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Durability of light steel framing in residential applications

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This paper presents a summary and analysis of research findings on the durability of galvanised cold-formed steel sections used in housing in order to deduce their design life. These cold-formed sections are produced from pre-galvanised strip steel. It reviews reports and publications from research projects carried out by Corus and the Steel Construction Institute on zinc-coated, cold-formed steel products. New data have also been gathered from measurements on houses and similar buildings that have used galvanised steel components. The data also extend to over-cladding applications in building renovation. The performance of galvanised (zinc-coated) steel components within warm-frame applications is very good. The research leading to this paper shows that the predicted design life of the standard G275 coating, based on the measured loss of zinc from the strip steel, is over 200 years, provided that the building envelope is well insulated and properly maintained. The evidence for this conclusion is based on measurement of zinc loss on light steel frames in various applications and locations. A formula for the loss of zinc over time in areas subject to low condensation risk is presented.

1. INTRODUCTION

Galvanised steel has been used successfully for over 30 years in light steel framing and other components in housing and low-rise residential buildings (Lawson *et al*., 2003a). In the UK, the current market for light steel framing is increasing rapidly, particularly for residential buildings of three to six storeys in height. Modern light steel framing systems use sections that are cold formed from rolls of pre-galvanised (zinc-coated) strip steel. The steel is delivered to BS EN 10326 (BSI, 2004), which has recently replaced BS EN 10147 (BSI, 1992). The zinc coating is able to protect the steel much more reliably than paint coatings because it chemically passivates the steel and is resistant to local damage.

Historically, many steel housing systems were built in the UK between 1920 and 1970 (Harrison, 1987) but the house building systems of the pre- and postwar period used painted, hot-rolled steel components, and were not insulated to modern standards. The performance of the earlier steel houses, which are now 30 to 70 years old, has generally been good despite some poor construction details employed when questions of building physics were less well understood.

Galvanised steel provides a much higher level of protection and, in modern building construction, the risk of moisture within the insulated building envelope is largely eliminated.

Maximum thermal transmission levels (U-values) of 0·15 to 0·25 W/m^2 °C are now required for all elements of the building envelope to meet the Building Regulations Part L (DCLG, 2006) and the UK Government's Code for Sustainable Homes (DCLG, 2007). The light steel components within a warm frame are subject to only minor temperature and humidity fluctuations in comparison with the external conditions, which leads to relatively benign conditions from a durability point of view.

The durability of light steel and its coatings in a range of climatic and exposure conditions is the subject of continuing research both in the UK (Popo-Ola *et al*., 2000) and internationally (ECSC, 2000). Further data are being collected through exposure trials and monitoring of buildings in the UK, Finland, Portugal, Japan (Honda and Nomura, 1999), Australia and the USA, and the present findings support the conclusions of this report.

1.1. Light steel framing in housing

Cold-formed sections are the primary components of light steel framing, the sections being produced from pre-galvanised steel strip by processes known as cold rolling. Smaller components and other sections of varying shape can be produced by press braking.

The advantages of light steel framing include speed of on-site construction, achieved by prefabrication of the wall panels and their easy assembly on site. This creates a dry working environment for following trades, allowing the brickwork cladding and roof tiling to follow off the critical path.

Light steel frames are constructed using light steel components, typically of C or Z section of 70 to 200 mm depth and 1·2 to 2·4 mm thickness. The sections are joined using bolting, self-drilling, self-tapping screws, riveting, clinching, welding (in the factory), or new methods such as press joining. Any factory-produced welds are painted over with zinc-rich paint to maintain the required level of protection.

There are three basic residential steel framing assembly methods

(*a*) stick built construction (site assembled)
(*b*) panelised systems (factory made and site assembled)
(*c*) mixed light steel panels (infill walls) and structural frames in steel or concrete.

Most light steel framing systems in residential construction use wall panel construction, as illustrated in Figure 1. This example shows the use of bonded expanded polystyrene to create a monolithic panel to which external insulation and cladding are attached. C-shaped sections are commonly used for the studs in walls and frames. Normally, a 'warm frame' is created in which the majority of insulation is placed externally to the frame, as illustrated in Figure 2. C or Z sections are widely used as floor joists, and composite decking is used in composite ground floor and suspended floors (see Case Study 4 in Section 3.4.).

Where U-values less than 0·25 W/m^2 ℃ are required, insulation may be placed between the wall studs, and it is necessary to ensure that there is sufficient insulation outside the studs to minimise cold bridging and therefore to avoid condensation on the steel studs.

Figure 1. Light steel framing in housing development, using bonded expanded polystyrene between the C sections (Fusion Building Systems)

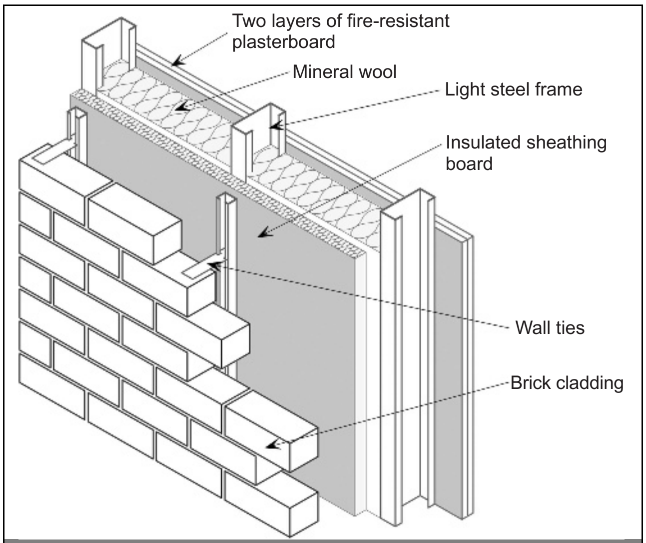

Figure 2. Warm frame construction showing external and inter-stud insulation

1.2. Roofs in steel-framed houses

Purpose-made light steel trusses and purlins have been widely used for many years, although less so in housing. Typically, trusses comprise cold-formed sections as the chords of the truss, with bent bars or C sections forming the bracing elements. They can be designed for spans of 8 to 15 m and can also be used for flat or slightly pitched roofs. Purlins span between cross-walls or structural frames and are the normal form of construction in large enclosures, warehouses and supermarkets.

There are two generic forms of roof design

(*a*) a 'cold' roof in which the roof acts only as a weather-tight barrier and insulation is placed at ceiling level to the floor beneath
(*b*) a 'warm' roof, in which the roof is insulated, so that the space under the roof is relatively warm.

In modern construction, 'warm' roofs are preferred, as the loft may be employed for habitable use during the building's life. Modern roofs are insulated to achieve a U-value of typically 0·16 W/m^2 ℃.

1.3. Floors

Steel floor joists of C or Z section or fabricated lattice joists may be used in place of timber joists. The joists may be built into walls or supported on continuous Z section hangers placed over the load-bearing walls. Internal floors are in the warm internal environment, but there may be cases where this is not the case – for example, joists built into solid masonry walls. In these applications, care should be taken to ensure adequate ventilation where the steel can be exposed to moisture over an extended period. A thicker galvanising layer, or some additional form of protection, may be required.

1.4. Ground floors

Suspended composite ground floors have been used successfully in buildings with a sufficient air gap so that risk of exposure to moisture is small. This form of construction uses galvanised steel decking acting together with an in situ concrete slab to achieve spans up to 4·5 m. The degree of exposure is mild, as long as good ventilation is provided in the void beneath the floor and an over-site membrane is used so that contact with soil is avoided. The required level of insulation is provided by rigid insulation boards placed on top of or suspended below the decking.

1.5. Infill walls in primary frames

Non-load-bearing walls in steel or concrete frames have become a common form of construction in recent years due to their speed on installation, low weight and zero waste on site. A typical form of construction is shown in Figure 3. Infill walls are generally placed between the slab and beam on the floor above. Insulation is placed externally and lightweight cladding may be attached through the insulation. Brickwork is generally ground supported or supported on stainless steel angles attached to the perimeter steelwork.

Figure 3. Light steel infill walls used in a multi-storey residential building

1.6. Modular or hybrid construction

Modular construction comprises light steel floors, walls and ceilings and often additional corner posts, which are constructed in factory-controlled conditions often with additional sheathing boards or protective coverings. The size of the modules is limited by transportation, and their maximum size is typically 4·2 m wide × 12 m long. There are three generic forms of modular construction which are defined in Lawson *et al.* (2003b)

(*a*) four-sided modules with load-bearing walls, as illustrated in Figure 4
(*b*) open-sided modules with corner posts and edge beams
(*c*) non-load-bearing modules with a separate support structure.

Many 'hybrid' forms of modular construction exist, such as modules and panels, or modules and structural frames, which permit use of more open plan space or higher-rise buildings.

2. GALVANISING AS CORROSION PROTECTION FOR STEEL

In external environments, the surface of bare carbon steel is unstable, reacting with air and airborne pollutants to form the complex series of oxides generically known as rust. In dry, warm environments this process does not occur and no protection is required. For example, most hot-rolled steelwork within multi-storey buildings is unprotected because of the low risk of corrosion, as evidenced by over 70 years of excellent performance.

Figure 4. Example of four-sided load-bearing module (by Terrapin)

In exposed environments, some form of protection against corrosion is required, and the main forms of protection are

(*a*) encapsulation, in which a coherent barrier is used to exclude corrosive agencies from the surface
(*b*) sacrificial, in which another metal, which corrodes preferentially to steel, is used in proximity to the surface.

The use of metallic zinc (in galvanising, sprayed metal coatings, plating, sherardising, zinc-rich paints, and cathodic protection) as corrosion protection may use one or both of these mechanisms. Hot-dip galvanising provides both forms of protection and is the most common form of protection to thin cold-formed steel sections.

2.1. The hot-dip galvanising process

Hot-dip galvanising involves dipping steel in almost pure molten zinc. The zinc and steel react to form a series of zinc–iron alloy layers bonded metallurgically to the steel. When the steel is lifted from the bath, molten zinc on the surface of the bonded alloy coating solidifies and becomes part of the coating itself.

Because of the casual use of the term galvanising within the building industry, it is not always appreciated that immersion of steel in molten zinc can create various products. Differing steels, different zinc alloys and variations in the process may be used to alter the character of the final coating.

Continuous galvanising onto steel coil tends to produce only a very thin zinc–iron alloy layer with a (relatively) thick pure zinc top layer, because of the speed at which the steel coil passes through the bath. Continuous zinc coating of the steel coil is controlled carefully to produce a range of coating weights for different specifications of corrosion protection.

In the UK, the normal standard has been 275 g/m^2 (i.e. a surface thickness of about 20 μm). This grade was formerly used in BS EN 10147 (BSI, 1992) and has now been incorporated into BS EN 10326 (BSI, 2004). The technology of coating has improved, and there are many sources of continuous zinc-coated steel strip.

In the field of continuous metal coatings, various zinc–aluminium alloys are available as an alternative to pure zinc coatings. One very well-known product is the original Bethlehem Steel formulation 55% aluminium–45% zinc, which is available as coated steel coil from several licensees. *Galfan* is the trade name for a coating with 95% zinc and 5% aluminium.

Post-galvanising treatments may be offered to protect the zinc coating during storage. These treatments include chromate passivation to suppress the development of white zinc corrosion products that can form in continuously wet conditions, such as when water is trapped between the sheets. A thin film of mineral oil is applied to the surface for the same purpose. This oil must be removed if the product is to receive further treatment such as painting or welding.

2.2. Performance of galvanised coatings

Zinc coatings provide a barrier that prevents oxygen, moisture and other atmospheric pollutants from reaching the steel. Furthermore, zinc is a reactive metal and, on exposure to the atmosphere, a complex mixture of zinc compounds forms readily on a galvanised surface. As many of the products formed are partially soluble in water, the zinc is consumed over a period of time in any damp location. The loss of zinc is accelerated in situations where the galvanised surface is exposed to the atmosphere and to water running over the surface.

Galvanising has the advantage that, when the encapsulation is breached, for example at cut edges or drilled holes, or when the zinc has been eroded away locally, significant corrosion of the steel substrate will not necessarily occur. This is because zinc in close proximity to the exposed steel will still corrode preferentially, acting as a consumable anode in an electrochemical cell (i.e. it protects the steel cathodically). The use of a sacrificial metallic layer is known as galvanic action. Only when the distance between the zinc and steel is too great will the steel begin to corrode.

The galvanic series of metals is shown in Table 1. The more anodic (electronegative) metal will corrode preferentially to the more cathodic metal (in the presence of water and oxygen). Therefore common coating metals such as zinc and aluminium will protect the steel substrate against corrosion. Conversely, stainless steel or more electropositive metals may lead to preferential corrosion of mild steel, if directly connected and subject to prolonged moisture.

In more benign exposures, an initial layer of zinc hydroxide often changes to a hard, stable layer of zinc carbonate by the absorption of carbon dioxide, and this provides a further barrier layer to any further loss of zinc from beneath. The loss of zinc, and hence the life of zinc-coated steels, can be calculated with reasonable accuracy for specific environments from research data. This loss of zinc with time is part of its protective mechanism, and should not be considered as a failure of the protective system.

2.3. Loss of thickness of zinc with time

The expected product lifetime of the zinc coating in external atmospheres has almost doubled over the last 20 years in the UK, which is a consequence of improved air quality, as in most European countries. This has enabled hot-dip galvanised coatings to protect steel for longer periods, and newly manufactured components are given a much longer life expectancy than would have been predicted 20 years ago, and old coatings are expected to exceed the original predicted life expectancy.

Anodic:	Magnesium	(Electronegative)
	Zinc	
	Aluminium	
	Cadmium	
	Iron or steel	
	Stainless steels	
	Lead	
	Tin	
Cathodic:	Copper	(Electropositive)

Table 1. Galvanic series of metals

The effective life of galvanised coatings is inversely proportional to the levels of airborne sulphur dioxide; their life expectancy has increased as the pollution has decreased. Given that hot-dip galvanising is unaffected by ultraviolet (UV) light, it is also able to outperform other coating systems in countries where UV levels are high. In a mathematical model designed to investigate the relationship between sulphur dioxide levels and the reduction in thickness of zinc, lowering the sulphur dioxide concentration in the air by 1 mg/m^3 led to a reduction in loss of coating thickness of exposed zinc of about 0·2 g $zinc/m^2$, or 0·03 mm, per year (John, 1991).

The approximate performance of zinc coatings in different environments is shown in Table 2. The lifetime of zinc coatings has improved, and recent work suggests that these figures are very conservative.

The Galvanizer's Association in the UK produces a zinc corrosion 'map' which indicates the expected annual loss of zinc in various geographical locations. The rate of zinc loss is typically $0{\cdot}5$ to $1{\cdot}5 \times 10^{-3}$ mm depending on location, the higher rates applying to industrial areas (Table 2).

The zinc-galvanised coating attains its anti-corrosion characteristic because a protective layer forms at its surface. This protective layer, or patina (see Figure 5), consists of a mixture of zinc compounds including zinc carbonate, zinc oxide and zinc hydroxide. Environmental factors dictate which of these compounds are formed.

In dry air, a film of zinc oxide is initially formed by the influence of oxygen in the atmosphere, but this is soon converted to zinc hydroxide, zinc carbonate and other zinc compounds by water, carbon dioxide and chemical impurities present in the atmosphere. The patina of zinc carbonate, when fully formed across the entire surface, has excellent anti-corrosion qualities that are long-lasting because rainwater cannot easily dissolve the zinc compound. However, if sulphur dioxide is present in the atmosphere when the patina is forming, zinc sulfate will form along with the zinc carbonate. The zinc sulfate is more soluble and thus significantly more susceptible to the effects of rainwater. Rainwater gradually reduces the coating thickness and its protective capabilities.

Falling levels of sulphur dioxide have reduced the rate of build-up of zinc sulfates in the protective patina. The consequent improved resistance to corrosion leads to a marked increase in the lifetime of galvanised coatings. Further reductions in sulphur dioxide levels are anticipated over the next decade, with a commensurate increase in life expectancy for galvanised coatings.

2.4. White rust on galvanised steel sections

White rust is a corrosion product of zinc formed from hydrated zinc carbonate/zinc hydroxide under specific conditions of exposure. White rust cannot be seen until the steel is dry, when it appears as a white film. White rust may occur due to ingress of water between the adjacent surfaces in a stack of galvanised steel sheets.

White rust does not usually indicate a serious degradation of the zinc coating or that the product life has reduced, but removal of white rust may accelerate the loss of zinc. A chromated layer is

Environment			Corrosivity of environment	Average reduction in coating thickness: μm/year
C1	Interior:	Dry	Very low	0·1
C2	Interior:	Occasional condensation	Low	0·1–0·7
	Exterior:	Inland and rural		
C3	Interior:	High humidity, some air pollution	Medium	0·7–2·0
	Exterior:	Industrial and urban inland or mild coastal		
C4	Interior:	Swimming pools, chemical plants, etc.	High	2·0–4·0
	Exterior:	Industrial inland or urban coastal (chloride-rich environment)		
C5	Interior:	Industrial with high humidity or high salinity coastal	Very high	4·0–8·0
	Exterior:			

Table 2. Performance of zinc coatings in different environments

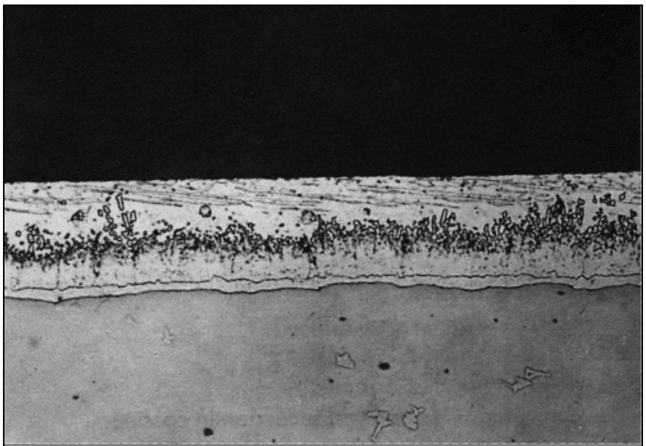

Figure 5. Typical micrograph of hot-dip galvanised coating

used as the standard coated product in the UK to inhibit the formation of white rust.

2.5. Factors affecting durability in the building envelope

When considering the durability of galvanised steel sections, it is necessary to consider two main criteria: the duration of wetness and the general atmospheric or exposure condition. The shorter the time of wetness and the drier the atmosphere, the better will be the durability. The rate of zinc loss in an internal environment is less than 10% of that in an external environment because of the drier indoor conditions. However, if the building envelope is of poor quality, the time of wetness can be greater, due to condensation and possible external water ingress. Transient moist conditions due to condensation are much less critical than the case of water washing over the zinc surface because zinc hydroxide, which is produced by contact with moisture, is soluble and can be washed away.

Good building practice, thermal insulation and proper ventilation ensure that the design of modern houses conforms to a warm dry environment, even though humidity is created by the occupants or activities inside. There is long experience of using galvanised steel in housing, and even within the building envelope, exposure conditions can vary considerably.

2.6. Design life of galvanised steel

The design life of a galvanised steel component comprises the life of the protection system plus that of the substrate. The design life of the protection system may be defined as the time period to the first major maintenance of the coating, when recoating or some other treatment is required to restore the total effectiveness of the protection. If there is no maintenance at this time, the coating would continue to deteriorate and the underlying steel may start to corrode, eventually leading to serviceability problems. The design life does not represent structural failure of the component, and there will be a considerable margin between the design life and potential failure.

Two categories of use may be defined that influence the requirements for design life.

(*a*) Category A: concealment of structure components so that they cannot be inspected during their service life.
(*b*) Category B: location of components so that they can be inspected readily, such as by removal of inspection panels or trapdoors, etc.

Examples of category A are wall frames, window lintels, wall ties and possibly suspended ground floors. Examples of category B are roof trusses, purlins, internal floors and external elements.

The required design life depends on the conditions of use, as there should be a greater reserve of life for components that cannot be inspected and therefore cannot be assured for recoating, repair or replacement. Typically for residential buildings, the required design life is 60 years, representing a sensible time to major maintenance of the primary components. For infill walling, a design life of 30 to 60 years may be specified depending on the importance of the infill walling to the support of the cladding elements.

In the context of galvanised steel, the definition of the actual design life depends on the degree of loss of zinc from the surface. The rate of zinc loss is likely to be uneven, and experience shows that some surface rusting may appear when an average of 50% of the original weight of zinc coating has been lost. To cater for this variability, a general basis of evaluation must be conservative, and the design life may be defined as a function of the conditions of use.

(*a*) Category A: when 50% of the weight of zinc has been lost from the exposed surface (which for G275 coating is 137 g/m^2).
(*b*) Category B: when 80% of the weight of zinc has been lost

from the exposed surface (which for G275 coating is 220 g/m^2).

This is then consistent with other coated light steel products, such as roof sheeting, where the design life is related to the performance of the coating rather than the steel substrate.

3. CASE STUDIES

The following case studies present information on the long-term performance of galvanised steel sections in various examples in which measurements of zinc loss have been made.

3.1. Case 1: Environmental and performance monitoring of modern steel-framed housing

The former Department of the Environment sponsored a 3-year corrosion and environmental monitoring exercise in 15 houses in Manchester, London and South Wales (John, 1991). Galvanised steel test panels were left uncovered at opposite ends of each (unheated) house loft and were exposed to the atmosphere. The zinc corrosion rate was measured together with relative humidity, temperature and the time-of-wetness of any condensation. In addition, some laboratory experiments tested galvanised steel that was freely exposed to mortar and gypsum plaster in accelerated corrosion test environments.

The results showed that there was no significant difference in relative humidity or temperature values at the three geographical locations. Data-logging indicated that conditions that may lead to condensation can exist in roof spaces up to 21% of the time averaged over a year. Only one cavity wall was monitored, but it showed that conditions that may lead to condensation can exist for up to 16% of an average year.

3.1.1. Exposure conditions. The average weight loss measured over a 3-year period (John, 1991) in a loft environment is given in Table 3. The average rate of zinc loss per year may be expressed as the total weight loss divided by the time period. From these data, the average rate of zinc loss was approximately 0·3 g/m^2 per year. Chromated galvanised steel was found to have a lower rate of zinc loss than non-chromated galvanised steel. The data are subject to some variability because the specimens were removed and measured but were not replaced. There could therefore be some variation in exposure conditions and surface characteristics among the specimens.

No significant difference was found between the corrosion rate of galvanised steel panels exposed at the north or south sides of each loft, and no significant difference was found in the corrosion rate of the panels in the three geographical areas.

For comparison, the equivalent uncoated mild steel specimens stored in the same locations lost weight at a rate of approximately 2·5 g/m^2 per year (or 30 μm thickness of steel per year).

3.1.2. Interpretation of zinc loss. From the results of these studies, the zinc weight loss (g/m^2) for galvanised steel exposed over a 3-year period was found by linear regression analysis to follow a relationship of the form

$$\text{Weight loss} = a(time)^b \qquad (1)$$

where *time* is measured in years.

A difference in performance was observed between chromated and non-chromated zinc specimens (a chromate layer is the standard product in the UK).

The value of b was found to be 0·64, indicating that the rate of zinc loss decreased with time. This occurred because the protective oxide film that formed on the zinc surface in dry conditions reduced the exposure of the zinc. Figure 6 shows the individual test results over time (marked as x), and also the mean line and the mean plus 2 standard deviations of the data (both drawn as solid lines). The best fit for the mean of the test data was for $a = 0{\cdot}4$. The characteristic value of weight loss corresponds to 95% probability that all results lie below the line given by the mean plus 2 × standard deviations of the data (Figure 6). This line is obtained for $a = 1{\cdot}0$ and the expression becomes

$$\text{Weight loss} = 1{\cdot}0(time)^{0{\cdot}64} \qquad (2)$$

3.2. Case 2: Environmental and performance monitoring of the light steel-framed building at Ullenwood

This building is situated at the National Star Centre for disabled persons at Ullenwood near Cheltenham, and was one of the first light steel framing systems constructed by PMF (now Corus Panels and Profiles) in 1982. The residential building, illustrated in Figure 7, was monitored to gain more data on in-service performance. Areas investigated were the environmental conditions in the wall cavity, the loft and below the suspended ground floor. The loft was monitored in the south corner, north corner, near the water tank and at the centre near the flue. The exercise included the measurement of the weight of zinc-plated coupons, which were removed annually over the 5-year period (John, 1991).

In the wall space and loft, the galvanised steel suffered very little weight loss, as shown in Table 4. The annual weight loss on the galvanised steel specimens was extremely low (0·2 g/m^2)

Materials	Number of years: 1	2	3
Non-chromated galvanised steel	0·44	0·75	0·71
Chromated galvanised steel	0·28	0·69	0·47
Electro-galvanised steel	0·75	1·26	1·24
Mild steel (unprotected)	2·60	5·70	7·00

Table 3. Average weight loss (g/m^2) for exposed specimens in loft environment (after 1, 2 and 3 years) in the BRE investigations

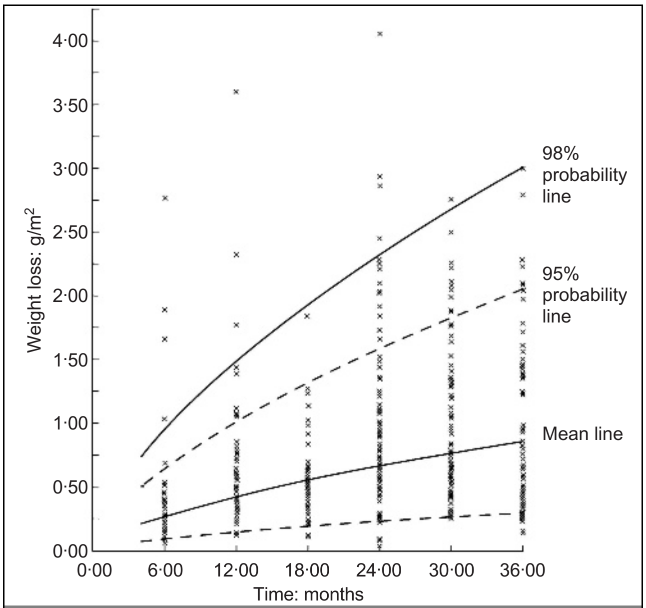

Figure 6. Zinc weight loss with time for exposed hot-dip galvanised steel specimens (upper line corresponds to the characteristic value of weight loss)

Figure 7. Steel-framed building for disabled persons at Ullenwood, Gloucestershire, UK

compared with the mild steel specimens (1·26 and 1·62 g/m^2 in wall space and loft, respectively) despite the wide fluctuations in temperature and relative humidity in these locations.

Over the 5-year study period, the annual rate of zinc loss was approximately uniform. In February 1996 (after 14 years), the building was inspected and internal plasterboard panels were removed. Only slight tarnishing (i.e. loss of normal bright appearance as in Figure 8) was observed. In situ measurements were taken of the standard galvanising on the wall studs, and could not detect any significant loss of the zinc coating. The rate of zinc loss is therefore negligible and is considered to correspond to a long-term rate of zinc loss of no more than 0·2 g/m^2 per year.

Location	Time: months	Measured zinc loss: g/m^2	Annual zinc loss: g/m^2 per year
Wall space	6	0·09	0·18
	12	0·27	0·27
	18	0·30	0·20
	24	0·41	0·20
	60	1·20	0·24
Loft space	6	0·09	0·18
	12	0·19	0·19
	18	0·32	0·22
	24	0·29	0·15
	48	0·55	0·14
	60	0·59	0·12

Rate of weight of zinc loss is averaged over the exposure time.

Table 4. Results of measurements on galvanised steel coupons installed in the wall space and loft of the Ullenwood building

The measurements taken of the specimens under the ground floor were affected by their proximity to an air brick in the external cladding. The rate of zinc loss after 5 years was 1·22 g/m^2 per year. The conditions under the ground floor are not as severe as external conditions, but clearly the galvanised steel is exposed to moisture over a longer period than in warm frame applications. The exposure can be reduced by additional insulation or a membrane placed below the floor.

3.3. Case 3: Monitoring of over-cladding panels at Edinburgh University

This study concerns the environmental monitoring of two types of steel over-cladding panels constructed on the eighth floor of the James Clerk Maxwell building on the Edinburgh University campus, where the wind and rainfall regime is severe (Figure 9). Two panel types were monitored.

(*a*) Composite (sandwich) panels 50 mm thick fixed to horizontal rails (C section) at 2·4 m spacing vertically (Figure 10). These panels were installed in August 1994.
(*b*) Steel cassette panels (flat panels with rigidised backing) fixed to vertical rails (Figure 10). These panels were installed in October 1996.

In both cases, the external face of the panel is in colour-coated steel suitable for at least 30-year design life in cladding applications. In over-cladding applications, the environmental conditions behind the new cladding are potentially more severe than in internal conditions, as although the cavity space is ventilated, the galvanised steel is subject to periodic wetness due to condensation and possibly to direct rain ingress.

Over 200 galvanised steel coupons were positioned behind both over-cladding panels. For the composite panels, L-shaped coupons were used in order to trap any moisture that might enter the cavity space. Chromated and non-chromated zinc coupons were installed behind the composite panels in order to assess the effect of the passivation through the chromate finish. The original zinc coating in both cases was 275 g/m^2 or approximately 20 μm per face.

For the cassette panels, flat coupons were installed behind the panels, as shown in Figure 11. Zinc (non-chromated) and zinc–aluminium coupons were installed in this case. Zinc–aluminium is an alternative coating system that is used in some countries and the product *Galfan* that was tested has about 95% zinc. Its original coating was 250 g/m^2.

The location of the coupons was chosen to be easily accessible. The coupons were removed initially over 4- to 12-month periods and then over a gap of 5 years. The final measurements were taken in mid-2007 after 13 and 11 years, respectively, in order

Figure 8. Wall panel removed, showing no trace of corrosion on the members after 15 years (the connections are coated in zinc-rich paint)

to determine the loss in weight of the samples and to observe signs of possible corrosion (Figure 12).

The results of the samples removed at various stages are given in Table 5. The total weight loss was measured from samples that were removed from behind the composite panels and weighed at the stated exposure time. The rate of zinc loss was the equivalent annual rate of loss averaged over the exposure time.

For chromated zinc samples, the average rate of zinc loss after 13 years was 0·30 g/m^2 per year, although the rate of loss in the early months was much higher. For non-chromated zinc samples, the average rate of zinc loss was 0·43 g/m^2 per year after 13 years and, in this case, the rate of zinc loss tends to be linear with time. As noted earlier, chromated zinc is currently the standard finishing later used for production of cold-formed steel sections.

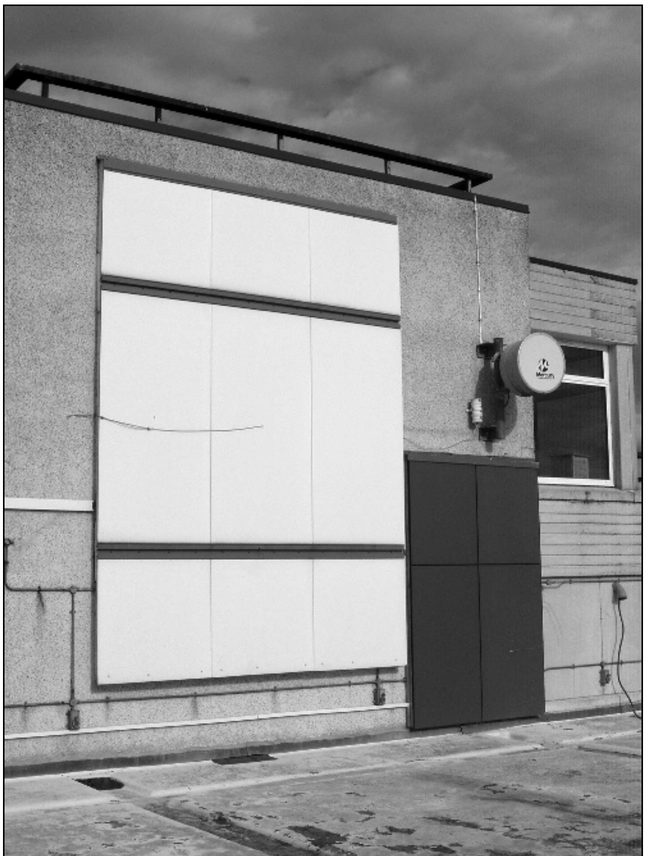

Figure 9. Two types of over-cladding panels in exposure tests at Edinburgh University

The results for the zinc and zinc–aluminium (*Galfan*) coupons installed behind the cassette panels are presented in Table 6. In this case, the average rate of zinc loss is 0·30 g/m^2 per year, which is consistent with the other over-cladding results. However, the results for *Galfan* are higher at 0·55 g/m^2 per year.

These results are lower than for the L-shaped coupons in the adjacent composite panel tests, and suggest that the long-term coating loss is about 0·3 g/m^2 for zinc and 0·6 g/m^2 for zinc–aluminium.

Despite the more severe conditions present in the cavity behind the over-cladding panels, the rate of zinc loss is not significantly higher than in the loft measurements of case study 1.

3.4. Case 4: Monitoring the Oxford Brookes demonstration building

In 1996, a student residence was constructed at Oxford Brookes University as part of a European demonstration project. It used Corus's *Surebuild* light steel framing system. The building comprised a four-bedroom house and an adjacent six-room apartment building (Figure 13). The house and apartments are occupied by postgraduate students.

The innovative feature of the building was the use of two alternative habitable roof systems, and a composite suspended ground-floor system using a perimeter G-shaped galvanised steel edge beam with Corus' CF70 decking and an in-situ concrete slab spanning between these edge beams. The light steel framing and roof are also highly insulated to a U-value of 0·2 W/m^2 °C. The open habitable roof system is illustrated in Figure 14 and the suspended ground floor is illustrated in Figure 15.

The building was monitored in the first 2 years to assess its energy performance and the local temperature and humidity conditions that may exist in the building fabric. Crawl access was provided beneath the suspended ground floor to permit assessment of the performance of the galvanised steel sub-structure and composite floor. Data for the first 3 years indicated that no wetness had occurred in the light steel frame, even adjacent to bathrooms, kitchens and in the roof space.

A series of zinc coupons was suspended in the wall cavity and in the ventilated void below the suspended ground floor. These coupons were removed at various intervals to assess the weight loss. The results are presented after 30 months and 10 years for four locations in the loft, wall and below the composite deck floor. The 30-month data are the average of three coupons, whereas the actual results for the two coupons removed from each location after 10 years are given. The final case represents a more severe condition, which although not wet, is subject to higher humidity conditions and more condensation risk than internally.

From the results in Table 7, it is apparent that the rate of zinc loss averaged over 10 years was only about half of the 2·5-year results. The rate of zinc loss in internal conditions was 0·1 to 0·2

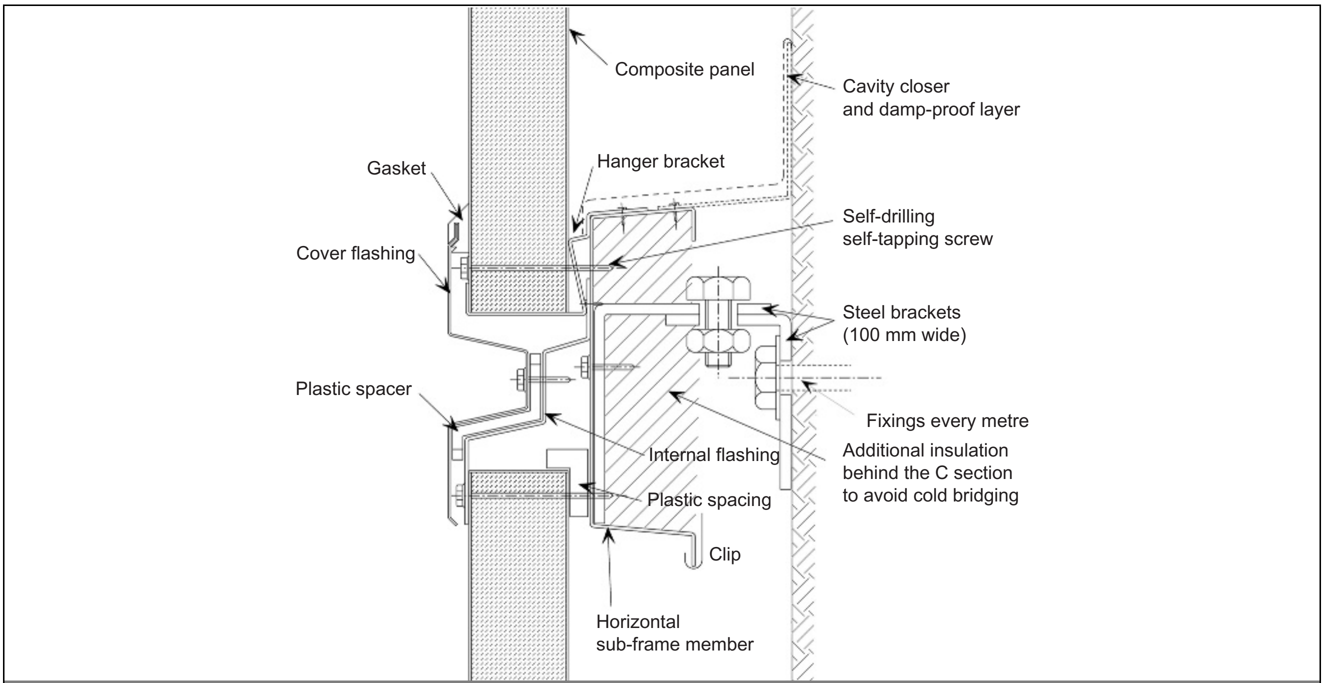

Figure 10. Details of support to composite panels

g/m^2, and even in the below ground floor application was only 0·3 g/m^2. The predicted design life is over 200 years.

3.5. Case 5: Monitoring of the Britspace house, York

In 1998, a pair of two-storey houses were constructed using light steel modules on the site of the modular company *Britspace*, Gilbertdyke near York. The modules are 8 m long × 2·4 m wide and four modules make one house. The building is illustrated in Figure 16. The opportunity was taken to install zinc coupons in the following locations

(*a*) six coupons on the suspended ground floor of the modules
(*b*) three coupons at first-floor level
(*c*) three coupons below the rear windows
(*d*) twelve coupons at various locations in the unoccupied (cold) roof spaces of the two buildings.

The coupons were installed in May 2001; the selected coupons were removed in January 2008. Other coupons were left in place in order to give a measure of the longer-term performance of the modular components. The results from the 7-year data are presented in Table 8.

At the same time, a statistical survey was made of the actual zinc coating of the galvanised steel members in comparison with

Figure 11. Zinc coupons being installed behind the cassette panels

Figure 12. Galvanised steel coupons removed from behind the over-cladding panel after 13 years (non-chromated zinc on the right)

Exposure time: months	Chromated zinc		Non-chromated zinc	
	Total loss: g/m^2	Rate of loss: g/m^2 per year	Total loss: g/m^2	Rate of loss: g/m^2 per year
6	0·98	1·96	1·78	3·56
15	0·97	0·78	2·10	1·68
24	0·76	0·38	3·30	1·65
57	1·83	0·38	4·05	0·85
156	3·87	0·30	5·60	0·43

G275 coating thickness. Data averaged over three specimens for each exposure time.

Table 5. Results of measurements on galvanised steel coupons installed behind the composite over-cladding panel at Edinburgh University

Exposure time: months	Non-chromated zinc		Zinc aluminium (*Galfan*)	
	Total loss: g/m^2	Rate of loss: g/m^2 per year	Total loss: g/m^2	Rate of loss; g/m^2 per year
12		0·20		0·50
36		0·15		0·20
60	0·47/0·57	0·10	1·13/1·14	0·23
128	0·98/1·09	0·10	1·79/2·13	0·18

G250 original coating thickness for *Galfan*. Data averaged over three specimens for each exposure time.

Table 6. Results of measurements on the zinc and *Galfan* coupons behind the cassette panels at Edinburgh University

Figure 13. Oxford Brookes demonstration building constructed using light steel framing

similar data recorded when the building was constructed. Although not as meaningful as the measurements from the coupons, these results, as presented in Table 9, give some general correlation of the likely variation that may be experienced.

The results from Table 8 confirm that the zinc loss within the building was generally small (less than 0·3 g/m^2 per year). However, relatively high zinc losses were measured for the coupons located in the floor of the ground-floor module, which was not protected other than by insulation. The zinc loss was in the range 0·5–2·1 g/m^2 per year, which indicates a shorter design life. The below window result was 0·9 g/m^2 per year indicating some evidence of condensation.

When the building was constructed, the U-value of the façade roof and ground floor was specified as 0·35 W/m^2 °C, which is much higher than the level stipulated by the current regulations.

Figure 14. Open-roof system in the OBU house (kept open for demonstration purposes)

Figure 15. Ground-floor system in the OBU house (using composite decking and perimeter C sections)

Location of coupons	Total zinc loss: g/m^2 after: 30 months	60 months	124 months	Rate of zinc loss: g/m^2 per year over: 30 months	60 months	124 months
Cold loft space	0·53	0·57	0·63	0·21	0·13	0·08
Suspended in cavity wall:						
high level	0·30	0·47	0·45	0·12	0·10	0·09
low level	0·48	1·25	1·31	0·19	0·25	0·16
Below suspended ground floor	1·25	2·13	2·04	0·50	0·43	0·25

All data are for chromated zinc specimens.

Table 7. Measured weight loss of the galvanised steel coupons installed in the demonstration building at Oxford Brookes University

It is expected that the long-term performance of light steel frames and modules will be much better.

The on-site measurements may be compared to an original zinc coating of 20–21 μm (or 275 g/m^2). The percentage zinc loss is equivalent to a weight loss of 0·15 g/m^2 per year, which is consistent with previous results.

4. CONCLUSIONS FROM CASE STUDIES: DESIGN LIFE OF GALVANISED LIGHT STEEL FRAMING

4.1. Warm frame applications

The monitoring studies have shown that the environmental conditions present in 'warm frame' construction are such that moisture levels are very low and that the galvanised steel components are not subject to a risk of significant corrosion within the expected life of well-maintained modern buildings.

The rates of zinc loss on chromated galvanised steel coupons were very low at less than 0·3 g/m^2 per year and, taking into account statistical accuracy, it has been observed that the rate of zinc loss reduces with time in dry environments. This is because the zinc oxide layer that forms on the surface also protects the zinc beneath. However, it was observed that a linear rate of zinc loss with time was more appropriate for non-chromated zinc and for conditions with a potentially greater time of wetness. Chromated zinc is the coating normally used for the production of cold-formed steel sections.

The following approach may be used to evaluate the design life of components that are concealed and cannot be inspected or repaired easily (Category A in Section 2.6).

Figure 16. Britspace demonstration house using fully modular construction

(*a*) Assume a linear rate of zinc loss with time (which is a more conservative extrapolation of the data given by Equation 2).
(*b*) Assume that a loss of 50% of the total zinc coating may lead to some rusting of the surface (see design life definition in Section 2.6).

As the measurements were taken only from the average of three specimens, assume that the 95% probability level is double the average rate of loss. In principle, the use of the 95% probability level means that the design life corresponds to the characteristic value, namely that only 5% of the structure may suffer a more severe rate of zinc loss.

Therefore, the design life (in years) may be estimated from

$$\text{Design life} = 0{\cdot}25 \times \frac{\text{Total weight of zinc coating}}{\text{Average rate of the zinc loss/year}} \qquad (3)$$

The weight of zinc coating is expressed as the total weight (i.e. 275 g/m^2 for G275 specification); the rate of zinc loss is the weight loss summed over both faces. From the data in case studies 1, 2 and 4, the average rate of zinc loss of the frame components does not exceed 0·3 g/m^2 per year. For G275 galvanising, it follows that the design life is at least 230 years.

In comparison, Equation 2 would lead to a design life (calculated for 50% loss of zinc) given by

$$137 = 1{\cdot}0(time)^{0.64}$$
$$\text{or } time = 2150 \text{ years}$$

This is almost 10 times longer than the linear estimate in Equation 3, because in Equation 2 the long-term rate of zinc loss is assumed to reduce in warm frame applications.

4.2. Roof space of houses

The roof space of houses may represent a more severe environment than a 'warm frame' application; however, from the data in case studies 1 and 2, the rate of zinc loss was not significantly higher. In the Oxford Brookes building, the roof space was insulated and the rate of zinc loss was very low. The data in case study 1 also include uninsulated lofts and the average rate of zinc loss was approximately 0·3 g/m^2 per year.

Equation 3 predicts a design life of over 200 years but, given the potentially more variable conditions in lofts, it is considered that

Location of coupons	Total zinc loss after 85 months: g/m^2	Rate of zinc loss: g/m^2 per year
Roof space (cold)	0·59, 0·90, 0·91, 0·92, 1·69	0·08 to 0·24
Wall (below window)	1·18, 7·05	0·17 to 10·01
First floor (between modules)	0·79	0·11
Ground floor (between modules)	3·37, 10·4, 14·83	0·48 to 2·12

Table 8. Measured weight loss of the galvanised steel coupons installed in the Britspace building, near Hull

Member type and location	Average zinc coating: μm	Standard deviation	Coefficient of variance: %	Change over 6·8 years: %
House A: unfurnished				
Vertical studs: back of house A	10·47	1·53	7·5	−0·03
Vertical studs: front of house A	19·96	1·32	6·5	−0·77
Floor joists: back of house A	21·25	1·99	9·4	−0·10
Floor joists: front of house A	20·83	1·32	6·3	−0·09
Floor joists: side of house A	20·58	1·48	7·3	−0·83
Roof joists in house A	20·33	2·17	10·6	−0·09
Roof rafters – 1: back of house A	20·75	2·16	10·4	−0·10
Roof rafters – 2: front of house A	19·38	1·28	6·6	−0·75
House B: fully furnished				
Vertical studs: back of house B	19·11	2·05	10·7	−0·06
Horizontal joists: back of house B	20·75	1·13	5·4	−0·30
Roof rafters in house B	20·47	1·51	7·4	−0·74
Average values	19·60	1·80	9·2	−0·35

Table 9. Measured zinc coating thickness at Britspace Demonstration house

Applications	Environmental conditions		Special measures
External walls	Warm:	Properly insulated and ventilated	No special measures required
	Cold:	Uninsulated, some risk of condensation	Provide proper ventilation and reduce exposure Over-cladding to an existing wall improves the insulation and life of the existing wall
Suspended ground floors	Cold:	Moisture from the ground and from the atmosphere	Provide good ventilation and avoid contact with ground Use damp-proof course at supports. See note 1 for further protection
Roofs	Warm:	Properly insulated and ventilated	No special precautions needed
	Cold:	Uninsulated, some risk of condensation	Provide proper ventilation. Over-roofing improves the life of an existing flat roof
Steel lintels	Wet:	Potential water ingress from cracks in brickwork	Use thicker grade of zinc coating. See note 1 for further protection. Also see BSI (1983)
	Dry:	No water ingress, properly drained	No special measures required
Over-cladding	Drained and back-ventilated Pressure equalisation		Generally, no special precautions for weathertightness
Over-roofing	Cold environment, some risk of condensation		Generally, good ventilation is provided Detail carefully at eaves level to prevent water ingress
Infill walls for multi-storey buildings	Warm:	Properly insulated and ventilated	No special precautions needed
Contact with other materials	Contact with other metals Contact with plaster, etc.		See notes 2 and 3 below

Notes:
1. Where further protection is required, the surface may be painted or powder-coated. If aesthetic effects are unimportant, a well-proven form of protection is to use a brush coat of zinc-rich paint or bituminous paint.
2 Bimetallic corrosion of dissimilar metals should be avoided by using inert separators, especially between the fixings and cladding.
3. Zinc can be affected by contact with various building materials in damp conditions, for instance fresh concrete (highly alkaline), mortars, certain natural materials (which may contain inorganic salts, organic acids, or may just act as a source of moisture) woods (oak and WRC are acidic), timber treatments (CCA is well known but also phosphate fire retardants), and some insulation.

Table 10. Good construction practice to ensure durability in new and existing construction

the design life of galvanised steel in these applications should be taken as over

(*a*) 100 years for insulated roof space
(*b*) 60 years for uninsulated roof space.

These predictions assume that the integrity of the roof is not impaired and that leaks are prevented.

4.3. Suspended ground floors

Suspended ground floors can incorporate light steel sections or decking. They are not exposed directly to moisture but may be subject to periodic condensation from humid air flow; however, the risk of condensation is much reduced if the floor is insulated from below.

Case studies 1, 2 and 4 provided data on the performance of uninsulated composite ground floors using light gauge decking. Case study 5 provided comparative data for floors in modular construction. In case study 1, the rate of zinc loss was 1·22 g/m^2 per year after 5 years, and in case study 4, the rate was 0·5 g/m^2 per year. In case study 5, the rate was much higher at 2·14 g/m^2 per year. Equation 3 predicts a design life of 50 to 100 years in these conditions. However, the exposure severity can be reduced by using an external insulation layer beneath the floor, leading potentially to a design life of over 100 years. This type of ground floor is being further developed.

Any extrapolation from these data assumes that leaks from outside or inside the building envelope are prevented, that steel is not in direct contact with soil and is properly protected from other potential sources of moisture. Further data are being collected on all types of suspended ground floors.

4.4. Over-cladding applications

The light steel sub-frames to over-cladding systems are subject to variable conditions, depending on the exposure and type of cladding that is used. The Edinburgh University tests showed a rate of zinc loss of 0·38 g/m^2 per year, which is relatively low for these exposure conditions. For these data, Equation 3 would lead to a design life of 180 years.

It is difficult to estimate the exposure conditions for all types of over-cladding system. With good detailing to avoid ingress of wind-driven rain, and to allow for some air movement in the cavity, a design life of at least 60 years may be expected for the sub-frame members; that is, the rate of zinc loss would be less than 1·1 g/m^2 per year. The more exposed members at the joints in the cladding should be additionally protected where they are subject to prolonged moisture.

Other design guidance on the use of galvanised steel in exposed or external environments is given in BS EN 14713 (British Standards Institution, 1999).

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