2.1.2 Chlorides

Inorganic salts such as chlorides in the mortar may occur naturally in the sand, or are added as a set accelerator or anti-freeze to mortar, or derived from deicing salts.

There is little direct evidence in Britain to date that chlorides are a significant factor in increasing the rate of zinc loss on ties embedded in mortars [de Vekey 1990a]. Heidersbach et al [1987] state chlorides from cleaning compounds and admixtures only have a small effect on increasing the corrosion in masonry. On the other hand, claims have been made in the United States that chlorides leached from a mortar additive called Sarabond (saran latex polymeric emulsion) have caused corrosion damage [ENR 1979 & 1986]. Hime [1985] stated "in our experience chloride corrodes galvanized steel. Cadmium coats are better, and epoxy-coated or stainless steels may be necessary in adverse environments."

Tests on concrete specimens have shown that the presence of chloride salts, even at levels that would be considered acceptable in uncarbonated concrete, tend to enhance corrosion rates of steel in carbonated specimens [Page 1990]. Accelerated tests on galvanized truss ties in small clay brick walls also showed increased corrosion when 2% calcium chloride was added to the mortar [Pfeffermann & Baty 1981]. This may be due to the formation of zinc chloride which is more soluble and thereby accelerates zinc dissolution [BRE 1986].

Chlorides seem to affect the corrosion process in different ways:
- maintaining higher moisture levels (deliquescent)
- direct participation in the corrosion reactions such as increasing the electrical conductivity
- causing pitting corrosion in steel by locally affecting the passive protective layer.

Alternative concrete set accelerators which also inhibit corrosion have been suggested. They seem to reduce the corrosion rate in the short term but the long term effectiveness is less certain. Further discussion is given in Appendix A (section 4).

5.2.2 Masonry Units

5.2.2.1 Brick

Denser more impermeable bricks concentrate any moisture in the more permeable mortar joints. On the other hand, they reduce the rate of carbonation in the mortar.

5.2.2.2 Concrete

Pfeffermann & Baty [1981] found in accelerated tests that concrete masonry gave better protection than clay masonry (see Appendix A, section 5.2). This may only be a short term effect due to the extra alkalinity provided by the concrete.

5.2.2.3 Stone
The stone industry has traditionally specified anchors and ties made from materials with a high inherent corrosion resistance. This is probably because the number of fixings are often less than in brick masonry cladding, so that the failure of an individual tie becomes more important. In the past, buildings clad with stone have also tended to be the more important ones and therefore were likely to have a longer life than normal. This is less likely to be the case with modern buildings.

5.2.3 Insulation
Cavity insulation may increase corrosion rates by reducing the drying rate of the brick cladding, but there is no statistical evidence to support this to date [de Vekey 1990a]. Corrosion may also occur within wet insulation such as mineral wool, glass fibre, calcium silicate and organic cellular materials. Any salts leached out from the insulation may influence corrosion [Simm 1983]. Formaldehyde has a strong effect on the corrosion of zinc [Graedel & McGill 1986]. Although urea formaldehyde insulation has been extensively used in the UK, there are no reports of it directly affecting the corrosion rate of galvanized ties. In Germany, Kirtschig & Metje [1988] found corrosion of galvanized ties in test walls containing urea formaldehyde. With other types of insulation there was less corrosion or none.

5.3 ENVIRONMENTAL FACTORS

5.3.1 Exposure to moisture

5.3.1.1 Rain
Figure 2 shows maps of a driving rain index for Canada and USA [Boyd 1963; Grimm 1982]. For comparison a map for the United Kingdom and Ireland is shown in Fig. 3 [Lacy 1971]. The maps are divided into three exposure gradings: sheltered, moderate and severe. All buildings within 8 km from the sea, a large lake or an estuary would be classified one exposure grade higher than shown on the map. The maps give a rough indication of areas of the country where the cladding is likely to be wetter; they relate to the intensity of rain and wind rather than time-of-wetness which is a better representation of the potential severity of corrosion [Moore 1981b]. The Canadian and US maps show the most severe exposures are along the sea coast and the least severe within the western prairie regions. In an investigation of building damage after an earthquake in Australia, wall tie corrosion was found to be particularly bad in areas close to the coast where salts from marine spray may have aggravated the situation [Page 1991].

The wind direction during rain is also important since this indicates which sides of a building are likely to be wettest. Figure 4 shows the frequencies of wind during rain by direction and month for Toronto [Robinson & Baker 1975]. The areas of the building likely to become wettest from wind driven rain are those near the top and near the corners. In an investigation of ties in Britain, no correlations could be drawn between corrosion and aspect of the wall; nor between corrosion and height [Moore 1981b]. This is not surprising because many ties would have to be observed on a particular building before conclusions

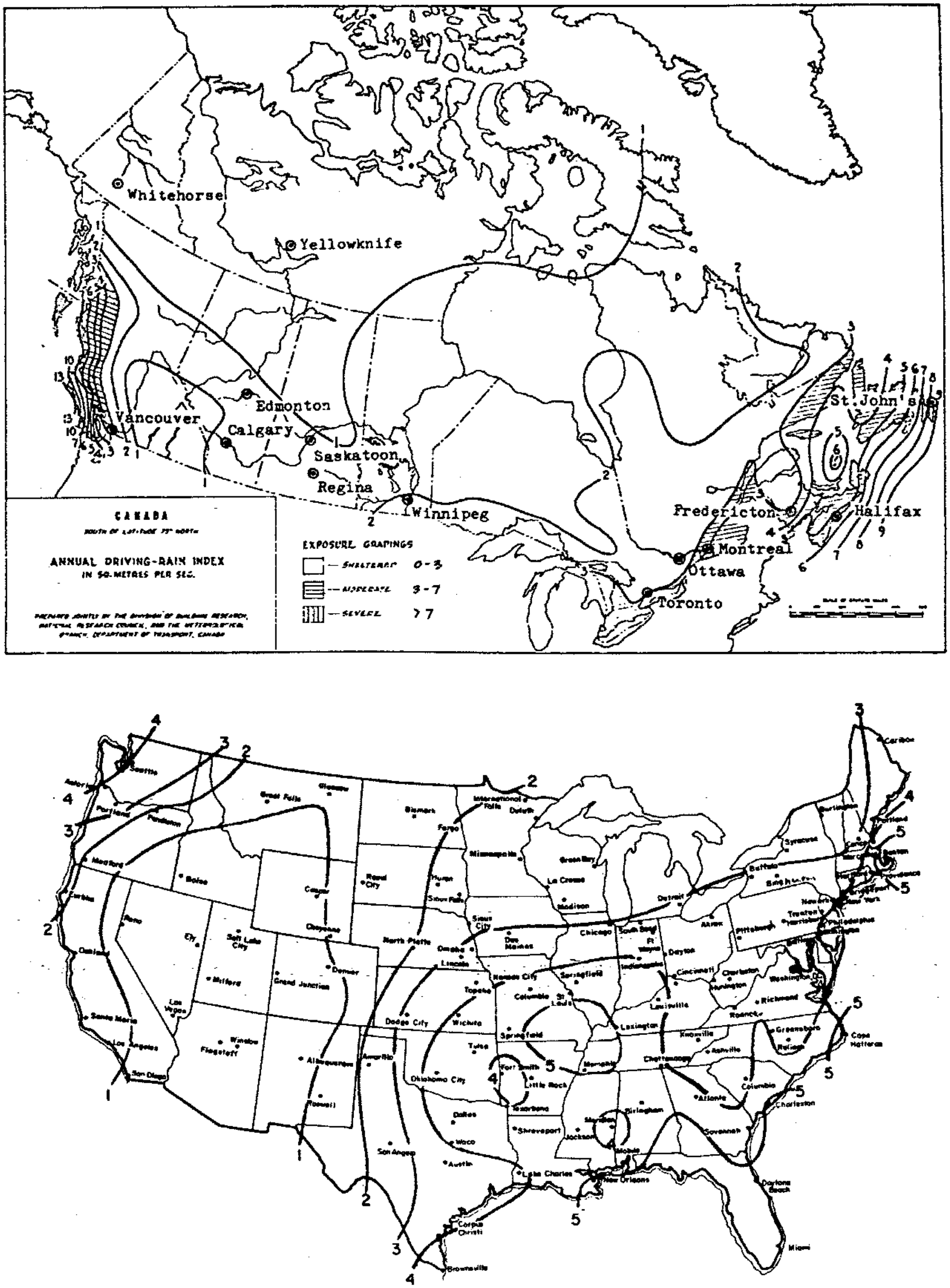

Figure 2 Driving-rain index map for Canada and USA (m^2/s)

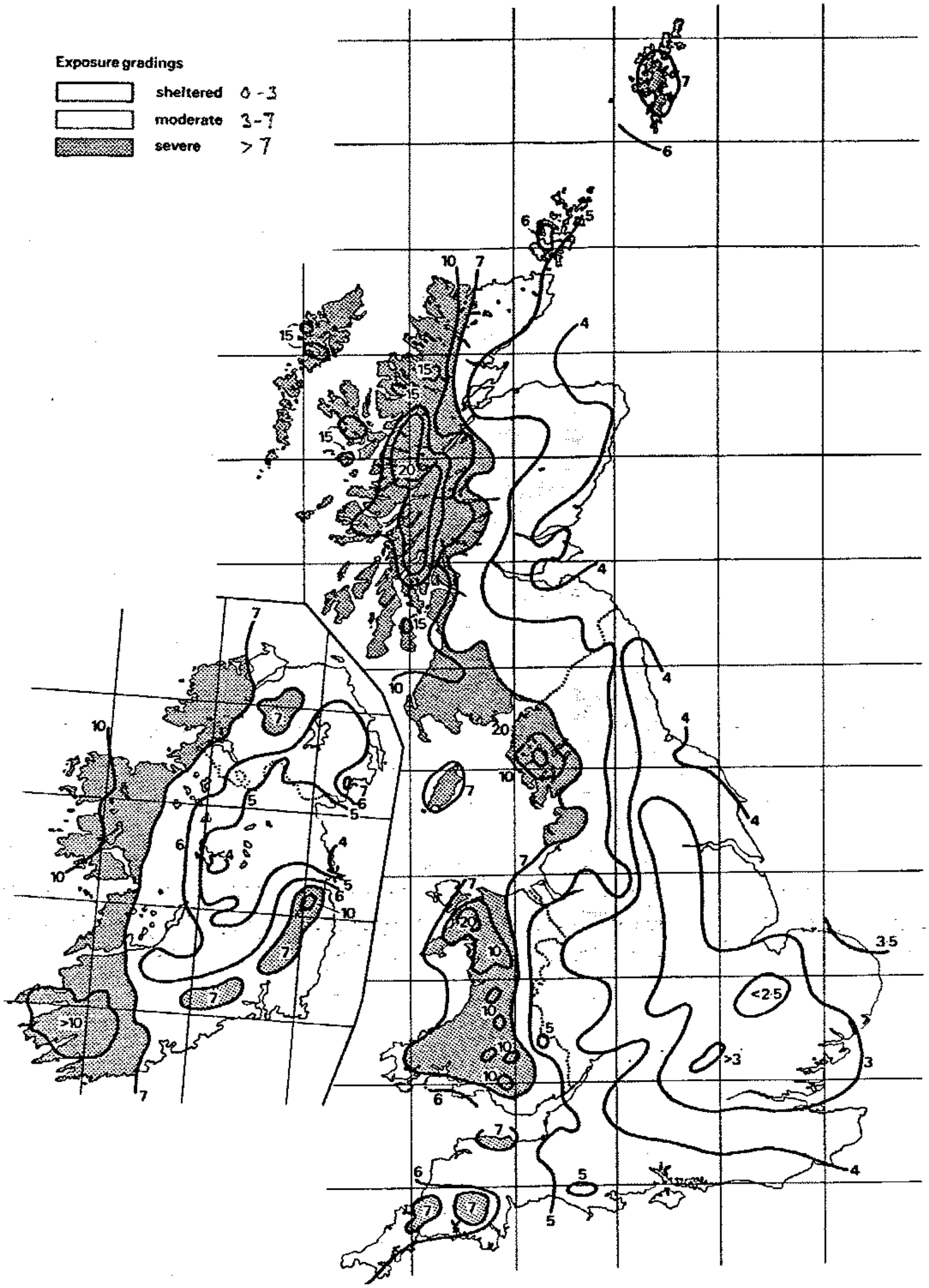

Figure 3 Driving-rain index map for UK and Ireland (m^2/s)

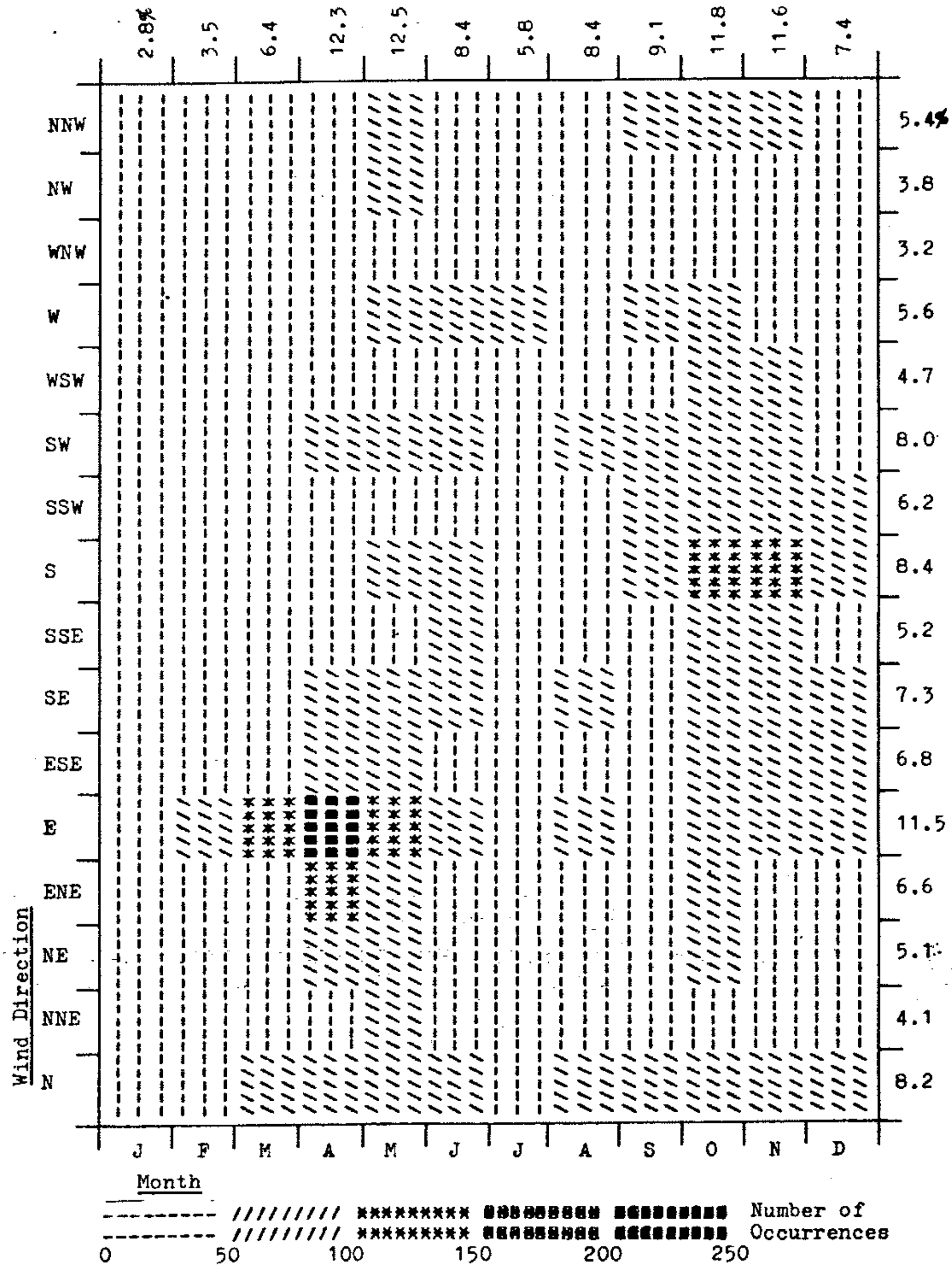

Figure 4 Wind direction frequency during rain
Toronto International Airport 1953-68

could be drawn on the effect of orientation and height. This can only be done on buildings which are being demolished or are having their cladding replaced.

5.3.1.2 WETNESS

Although wetting can be relatively rapid, drying is a slower process especially within a wall. There the total periods of wetness are likely to be greater than for metals directly exposed to the atmosphere (wind and sun promote drying). The duration of wetness will depend on the incident rain and wind, the permeability of the masonry units and mortar, and the quality of joint filling. The ability of water to permeate a mortar joint will also imply generally the penetration of air or oxygen, either free or dissolved in the water. Frequent recharging of the water present will also ensure an adequate supply of oxygen. It should be noted that the quantity of water necessary for corrosion is less than that which will cause dampness to be visible to the unaided eye. [Moore 1981b].

Corrosion is usually found to occur in that part of the tie embedded in the outer brick wythe of a cavity wall and parts covered with mortar droppings adjacent to the outer wythe [Moore 1981b; Page 1991; Cowie & Ameny 1990]. If there is exfiltration of interior air from a building, corrosion is also likely in the inner portions of the exterior wall.

5.3.2 Pollution

Sulphur and nitrogen oxides are major pollutants causing increasing acidity in rain water. In eastern North America about two-thirds of the increase is due to sulphur [Lipfert 1987]. Figure 5 shows the SO_2 levels in sixteen cities across Canada. In most cases, the current levels are at the low end of the ranges shown in the figure. Figure 6 shows the acidity of the rain in eastern Canada and USA. The higher levels of SO_2 in eastern North America are reflected in the greater acidity of the rain there. A pH of 4.3 indicates a 20 fold increase in acidity compared with clean rain, which has a pH of 5.6. The acidity in clean rain is due to the carbon dioxide in the air. Other compounds from natural sources may drop this to 5.0. Sulfur dioxide is the pollutant with the greatest effect on corrosion of zinc in the atmosphere; zinc loss is closely proportional to the concentration of SO_2 in the atmosphere [Timmins 1974].

5.3.3 Temperature

An increase in temperature of 10 °C doubles the corrosion rate of steel in concrete [CEB 1989].

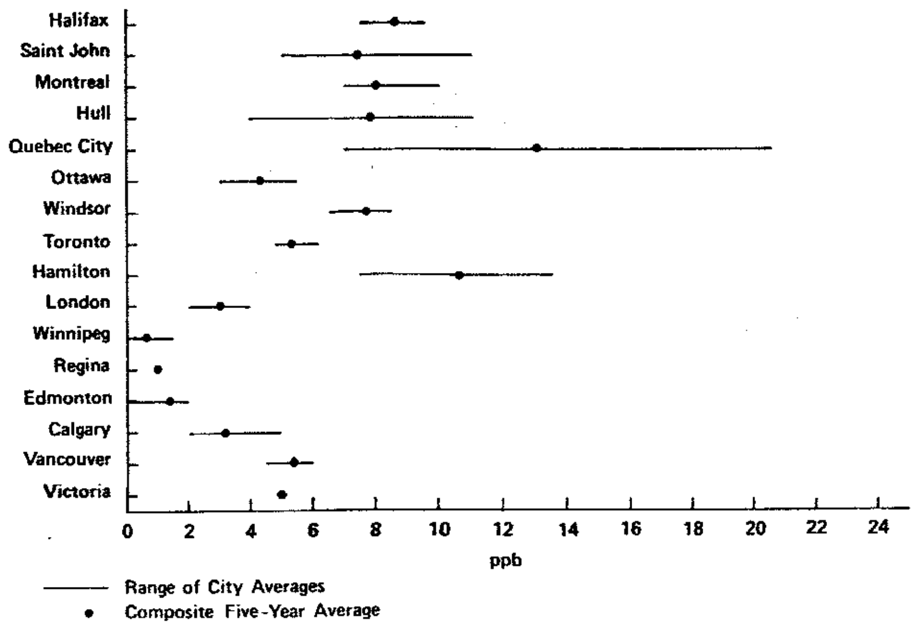

Figure 5 Annual average levels of sulphur dioxide in selected Canadian cities (parts per billion) 1983-1987 [Environment Canada 1990]

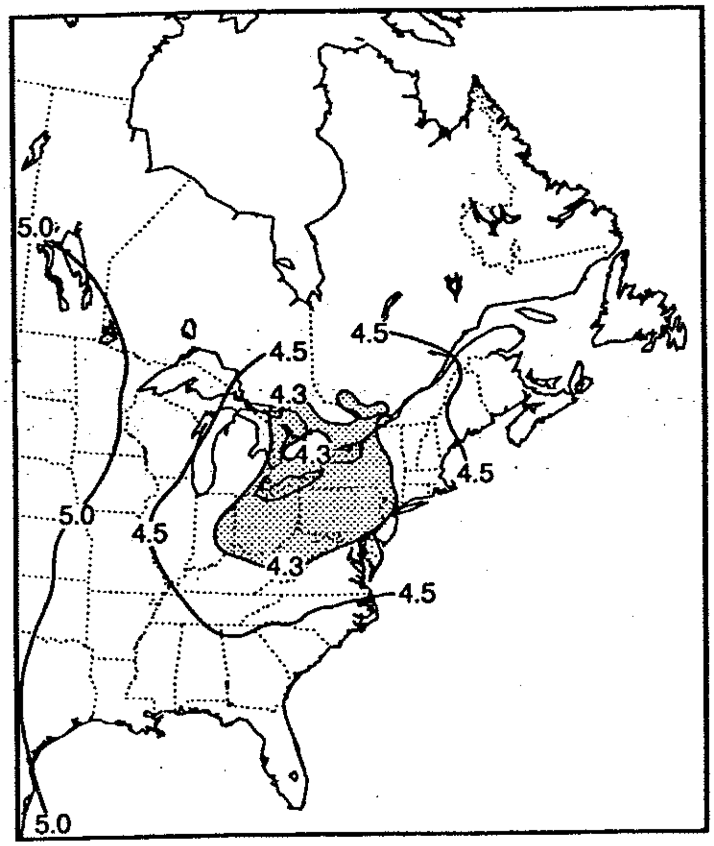

Figure 6 Six-year mean pH distribution in eastern North America (1982-87) [RMCC 1990]

5.4 CONSTRUCTION DETAILS

5.4.1 Design

5.4.1.1 CONTROL OF MOISTURE

Poor detailing which allows increased water ingress or retention is one of the causes for increased damage. Such details include recessed mortar joints, inadequate flashings and drips, and improperly installed air barriers which allow leakage of humid indoor air to the exterior.

The life expectancy of connectors can therefore be extended by building details which keep water ingress into the wall to a minimum. Common sources of moisture are rain and melting snow from the exterior, and condensation of moisture caused by inside air leaking to the exterior. Flashings, drips, venting, drainage, air barriers and the finish of the mortar joints are all details to be considered. Design details should be easy to build thereby reducing workmanship faults.

Although water ingress should be kept to a minimum, masonry veneer walls must be designed assuming water will get into the cavity behind it. This means flashings must be installed over windows in the wall and at shelf angles. The flashing should extend to the face of the brickwork to ensure drainage away from the wall and laps in the flashing should be sealed to prevent water from reaching lintels and shelf angles.

Reduce the projected horizontal area of the tie to a minimum so that it does not act as a platform for mortar droppings and retained moisture. This will also reduce mortar bridging that allows water to cross the cavity to cause corrosion at the other end of the ties as well.

5.4.1.2 CONNECTORS

The compatibility of materials making up the connectors should be carefully considered. Combining metals with large electrochemical potential differences should be avoided. If different metals are combined, they should, preferably, be isolated electrically from each other, or, at least, the *smaller* component should be the more corrosion resistant (the one with the higher electrical potential). For example, galvanized mild screws or nails should not be used to fix stainless steel ties to a building.

5.4.2 Site Practices

Incorrect ties may be delivered to the site due to poor specification, ignorance or cost-cutting. Packaging for wall ties delivered to the site should therefore be clearly labelled with the manufacturer's name, the type of tie, the material type and the thickness and type of any coating. For the inexperienced, the difference between plain, galvanized and stainless steels are often not obvious. With practice hot-dip galvanized ties are relatively easy to recognize because of the their rougher surface. Ties should not have coating weights below those specified and have the correct dimensions. There should be no coating defects such as uncoated areas, flux residues, lumpiness, runs, blisters and cracks [Simm 1985]. Austenitic stainless steel can be separated from plain or galvanized steel because it is not attracted by a magnet. The architect or engineer should make sure that the specified ties are delivered.

Workmanship faults to be avoided are unfilled mortar joints (especially head joints), mortar droppings and other debris in the cavity which may retain moisture, and unspecified additives such as calcium chloride added to the mortar. Even though mortar specifications may restrict or forbid chlorides, they still could be used on site if masons are not supervised (some masons firmly believe in its use to help stop the mortar freezing).

Hot-dip galvanized ties with the thicker coatings should not be bent; the zinc coating may flake off or crack. Welded connections should be checked to see that they were not made after the tie was galvanized. Unprotected welded connections are likely to be more susceptible to corrosion because of inbuilt stresses and varying material properties.

5.5 OVERALL EFFECTS ON CORROSION

Corrosion of metal components is likely to be an increasing problem in future especially in wetter areas of the country. Many ties only have a nominal zinc coating, much less than required by current standards; this may explain why some ties have suffered severe corrosion in only 4 years [Toft 1983].

Graphs of the life of zinc coatings in different environments ranging from interior:dry to sea water:immersed have been produced [BSI BS5493; ASM 1985]. However, these do not address specifically the corrosion of zinc within mortar.

The estimated rate of loss of the zinc coating on corroded wall ties taken from 11 buildings in Canada is shown in Fig. 7 [Keller et al 1992; unpublished IRC data (see Appendix B)]. Superimposed on this figure are rates of zinc loss from ties obtained during a survey in Britain [Moore 1981b]. The loss found in Canada ranges from 8 to 55 g/m^2 a year which is similar to the range found in Britain.

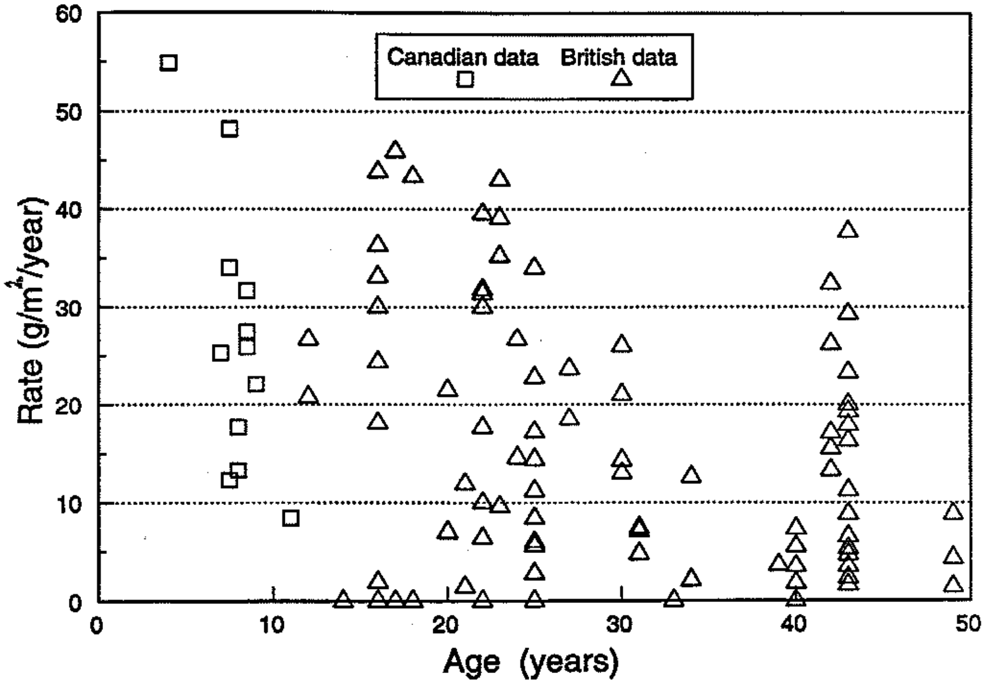

Figure 7 Annual rate of zinc loss on galvanized ties

Britain, based on extensive surveys, has assumed for design that the rate of zinc loss is 10 to 20 g/m^2 a year for ties exposed to air and moisture for a significant part of their life. If a value of 15 g/m^2 were taken for Canada, then the minimum required zinc coats in CSA standard A370 will last from 20 to 40 years depending on the type of tie. This is less than the minimum of 50 years suggested in the standard.

The tie would perform adequately until the cross-section of the steel was significantly reduced or rust expansion caused horizontal cracking in the mortar joints. The corrosion rate of unprotected steel can range from 25 to 125 μm/year [Moore 1981b]. Assuming a uniform corrosion rate of 75 μm/year, and an allowable loss of one-third of the tie cross-section, a 0.7 mm strip tie which has lost its zinc coating would be effective for a further 1.5 years and corrode through in 5 years. A 1.5 mm dovetail tie would be effective for a further 3 years assuming there was no disruption caused by the expansive effects of corrosion. A 3.65 mm wire tie would be effective for a further 4.5 years.

The possibility of cladding failure due to corrosion depends on the location and number of ties affected, the loads on the cladding and any alternative support the cladding may have. Seldom does one shortcoming alone lead to failure. Shortcomings include corrosion, not enough ties, poor embedment in the mortar joints and wrong type of tie. The cladding most at risk is on high rise buildings (especially where there are frequent movement joints), and on low buildings where the brick is in panels (no returns to give extra support).

6. CASE HISTORIES

6.1 NORTH AMERICA

In North America, there have been no detailed surveys of the corrosion of metal connectors in masonry cladding. Several papers have discussed corrosion in individual cases. These show that corrosion is a problem but there is not enough data to indicate its seriousness nor extent. A list of known cases is given in Appendix B.

6.1.1 Canada

WALL TIES

Warnock-Hersey [1985] evaluated the condition of masonry wall ties in 11 Ontario government buildings with insulated cavity walls, all built since 1974. Brickwork was normally removed at two locations in each building. Galvanized wire and dovetail ties were found. The thickness of the zinc coating was not determined. In all cases corrosion was not considered to be significant in terms of strength. Nevertheless surface corrosion, usually minor, was observed in many buildings showing that the zinc coating was inadequate. The zinc coat should last at least 50 years.

Keller et al [1992] discuss the durability of metal components in eight high-rise apartment buildings across Canada (4 to 10 years old). The buildings all had clay brick cladding with steel-stud backup. Corrosion of ties was observed in six of the eight buildings (at openings made in the wall from the inside). The rate of zinc corrosion was found to be similar to the extensive survey of ties carried out in Britain. The extent of corrosion over the building was not determined. In St John's, Newfoundland, it is likely to be extensive on faces of the building exposed to wind-driven rain; the inside of the brick cladding was damp at a test opening.

The Institute for Research in Construction has unpublished case records of wall tie durability mainly in residential housing. These show a large variation from almost no corrosion to extensive corrosion. They also show the need to look at many wall ties over a building to get adequate information. This can usually only be obtained if the cladding is removed. For example, an 8 year old house, with recessed mortar joints and in an exposed, rural location, had its cladding taken off to remove urea formaldehyde insulation which had been injected into the cavity. Corrugated, strip ties had been used. The west wall, protected by a porch, had no corroded ties, but in the south facing wall 98% showed corrosion, in the north facing wall 58%, in the east facing 92% except at an overhang where it was 59%. Figure 8 shows a corroded wall tie on the south face; note that corrosion occurred on the part of the tie which had been in the mortar joint. On the other hand there were houses in urban locations where most of the ties were in good condition. There the ties with corrosion were located in areas subject to higher moisture levels such the area beneath window sills with inadequate drips.

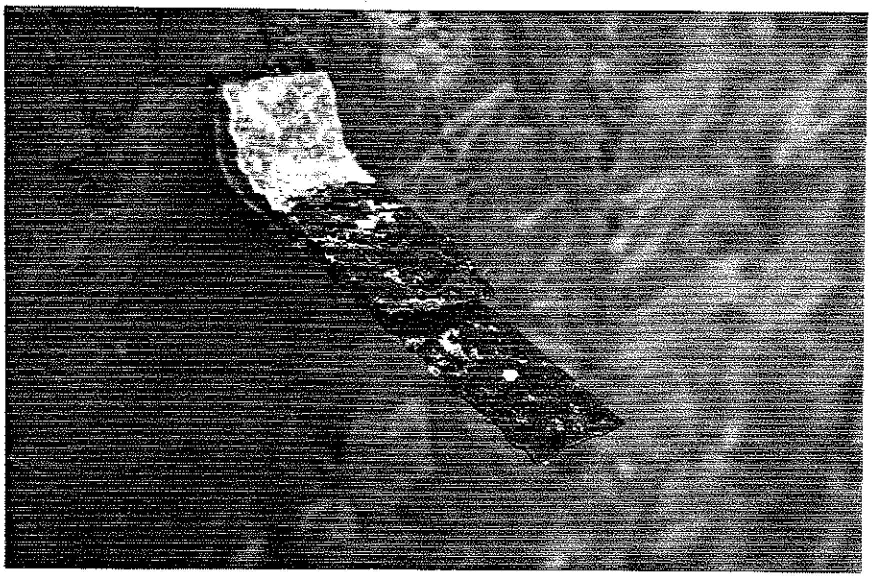

Figure 8 Corrosion on a galvanized, corrugated strip tie

In Atlantic Canada, Cowie & Ameny [1990] have looked at 'numerous' buildings where some hot-dip galvanized ties were severely rusted. The portion of the ties within the mortar joints of the brick veneer had rusted while the portion within the cavity of the wall showed no rust.

An investigation in 1978 of a high-rise condominium in Ottawa showed that about a quarter of the metal ties had corroded to the point of failure in just four years [Toft 1983]. The cavity had been insulated with urea formaldehyde insulation.

Brand [1980] investigated an office building in Ottawa which had been converted to a museum. The interior air was kept at 21 °C and 50% relative humidity. Air leakage caused moisture to condense within the exterior brick and stone cladding. Many ties showed rust damage ranging from surface rust to complete penetration of the metal section (the author did not describe the tie, but it is likely to have been galvanized steel). Bronze (probably brass?) tie rods had also been used. These had been cold formed beyond their elastic limit, and could be broken with the fingers.

Shelf Angles

Extensive corrosion of steel shelf angles was found on a 60 year old, 28 storey steel frame building clad with stone panels and brickwork [Halsall 1988]. Brass rod connectors, 9.5 mm diameter, were in good condition.

6.1.2 USA

TIES & REINFORCEMENT WITHIN THE CLADDING

- Kumar et al [1986] and Haver et al [1990] discuss a 12 years old single storey building, with brick veneer supported by a steel-stud backup. Leaks caused corrosion of corrugated strip ties and of the outer face of the steel studs. The rate of zinc loss on one of the corroded ties was approximately 15 g/m^2/year.
- Grimm [1985] observed galvanized strip ties in two buildings (9 & 10 years old); in both corrosion was severe. A photo of a tie in one of the buildings shows severe corrosion of the portion which had been within a mortar joint of the brick veneer.

SHELF ANGLES

- Corrosion of shelf angles caused spalling of the masonry in two 55 year old buildings [Parise 1982]. The shelf angles had no flashing over them. The expansive corrosion products had increased the thickness of the shelf angle by 6 to 10 mm.

- Grimm [1985] lists the results of a survey of the condition of lintels and shelf angles in 16 buildings with 'some exterior indication of possible corrosion'. All lintels and shelf angles, except one assumed to have had no coating, had been coated with a paint, and flashings had been installed on most of them. Corrosion was rated as severe in 12 of the buildings. Of these six buildings were 10 years old or less.

COMMENTS

It should be pointed out that most of the U.S. investigations occurred in buildings which had other problems such as water leakage and spalling of masonry. Corrosion can be expected in such cases since the wall will have been exposed to moisture over extended periods of time. Many buildings were less than 15 years old indicating the metal components probably had much lower levels of corrosion resistance than required by current standards.

6.2 EUROPE

6.2.1 Britain

In Britain most wall tie failures have occurred in one or more of the following circumstances [de Vekey 1990b]:

- the use of inferior coatings, especially thin layers of bitumen, or no coating at all to protect the steel.
- the use of substandard thicknesses of zinc galvanizing on mild steel.
- the use of permeable mortars, particularly lime mortars, in the outer leaf which permit rapid carbonation.
- the use of aggressive mortars, commonly the black ash type (mortars with a mixture of coal ash, sand and lime; usually contain sulphur oxides which acidify the mortar quite quickly) [de Vekey 1989].
- exposure to severe, especially marine, climates where the walls are likely to stay wet for long periods.

A survey of the condition of galvanized wall ties in housing showed that the minimum required zinc coatings then in existence would be unlikely to achieve a life of 60 years. The minimum levels were 460 g/m^2 for vertical-twist ties (twisted steel strip) and 260 g/m^2 for wire ties. The rates of corrosion deduced from the field data indicated that vertical-twist ties exposed to air and moisture for a significant part of their lives would lose their zinc coating within 23-46 years, and wire ties would lose their zinc within 13-26 years.

6.2.2 Netherlands

A recent Dutch report states that cases of collapse of masonry cladding due to corrosion are infrequent [Verhoef 1991]. Collapses were mainly due to missing ties or poor workmanship. One reason given for the small number of failures is the probable location of corrosion on a building. This is most likely at the top edge and corners of a building where wind is most likely to cause wetting. At these locations corrosion of ties is often not critical because the cladding has alternative support. Nevertheless the report recommends the use of non-corroding ties, anchors and wall reinforcement for the exposed outer wythe of the wall. An investigation is currently underway to check the corrosion performance of wall ties.

6.3 OTHER COUNTRIES

6.3.1 Australia

In Australia an earthquake caused collapse of masonry cladding. Loss of support due to wall tie corrosion was a major cause of failure [Page 1991].

7. FURTHER WORK

7.1 SURVEY OF CONNECTOR PERFORMANCE IN CANADA & USA

Performance feedback and better transfer of existing information is needed to alert engineers and architects about the dangers of corrosion of metal components in masonry cladding. Good documented information on the durability of wall ties in North America will persuade designers to improve corrosion resistance. More extensive investigations of ties in existing buildings are therefore needed to define factors influencing corrosion. This includes defining areas of the country more likely to have corrosion, and where corrosion occurs to define the extent of it over the building. Determining wetting patterns and time-of-wetness on the cladding may help locate areas on a building with higher rates of corrosion.

7.2 REPLACEMENT OF CORRODED TIES IN CLADDING

The future will see an increasing need for replacement of wall ties, especially for claddings in more exposed locations which used ties that do not conform with current standards. Detection of corrosion of thicker ties such as dovetail ties may be relatively easy since expanding corrosion products may cause horizontal cracks in the mortar joints. Detection of wire or strip tie corrosion will not be easy since most of it will take place within the mortar joint without causing cracking. Simple corrosion detection systems are urgently needed. At the moment, removal of a brick at a tie location appears to be the only reliable method.

The market for retrofit ties is expanding. The number of different types of tie is increasing; in most cases they are made from stainless steel. Better analysis programs are needed to identify the number and best location for these retrofit ties.

7.3 TESTS

The emphasis should be on long-term exposure tests with laboratory tests for comparative purposes. Accelerated corrosion tests are generally not considered reliable since they do not accurately simulate conditions seen in practice. They are therefore not suitable for predicting the lifetime of corrosion resistant coatings. They can be used for comparative testing of different materials and for investigating possible corrosion mechanisms. They are also suitable for determining the effects of corrosion such as cracking of masonry [Simm 1985].

Items to check:

- Effect of chlorides on the corrosion of both galvanized and stainless steel embedded in mortars. Include samples where the protective coating on the steel has been damaged.
- Effectiveness of inhibitors added to the mortar in preventing corrosion.

- Effect on corrosion rate of two different metals in contact. For example, stainless steel with galvanized steel.
- More long term corrosion tests on ties in masonry samples.

8. SUMMARY & CONCLUSIONS

Where components in masonry cladding such as ties are hidden from view by subsequent construction, making repair and maintenance very difficult, durability must be a prime consideration in design and construction.

The life expectancy of connectors can be extended by building details which keep water ingress into the wall to a minimum.

The protective zinc coating on ties in masonry cladding in existing buildings is often below that required by current standards. Furthermore even the required minimum zinc coatings in current North American standards do not provide sufficient protection to ties exposed to air and moisture for a significant part of their lives.

The possibility of cladding failure due to corrosion depends on the location and number of ties affected, any alternative support the cladding may have, the needed tie strength, and the loads on the cladding. The consequences of failure depend on the size and location of the cladding. They are likely to be more serious for high-rise buildings. In some cases there may be early warning signs such bowing or cracking in the mortar joints. But in other cases there may be no warning.

Until further studies show otherwise, ties with a greater corrosion resistance than specified in current North American standards should be considered for high-rise buildings, buildings with a known long life, buildings adjacent to heavy industry and buildings in areas directly exposed to marine climates, or severe or moderate driving rain.

Appendix A Corrosion resistance

1. BASIC PRINCIPLES

Most metals, including iron and steel, are unstable with respect to their oxides. This means that these metals will in time convert to their more stable oxide form. This oxidation is often termed corrosion, an attack on a material by reaction with the environment with a consequent deterioration of properties [Gellings 1985]. If a compact, intact oxide layer forms, it can greatly reduce the rate of corrosion. The durability of the film is strongly dependent on the solubility of the oxide layer in the surrounding environment (e.g. depending on its acidity or alkalinity).

For corrosion to occur both oxygen and water (an electrolyte) are required. In addition a difference is needed in electrochemical potential between different parts of the metal or between different metals. The differences can be induced by different concentrations of oxygen in solution, chlorides or localized differences in material properties. There are two general corrosion mechanisms [Gellings 1985]. The first leads to a generally uniform corrosion over the surface of the metal leading to a slow deterioration of the metals properties. The second causes localized corrosion such as pitting which can have serious consequences even though the total metal corroded is small.

If two metals are connected together in the presence of moisture, electrons will flow from the less corrosion resistant metal (the anode) towards the more corrosion resistant one (the cathode). A potential difference can be developed equally well on the same metal if the properties of the electrolyte in contact with it vary. This is what happens when steel reinforcement corrodes; the electrolyte, the liquid in the pore structure of the concrete, can vary along the bar and electrolytic cells can develop between points of different potential. The reactions that occur in normal conditions are as follows [Beeby 1982b]:

(1) iron ions pass into the electrolyte at the anode $Fe \rightarrow Fe^{++} + 2e^{-}$ or $Fe^{+++} + 3e^{-}$

(2) at the cathode, the electrons produced at the anode associate with water and oxygen to produce hydroxyl ions (cathodic reaction): $2H_2O + O_2 + 4e^{-} = 4(OH)^{-}$

(3) the hydroxyl ions flow towards the anode and react with the metal ions and additional oxygen to produce rust (anodic reaction):
$Fe^{++} + 2(OH)^{-} = Fe(OH)_2$ or $2Fe^{+++} + 6(OH)^{-} = 2Fe(OH)_3$
$Fe(OH)_2$ and $Fe(OH)_3 \rightarrow FeO$ and $Fe_2O_3 + H_2O$ (rust)

The proportions of the corrosion product (rust) and the increase in volume caused by the rust varies greatly depending upon environmental conditions.

A fourfold expansion in volume (1 to 4.9) has been quoted by de Vekey [1990a]. Grimm [1982] gave calculated relative volume ratios of the more likely corrosion products ranging from 1.77 to 3.72. Stark [1989] quoted values from 1.8 to 6.4. In practice volume increases of seven have been observed on corroded wall ties; this includes discontinuities and voids formed in the corrosion product during its formation [de Vekey 1982; Cox 1982].

2. TYPES OF CORROSION

Corrosion may be uniform over the surface of the metal or it may be localized. An example of uniform corrosion is general atmospheric rusting on the surface of a metal. Localized corrosion is more unpredictable. The following paragraphs give some examples [Gellings 1985; Derrien 1990].

2.1 Pitting corrosion

Pitting corrosion occurs when there is a local breakdown of the protective oxide layer. This may be caused by impurities on the metal or within the metal. Chlorides can inhibit the reformation of a passive oxide layer where the layer has been damaged. Corrosion then causes holes or pits to form.

2.2 Corrosion caused by differential aeration (crevice corrosion)

Crevice corrosion may occur at joints between two metallic components (e.g. a nut and bolt) or between a dense grout and a fixing. Water drawn into the crevice may end up having a varying concentration of oxygen, the area furthest from the opening having least. The end of the crevice with little or no oxygen then acts as an anode and corrodes. The lack of oxygen also prevents the formation of an oxide layer should this layer be damaged or non-existent. Chlorides in the solution may further aggravate the situation.

2.3 Selective dissolution

Selective dissolution may occur of one of the less noble components of a two phase alloy, leaving the more noble component as a porous residue. This type of corrosion occurs under deposits such as dirt or scale. The most common examples of this are the dissolution of zinc in brass, and ferrite in some cast irons.

2.4 Intergranular corrosion

All metals used in practice are polycrystalline; they consist of a large number of small granular regions. Intergranular corrosion occurs when the boundaries between them are attacked. The adhesion between crystals or grains is lost and the material disintegrates.

2.5 Stress corrosion

Stress corrosion is caused by the combined effect of a corrosive environment and a high tensile stress in the metal (either applied or residual from forming or welding operations). This can result in cracking and sudden failure. The cracks are approximately perpendicular to the tensile stress. The risk of stress corrosion can be reduced by reducing stresses (e.g. by increasing fixing size or number) and in particular stress concentrations.

3. TIE COMPOSITION

Mild (low-carbon) steel should only be used in interior locations. Although the alkaline conditions of mortar may initially protect it, corrosion can be rapid when the alkalinity of the mortar decreases, or if the mortar contains chlorides. The corrosion rate of unprotected steel can range from 25 to 125 μm/year [Moore 1981b]. Steel can be coated to improve its corrosion resistance, or alternatively materials with a high inherent corrosion resistance can be used.

3.1 Corrosion resistant coatings on steel

3.1.1 ZINC

Zinc provides a protective layer to steel and also provides galvanic (sacrificial) protection (galvanized steel). This protective layer for connectors is very thin. The maximum level so far specified is 940 g/m^2 which is equivalent to 0.13 mm. When zinc corrodes it has 2 to 3 times less expansion than steel [Derrien 1991].

There are different methods of applying zinc to steel: sherardising, hot-dip galvanizing, electroplating, zinc spraying and zinc rich paints. Galvanized steel components in masonry are usually hot-dip galvanized or electroplated.

Hot-dip galvanizing

Hot-dipping is the most common method of applying zinc to galvanized steel components used in masonry. Zinc is applied by immersing prepared steel into a bath of molten zinc (445-465 °C). The rate of reaction between the zinc and iron is very rapid, and temperatures above 480 °C lead to the formation of thick, brittle coatings. In principle, the reaction produces a coating of zinc-iron alloys that are progressively richer in zinc as they approach the outer surface, which is essentially pure zinc. In practice the process is not so simple and many factors influence the formation of a satisfactory coating. The thickness of the coating depends on bath temperature, time of immersion, speed of removal from the bath and subsequent wiping operations. The composition of the steel and certain metallic additions to the zinc bath also greatly influence the thickness and composition of the zinc coating. Hot dipping can be carried out either as a batch process or a continuous process (e.g. wire or strip). Steel galvanized by the continuous process is known in North America as mill galvanized steel; metal ties and anchors are fabricated afterwards which means cut edges are not coated with zinc [BRE 1986; Simm 1983]. Ties made from mill galvanized steel do not have sufficient zinc on them to conform to the CSA standard on masonry connectors. In the continuous zinc coating process small amounts of aluminum (0.3%) are added to suppress alloy layer growth and produce a thinner coating that withstands the stresses of subsequent fabrication processes [Simm 1983]. Thicker coatings require the use of fully killed silicon steel [BDA 1986].

If the material is to be bent or fabricated after hot-dip galvanizing, coating thickness should be limited as thick coatings may crack or flake at the interface of the zinc and steel where a brittle iron/zinc alloy is formed. This is another reason for galvanizing ties after fabrication.

Coating is usually given in terms of g/m^2 (oz/ft^2) of surface except for galvanized sheet which is usually given in terms of total weight over both top and bottom surface. The following conversion factors relate coating weight to thickness:

$1\ oz/ft^2 \equiv 305\ g/m^2$
$1\ oz/ft^2 \equiv 43\ \mu m$
$1\ \mu m \equiv 7.09\ g/m^2$

Electrolytically applied zinc
Electrolytic coatings are applied to a steel in an electrolysis bath [BRE 1986]. The deposits are pure zinc and are sufficiently ductile to allow fabrication without damage. Coatings can be applied in a batch or continuous process. The thickness of the coating depends upon the time of immersion and the electric current. Accurate control of coating thickness is possible. In Britain, wire for wall ties is coated by this procedure (940 g/m^2). The wire can be formed into wall ties without damaging the coating (for coatings up to approximately 1000 g/m^2).

3.1.2 Galvalum
Galvalum is a zinc aluminum alloy providing better corrosion resistance than zinc in atmospheric environments, with good ductility and good paintability at very little extra cost over a zinc coating [Anon 1987b]. Corrosion resistance, based on accelerated tests, is 2 to 3 times better than galvanized coatings. Long term tests so far confirm this trend. Brittle intermetallic layers are also absent. It is specified in ASTM standard B750. Its durability within an alkaline mortar environment needs to be determined. For example, is there a potential for corrosion at the grain boundaries?

3.1.3 Cadmium
Cadmium provides a protective layer to steel, and like zinc gives galvanic protection to the steel [Barton 1976]. It is applied by an electroplating procedure. It is more expensive than zinc and care has to be taken during the coating process because of the toxicity of cadmium. Cadmium corrodes faster than zinc in an environment containing sulfur dioxide, and corrodes at a similar rate in chloride environments. The corrosion products are less voluminous than zinc. In general it gives similar protection to electroplated zinc.

3.2 Corrosion resistant materials

3.2.1 Wrought and cast iron
Wrought iron is a fairly pure, low carbon, ductile form of iron. Because of its greater purity, it seems to corrode very slowly even in fairly poor conditions such as external walls subject to marine exposure. Cast iron is a high carbon, brittle material but it also has been recorded as corroding moderately slowly in normal exposure conditions [de Vekey 1989]. Cast iron with a high silicon content develops a protective SiO_2 coating [Derrien 1990].

3.2.2 Aluminum
Aluminum forms a stable oxide layer in atmospheric conditions. Anodising is a procedure for forming a thicker oxide layer than would occur under natural conditions. Aluminum is unsuitable for use as ties in mortar or concrete because it is readily attacked by alkalis in

cement [de Vekey 1984]. Aluminum is susceptible to pitting corrosion in specific environments (e.g. chloride containing solutions) [Gellings 1985].

3.2.3 Stainless steel

Stainless steel owes its corrosion resistance to its chromium content. When the amount of chromium present is greater than approximately 12%, it reacts with the oxygen in the air to form a hard, impenetrable layer of chromium oxide. Nickel is often added to improve strength and further enhance corrosion resistance. Although stainless steel is very resistant in many situations there are environments in which it does not work well. For example, when it is under stress in environments with high levels of chlorides. [Branz 1992]

Austenitic stainless steels

This family of steels is derived from the steel often referred to as 18/8 (18% chromium, 8% nickel) [NiDI 1990]. For all normal applications (plain reinforcement and low moderately prestressed reinforcement up to 15% of the ultimate tensile strength) in a range of conditions up to the more severe, austenitic stainless steels should be very durable. Evidence so far available indicates that the protective oxide film is effective when such steels are buried in concrete and mortar even after full carbonation [de Vekey 1982]. Treadway [1985] reports that austenitic stainless steel has behaved well in reinforced concrete with high chloride levels over a 10 year test period.

The most common grades of stainless steel used for connectors are grades 304 and 316. The nominal composition of grade 304, sometimes referred to as 18-8, is 19% chromium, 9.5% nickel [NiDI 1990]. It is suitable for most situations. But it is susceptible to crevice-corrosion and pitting corrosion in the presence of chloride solutions. Grade 316 is more resistant. It contains molybdenum which gives it added resistance (nominal composition is 17% chromium, 12% nickel, 2.5% molybdenum; often referred to as 18-10-3). It is therefore recommended in areas exposed to high salt contents (e.g. road salts and marine spray). BRE [1990] and de Vekey [1989] discuss this in more detail.

As with most alloys, stress corrosion is a possibility. Stress cracking may occur, depending on the level of stress, in warm, high chloride environments. In temperatures below 60 °C this was thought not to be a problem [Gellings 1985]. Recent failures of both 304 and 316 stainless steels in warm, indoor, swimming pool environments have led to extensive studies. A combination of high chloride levels and a very low pH is thought to be the most probable condition for this to occur [Oldfield 1990]. This is only likely in indoor, pool environments; failures have not occurred in outdoor pools. This particular condition is therefore very unlikely in connectors within cladding exposed to outdoor environments.

Intergranular corrosion may occur in stainless steels which have been heat treated in the range of 600 to 750 °C or where welding has heated the steel in this range [Gellings 1985]. It can be prevented by heat treatments to a higher temperature, using low-carbon stainless steels, or by adding titanium or niobium. Such corrosion is more likely to occur in warm, moist environments [Derrien 1990].

3.2.4 COPPER AND ITS ALLOYS

Copper, phosphor-bronze & aluminum bronze

Copper, and phosphor or aluminum bronze (copper/tin alloys) are suitable. Such ties are specified where special requirements exist since they are normally too expensive [de Vekey 1984].

Brass

Brass is an alloy of copper and 5% to 45% zinc [Derrien 1990; ISE 1989]. High-tensile brass, sometimes erroneously called manganese bronze, contains in addition between 0.2% to 2.5% manganese to increase tensile strength and hardness with only a slight reduction in ductility. Brasses are subject to dissolution of zinc in the alloy and stress-corrosion cracking. The resistance to the former can be improved by having lower zinc contents and adding arsenic. The resistance to the latter is dependent on the alloy composition (higher zinc contents are more susceptible), the level of applied stress, and the concentration of environmental contaminants, particularly ammonia and oxides of nitrogen but also sulfate and chloride anions. Because of this problem, it is not recommended for structural fixings [CIRIA 1991]. Brand [1980] reported bronze (brass?) tie rods, used to tie stone cladding to a building, had been cold formed beyond their elastic limit and could be broken with the fingers. Heat treatment would relieve these inbuilt stresses.

3.3 Interaction between different metals

Increased corrosion may occur if two different metals are in contact (directly or indirectly) in the presence of moisture. Under atmospheric conditions, the corrosion is usually localized near the points of contact. The severity of the corrosion depends on the time the contact remains wet. Type and relative areas of the metals in contact can also affect corrosion.

The further the metals are apart in the galvanic series the more likelihood of increased corrosion. The galvanic series for a number of metals and alloys is given below but it should only be used as a rough indication [Gellings 1985]. The relative positions may change with changing conditions.

Galvanic Series (in air saturated, neutral sea water)

Zinc	-0.78 Volt
Aluminum 99.5%	-0.67
Cadmium	--
Mild steel	-0.40
Cast iron GG22	-0.35
18%Cr-8%Ni-steel (active)	-0.30
Lead 99.9%	-0.26
Brass 60-40	-0.07
Copper	+0.10
70-30 cupronickel	+0.34
Cr & Cr-Ni steels (passive)	+0.40

Table 1 gives estimates of the severity of increased corrosion for mild steel, zinc and austenitic stainless steel in contact with other metals in atmospheric conditions.

CIRIA [1991] has also estimated the likelihood of increased corrosion hazard when metals are in contact with other metals or cementitious materials:

Aluminum alloys: Contact under moist conditions with copper, brass, bronze or large areas of lead, carbon steel, or stainless steel. Contact with moist fresh concrete or cement grout, aggravated if concrete contains calcium chloride.

Bronzes (copper alloy with aluminum or tin): Contact under moist conditions with large areas of stainless steel. Can suffer stress corrosion cracking like copper and brass, but rather less susceptible.

High tensile brass (manganese bronze): Contact with other bronzes, copper, large areas of stainless steel. Susceptible to stress corrosion cracking like copper and brass.

Phosphor bronze: Contact with mild steel under moist conditions and with stainless steel.

Copper and brass: Contact under moist conditions with large areas of bronze or stainless steel. Under similar conditions can suffer stress corrosion cracking in the presence of oxygen and oxides of nitrogen or traces of ammonia.

Zinc, zinc coatings: Contact under moist conditions with brass, bronze, copper or large areas of lead, stainless steel. Slight attack when in contact with fresh moist concrete or cement grout.

Austenitic stainless steel: Type 304: Resistant to all bimetallic contacts. Type 316: Resistant under nearly all conditions.

Methods of preventing or reducing bimetallic corrosion are [BDA & BSC 1986]:

1) Insulate dissimilar metals from each other by using washers or gaskets made from a non-conductive material such as neoprene, nylon or PTFE (polytetrafluorethylene).
2) Exclude water from the joint (e.g. by an impervious coating)
3) Keep the volume of the more corrosion resistant material small in comparison to the less resistant material.

TABLE 1 Additional corrosion resulting from contact with other metals in atmospheric conditions [based on BSI, PD6484]

	Steel[1] (Carbon & low alloy)			Zinc and its alloys[2]			Austenitic stainless steel[3]		
Metal in contact	Rural	Indus-trial/ Urban	Marine	Rural	Indus-trial/ Urban	Marine	Rural	Indus-trial/ urban	Marine
Aluminum and its alloys	0	0	0	0	0-1	0-1	0	0^{4}	0
Aluminum bronzes	2-3	2-3	3	0-1	1	1-2	0	0^{5}	$(0\text{-}1)^{4,5}$
Brasses including high tensile brass	2-3	2-3	3	0-1	1	0-2	0	0^{5}	$(0\text{-}1)^{4,5}$
Cadmium	0	0	0	0	0	0	0	0	0
Cast irons	0-1	0-1	2	0-1	1	1-2	0^{4}	0^{4}	-
Cast iron (austenitic)	(0-1)	(0-1)	(0-2)	0-1	1	1-2	-	(0)	-
Copper	1-2	1-2	(2-3)	0-1	1-2	1-2	0	$1^{4,5}$	$(0\text{-}2)^{4,5}$
Cupro-nickels	1-2	1-2	3	0-1	0-1	1-2	(0)	$1^{4,5}$	$(0\text{-}2)^{4,5}$
Gunmetal, phosphor bronzes and tin bronzes	1-2	1-2	3	0-1	1	1-2	(0)	(0)	(0)
Lead	0-1	0-1	0-1	0	0-1	0-1	0	-	0
Stainless steel (Austenitic; approx 18% Cr)	1	-	2-3	0-1	0-1	0-1	....	....	....
Steel (carbon & low alloy)	....	....	....	0-1	1	1-2	0^{4}	0^{4}	$0\text{-}1^{4}$
Zinc & its alloys	0	0	0	....	....	....	0^{4}	0	0

Key

0 Will suffer either no additional corrosion, or at the most only very slight additional corrosion, usually tolerable in service

1 Will suffer slight or moderate additional corrosion which may be tolerable in some circumstances

2 May suffer fairly severe additional corrosion and protective measures may be necessary.

3 May suffer severe additional corrosion and the contact should be avoided

Notes

Ratings in brackets are based on very limited evidence and hence are less certain than other values shown.
Dash indicates that no evidence is available and no general guidance can be given.
The table is in terms of *additional corrosion* and the symbol 0 should not be taken to imply that the metals in contact need no protection under all conditions of exposure.

[1] Under atmospheric conditions other factors, such as area wetted, presence of spray, degree of shelter and crevices, will assume importance. Additional corrosion will depend on the relative areas of the metals in contact. If the area of carbon steel or low alloy steel is equal to that of the metal with which it is in contact, then the effect will be as shown in the table. If the area of the carbon steel or low alloy steel is small in relation to the area of the other metal, then considerable extra corrosion may result. If the area of carbon steel or low alloy steel is large then the effect may not be so marked.
[2] Zinc is frequently used as a sacrificial coating on other metals. Additional corrosion will reduce the life of the coating.
[3] Crevice corrosion may occur.
[4] Corrosion products from the metal in contact may be deposited on the stainless steel, at best discolouring the stainless steel and at worst promoting corrosion of the stainless steel under the deposit.
[5] Effect will depend on relative areas over which water, e.g. rain or condensation, may be retained.

4. CORROSION INHIBITORS IN MORTAR

Calcium nitrite has been proposed as an alternative to calcium chloride as an accelerator for mortar [Berke 1990]. It also acts as an anodic inhibitor to corrosion in reinforced concrete. The nitrite acts to passivate the metal surface; nitrite ions react with ferrous ions to produce ferrous oxide. Tests with galvanized wire in type S mortars ponded in a 3% NaCl solution showed nitrite reduced the rate of corrosion [Berke 1990]. After 3 months the loss in coating was 12 to 23 % for mortar with nitrite compared to 37 to 44% with mortar without nitrite. The water/cement ratio of the mortar, 0.60 & 0.55, was much lower than occurs in mortars used for masonry cladding which have water/cement ratios greater than 1. A more porous mortar may not behave as well; in addition the long term effectiveness has not been established. Heidersbach [1985] stated attempts to market corrosion inhibitors for concrete have been unsuccessful in the past; new inhibitors should be carefully evaluated. Pfeffermann & Baty [1981] recommend adding a chromate inhibitor to the mortar (roughly 0.2% by weight of mortar).

5. SHORT AND LONG TERM TESTS OF STEEL IN MASONRY

5.1 Britain

Southcombe et al [1986] tested plain, galvanized (460 g/m^2), resin coated and bitumen coated (plain & galvanized) bed joint reinforcement in clay brick panels exposed on a site close to a marine estuary. The mortar was a 1:4½ cement:sand and a 1:½:4½ cement:resin:sand by volume mix. After two years twelve panels were broken open (further sets of twelve would be checked after 5 and 10 years). Corrosion was greatest in the wire closest to the weather face. It took place mainly on the underside of the reinforcement which had been laid dry onto the brick and then covered in mortar. Corrosion in order of severity: plain steel, resin coated steel, bitumen coated steel & galvanized steel. The bitumen coated galvanized steel had no corrosion.

Foster et al [1975] gave results of tests on plain & grouted, clay brick panels exposed to marine and rural climates over a period of 2 and 5 years. Panels contained plain and galvanized bars (vertical and horizontal), and galvanized ladder reinforcement. The mortars used were 1:½:4½ and 1:¼:3 cement:lime:sand mixes by volume. After two years exposure, plain bars had severe corrosion while galvanized bars behaved better with little if any corrosion of the steel although there was zinc loss (worst in marine climates). The galvanized ladder reinforcement 'affords protection' but in one instance there was heavy pitting and stripping of the zinc from the outer wire. The thickness of the zinc coatings is not given. Dipping plain bars in a sodium nitrite/sodium benzoate solution did not increase corrosion resistance.

5.2 Belgium

Pfeffermann & Baty [1981] carried out accelerated corrosion tests on galvanized wire truss ties (min. 70 g/m^2) in the bed joints of small masonry walls (1.25 m x 1.25 m). Mortar composed of 1 part cement to 4 parts sand by volume (in one test series 2% $CaCl_2$ was added to the mortar). Solid and cavity wall specimens were tested using clay brick, clay block, hollow concrete block and solid concrete block. One side of the walls was exposed to normal laboratory conditions (20 °C & 60% RH) and on the other side to extreme conditions (40 °C & 100% RH).

After eight months the average zinc coat left on the ties was measured at locations of least and most corrosion. Of the cavity walls, the clay brick cavity wall with the mortar containing $CaCl_2$ fared worst (50% of surface area with severe corrosion). Residual zinc was 51 and 24 g/m^2, and at several locations the zinc cover was penetrated. No corrosion on the part of the tie crossing the cavity. For comparison the residual zinc in the same wall without $CaCl_2$ was 83 and 32 g/m^2 (80% of surface corroded on humid side, 35% on drier side). The concrete block cavity wall had least corrosion (81 and 60 g/m^2 left). The humid side had corrosion over 13% of the surface area while the drier side had no corrosion. Diagonals across the cavity were corroded at their intersection with the masonry.

Long-term, outdoor exposure tests in an industrial atmosphere were also carried out [Pfeffermann 1987, 1991, 1992]. Small walls (1.2 m long x 1.4 & 1.5 m high; solid and cavity) were built using:
- clay brick (290*l* x 140*h* x 190*t* mm) with a 1:4 cement:sand by volume mortar
- concrete block (390x190x190 mm) with a 1:3 cement:sand mortar
- expanded clay block (390x140x190 mm) with a 1:0.44:4.9 cement:lime:sand mortar
- lightweight concrete block (500x240x200 mm) with a resin based mortar using thin, 3 mm joints.

Different types of corrosion resistant wire truss reinforcement were tested:
- hot-dip galvanized steel (min 60 and 275 g/m^2 zinc)
- galvalum coated steel (55%Al, 40%Zn, 5%Si)
- epoxy coated galvanized steel (min. 80 U epoxy on 60 g/m^2 zinc)
- stainless steel (type 304)

Demolition and inspection of the reinforcement took place at 1, 2, 4, 8 and 10 year intervals. The epoxy coated galvanized steel and the stainless steel reinforcement had no corrosion. Loss of weight occurred with the galvanized and galvalum reinforcement, with the least in the concrete block walls. There was uniform surface corrosion of the reinforcement in the concrete block walls in contrast to the clay brick walls where local more severe corrosion also occurred. The reinforcement in the thin bed joints was so well protected by the special mortar that almost no corrosion was noticed after 10 years of exposure.

5.3 Germany

Kirtschig & Metje [1982] conducted laboratory tests to determine the long term water repellent qualities of insulation which completely fills the cavity in masonry cavity walls, and the effect of insulation on corrosion of galvanized and stainless steel ties. The insulation types tested included urea-formaldehyde (UF) foam, perlite granules, foam glass and plastic boards, and mineral fibre batts. Wall ties were tested by inserting them in insulation kept at 20 °C and 95% relative humidity, and by building them into wall panels which were then subjected to a water spray. The galvanized ties "showed symptoms of corrosion with certain insulating materials". Further long-term outdoor exposure tests were carried out using small masonry walls facing west [Kirtschig & Metje 1988]. After 6 years, the stainless steel ties showed no damage. The galvanized ties behaved well in a wall with no insulation, and in walls with foam glass (and plastic?) boards. There was corrosion in all walls with UF foam insulation over the whole area of the wall. The thickness of the zinc coating on the ties, and the severity of the corrosion were not given. The author states, that although no corrosion of the galvanized ties was observed in walls with no insulation, unpublished results of investigations in actual buildings do show corrosion.

Kropp & Hilsdorf [1979] tested brick couplets to check the rate of carbonation of mortar in between bricks. Bricks of porosity 6 to 36% were used together with three cement:lime:sand mortar mixes 1:0:4, 1:0.2:4 & 1:0:5 (water/cement ratios 1.1 to 1.4). Mortar joint thickness varied from 10 to 30 mm. After 5 months storage in air at 60% RH (0.03% CO_2) the maximum depth of carbonation was 11 mm (over a joint width of 115 mm). The more porous bricks also showed carbonation extending to a greater depth along the brick mortar interface. After a further two months in an atmosphere with a CO_2 content of 2% all the mortar joints were fully carbonated except for a small region at the centre of the joint where low porosity bricks were used.

Corrosion of steel bars inserted in similar couplets was also investigated. The specimens were stored at 60% RH in air for 5 months, in air with 2% CO_2 for a further 2 months, then a further 6 months in air at 90% RH. All plain bars had uniform corrosion with weight losses ranging from 26 to 128 g/m^2. Galvanized bars showed no corrosion except where they had been bent causing cracking of the zinc cover.

Further tests on mortar samples showed there was adequate corrosion protection for plain steel if mortars and dense bricks of low CO_2 diffusivity were used in combination with a minimum mortar cover of 40 mm [Kropp & Hilsdorf 1982]. Mortars complying with this criteria had water/cement ratios below 0.75 (eg 1:2½ to 1:3 cement:sand mixes). This conclusion is not valid for severe environments (e.g. where chlorides and sulphates are present). In such cases, and where higher CO_2 diffusivity materials were used, the steel would need added protection.

5.4 USA

Fishburn [1943] carried out indoor and outdoor weathering tests for 6 months on ties made of plain steel, and plain steel coated with mortar, cement paste, coal-tar paint, copper and zinc. No details on thickness of copper and zinc coatings. Ties set in small brick specimens, using type M mortar, simulating a section of a cavity wall (50 mm cavity). Indoor specimens were kept at 35-38 °C and covered in damp burlap. The outdoor specimens were exposed to the weather in Washington D.C. from June 1942. Corrosion observed on all except the copper and zinc coated ties. The coal-tar painted ties were corroded adjacent to brick interface probably because the coating had been knicked. Zinc coated ties did show some white discoloration indicating corrosion of the zinc, and in the indoor specimens barely perceptible spots of corrosion on one tie at a cut edge.

Appendix B   Case studies in Canada & USA

1. CANADA

Dovetail ties (galvanized steel unless otherwise stated)

- Apartment building; 8 years old; Montreal, Que. Clay brick cladding. Tie thickness = 1.40 mm; Corrosion in portion in mortar joint. Thickness of zinc coating 57-140 g/m^2; the rate of corrosion of zinc, assuming 140 g/m^2 original thickness, is 18 $g/m^2/yr$. CS9003
- Hospital, Kingston, Ont. Age ≤ 11 years. Minor surface corrosion only. Ties observed on west elevation by main entrance. WH4
- Courthouse, Barrie, Ont. Age ≤ 11 years. Surface corrosion at east wall, in portion within mortar joint. WH6
- Prison, Hamilton, Ont. Age ≤ 11 years. Severe corrosion of ties in portion which had been in the mortar joint (from free standing wall?). WH8

Nails (not protected by a zinc coating)

- Apartment building, Montreal, Que. 78 years old; Nail diameter = 5 mm. Worst corrosion in portion of nail in mortar joint (head of nail corroded away); hardly any in portion in the wood. Urea formaldehyde foam insulation (UFFI) in cavity space. Portion of brick cladding had collapsed. CS8205
- Bungalow, near Montreal, Que. 18 years old; Nail diameter = 4.5 & 4.9 mm; Of 160 nails saved by owner, about 90 had more than surface rust. Little or no corrosion of portion which had been in the wood. Corrosion on portion which had been within mortar joint, but worst seemed to be portion in cavity (part which had been bent?). Corrosion worst on sides of house (front and back had a bigger roof overhang). Brickwork removed because of UFFI. CS8207
- Two storey house, Laval, Que. 37 years old; Nail diameter = 4.8 to 5.1 mm; Nails very rusty; brickwork taken off to remove UFFI. CS8216
- Two storey house, Ottawa, Ont. Age? Nail diameter = 5.8 mm; many nails corroded along portion which had been in the mortar joint. Only could see N and E sides. E side worse. Renovation. FN8304
- Two storey house, Ottawa, Ont. Age > 50 years?. Square nails. Of 53 nails collected 17 had more than just surface corrosion (6 badly corroded). Areas beneath windows especially susceptible; corrosion mainly in portion in mortar joint; house being reclad with vinyl siding. FN8302

Strip ties (galvanized steel unless otherwise stated)

- Church, Montreal, Que. 10 years old; tie thickness = 0.5 mm; many ties badly corroded, one right through (mainly section of the tie spanning the cavity; extensive mortar droppings on the ties). Cladding replaced because of frost damage to brick. CS7801
- 1 to 2 storey house clad with clay brick, Ottawa, Ont. 30 years old; tie thickness = 0.43-0.70 mm; section of wall removed for an extension; most of this had been protected by a

porch except far right. Wall facing north-west. Ties in good condition except for some ungalvanized ties which had surface rust. CS8213

- Hotel, Saint John, NB; 3 storeys; age unknown but modern construction; tie thickness = 0.5 mm; photo of one tie showing corrosion on portion in mortar joint. Portion of cladding collapsed during high winds. Inadequate ties and connections. CS8214
- Residential apartments, Ottawa, Ont. 2 1/2 storeys; age >30 years. Tie thickness = 0.50-0.80 mm. Of 53 ties collected, 13 had no corrosion, 19 touches and 21 obvious. Of the 21, 15 showed full surface corrosion on the area in contact with the mortar but not the opposite face, while 6 had corrosion on both faces. Of the latter, 3 had corroded right through. Cladding removed because of demolition. CS8218
- Bungalow, Ottawa, Ont. Estimated age 30 years; tie thickness = 0.47-1.26 mm (varying thickness). Ties along bottom worst; front of house 50% ties with corrosion (south facing); part of west wall 30% corrosion. Cladding replaced because of UFFI. CS8303
- House, near Ottawa (Russell), Ont. 2 storey. Bottom clad with clay brick, top with vinyl siding. 8 years old; Tie thickness = 0.52 mm; thickness of zinc coating on one tie = 0 to 106 g/m^2 one side, 0 to 70 g/m^2 the other; estimated rate of zinc corrosion, assuming an original thickness of 106 g/m^2 is 13 g/m^2/year. South wall 98% corrosion, East 92% except at overhang 59%, North 58%, West under porch 0%. Exposed site, mortar joints recessed by 12 mm. Cladding replaced because of UFFI installed 7 years ago. CS8308
- House, Montreal, Que. Ties not galvanized. tie thickness = 1.1 mm. A photo received showing 2 corroded ties under a window. Cladding removed to take out UFFI. CS8309
- Two storey commercial building, Ottawa, Ont. tie thickness = 0.40 mm. All ties looked at (on east wall) had some corrosion mainly in the part attached to the brickwork; Demolition. CS8501
- Hospital, Edmonton, Alberta. 20 years old; tie thickness = 0.5 mm. Received sample of one tie in good condition. Shelf angle reported to be in good condition. FN8203
- 2 1/2 storey apt building, Ottawa, Ont. tie thickness = 0.47 mm. Ties generally in good condition except some attaching brickwork to end of blockwork side wall which looked badly corroded. Demolition. FN8409
- 2 storey office building, Ottawa, Ont. tie thickness = 0.54 mm. Sample of one tie with corrosion in portion which was in mortar joint. Section of brickwork came off because a snow plow caught the edge of it. FN8501
- School, Alberta. 58 years old. Ties reported to be in good condition. FN8503
- 4 storey, office building, Bathurst, NB. Concrete block cladding. Portion of west wall collapsed during a blizzard. Corrosion had not been observed on ties at the collapsed portion. FN8908
- Apartment building, 7 storeys, St John's, Nfld. 7 years old. Corrosion of ties on two openings south face; slight on north face. Sample tie: thickness = 0.64 mm; zinc coat 255 g/m^2. HK1
- Apartment building, 8 storeys, Montreal, Que. 9 years old. Corrosion at two of three inspection openings (ties not observed at third). Sample tie: thickness = 0.30 mm. Zinc coat 200 g/m^2. Chloride content of two mortar samples 1.10 & 0.58% by wt of cement. HK3
- Apartment building, 6 storeys, Montreal, Que. 4 years old. Minor corrosion observed at two of four inspection openings. Two sample ties: thickness = 0.91 & 1.09 mm. Zinc coat

220 & 362 g/m^2 respectively. Corrosion on the thinner tie. Chloride content of two mortar samples 0.05 & 0.14% by wt of cement. HK4

- Apartment building, 11 storeys, Calgary, Alberta. 8.5 years old. Corrosion of ties light to moderate (at three of five openings). Four tie samples: thickness = 0.33 to 0.37 mm. Zinc coat 220-269 g/m^2. Chloride content of two mortar samples 0.26 & 0.29% by wt of cement. HK7
- Apartment building, 18 storeys, Calgary, Alberta. 8.5 years old. No corrosion observed on ties but there was corrosion in steel stud backup at one of two inspection openings. No tie samples taken. Chloride content of two mortar samples 1.63 & 0.02% by wt of cement. HK8

Wire Ties (galvanized steel unless otherwise stated)

- Swimming pool, Nepean, Ont. 7 years old. Truss type tie. Concrete block cladding. Wire diameter = 3.6 mm. Thickness of zinc 0-177 g/m^2 with most area in range 0-35 g/m^2. Corrosion most on inner block wythe (condensation of moisture due to air exfiltration). Assuming an original coating thickness of 177 g/m^2, the rate of zinc corrosion is 25 $g/m^2/yr$. CS8101
- School, near Sudbury, Ont. 15 years old. Truss type tie. diameter = 3.8 mm. Tie portion in cavity observed by fibre optic probe. Some had surface corrosion especially at part next to brick cladding. CS8212
- Apartment building, Toronto, Ont. 7 years old. Tie diameter = 4.8 mm. Thickness of zinc coating 92 g/m^2. Estimated rate of zinc loss = 13 $g/m^2/yr$. Chloride content of two mortar samples 0.77 & 0.05% by wt of cement. HK5
- Apartment building. Toronto, Ont. 11 years old. Tie diameter = 4.8 mm. Thickness of zinc coat = 92 g/m^2. Estimated rate of zinc loss = 8 $g/m^2/yr$. Chloride content of two mortar samples 0.03 & 0.04% by wt of cement. HK6
- One storey equipment building, Sarnia, Ont. Age ≤ 11 years. Two wire truss type tie. Minor surface corrosion on south wall; more severe corrosion on east wall. WH1
- Police station, London, Ont. Age ≤ 11 years. Adjustable single wire pintle type tie. No significant corrosion at openings at north and west side. WH2
- Police station, Kanata, Ont. 3 years old. 2 wire truss type tie. Two openings on north elevation. Minor surface corrosion. WH3
- Hospital, Kingston, Ont. Age ≤ 11 years. 2 wire truss type tie. Opening on west elevation. Minor surface corrosion. WH4
- Testing lab, North Bay, Ont. Age ≤ 11 years. Box type tie. Openings on west elevation. Surface corrosion. WH5
- Courthouse, Barrie, Ont. Age ≤ 11 years. Box tie. Two openings on east elevations. Corrosion in portion within insulation? WH6
- Hospital, Toronto, Ont. Age ≤ 11 years. Adjustable wire tie. Openings south & north elevations. Little corrosion evident. WH7
- Jail, Hamilton, Ont. Age ≤ 11 years. Adjustable wire box tie. Corrosion of tie taken from delivery yard alley. No corrosion of tie from gymnasium yard. WH8
- Office building, Thunder Bay, Ont. Age ≤ 11 years. 3 wire truss type tie. Openings south & west elevations. Good condition. WH9

- Courthouse, Thunder Bay, Ont. Age ≤ 11 years. Two openings on north elevation. 3 wire truss and ladder type ties. Slight surface corrosion. WH10
- Office building, Dryden, Ont. Age ≤ 11 years. Truss tie and box tie. Slight corrosion of truss tie. WH11
- Workshop, New Liskeard, Ont. Age ≤ 11 years. Ladder tie. Openings on SW and NE elevations. Surface corrosion of portion of tie within mortar joint in NE wall below office window. WH12

Reference numbers at the end each case study identify the source. Ones starting with CS & FN are unpublished case studies collected by the Institute for Research in Construction, National Research Council of Canada. Ones starting with HK are derived from Keller et al [1992] and ones starting with WH are derived from Warnock-Hersey [1985]. Also see the Canadian case histories in section 6.1.1 of this report.

2. USA

Strip Ties

- Health care facility, Tinley Park, Illinois [Kumar & al 1986; Haver et al 1990]. Single storey residences. Brick cladding with steel stud backup. Leaks caused corrosion of corrugated strip ties and the outer face of steel studs. Veneer inspected when the building was 12 years old. The measured thickness of non-corroded locations on one stud and one wall tie indicated a zinc coating thickness of 140 to 177 g/m^2. Assuming an original thickness of 177 g/m^2, the corrosion rate is 15 $g/m^2/yr$. Only trace levels of chloride in the mortar (0.06% by weight of mortar).
- Corrosion of galvanized strip ties in an approx. 5 year old building in Lubbock, Texas [Keeling et al 1989]. It seems to have occurred in the part of the cavity which had standing water. Mortar had a pH of 6.5. Mortar covered locations had not corroded. In a 40 year old building in Lansing, Michigan corrosion of zinc coating on strip ties but not of steel. Mortar had a pH of 6.5. Conclusion that corrosion is prevented by the presence of mortar even if it has carbonated down to pH 6.5.
- Galvanized (strip) ties were observed in two buildings in Michigan (9 & 10 years old); in both corrosion was severe [Grimm 1985]. A photo of a tie in one of the buildings shows severe corrosion of the portion which had been in a mortar joint of the brick cladding.

General

- Concrete block wall on beach at Cayucos, California [Haver 1989; Haver et al 1990]. The wall was at least 7 years old (probably much older). Plain steel bars had been placed in mortar grouted cavities. The portions of the bars within the grout were not corroded, while portions exposed to the atmosphere were. The grout was partly carbonated (samples had a pH 8.5 to 9.5).
- Sarabond, a mortar additive which contains a vinyldine chloride polymer, may cause steel to rust [ENR 1979, 1983, 1986]. Over 150 buildings in the US have used this additive. Sarabond leaches out chloride ions which could lead to an increase in the corrosion rate of any steel components embedded in the mortar.

Shelf angles

- Corrosion of shelf angles caused spalling of the masonry in two 55 year old buildings [Parise 1982]. The shelf angles has no flashing over them. Expansion due to corrosion was 6 to 10 mm.
- Grimm [1985] lists the results of a survey of the condition of lintels and shelf angles in 16 buildings with some exterior indication of damage or moisture problems (in Cleveland, Ohio and Detroit, Michigan). Age of the buildings varied from 4 to 26 years. All lintels and shelf angles, except one which was assumed to have had no coating, had been coated with a paint, and flashings had been installed in most of them. Corrosion was rated as severe in 12 of the buildings. Six of the twelve were 10 years old or less.

Appendix C Current code requirements

1. CANADA

1.1 CSA Standard A370:1984 Connectors for Masonry

Background to the development of this standard is given by Hastings [1980].

Connectors intended for use in exterior walls, walls in moist environments, and walls that are exposed to weather or in contact with the ground shall be *corrosion resistant* or *noncorroding*. Connectors in walls or partitions not subjected to moisture may be unprotected steel. All elements of anchors for cut stone in contact with the stone shall be *noncorroding*. All other elements of cut stone shall be *corrosion resistant* or *noncorroding*.

Carbon steel connectors required to be *corrosion resistant* shall be galvanized to at least the following minimum coating thickness (coating per square metre of surface area on each face). Other coating materials may be used, provided they have equivalent corrosion resistance.

- Wire ties and continuous reinforcing (hot-dip galvanized to ASTM A153)	458 g/m^2 Class B
- Hardware and bolts	See ASTM A153
- Strip, plate, bars and rolled sections (minimum thickness 3.18 mm) ASTM A123	610 g/m^2
- Sheet (0.76 mm to 3.18 mm thick) ASTM A123	305 to 610 g/m^2

ASTM standards A123 and A153 apply to items hot-dip galvanized after fabrication. Connectors shall not be knurled, welded, or bent after hot-dip galvanizing where these operations would damage the zinc coating or impair the corrosion resistance of the connector assembly.

Noncorroding materials for connectors shall be stainless steel, type 304, or other material of equivalent durability.

1.2 National Building Code

Part 4 Structural Design

Buildings covered by this section of the code are required to conform with CSA standard S304 Masonry Design for Buildings. The 1984 edition of this standard in turn refers to CSA standard A370 Connectors for Masonry.

Part 9 Housing and Small Buildings, Section 9.20 Above-Grade Masonry
The 1990 edition requires *corrosion resistant* ties with the same level of protection as that given in CSA Standard A370. Earlier editions of the code also required ties to be *corrosion resistant* but gave no minimum requirements.

The minimum thickness of strip ties, for use in masonry veneers, is 0.76 mm in the 1990 edition (same as CSA A370). In earlier editions it was less: 0.41 mm since the 1977 edition and 0.33 mm in the 1975 edition. For cavity walls all the editions since 1975 have specified the equivalent of a 4.8 mm diameter Z wire tie (same as CSA A370).

2. USA

The requirements for the Standard and Basic Building Codes are taken from a paper by Catani [1991].

2.1 Standard Building Code 1989 revision to 1988 edition

Section 1402.11.2.
Metal accessories (ties, anchors, joint reinforcement) for use in exterior wall construction shall be hot-dip galvanized after fabrication in accordance with ASTM A153 Class B (458 g/m^2).

2.2 Basic Building Code 1989 supplement to 1987 edition

Section 1401.10.1.
Metal accessories (ties, anchors, joint reinforcement) for use in exterior wall construction shall be hot-dip galvanized after fabrication with a minimum coating of 1.50 oz/ft^2 (458 g/m^2) in accordance with ASTM A153.

2.3 Uniform Building Code 1988 edition

Chapter 24 Masonry, Section 2402(b)7B Metal ties and anchors
All such items not fully embedded in mortar or grout shall be coated with copper, cadmium, zinc or a metal having at least equivalent corrosion-resistant properties.
Chapter 24 Masonry, Section 2407(h)4F(ii) Reinforcement
Joint reinforcement used in exterior walls and considered in the determination of shear strength of the member shall be hot-dip galvanized in accordance with UBC standard No 24-15. This standard defines hot-dip galvanizing as a zinc coating with a minimum of 1.5 oz/ft^2 (458 g/m^2) of surface area; the coating to be applied after fabrication.
Chapter 30 Veneer, Section 3003 Materials
Anchors, supports and ties shall be noncombustible and corrosion resistant. When the terms *corrosion resistant* or *non-corrosive* are used in this chapter they shall mean having a corrosion resistance equal to or greater than a hot dipped galvanized coating of 1.5 oz/ft^2 (458 g/m^2) of surface area. When an element is required to be corrosion resistant or non-corrosive, all of the parts shall be corrosion resistant such as screws, nails, wire, dowels, bolts, nuts, washers, shims, anchors, ties and attachments.

2.4 ACI 530.1-88/ASCE 6-88 Specifications for Masonry Structures

Section 3.2.1.4 Coatings for corrosion protection

Unless otherwise required, protect joint reinforcement, ties, and anchors not meeting the requirements of Article 3.2.1.3 (specifying type 304 stainless steel) by galvanizing in conformance with the following:

- Wire ties or anchors in exterior walls completely embedded in mortar or grout	ASTM A641 Class 3 244 g/m^2 (0.80 oz/ft^2)
Revisions proposed in 1992 will increase it to 458 g/m^2.	
- Wire ties or anchors in exterior walls not completely embedded in mortar or grout	ASTM A153 Class B2 458 g/m^2 (1.5 oz/ft^2)
- Joint reinforcement in exterior walls or interior walls exposed to moist environments (e.g. swimming pools or food processing)	ASTM A153 Class B2 458 g/m^2 (1.5 oz/ft^2)
- Sheet metal ties or anchors exposed to the weather	ASTM A153 Class B2 458 g/m^2 (1.5 oz/ft^2)
- Sheet metal ties or anchors completely embedded in mortar or grout	ASTM A525 Class G60 180 g/m^2 (0.60 oz/ft^2)

3. EUROPE

3.1 EEC

The draft standard on ancillary components in masonry states the materials to be used shall be sufficiently durable to maintain strength & stiffness for an economic working life [CEN 1990]. This may be based on experience, exposure durability data, or an accepted accelerated durability test. Materials for which there is existing durability data are listed in Table 2. They are listed in order of durability under external unpolluted exposure conditions.

3.2 Denmark

Knuttson [1988] states wall ties are required to be austenitic stainless steel (18/8) or in special conditions bronze.

3.3 France

For self supporting masonry cladding in accordance with Document Technique Unifie (DTU) 55.2, the ties and anchors are required to be completely made from non-corroding material [CSTB 1984]. Examples given are brass, bronze (but not cast because of risk of cracks during casting), and austenitic stainless steel (type 304 & 316; the latter gives better resistance to crevice corrosion in marine and industrial atmospheres).

3.4 Germany

DIN 1053, Part 1 [1974] states ties must be austenitic stainless steel wire ties, type 1.4401, 1.4571 or 1.4580 in accordance with DIN 17440. Diameter ≥3 mm; if wall height >12 m or cavity width >70 mm then diameter ≥4 mm. Type 1.4401 is equivalent to type 316. Types 1.4571 and 1.4580 are similar but have small added quantities of titanium (Ti) and niobium (Nb) respectively.

Support angles to be stainless steel 1.4571 as specified in the Information Circular of the Institute for Building Technology, Berlin (1975) for fastening accessories for facade elements [Smeets 1977].

3.5 Netherlands

The Dutch building model code specifies galvanized wire ties, 4 to 6 mm diameter, for masonry cavity walls. Materials of equivalent corrosion resistance may also be used. Local regulations may be stricter. For example, Amsterdam requires copper, bronze or stainless steel. SBR [1981] recommends that galvanized ties be protected with two coats of epoxy coal tar.

3.6 Sweden

The Swedish standard specifies two types of material for ties: stainless steel (grade SIS 2343) and galvanized carbon steel (grade SIS 1300). The Swedish building code requires stainless steel ties for veneer exceeding a height of 6 m [Bergquist 1979]. Grade SIS 2343 is equivalent to type 316.

3.7 Switzerland

Swiss standard Norm 177 [1980] specifies non-corroding anchors (Clause 2.213.2).

3.8 United Kingdom

<u>BS 1243 Metal ties for cavity wall construction [1974]</u>

The minimum required zinc coatings for mild steel were increased to 940 g/m^2 in 1982. This also applies to steel joist hangers [BS6178 Part1 1982]. Alternative materials for ties are plastic-coated zinc-coated mild steel, austenitic stainless steel, copper, copper alloys, phosphor-bronze and aluminum bronze. Stricter requirements are in force in London which since 1972 has prohibited the use of galvanized ties in buildings exceeding three storeys in height [Moore 1981b].

<u>DD140 Wall ties, Part 2: Recommendations for design of wall ties [1987]</u>

This document recommends the materials given in BS 1243. It also recommends injection moulded polypropylene, but only for two storey, box form dwellings not higher than 10 m. The recommended materials have an estimated minimum service life of 60 years when embedded in the outer leaf of masonry. All parts of the tie and associated fixings should be made either of the same material or from materials compatible with each other, i.e. not be liable to any deleterious chemical or electrochemical interaction. Shot-firing nails will normally be incompatible with any of the specified body metals and should only be used where special coatings and grommets are provided to isolate the nail electrically from the tie. If protected in this way, the tie may be suitable for tying back to concrete or steel frames or slabs at the discretion of the designer.

BS 5628 Use of Masonry, Part 3. Materials and components, design and workmanship [1985]

This standard gives four different levels of corrosion resistance for metal components other than ties (levels A, B, C, D). The first two levels, A & B, are for interior use only. For metal components, other than ties and lintels, in the outer exposed wythe, only level D is allowed in buildings higher than 3 storeys. Level D is provided by copper, copper alloys and austenitic stainless steel. Where there is severe and very severe exposure to local wind-driven rain, level D should also be used in buildings less than 3 storeys. It also recommends this for wall ties. Metal ties used in chimneys should be stainless steel. Level C corrosion resistance is provided by mild steel with a minimum zinc coat of 940 g/m^2. Lintels are required to conform to BS 5977:Part 2.

BS 5628 Use of Masonry, Part 2. Structural use of reinforced and prestressed masonry [1985]

This standard gives durability requirements for reinforcement in masonry located in four exposure situations ranging from internal masonry to masonry exposed to marine spray. The degree of protection varies according to the location of the steel in the wall. Better protection is required in (i) mortar joints or within clay units, (ii) areas of the building subject to greater exposure such as chimneys, parapets and sills, and (iii) low density units. A lower degree is allowed for steel in grouted cavities provided minimum cover is provided. The type of steel allowed depends on location and exposure situation. Four types are given: carbon steel, carbon steel with a zinc coating of 940 g/m^2, carbon steel coated with at least 1 mm stainless steel and austenitic stainless steel.

4. OTHER COUNTRIES

4.1 Australia

AS 3700-1988 Masonry in Buildings

This standard has three different levels of corrosion resistance (E1, E2 & E3), and five environmental zones: temperate, tropical, arid, all areas within 1 km of the coast, and all areas within 3 km of industries which discharge atmospheric pollutants. The latter two zones require the highest level of corrosion resistance (E3). Materials conforming to E3 are galvanized steel (sheet steel 600 g/m^2), cadmium plated steel and type 316 austenitic stainless steel. Temperate and tropical zones require E2, and arid zones E1.

TABLE 2 Materials for connectors and supports in masonry
[CEN 1990]

MATERIAL	SPECIFICATIONS FOR BODY MATERIAL	Minimum coating specifications Weight 1 side * g/m^2	Weight 2 sides * g/m^2	Thickness per side ** um	DURABILITY REFERENCE NO. ***
austenitic stainless steel	EN88-71 X3CrNiMo17 13 3	-	-	-	1
(molybdenum chrome nickel alloys)	EN88-71 X6CrNiMo17 13 3	-	-	-	1
	EN88-71 X6CrNiMoTi17 13 3	-	-	-	1
Plastic used for the body of ties	Polypropylene meets specn.of Table 1c.	-	-	-	2
18/8 austenitic stainless steel	EN88-71 X3CrNi18 10	-	-	-	3
(chrome nickel alloys)	EN88-71 X6CrNi18 10	-	-	-	3
	EN88-71 X10CrNi18 9	-	-	-	3
Phosphor bronze	ISO CuSn4, CuSn5, CuSn7	-	-		4
Aluminium bronze	ISO CuAl7	-	-		4
copper	ISO Cu-ETP, Cu-FRTP, Cu-OF ISO Cu-DHP	-	-		5
Zinc coated steel wire	ISO7989 zinc coated steel()	940	-	132	6
Zinc coated steel component	Steel() - all surfaces coated	940	-	132	7
Zinc coated steel component	Steel() - all surfaces coated	710	-	100	8
Zinc coated steel component	Steel() - all surfaces coated	460	-	65	9
Zinc/organic coated steel plate	Fe E()G,Z600,N,A EN147-79				10
	zinc pre-coating	-	600	36	
With organic coating over all	either organic coating type 1	-	-	25	
surfaces of finished component	or organic coating types 2	****	-	****	
Zinc coated steel wire	ISO7989 zinc coated steel()	260	-	36	11
Zinc/organic coated steel plate	Fe E()G,Z600,N,A EN147-79				12
	zinc pre-coating	-	600	36	
All cut edges organic coated	organic coating type 1	-	-	25	
zinc pre-coated steel plate	Steel()	-	920	54	13
Zinc/organic coated steel plate	Fe E()G,Z275,N,A EN147-79				14
With organic coating over all	zinc pre-coating	-	275	16	
surfaces of finished component	either organic coating type 1	-	-	25	
	or organic coating type 2	**	-	**	
Zinc/organic coated steel wire	ISO7989 zinc coated steel()				15
With organic coating over all	zinc pre-coating	75	-	10	
surfaces of finished component	organic coating type 3	-	-	100	
Zinc coated steel wire	ISO7989 zinc coated steel()	120	-	16	16
Zinc coated steel wire	ISO7989 zinc coated steel()	75	-	10	17
zinc pre-coated steel plate	Steel()	-	275	16	18
Uncoated steel with concrete cover	Refer to subsidiary table 1d	-	-	-	19

* Coating weight is either given for one side for wire and post fabrication coatings or as two sides for pre-galvanised sheet products. The mean one side figure will be 50% of the two side figure.
** Coating thickness refers to the minimum thickness of metallic protective coating on any uncut surface of a product or any surface of a postfabrication galvanised product and the minimum thickness of organic coatings on any specified surface of a product.
*** The durability reference number is intended to be in approximate order of durability under external unpolluted exposure conditions. For some conditions, particularly industrial or marine exposure, the order may change profoundly.
() (Empty brackets) indicate that the manufacturer may choose an apropriate grade.
**** Organic coating type 2 is specified by performance testing and not by thickness.

Appendix D Wall tie manufacturers in Canada & USA

The following lists are not complete.

1. CANADA

Acrow-Richmond
110 Belfield Road
Rexdale, Ontario M9W 1G1
tel (416) 245 4720 fax (416) 242 2727

Bailey Metal Products Ltd
151 Bentworth Avenue
Toronto, Ontario M6A 1P6
tel (416) 781 9371 fax (416) 781 9170
Sells an adjustable tie for use with brick veneer with steel stud backup.

Blok-Lok Ltd
30 Millwick Drive
Weston, Ontario M9L 1Y3
tel (416) 749 1010 fax (416) 749 1017

Dur-O-Wal Ltd
1750 Bonhill Road
Mississauga, Ontario L5T 1C8
tel (416) 670 4470 fax (416) 670 4474

Fero Holdings Ltd
16224 - 116 Avenue
Edmonton, Alberta T5M 3V4
tel (403) 455 5098 fax (403) 452 5969

Majestic Wire & Metal Products Ltd
PO Box 75
Ste-Marguerite-du-Lac-Masson, Quebec J0T 1L0
tel (514) 228 2531

Other manufacturers:
Bauer Metal Products Ltd, Cambridge, Ontario
Cochrane Tool & Design Ltd, Markham, Ontario
Debro, Dorval, Quebec
Guy Guenette Ltd, Montreal, Quebec
Irving Industries Ltd, Calgary, Alberta
Preston Metal & Roofing Products Ltd, Ontario
Renown Specialities Co, Concord, Ontario
Stelco-Constant Airflow, Montreal, Quebec
Wolco Metal Products Ltd, Queensville, Ontario

2. USA

AA Wire Products Company
6100 South New England Avenue
Chicago, Illinois 60638
tel (312) 586 6700 fax (312) 586 6710

Dur-O-Wal Incorporated
3115A North Wilke Road
Arlington Heights, IL 60004
tel (708) 577 6400 fax (708) 577 6418
Other locations in Alabama, Arizona, Colorado, Illinois, Indiana, Maryland, Texas.

Halfen Anchoring Systems
PO Box 410203
Charlotte, North Carolina 28241-0203
tel (704) 588 2055 fax (704) 588 2144
Manufactures shelf angle supports, and supports & ties for stone cladding.

Heckmann Building Products Inc
4015 West Carroll Ave
Chicago, Illinois 60624
tel (312) 826 8564 fax (312) 826 4919

Hohmann & Barnard Inc
30 Rasons Court
PO Box 5270
Happauge, NY 11788
tel (516) 234 0600 fax (516) 234 0683

Masonry Reinforcing Corporation of America
PO Box 240988
400 Roundtree Road
Charlotte, North Carolina 28224
tel (704) 525 5554 fax (704) 525 3761

National Wire Products Inc
8203 Fischer Road
Baltimore, Maryland 21222
tel (301) 477 1700 fax (301) 388 0770

Appendix E Bibliography

This bibliography is divided into general references, and codes & standards.

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