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Empirical vs Theoretical Life Prediction for Subfloor Structural Connectors

P.W. Haberecht and C.D. Kane

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EMPIRICAL Vs THEORETICAL LIFE PREDICTION FOR SUBFLOOR STRUCTURAL CONNECTORS

Short title: Predicting service life of subfloor hardware.

P.W. HABERECHT
Building Research Association of New Zealand, Judgeford, Wellington, New Zealand.
C.D. KANE
Building Research Association of New Zealand, Judgeford, Wellington, New Zealand.

ABSTRACT

Using model subfloor enclosures built in a very severe marine environment, corrosivity was measured as a function of four different ventilation regimes. Corrosion-related parameters were measured simultaneously in the same enclosures, and used to determine corrosion rates based on three predictive tools; the ISO 9223, ISO-CORRAG, and MICAT corrosion prediction algorithms. The predicted corrosion rates did not match the observed rates in all cases, with the ISO-CORRAG flat zinc corrosion rate prediction equation providing the closest match within the experimental limits. It is believed that the Time of Wetness (ToW) is a significant factor in the corrosion rates observed, with the actual times of wetness on the specimens being significantly higher than those predicted from humidity measurements. This is due to the presence of chlorides (sea salt) on the panel surfaces. A very good correlation was found between the surface area of the vent and the corrosion rates of zinc and steel, and chloride deposition rates. In New Zealand the severity of the corrosivity in subfloor conditions with restricted ventilation indicates that steel or galvanized subfloor components would not survive the 50 years normally required by the New Zealand Building Code (NZBC).

Keywords: Corrosion rate, Chloride deposition, Marine, Steel, Subfloor, Vent, Zinc

1 Introduction

Figure 1: Common subfloor fittings

Galvanised subfloor connectors are normally required by the New Zealand Building Code (NZBC) to be durable for 50 years, but previous studies by Holcroft (1996) have shown that they can be rendered unserviceable by corrosion after a relatively short exposure. Concerns have been raised over the ability of the corroded galvanised components used in the domestic building industry to continue to function in severe marine/coastal environments (Cole *et al*, 1996). Subfloor connectors (Figure 1) used in New Zealand are usually made of hot-dip galvanised steel and come in a variety of forms. Traditionally they were galvanised wire which was stapled to timber piles and bearers (or looped through, or embedded in concrete piles). More recently, because of increased structural requirements in modern building codes, they have tended to be proprietary nail plate systems, including nail plates, cleats and 'wire dogs'. The most significant factor that causes the corrosion is the prevailing moist salt air from the coastline, and most New Zealand cities are coastal. In New Zealand, a marine zone surrounds both main islands, with a severe marine zone on much of the west coast of both islands (Duncan and Whitney 1982; Kane 1995). Previous studies show that high chloride deposition rates were measured up to 30 kms inland (Ballance and Duncan, 1985), which is substantially further inland than normally expected.

This work compares three predictive corrosion rate models, developed for outdoor environmental corrosivity, against the actual subfloor corrosion rate results, and also evaluates the effect of vent size on subfloor corrosion rates. This provides a greater understanding of the variations in microclimates and corrosion rates that exist in subfloor conditions near coastal environments.

1.1 Previous studies

Many empirical studies have measured environmental corrosivity and developed a predictive equation (Morcillo *et al* 1995; King 1988; Duncan and Ballance 1988). Other studies have been based on measurements of the prevailing environmental conditions using data such as rainfall, temperature, relative humidity, cloud cover and aerosol contaminants (Hyland and Enzensberger 1998; Cramer *et al* 1996; Spence *et al* 1992; Pourbaix 1982; Summitt *et al* 1982).

Subfloor environmental conditions are different from the outside environment, simply because the sub-floor is shielded from rain, and there is some thermal insulation or heating provided by the building above. Depending upon the type of ventilation, there may be limited air movement. Studies by King *et al* 1995, found that the microclimate under sheltered conditions can result in a significant increase in corrosion rates for galvanised steel. They found corrosion rates were 2.4 times greater in severe marine and 2.1 times in moderate marine environments. In contrast, Holcroft (1996) found that components shielded from the prevailing moist salt laden wind were significantly less corroded.

The corrosion process for the exposed zinc surface of galvanised components, on contact with dew, fog, mist or rain, is as follows. Zinc will form zinc hydroxide, which reacts with carbon dioxide from the atmosphere to form an insoluble basic zinc carbonate (Legault *et al* 1978; Cole and Bradbury *et al* 1996). This corrosion product film tends to inhibit any continuation of the corrosion process. The development of the film is a continuous process and it has been found that rain can wash away a substantial amount of the non-adherent zinc hydroxide and expose fresh zinc. This results in further corrosion of the zinc and over a year, the corrosion rate for outside coupons was found to be greater for surfaces exposed to the rain than for surfaces facing the ground (Legault *et al* 1978). However, in environments strongly influenced by the deposition of sea salt, the groundward surfaces of coupons exposed for ten years in New Zealand corroded faster than the skyward surfaces. This was basically because of the influence of accumulated sea salt on the groundward surface, plus a correspondingly increased period of surface wetness or ToW (Haberecht, *et al* 1998), and the corrosion product could be zinc hydroxychlorides instead of the zinc hydroxycarbonates (Cole and Bradbury *et al* 1996).

Sheltered corrosion studies by Norberg *et al* (1996) in severe marine conditions in Australia found that the ToW period was between 5% and 35% greater than fully exposed surfaces and a 10 to 25% increase in zinc corrosion rates had occurred. As part of their experiment, identical zinc specimens were regularly doped with salt solution for a year, at the rate of 50 $mg/m^2/day$ and 500 $mg/m^2/day$ while under the shelter. On average, the corrosion rate was 17% greater for the high salt concentration. Considering the salt concentration was 10 times greater, the corrosion rate increased by a relatively small amount. These results indicate that there is a threshold of surface chloride deposition that has a significant effect on the corrosion rate.

Guttman and Sereda (1968) found that increasing the chloride deposition rate from 10 to 40 $mg/m^2/day$, and maintaining the ToW at 0.40 (fraction of the year above 80% RH), increased the corrosion rate of zinc by 56%. Their study in Panama also found that increasing the ToW fraction from 0.3 to 0.7, increased the corrosion rate by 79%, regardless of the chloride deposition rates previously mentioned. This indicates that the ToW appears to be more significant once chloride is on the surface.

The ToW period is influenced by the deposition of sea salt on to the surface, which results in a layer consisting of NaCl and $MgCl_2.6H_2O$, where NaCl has an equilibrium relative humidity of 77%, and the $MgCl_2.6H_2O$ is at an equilibrium of 33% (Cole *et al* 1996). This means that if enough sea salt is deposited onto a surface and the ambient conditions are above 33% relative humidity, then the surface will have some condensation present. Evans (1976) noted that the corrosion rate on surfaces contaminated with sea salt increased at 50% RH, and not 33%. The empirical value of 50% RH may take into account the accumulation of enough condensed moisture to actually cause a measurable acceleration of the corrosion process.

Many European corrosion rate models place a heavy emphasis on sulphur dioxide (Haynie 1980; Cramer *et al* 1988). New Zealand has a very low sulphur dioxide concentration and in fact has one of the least industrially polluted atmospheres in the world (Walker *et al* 1996). On this basis the most significant factors that influence the corrosion rate in New Zealand are most likely to be the ToW and chloride deposition rates.

2 Experimental

This study investigated 12 months of salt deposition in subfloor conditions in a specially constructed facility on the south coast of Wellington, New Zealand, at Oteranga Bay as shown in Figure 2. The facility comprised eight adjacent enclosures, each with identical dimensions, replicated subfloor conditions open to onshore winds, as shown in Figure 3. Each enclosure measures 1.2m (W) x 1.2m (H) x 3.6m (L) with the south end facing the sea, and is fully fibre-cement sheet lined, including the roof. The roof of the structure has a minimum air gap, open to the environment, of 100mm between the galvanised steel roof and the fibre-cement sheet lining.

The surface area of the ventilation was based upon NZS 3604 (Standards New Zealand 1990). This requires a minimum subfloor ventilation area of $0.0035m^2$ per m^2 of floor area. The floor area of each enclosure was 4.32 m^2, requiring a minimum ventilation surface area of 0.00756 m^2 for each end of the enclosure, and this was exceeded as noted in Table 1.

Table 1: Types of ventilation at each enclosure and total surface area at each end.

Enclosure	Vent surface area (m^2)	Description of ventilation (enclosures same at both ends)
O	1.4400	Open
4S	0.1320	4 slotted gaps each 1100 x 30 mm
PB	0.0078	'Post box' slot 30 x 260 mm
C	nil	Closed

The corrosion rate studies (weight loss) used two 100mm x 150mm Z275 coil galvanised steel coupons and two mild steel SAE1010 coupons in a vertical rack at the middle of each enclosure. The backs of the steel and galvanised steel coupons were sealed with wax so that one exposed surface faced either the seaward or the landward ends of the enclosure. Similar mild steel coupons were also used to measure the corrosion rate as a function of distance from the vents and were attached horizontally to stakes 100mm above the ground, spaced at 600mm intervals. The stakes were numbered from the seaward end of the enclosure, with coupon number #1 being closest to the sea.

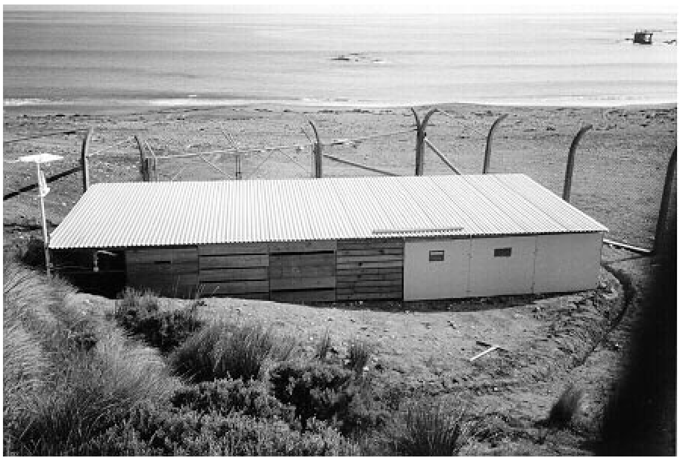

Figure 2: The eight enclosures with interchangeable vent panels.

The environmental conditions were also measured inside each enclosure, 300mm from the internal roof using a calibrated Phillips humidity probe and thermocouple with data logging every 15 minutes. In addition, four salt candles, as described in International Organisation for Standardisation ISO 9225 (1992), were used to determine the chloride deposition rate every 28 days for a year at four positions, as noted Table A2. The salt candles placed beside each other near the seaward vent should generally record the same result, as they were positioned the same distance from the vent or opening, to give a measure of within-site variance. In the middle of each enclosure was a shelf spanning the width of the enclosure at a height of 800mm, which provided a site for the middle salt candle and a rack for supporting the weight loss panels. After one year's exposure, all weight loss coupons were analysed in the laboratory by removing the corrosion products with chemical stripping, as recommended in American Society for Testing and Materials (ASTM) G1 1981, and reported in g/m^2/year units.

3 Results

The average relative humidity (% RH), temperature, and the fraction of the year where the humidity exceeds 75 or 80% RH are shown in Table A1. It was common to record periods of 1.00 ie. 100% RH in the wet winter months, and it appears to be rare for subfloors with restricted air flow to have a humidity level below 75% RH. The temperature and some humidity data in the open enclosure were not available for two months, due to a fault in the data logger. The salt deposition rates and corrosion rates are found in Appendix 1.

3.1 Corrosion rates and vent surface area

The volume and speed of the wind in building subfloor environments are linked to the surface area of subfloor vents. By reducing the size of the vent, a reduction of volume and wind speed is expected. This reduces the ability of the wind to carry large (>7.2μm) aerosols (Walker 1996). The overall effect is a significant reduction of salt deposition rates and subsequently the corrosion rates, and this can be observed in Figure 3. It is interesting to note that the equation of the plot is a simple power law, and this is the same as the common corrosion rate law ($C=At^n$), where C is weight loss, t is time, a & n are coefficients where n is often in the 0.5 to 1 range (Espada *et al* 1996). The results and the equations derived should be considered as indicative and not conclusive, due to the small range of vent surface areas evaluated.

3.2 Three predictive equations

This work investigates three predictive models, which are based on climatic and environmental (pollution) measurements, and include the ISO 9223 (1992), the ISO CORRAG (Knotkova *et al* 1995), and the MICAT (Morcillo 1995) equations. These three equations were selected because they represented a substantial amount of data from around the world on zinc exposed in the open. Since limited investigations have been carried out on predicting subfloor rain-sheltered corrosion rates, it was of interest to compare the common corrosion predictive (outdoor) equations against subfloor (sheltered) conditions. In the ISO CORRAG and the MICAT equations, the 50% RH value was included because Evans 1976 noted an increase in corrosion rates on surfaces coated with sea salt at 50% RH and the main constituent of sea salt is NaCl. The 75% RH was included because water condenses on NaCl at approximately 75% RH and is considered to be a better estimate (Spence *et al* 1992). This may be in dispute since Cole and Bradbury *et al* (1996) found that reducing the humidity from 90 to 60% RH at the high chloride (sea salt) deposition rates (120 mg/m^2/d) did not affect the corrosion rate of the galvanised steel. This indicated that in their study there is probably a greater dependency on salt deposition rates than on ToW.

Table 2: ISO 9223 classifications compared to actual corrosion rates of galvanised zinc panels.

	Classification				
Site	**ToW** (% of year)	**P** (mg/m^2/d)	**S** (mg/m^2/d)	**C** (predicted) (g/m^2/yr)	**Actual** (g/m^2/yr)
75% RH					
Open	(76) *t*5	(0) *P*0	(609) *S*3	C5 (30 to 60)	166 or C5*
Four slots	(95) *t*5	(0) *P*0	(26) *S*1	C3 or C4 (5 to 30)	82 or C5*
Post box vent	(97) *t*5	(0) *P*0	(10) *S*1	**C3 or C4 (5 to 30)**	**18 or C4**
80% RH					
Open	(59) *t*4	(0) *P*0	(609) *S*3	C5 (30 to 60)	166 or C5*
Four slots	(87) *t*5	(0) *P*0	(26) *S*1	C3 or C4 (5 to 30)	82 or C5*
Post box vent	(90) *t*5	(0) *P*0	(10) *S*1	**C3 or C4 (5 to 30)**	**18 or C4**

Note 1: The bold highlights the predicted results that matched the experimental results.
Note 2: The values were obtained from Appendix 1, Tables A1 to A4.
*The predicted corrosion rate is greater than the upper classification limit of 60 g/m^2/yr for C5.

3.2.1. Equation 1: ISO 9223 Procedures   Reference: ISO 1992

This method integrates the major factors involved in the corrosion process. The factors are ToW (*t*), pollution (SO_2) deposition (P), chloride (salt) deposition (S), and provides an estimated corrosion rate (C) range. The result in Table 2 is not a quantitative result, but a classification of the severity of the corrosion hazard at the location monitored. The results give an expected range of weight loss for each classification only. The input ranges for the model are found in ISO 9223, with level '5' being the upper limit.

3.2.2 Equation 2: ISO CORRAG (Outdoor)   Reference: Knotkova *et al* (1995)

$$\text{CorrLoss}_{\text{FlatZinc}} = a_1 + B_1(SO_2) + B_2(ToW) + B_3(Cl) = 0.2098 + 0.15(ToW) + 0.31(Cl)$$

Table 3: Results of ISO CORRAG equation predictions against measured corrosion rates for galvanised steel.

Site	ToW (%/year)	SO2 ($mg/m^2/d$)	Cl ($mg/m^2/d$)	Predicted Corrosion rate	Actual Corrosion rate ($g/m^2/yr$)
Open*	76	0	609	**200**	**166**
Four slots	95	0	26	23	82
Post box vent	97	0	10	**18**	**18**
Open**	98	0	609	**204**	**166**

* At 75% RH the surface is wet when NaCl is present (Spence *et al*, 1992).
** At 50% RH the surface is wet when sea salt is present (Evans 1976).

The coefficients (a_1, B_{1-3}), were obtained from Knotkova *et al* (1995). In Table 3, comparing the ToW period for the surface at 75% RH against the 50% RH, resulted in the ToW increasing from 76% to 98%, but had a minimal effect on the predicted corrosion rate.

3.2.3 Equation 3: MICAT (Outdoor)   Reference: Morcillo (1995)

$$C_{\text{Zinc}} = a_1 + B_1(ToW) + B_2(Cl) = 0.03 + 2.73(ToW) + 0.017(Cl)$$

Table 4: Results of MICAT equation predictions against measured corrosion rates for galvanised steel.

Site	ToW (%/year)	SO2 ($mg/m^2/d$)	Cl ($mg/m^2/d$)	Predicted Corrosion rate	Actual Corrosion rate ($g/m^2/yr$)
Open*	76	0	609	218	166
Four slots	95	0	26	260	82
Post box vent	97	0	10	265	18
Open**	98	0	609	278	166

* At 75%RH the surface is wet when NaCl is present (Spence *et al*, 1992).
** At 50%RH the surface is wet when sea salt is present (Evans, 1996).
Note: The coefficients (a_1, B_{1-2}), were obtained from Morcillo 1995.

4 Discussion

The corrosion rate of zinc is predominantly affected by the time of wetness the surface experiences and the environmental pollutants that arrive on the surface. The

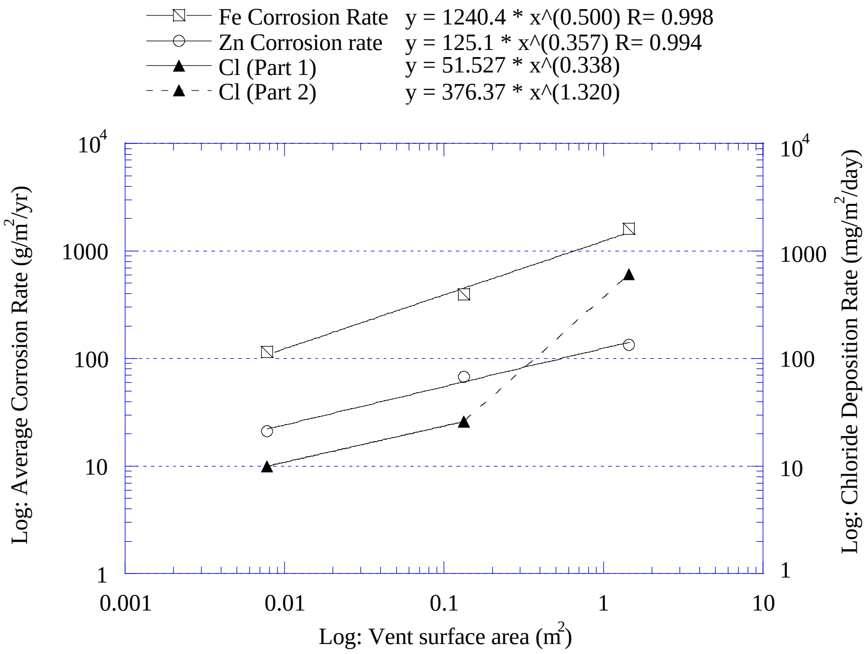

Figure 3: Log plot of vent surface area (*X*) Vs Average corrosion rate (Y_1)and Chloride deposition (Y_2), including simple power law equations.

period of surface wetness is substantially extended by the presence of sea salts on the surface. The continual flow of moist, salt laden air over the zinc provides both water and salt. Increasing the vent size allows a greater flow of air and an increase in the corrosion rate was noted, as shown in Figure 3. The corrosion products that develop in sheltered areas may not form the insoluble barrier film that has been seen to reduce the zinc corrosion rate on unsheltered coupons. In addition, the lack of rain to physically remove the accumulated corrosion products and other chemically aggressive agents, such as salt, is also responsible for increasing the corrosion rate. A predictive relationship was determined for the New Zealand coastal conditions for zinc and steel.

On reviewing the predictive corrosion rate equations in Figure 3, it appears that the corrosion rates for steel and zinc are very similar, with coefficients of 0.500 and 0.357 respectively. On further inspection, the first section (Part 1) of the chloride deposition rate has a coefficient of 0.338, which is very close to that of zinc. This indicates that there is a very good predictive relationship between the chloride deposition rate and the corrosion rate of zinc. This result compares favourably to a previous study by King *et al* (1995), for sheltered specimens in Australia, at nearly the same latitude. The King *et al* (1995) study identified a strong linear relationship between chloride deposition rates and the corrosion rate of zinc. By substituting the largest (average) zinc corrosion rate measured in this study of 134 g/m^2/yr (Table A4), into the derived linear equation $Corr_{Zn} = -6.3616 + 2.7312(\text{Chloride deposition rate})$ from King *et al* (1995), a predicted airborne chloride deposition rate of 51.4 mg/m^2/d was obtained. This is substantially less than the measured airborne chloride deposition rate of 609 mg/m^2/d recorded in this study. This indicates that an upper threshold for chloride deposition exists and on exceeding the threshold, the corrosion rate generally does not increase, which is similar to the results of Norberg *et al* (1996).

The environmental conditions present in the different subfloor enclosures varied significantly. Comparing the vent surface area (Table 1) to the environmental conditions (Table A1) indicated that a significant increase in the subfloor average humidity occurred as the surface area of the vent decreased. The average temperatures in the enclosures however, were generally less than outside conditions, by up to 2.7ºC and surprisingly, the subfloor temperature was not strongly influenced by the type of ventilation. The resulting environments in the four slot and post box slot enclosures were colder and recorded ToW periods exceeding 95% of the year. There were periods in these two enclosures where the surface would have remained continually wet for many days. The open-ended test facilities and the general atmospheric conditions generally recorded similar conditions, which indicates that the high air flow in the open enclosure maintained an equilibrium between that subfloor and the external environment.

The salt candle analysis provides a better understanding of the movement of aerosol salt in the subfloor. Table A2 shows that salt candles placed at the ends of the test facilities, nearest to the sea, provided the highest chloride concentrations, which exceeded 1100 $mg/m^2/d$ for the open-end test facility. The significant result was the 49% reduction in the chloride deposition rates half way along the 3.6m facility. This reduction can be accounted for by variations in the aerosol size, and a recent study in New Zealand (Walker *et al*, 1996) found that at the coast a fine aerosol and a coarse aerosol were present. They found that 40% of the aerosol was >7.20µm and 50% of the aerosol was between 0.49µm and 7.20µm. In previous studies, MacDonald (1982) in Walker *et al* (1996), noted that aerosols greater than 20 µm contributed only 13% of the total aerosol mass, but contributed 70% of the deposition. This indicates that large aerosols may constitute the majority of salt available for deposition.

The volume of air and the wind speed in the subfloor space will strongly influence the quantity of aerosol and the size of the aerosol present. If the vent reduces the wind speed or possibly introduces some turbulence, then the large aerosols would deposit in a relatively short distance from the vent. The enclosure and the vent may have an effect since Spence *et al* (1992) noted that the mass transport properties of the air and aerosol could be affected by resistance factors, which create friction and ultimately change a laminar flow into a turbulent flow, which results in significantly higher deposition rates of the salt. The present study found that from the front of the enclosure to the rear, a total of 3.6m, the average chloride deposition rate decreased from 1187 to 338 $mg/m^2/d$, a reduction of 72% (Table A2). This result accounts for the relatively high corrosion rate and chloride deposition rates found near the vent (Table A3), and the measured effect of varying the vent surface area (Figure 3). This effect was noted in a previous study in New Zealand by Holcroft (1996), where the subfloor space of a beach front building was inspected. A significant reduction in the corrosion present on the 40-year-old hot-dipped steel subfloor components was found, as the distance from the sea increased. It was also noted that the components nearest to the sea had already failed, with substantial flaking red rust present.

The comparison of coupons facing seaward and landward (Table A4) indicated that generally there was a small variation due to the orientation of the coupon, particularly for zinc, which compares favourably to a previous study by Cordner *et al* (1990).

The measured corrosion rates were generally very high, and in the open-ended facility the rate was in the range of 102 to 166 g/m^2/year. This rate would reduce the lifetime of typical hot-dip galvanised components (400 g/m^2 of zinc as per AS1650) to well below five years. In the slotted enclosures and Post Box slot enclosures, the corrosion rates were significantly lower, but would last perhaps 10 to 40 years respectively. This expectant life span is not the minimum 50 years as required by the NZBC. The estimates assume that the usual corrosion rate of zinc is linear from the first year, which is not valid for outdoor exposed zinc (Zoccola *et al* 1978). It may be valid for subfloor conditions considering the inability of the surface to be cleansed of the corrosion product or contaminating salt, which strongly influences corrosion rates.

It would be difficult to guarantee a 50-year life for hot-dip galvanised steel components used in the subfloor in severe marine environments in New Zealand, unless they were additionally protected in some other way. It follows that the use of stainless steel (type 304 or preferably 316) is worth considering as an alternative to galvanised steel for very severe coastal locations. If stainless steel were used, with a suitable maintenance/cleaning programme, the ventilation of the subfloor may be increased without compromising the connectors' durability, and subsequently gaining the benefits of a drier subfloor space. A solution, of course, is to minimize all ventilation but this will cause other problems to the timber foundations, such as increasing timber moisture content, increasing the potential for fungal decay, and rising damp. A method to reduce the ingress of moisture into the subfloor is to apply a damp-proof membrane (DPM), isolating the ground from the subfloor air space and reducing the ToW. This method does not isolate the foundations from the soil, which may cause the foundation uprights to become moisture wicks in the subfloor space. The balance between ventilation and using a DPM needs further investigation.

The three equations used to predict the performance of the galvanised steel components, although not designed for sheltered exposure, included ISO 9223, ISO CORRAG, and MICAT. In Table 2, the ISO 9223 methodology generally underestimated the corrosion rate, simply because of the limitations of the ISO 9223 classifications. The ISO 9223 procedure failed to sufficiently predict the corrosion rate where high humidity and high chloride deposition rates occurred.

The ISO CORRAG equation for flat zinc coupons (Table 3) is based on a substantial number of fully exposed studies and predicted the corrosion in the open-ended and the most shielded post box slot exposure quite well. The equation failed to predict the corrosion rate in the four slots (S4) vent enclosure. On reviewing Equation 2, the bias in the equation is placed on chloride deposition rather than ToW. The results obtained in this work indicate that high ToW levels and low chloride deposition rates, result in a high corrosion rate, which is an effect Guttman and Sereda (1968) noted. This again supports the concept that although corrosion rates can be increased with increasing chloride deposition rates, as noted by King *et al* (1995), there is a chloride deposition upper limit, above which corrosion rates do not increase. Significantly greater corrosion rates occur when ToW levels are increased in the presence of pollutants, such as sea salt.

The last predictive equation was the MICAT, which was based on South American data and failed to predict any of the results obtained empirically, as shown in Table 4.

The failure was due to an excessive reliance on ToW measurements and in fact the ToW for the sheltered subfloor spaces was extremely high and invalidated the equation.

5 Conclusions

The ISO 9223 and MICAT predictive corrosion rate equations (outdoor) failed to predict subfloor corrosion rates, but the ISO CORRAG (flat zinc) equation predicted two of the three environments. The results indicated that relatively high ToW levels and an upper limit to the chloride deposition rate may be the predominant factors in the corrosion of subfloor hardware, and controlling one or both will significantly reduce the corrosion rate.

Very good correlations between the corrosion rate of steel and zinc, a limited range of chloride deposition rates, and the size of subfloor vent areas were found for severe marine conditions and predictive equations were developed.

When the surface area of the vent to the subfloor was reduced, a very high ToW and a significant reduction in sea salt (chloride) deposition occurred. Salt deposition rates were reduced by 50 to 95% halfway (1.8m) along the length of enclosures, particularly with restricted ventilation levels. This is probably due to the early fallout of relatively large sea spray aerosols.

High corrosion rates were recorded in the severe marine subfloor conditions, which indicates that the life expectancy of galvanised steel structural components is less than the NZBC standard requirement of 50 years. The suggested remedies for this are: coat the galvanised steel with a barrier; use stainless steel (304 or 316); or possibly introduce a damp-proof membrane over the floor of the subfloor space, with some ventilation.

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6 References

AS1650 Standards Association of Australia, 1981, *Galvanised Coatings*, Sydney.

ASTM G1, 1981, *Recommended practice for preparing, cleaning and evaluating corrosion test specimens*, American Society for Testing and Materials, Philadelphia.

Ballance J.A., Duncan J.R., 1985, *Wind-borne transport of sea salt in New Zealand*, New Zealand Journal of Technology, Vol 1, Wellington, pp239-244.

Cole I.S., Norberg P., Ganther W.D.,1996, *Environmental factors promoting corrosion in building microclimates*, Proc13th International Corrosion Conference (ICC), Melbourne.

Cole I.S., Bradbury A., Neufeld A.K., Sherman N.,1996, *Response of galvanised steel, 55% aluminium zinc-coated steel and copper steel to well defined salt doses under controlled environments.*, Proc13th International Corrosion Conference (ICC), Melbourne.

Cordner R.J., Duncan J.R., Krouse D.P. ,1990, *Assessment of atmospheric corrosivity in Taranaki, New Zealand*, Corrosion Australasia, Vol 15, N01, pp11-13.

Cramer S., Carter J.P., Linstrom P.J., Flinn D.R., 1988. *Environmental effects in the atmospheric corrosion of zinc*, ASTM STP 965 Degradation of metals in the atmosphere, Eds Dean S.W., Lee T.S. American Society of Materials and Testing: Philadelphia, pp229-247.

Cramer S.D., Covino B.S., Holcomb G.R., 1996, *Cubic model describing the atmospheric corrosion of structural metals*, 13th International Corrosion Congress, Melbourne, Nov., pp32/1-8.

Duncan J. and Ballance J., 1988, *Marine Salts Contribution to Atmospheric Corrosion*, ASTM STP 965, Ed Dean S.W , American Society of Materials and Testing: Philadelphia, pp316-326

Duncan, J and Whitney, R, 1982, *Suggested zones of steel corrosion hazard in New Zealand atmospheres*. IPENZ Transactions, Vol 9. No 3, pp65-75.

Espada L., Vazquez M.E., Sanchez A., 1996, *Acid rain: It's influence on corrosion processes*, Proc. 13th International Corrosion Conference (ICC), Melbourne, Nov 1996, pp10/1-9.

Evans U.R., 1976, The corrosion and oxidation of metals, 2nd vol, Pub. Edward Arnold, London, p250.

Guttman H., Sereda P.J., 1968, *Measurement of atmospheric factors affecting the corrosion of metals*, ASTM STP 435 Metal corrosion in the atmosphere, Philadelphia, pp326-359.

Haynie F.H., 1980, *Theoretical air pollution and climate effects on materials confirmed by zinc corrosion data*, ASTM STP 691 Durability of building materials and components, Eds Sereda P.J., Litvan G.G., American Society of Materials and Testing: Philadelphia, pp 157-175.

Holcroft. G 1996 *An investigation of 62 coastal subfloors for fastener corrosion*, BRANZ Report No.72.

Hyland C.W.K., Enzensberger M.,1998, *Prediction of site-specific steel corrosion rates in New Zealand to assist coatings selection*, Proc. Australasian Structural Engineering, Auckland, NZ, pp835-842.

ISO9223 & 9225 International Organisation for Standardisation, 1992, *Corrosion of metals and alloys - corrosivity of atmospheres - classifications & measurement of pollution*, Geneva.

Kane C.D., 1995, *Atmospheric corrosion survey of New Zealand: Six year exposure results*, IPENZ Transactions, Vol 23, No.1, EMCh, Wellington, pp29-39.

King G.A. 1988, *A corrosivity survey on a grid of sites ranging from rural to moderately severe marine, Part 1*, Corrosion Australasia, Australasian Corrosion Association, Feb 1988, pp5-12.

King G.A., O'Brien 1995, *The influence of marine environments on metals and fabricated coated metal products, freely exposed and partially sheltered*, ASTM STP 1239 Atmospheric corrosion, Ed Kirk W.W. and Lawson H., American Society of Materials and Testing: Philadelphia, pp167-192.

Knotkova D., Boschek P., Kreislova K., 1995, *Results of ISO CORRAG program: Processing of one-year data in respect to corrosivity classification*, ASTM STP 1239 Atmospheric corrosion, Ed Kirk W.W. and Lawson H., American Society of Materials and Testing: Philadelphia, pp39-55.

Legault R.A., Pearson V.P., 1978, *Kinetics of the atmospheric corrosion of galvanized steel*, ASTM STP 646 Atmospheric factors affecting the corrosion engineering metals, Ed Coburn S.K. ASTM.

Haberecht P.W., Kane C.D., Meyer S.J., 1998, *Environmental corrosivity in New Zealand: Results after 10 years exposure*, submitted for publication.

Moricillo M., 1995, *Atmospheric corrosion in Ibero-America: The MICAT project*, ASTM STP 1239 Atmospheric corrosion, Ed Kirk W.W. and Lawson H., Philadelphia, pp257.

Morcillo M., Simancas J., Feliu S., 1995, *Long-term atmospheric corrosion in Spain: Results after 13-16 years of exposure and comparison with worldwide data*, ASTM STP 1239 Atmospheric corrosion, Ed Kirk W.W. and Lawson H., Philadelphia, pp316-326

Norberg P., King G.A., O'Brien D.J., 1996, *Corrosivity and microclimate measurements in open and sheltered marine environments*, Proc. 7DBMC, Stockholm, Sweden, Vol 2, pp181-190.

NZBC, 1992, Building Industry Authority, *New Zealand Building Code*, Wellington.

NZS 3604 Standards Association of New Zealand, 1990, *Code of Practice for Light Timber Frame Buildings Not Requiring Specific Design*, Wellington.

Pourbaix M.,1982, *The linear bilogarithmic law for atmospheric corrosion*, Ed. Ailor W.H., Atmospheric corrosion, John Wiley and sons, New York, pp107-121.

Summitt R., Fink F.T., 1982, *The USAF corrosion testing program and a corrosion severity index algorithm*, Ed. Ailor W.H., Atmospheric corrosion, John Wiley and sons, New York, pp245.

Spence J.W., Haynie F.H., Lipfert F.W., Cramer S.D., McDonald L.G., 1992, *Atmospheric corrosion model for galvanized steel structures*, Corrosion , Vol 48, No.12, NACE, Philadelphia, pp1009.

Walker C.F., Harvey M.J., Boyd I.S., 1996, *Background and urban aerosol chemistry in New Zealand*, National Institute for water and atmospheric research publication, Wellington, New Zealand.

Zoccola, J, Townsend, H, Borzillo, A and Horton, J, 1978, *Atmospheric corrosion behaviour of aluminium-zinc alloy-coated steel*, Atmospheric factors, ASTM STP 646, Philadelphia, pp165.

7 APPENDIX 1

Table A1: Summary of temperature and humidity results from the test site.

	OUTSIDE(1)	**OPEN ENDS**(2)	**FOUR SLOTS**(1)	**POST BOX SLOT**(1)
Max Temp	32.1	29.6	27.7	30.9
Min Temp	7.0	5.5	4.2	6.6
Average Temp	17.8	16.4	15.1	17.4
Temp Stdev	2.0	1.9	2.6	2.5
Average RH%	81.7	82.6	87.9	89.3
RH% Stdev	4.2	6.2	3.5	3.3
≥75% RH (Yr)	0.72	0.76	0.95	0.97
≥80% RH (Yr)	0.60	0.59	0.87	0.90

1) Excludes Jan Temp and all Feb results.
2) Excludes Jan Temp and all Feb results, Aug Temp and some % RH, Sept Temp and % RH.

Table A2: Complete results of salt deposition rates measured at Oteranga Bay.

Average Salt Deposition Rate mg/m^2/day	**HORIZONTAL PLATE**	**OPEN ENDS**	**FOUR SLOTS**	**POST BOX SLOT**
Seaward vent	--	1187	355	279
Seaward vent	--	1186	348	139
Middle of enclosure	--	609	26	10
Landward vent	--	338	21	6
Max deposition seaward end	2130 (May)	4187 (Jun)	1076 (Jun)	857 (Jun)
Min deposition seaward end	92 (Oct)	116 (Dec)	30 (Dec)	12 (Nov)
Horizontal plate average	790	--	--	--

Table A3: Corrosion rate of horizontal steel panels at 600mm spacings in various test facilities.

ENCLOSURE	**CORROSION RATE** (g/m^2/yr)							
	#1	#2	#3	#4	#5	#6	#7	***Average***
Open	2665	2081	1688	N/R	1525	1698	1309	1826
4 Slots	696	670	702	910	603	961	718	751
Post Box	670	605	440	400	447	335	409	472
Closed	206	140	125	220	134	243	318	198

N/R Not recorded

Table A4: Corrosion rate of vertical steel panels at the centre in various test facilities.

TEST COUPONS	**CORROSION RATE** (g/m^2/yr)			
	Open	4 Slots	Post Box	Closed
Steel: Vertical Facing seaward	1605	427	107	60
Steel: Vertical Facing landward	1595	330	124	20
Galvanised: Vertical Facing seaward	166	82	18	31
Galvanised: Vertical Facing landward	102	54	24	29