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Manual 6 – Embedded corrosion of fasteners in exposed timber structures

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MANUAL NO. 6

Embedded Corrosion of Fasteners in Timber Structures

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Acknowledgments

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Contents

Executive Summary

Service life is one of the most important considerations in the use of timber in construction. About 10 years ago, the Forestry and Wood Products Research and Development Corporation (FWPRDC), now Forest & Wood Products Australia (FWPA), initiated a major national project on the design for service life of timber structures. The intention was to develop procedures for assessing the service life of all types of timber construction located anywhere in Australia. A major part of this project was to develop prediction models for the attack of timber by decay fungi, termites, corrosion (for fasteners) and marine borers.

This Manual describes the development of the model to predict the corrosion of fasteners' part embedded in wood. The model was primarily developed based on expert opinions and data obtained from an extensive test program of about 70 nails embedded for 120 days in 15 different timber species and/or preservative treatments. The model was then fully developed so that it can be applied to all locations in Australia, and to numerous timber species used in practice. Checks and calibration of the model were then carried out with about 150 corrosion data of nails from a test of 2-year exposure of nail joints at various locations in 8 houses in VIC, NSW, and QLD; and with the results of a Lab study by BRANZ on corrosion of metallic fastener materials in Radiata pine untreated and treated with CCA.

From the predicted corrosion depth, the residual cross-sections of fasteners can be estimated. The strength predictions for the residual cross-sections can then be made. The strength predictions are in quantified form, and hence the model can be used for risk managements, cost-optimised design, engineering design, application to timber engineering standard, and manuals for good practice. For the major outputs of the project, the model is being used to develop a major part of an education software, a durability design guide, and a draft engineering code for timber durability design.

1. Model Equations

1.1 Introduction

This Section presents the final model and the calculation procedure for the design corrosion depths on embedded parts of metal fasteners, which can be used to estimate the corrosion depths for metal fasteners used in any timber construction located anywhere in Australia. Basis of the development of model equations will be given in Section 2. Then Section 3 will show how available data fit with the model.

1.2 Scope and Procedure

This Section provides the calculation procedures for the design corrosion depths on metal fasteners' parts that are tightly embedded in wood, such as the shank of nails, screws, and nailplate's teeth, as depicted in Figure 1.2.1.

To evaluate the design corrosion depths, the timber acidity class and hazard zone of the structure location are obtained from Section 1.2.1. Timber moisture content is estimated from Section 1.2.2. The mean corrosion depth is then estimated using the procedure in Section 1.2.3 for fasteners embedded in untreated wood, and Section 1.2.4 for fasteners embedded in CCA-treated wood. The design corrosion depths are then determined in Section 1.2.5.

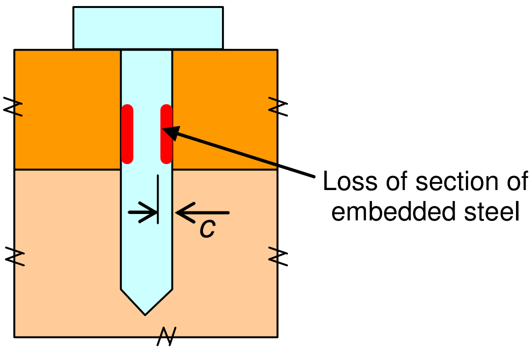


Figure 1.2.1 Embedded corrosion depth

1.3 Timber Acidity Classification and Hazard zones

Durability classification of timber is listed in Section 2.3.

The hazard zone map is shown in Figure 1.3.1. Three hazard zones and their representative mean annual surface equilibrium moisture content $SEMC_{mean}$ and the boundary $SEMC_{mean}$ are in Table 1.3.1.

Table 1.3.1 Effective $SEMC_{mean}$ values for the 3 hazard zones

Zone	$SEMC_{mean}$
A	9
B	12
C	15

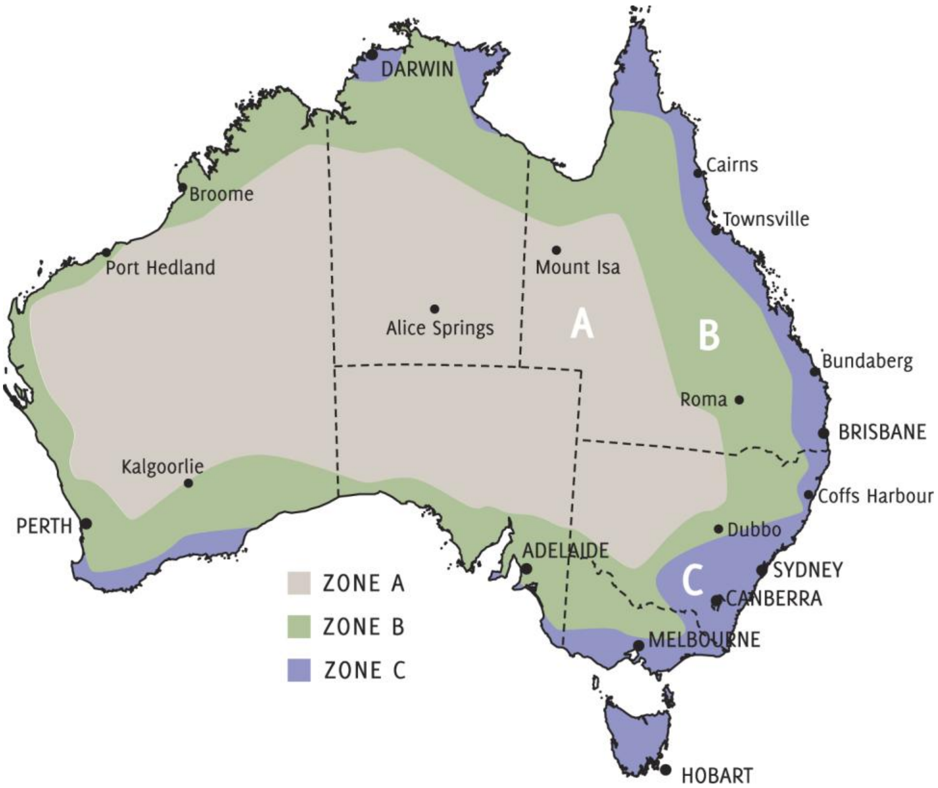


Figure 1.3.1 Embedded corrosion hazard zone map. Zone C is most hazardous.

1.4 Moisture Content of Timber

The mean annual surface equilibrium moisture content, $SEMC_{mean}$, is given in Table 1.3.1, depending on hazard zones. The mean seasonal moisture content of a piece of timber, TM_{mean} for one year is estimated as,

$$TM_{mean} = exp(1.9 + 0.05\ SEMC_{mean}) \tag{1.4.1}$$

The mean and maximum seasonal moisture contents of timber in building, BTM_{max} and BTM_{mean}, are:

$$BTM_{\text{mean}} = TM_{\text{mean}} + \Delta_{\text{climate}} + \Delta_{\text{rain}} \tag{1.4.2}$$

$$BTM_{\text{max}} = BTM_{\text{mean}} + 0.1\ D\ TM_{\text{mean}} \tag{1.4.3}$$

where the damping factor *(D)*, the adjustment factors for the climate (Δ_{climate}) are given in Tables 1.4.1. The adjustment factor for rain (Δ_{rain}) is given in Table 1.4.2.

Table 1.4.1 Damping factor and adjustment factor for climate

Climate zone	***D***	$\mathbf{\Delta_{climate}}$
Marine*	6.0	2.5
Other	2.0	0.5

* Marine: if the distance to coast < 1 km

Table 1.4.2 Adjustment factor Δ_{rain}

Outdoor (Facades)	$\mathbf{\Delta_{rain}}$		
	Hazard zone A	**Hazard zone B**	**Hazard zone C**
Sheltered / partly sheltered from rain	0	1	2
Vertical surface exposed to rain	1	4	8
Horizontal surface exposed to rain	3	9	17

Note: For corrosion of bolt's shank (see Section 2.5), this factor is increased by 1.5 times.

1.5 Corrosion Depth of embedded fasteners in untreated wood

For the case of untreated wood, corrosion depth for the first year (μm), c_o is computed as follows,

$$c_o = \frac{1}{2}\left[f_{120}(BTM_{max}) + 0.3 f_{120}(BTM_{mean})\right] \tag{1.5.1}$$

where $f_{120}(M)$ is the corrosion depth of connectors embedded in untreated wood for 120 days, given as a function of timber moisture content M (%),

$$f_{120}(M) = \begin{cases} 0 & \text{if } M \le M_0; \\ 0.2\ C_{120}(M - M_0) & \text{if } M_0 < M < (M_0 + 5\%); \\ C_{120} & \text{if } M \ge (M_0 + 5\%) \end{cases} \tag{1.5.2}$$

The function is illustrated in Figure 1.5.1. Values of C_{120} and M_0 are listed in Table 1.5.1 depending on the timber acidity class and timber type.

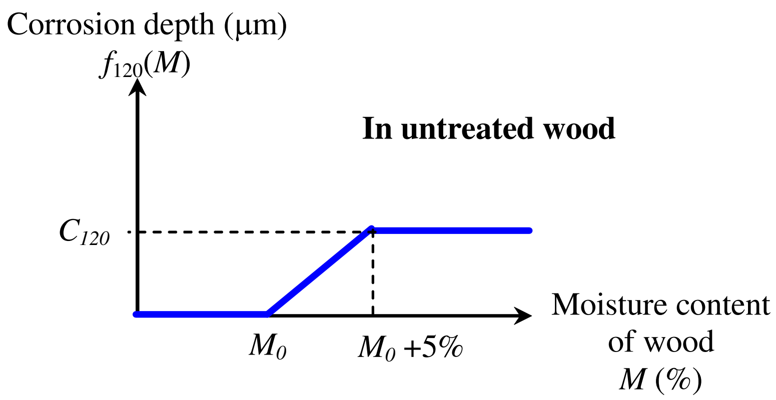


Figure 1.5.1. Base model of embedded corrosion in untreated wood.

Table 1.5.1 Parameters of the corrosion model of embedded fasteners in untreated wood

Material	Wood type	C_{120}			M_0 (%)
		Acidity class 1	Acidity class 2	Acidity class 3	
Zinc	Hardwood	2.0	7.0	12.0	10
	Softwood	4.0	5.0	6.0	15
Steel	Hardwood	2.0	8.0	14.0	15
	Softwood	2.0	6.0	10.0	15

The corrosion depth of embeeded fasteners in untreated wood, c, over the period t years is computed by

$$c = c_o\, t^n \tag{1.5.3}$$

where n= 0.5 for zinc and n = 0.6 for steel.

1.6 Corrosion Depth of Embedded Fasteners in CCA treated wood

For the case of CCA-treated wood, corrosion depth for the first year (mm), c_o is computed as follows,

For zinc $$c_o = 1.3 f_{120}(BTM_{mean}) \tag{1.6.1}$$

For steel $$c_o = 2.1 f_{120}(BTM_{mean}) \tag{1.6.2}$$

where $f_{120}(M)$ is the corrosion depth of connectors embedded in CCA-treated wood for 120 days, given by

$$f_{120}(M) = \begin{cases} 0 & \text{if } M \le M_0; \\ 0.7\ (M - M_0) & \text{if } M > M_0; \end{cases} \tag{1.6.3}$$

where M is moisture content, M_0 = 12%. The function is illustrated in Figure 1.6.1.

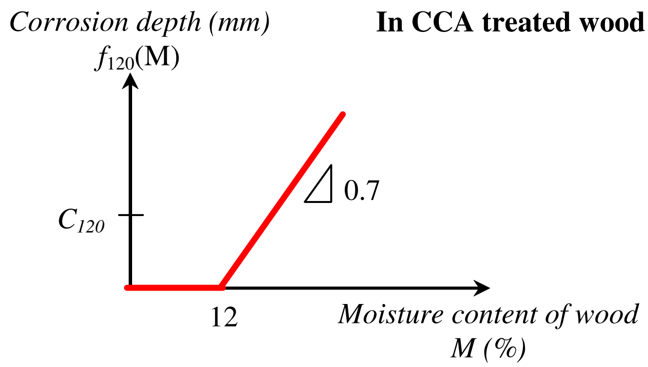


Figure 1.6.1. Base model of embedded corrosion in CCA-treated wood.

The corrosion depth of embedded fasteners in CCA-treated wood, c, over the period t years is computed by

$$c = c_o\, t^n \tag{1.6.4}$$

where n= 0.6 for zinc and n = 1.0 for steel.

1.7 Design Depth of Embedded Corrosion

The design depth of embedded corrosion, c_{design} will be given by

$$c_{design} = c\left(1+\alpha V_c\right) \tag{1.7.1}$$

where

- c is the mean depth of the loss in fastener cross-section due to embedded corrosion, computed by Eq.(1.5.3) or Eq.(1.6.4) for a chosen design life time.
- V_c is the coefficient of variation of c. From available data, it is recommended that V_c = 2.0.
- α is specified parameter related to the target reliability level.
  - α = 0.8 for normal consequence of failure elements.
  - α = 0.4 for low consequence of failure elements.

From the design depth of embedded corrosion, the residual cross-section is estimated; from which engineers compute the acceptable design load capacity by normal AS1720.1 procedure.

1.8 Corrosion of Bolts

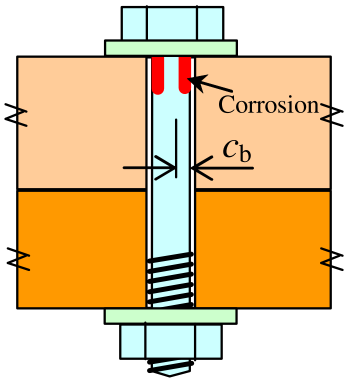


Figure 1.8.1 Depth of corrosion at the neck of the bolt

It is known that bolted joints can form a very special case of embedded fastener, because they are often placed in oversized holes pre-drilled into the timber, thus allowing moisture/water, salt and oxygen to enter, a situation that does not occur with other fasteners. To provide some sort of indication of the corrosion of bolts, an assumption is made that the worst corrosion occurs near the neck of the bolt, and this is either due to the embedded corrosion mechanism that is enhanced by water ingress into the bolt's hole; or due to atmospheric corrosion that is enhanced if the connector is near a beach. The procedures are as follows,

- To compute the corrosion depth due to the embedded corrosion, follow the procedure in Sections 1.2 to 1.7, with a modification that the adjusted factor Δ_{rain} (Table 1.4.2) is multiplied by factor of 1.5 to take into account the increasing of timber moisture content due to water ingress into the bolt's holes.
- To compute of the corrosion depth due to atmospheric corrosion that is enhanced if the connector is near a beach, follow the procedure in Manual No.5.

The corrosion depth c_b near the neck of the bolt is taken to be the higher of these two computed corrosion values.

2. Basis of Model Development

2.1 Introduction

This Chapter presents the basis of the development of the corrosion model for embedded part of fasteners (embedded corrosion) in wood. There are 2 main parameters contributing to the extent of the embedded corrosion in wood: (1) Timber moisture content, and (2) Acidity of wood or preservative used. These 2 main parameters will be addressed in the followings.

2.2 Timber Moisture Content model and Hazard Zones

2.2.1 Surface Equilibrium Moisture Content of Timber

The surface equilibrium moisture content (*SEMC*) for a given temperature and humidity is calculated according to Bramhall's equation (Siau, 1995) as follows:

$$SEMC = \frac{\log_e\left[\dfrac{\log_e(H/100) - 0.0251}{17.884 + 0.0002362(T+273)^2 - 0.1432(T+273)}\right]}{0.92 \times \log_e\left[1.0327 - 0.000674(T+273)\right]} \qquad (2.2.1.1)$$

where

T = the dry bulb temperature (C°)
H = relative humidity (%)

The *SEMC* can be calculated with time, using data from a nearby Bureau of Meteorology station, and then be averaged to obtain $SEMC_{\mathrm{mean}}$, the mean annual value of the *surface* moisture contents. This parameter will be used as the main parameter to predict the timber moisture content with a model developed in Section 2.3.

2.2.2 Hazard Zones and Climate Zones

2.2.2.1 Hazard zones

To simplify the calculation procedure, 3 hazard zones, namely A, B and C; are created as shown in Fig. 2.2.2.1. This original map is plotted from the computed $SEMC_{\mathrm{mean}}$ from weather data measured at hundreds of Bureau of Meteorology (BOM) stations across Australia, with an adjustment due to the simplification of the climate zones. The adjustment has been made to the tropical areas, which have latitudes less than 23˚ S, where the $SEMC_{\mathrm{mean}}$ data was increased 1% to compensate for using the simplified values of $\Delta_{\mathrm{microclimate}}$ for climate zone 'other', ie. non-marine, as in Table 2.4.3.3. This will be defined as the *Effective* $SEMC_{\mathrm{mean}}$. The simplified climate zonation is presented in the next section.

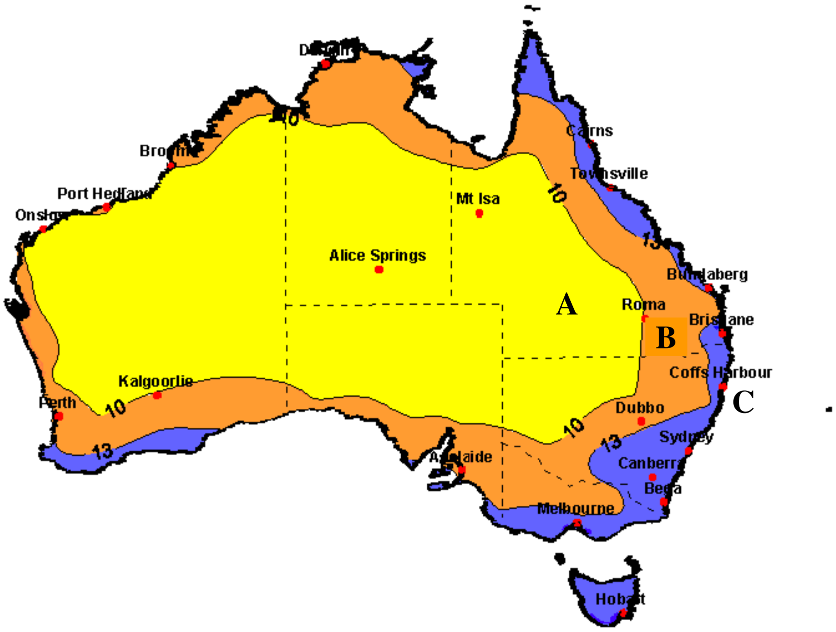


Figure 2.2.2.1. 'Original' hazard zone map based on $SEMC_{mean.}$

Furthermore, expert opinions (MacKenzie) suggested that zone C should not be cut out along the coast near Brisbane. Figure 2.2.2.2 is the modified map currently used. The modification was made by adjusting the $SEMC_{\mathrm{mean}}$ at Gympie (BOM data point C62) from 12.38% to 13%. The boundary and the zone effective $SEMC_{\mathrm{mean}}$ values are in Table 2.2.2.1.

Table 2.2.2.1 Effective $SEMC_{mean}$ values for the 3 hazard zones

Zone	**Zone effective $SEMC_{mean}$**	**Effective $SEMC_{mean}$ used for boundary**
A	9	
		10
B	12	
		13
C	15	

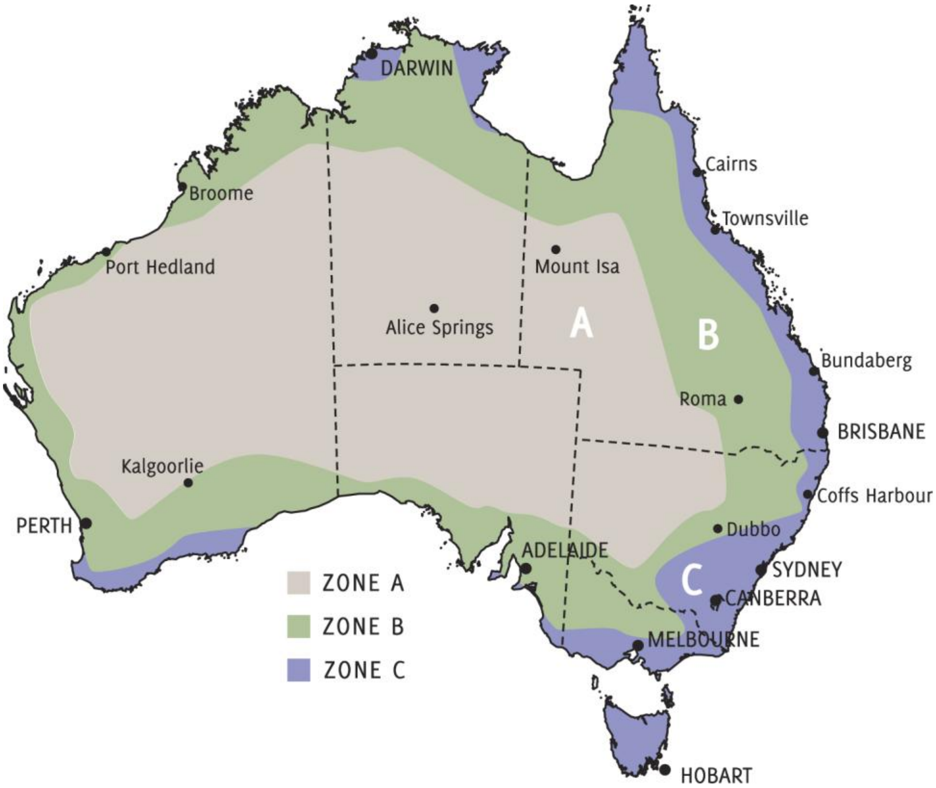


Figure 2.2.2.2. Hazard zone map

2.2.2.2 Climate Zones

In the early model presented in Appendix C, there were 6 climate zones, which were:

- Defined with a quite complicated procedure to determine the zone of a site
- Assigned with different values of many factors relating to climate and microclimate.

However, we noted that the factors relating to climate and microclimate were very rough estimates which were about right for some tested houses/sites only. And as long as we are only interested in the model for façade/exposed structures, significant differences of the values of these factors are only found between 'Marine' zone and the rest. Therefore, we simplified the climate zonation by defining only 2 climate zones:

- Marine: if the distance to coast < 1 km
- Other, ie. non-marine

The factors relating to climate and microclimate are also simplified, as listed in the next section.

2.2.3 Timber Moisture Content

The early model for moisture content of timber is presented in Appendix C, which was developed based on a test program presented in Cole et.al. (1996a, 1996b, 1999), Ganther & Cole (2000), and Cole (private communication and internal reports). A summary of the test program is provided in Section 3.1. In 2002, based on expert opinions from Mackenzie (2000), we modified the model with another factor Δ_{rain} to take into account the orientation and sheltering effects of the structures. The modified model in 2002 is presented in Appendix D.

This section presents the final model to estimate the moisture content of the timber. Borrowing some ideas of simplification made for the development of the Score System presented in Appendix A, the 2002 timber moisture content model in Appendix D is further simplified, as presented in the followings.

The mean and the maximum seasonal moisture contents of a piece of timber for one year as follows,

$$TM_{mean} = exp[1.9 + 0.05\ SEMC_{mean}] \quad (2.2.3.2)$$

$$TM_{max} = 1.1\ TM_{mean} \quad (2.2.3.3)$$

where TM_{max} = the maximum value out of the four *TM* seasonal values of moisture content in a piece of timber for one year, TM_{mean} = the mean annual value of timber moisture content. The mean surface equilibrium moisture content, $SEMC_{mean}$, can be computed from BOM data as in Section 2.2.1; or taken the representative value of the hazard zone given in Section 2.2.2. The constants '1.9' and '0.05' are the average of '*A*' and '*B'* in Table D.4.3.2, which is now can be taken out as *A* and *B* do not vary much with wood types. The simplification led to Eq.(2.2.3.3) is as in the derivation of the Score System presented in Appendix A.

The maximum and mean seasonal moisture contents of timber *in building*, BTM_{max} and BTM_{mean}, are:

$$BTM_{\mathrm{mean}} = TM_{\mathrm{mean}} + \Delta_{\mathrm{climate}} + \Delta_{\mathrm{rain}} \quad (2.2.3.4)$$

$$BTM_{\mathrm{max}} = BTM_{\mathrm{mean}} + D\left[TM_{\mathrm{max}} - TM_{\mathrm{mean}}\right] \approx BTM_{\mathrm{mean}} + 0.1\ D\ TM_{\mathrm{mean}} \quad (2.2.3.5)$$

where the damping factor *(D)*, the adjustment factors for the climate ($\Delta_{\mathrm{climate}}$) are given in Tables 4.4.3.2. The adjustment factor for rain (Δ_{rain}) is given in Table 4.4.3.3.

It is noted that compared with the earlier versions of the model (Appendices C and D), we decided to split the embedded corrosion model into 2 separate parts: one for exposed structures and one for structures within a building envelope. All model components related to the building envelope, i.e. roof space, sub-floor, and wall-cavity are therefore taken out of the model herein. The model for building envelope is developed in Manual No. 9 (Nguyen et.al. 2008b).

Table 2.2.3.1 Mean surface equilibrium moisture content

Hazard zone	$SEMC_{mean}$
A	9
B	12
C	15

Table 2.2.3.2 Damping factor and adjustment factor for climate and micro-climate

Climate zone	*D*	$\Delta_{climate}$
Marine	6.0	2.5
Other	2.0	0.5

Table 2.2.3.3 Adjustment factor Δ_{rain}

Outdoor (Facades)	Δ_{rain}		
	Hazard zone A	**Hazard zone B**	**Hazard zone C**
Sheltered / partly sheltered from rain	0	1	2
Vertical surface exposed to rain	1	4	8
Horizontal surface exposed to rain	3	9	17
Note: For corrosion of bolt's shank (see Section 2.5), this factor is increased by 1.5 times.			

2.3 Timber Acidity Classification

2.3.1 Timber Acidity

In this model it will be assumed that the corrosion of untreated timber is related to the acidity of timber, defined as (7− pH), where pH is the acidity of free water in contact with the wood. This is a new concept, and is introduced to make the design procedure more widely applicable. Acidity is used as the basis of the corrosion model since it is the most easily accessible parameter for corrosion of metal in contact with wood. It can be readily measured, and in fact measured values are available for a large number of timber species.

A collection of acidity values derived from CSIRO measurements and reports by Davis (1994) and Bootle (1983) are listed in Table C.2.1, Appendix C. It should be borne in mind that although the measurement of wood acidity is quick, simple and straightforward it does show considerable variability from piece to piece, and within the same piece of timber.

2.3.2 Timber Classification

Figure 2.3.1 presents the distribution of the recommended pH values for design of all species listed in Table C.2.1. From the figure, the acidity classification of timber is established according to the pH of the species, as defined in Table 2.3.1.

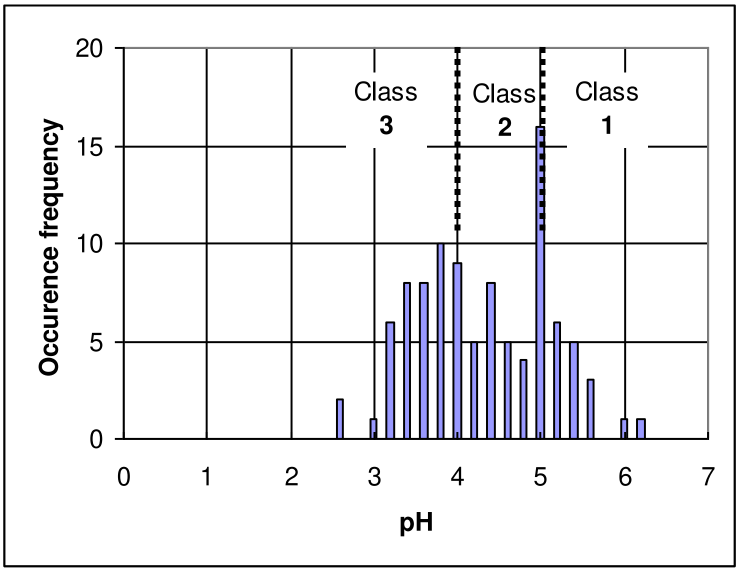


Figure 2.3.1 Histogram of pH values of all species in Table C.2.1 and Natural Acidity Classification.

Table 2.3.1 Natural acidity classification and representative pH values

Acidity Class	Representative pH value	Boundary pH value
1	5.5	
		5.0
2	4.5	
		4.0
3	3.5	

The species, which were either from Thornton's table (Thorton *et al.* 1997) or TRADAC table (TRADAC 1999) are listed in Table 2.3.3. The pH value of some species in this list has been tested and available from Table C.2.1 in Appendix C, and also listed in Table 2.3.3 as 'Measured pH'.

Figure 2.3.2 shows the Natural Acidity Class versus the density of the tested species divided into 3 groups: Eucalyptus, Non-Eucalyptus Hardwood and Softwood. The density is seasoned one determined at 12% moisture content. It can be seen that the acidity class is not in good correlation with the density of timber.

Therefore, to determine the acidity class of *untested* species in the list, it is assumed that the natural acidity class depends on the types of timber, which are divided into Eucalypts, Non-Eucalypt Hardwoods, and Softwoods. Summary of the simplified classification and representative pH values for untested species are in Table 2.3.2. Table 2.3.3 presented the acidity class of timber.

Table 2.3.2 Acidity Classification according to Types of Wood

Type of Wood	Acidity Class	Representative pH
Eucalypts	3	3.5
Non-Eucalypt Hardwoods	2	4.5
Softwoods	2	4.5

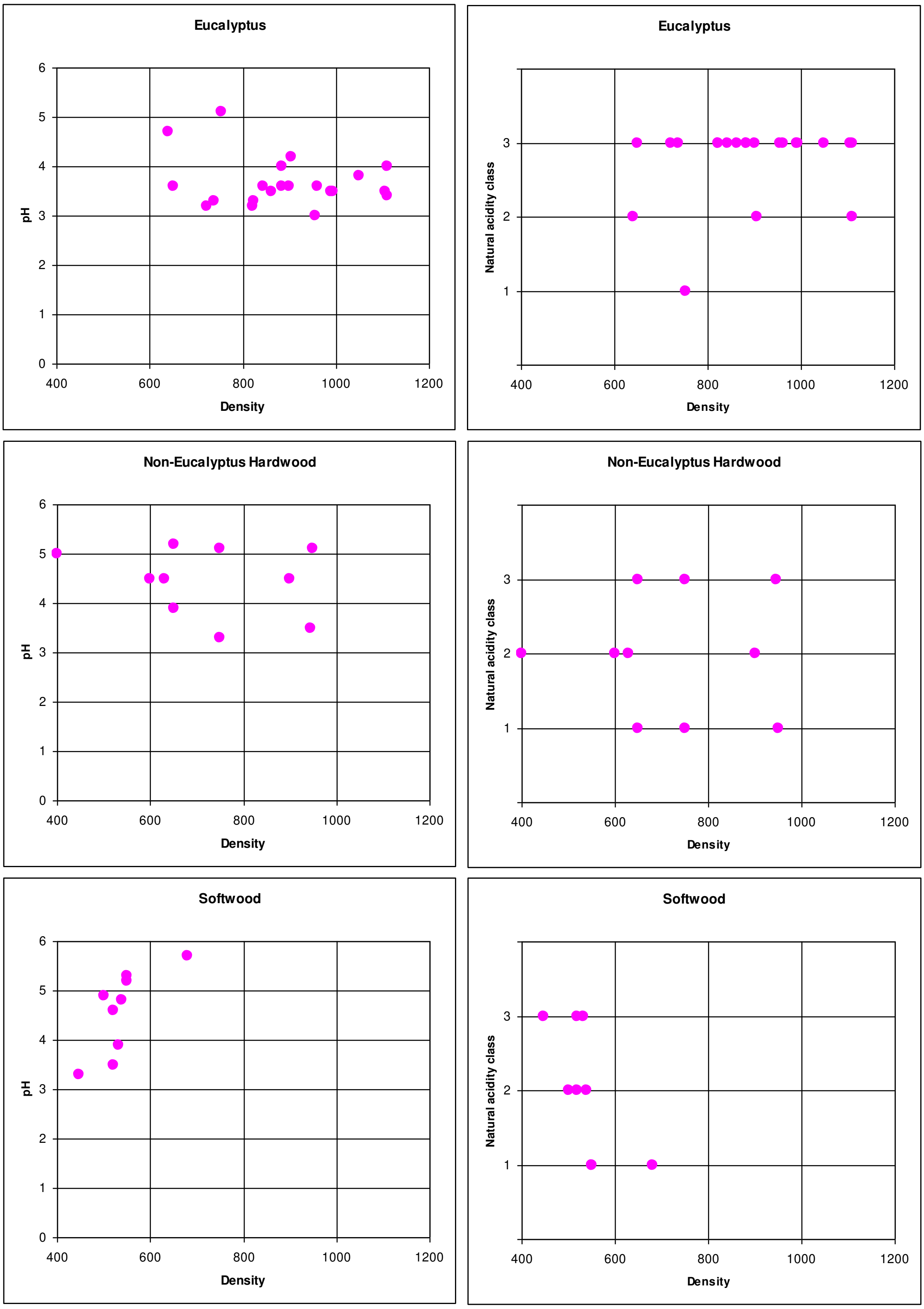


Figure 2.3.2. Design pH and acidity class versus density of tested species grouped into Eucalyptus, Non-Eucalyptus Hardwood, and Softwood – Data from Table 2.3.3.

Table 2.3.3 Natural acidity Classification

Standard Australia index	Trade name	Botanical name	Type	Density	Measured pH	Natural acidity class
22	Ash, alpine	Eucalyptus delegatensis	E	650	3.6	3
25	Ash, Crow's	Flindersia australis	H	950	5.1	1
30	Ash, mountain	Eucalyptus regnans	E	640	4.7	2
37	Ash, silvertop	Eucalyptus sieberi	E	862	3.5	3
-	Balau (selangan batu)	Shorea spp.	H	900	-	2
-	Bangkirai	Shorea laevifolia	H	850	-	2
65	Beech, myrtle	Nothofagus cunninghamii	H	705	-	2
-	Belian (ulin)	Eusideroxylon zwageri	H	1000	-	2
84	Blackbutt	Eucalyptus pilularis	E	884	3.6	3
86	Blackbutt, New England	Eucalyptus andrewsii	E	850	-	3
87	Blackbutt, WA	Eucalyptus patens	E	849	-	3
88	Blackwood	Acacia melanoxylon	H	650	-	2
97	Bloodwood, red	Corymbia gummifera	E	900	3.6	3
90	Bloodwood, white	Corymbia trachyphloia	E	1023	-	3
109	Bollywood	Litsea reticulata	S	532	3.9	3
121	Box, brush	Lophostemon confertus	H	900	4.5	2
126	Box, grey	Eucalyptus moluccana	E	1105	3.5	3
127	Box, grey, coast	Eucalyptus bosistoana	E	1110	3.4	3
134	Box, long leaved	Eucalyptus goniocalyx	E	873	-	3
138	Box, red	Eucalyptus polyanthemos	E	1064	-	3
144	Box, steel	Eucalyptus rummeryi	E	0	-	3
145	Box, swamp	Lophostemon suaveolens	H	850	-	2
150	Box, yellow	Eucalyptus melliodora	E	1075	-	3
148	Box,white	Eucalyptus albens	E	1112	-	3
162	Brigalow	Acacia harpophylla	H	1099	-	2
165	Brownbarrel	Eucalyptus fastigata	E	738	3.3	3
167	Bullich	Eucalyptus megacarpa	E	640	-	3
-	Calantas (kalantas)	Toona calantas	H	500	-	2
178	Candlebark	Eucalyptus rubida	E	750	-	3
73	Cedar, red, western	Thuja plicata	S	448	3.3	3
544	Cypress	Callitris glaucophylla	S	680	5.4	1
114	Fir, Douglas	Pseudotsuga menziesii	S	520	3.5	3
253	Gum, blue, southern	Eucalyptus globulus	E	900	-	3
254	Gum, blue, Sydney	Eucalyptus saligna	E	843	3.6	3
266	Gum, grey	Eucalyptus propinqua	E	1050	3.8	3
267	Gum, grey, mountain	Eucalyptus cypellocarpa	E	961	3.6	3
268	Gum, Maiden's	Eucalyptus maidenii	E	992	-	3
269	Gum, manna	Eucalyptus viminalis	E	814	-	3
272	Gum, mountain	Eucalyptus dalrympleana	E	700	-	3
281	Gum, red, forest	Eucalyptus tereticornis	E	737	4.2	2
281	Gum, red, river	Eucalyptus camaldulensis	E	913	-	3
284	Gum, rose	Eucalyptus grandis	E	753	5.1	1
286	Gum, salmon	Eucalyptus salmonophloia	E	1070	-	3
288	Gum, scribbly	Eucalyptus haemastoma	E	907	-	3
289	Gum, shining	Eucalyptus nitens	E	530	-	3
293	Gum, spotted	Corymbia maculata	E	988	4.5	2
294	Gum, sugar	Eucalyptus cladocalyx	E	1105	-	3
305	Gum, yellow	Eucalyptus leucoxylon	E	1008	-	3
310	Hardwood, Johnstone	Backhousia bancroftii	H	950	-	2

	River					
-	Hemlock, western	Tsuga heterophylla	S	500	4.9	2
322	Ironbark, grey	Eucalyptus paniculata	E	1110	4.0	3
325	Ironbark, red	Eucalyptus sideroxylon	E	1086	-	3
326	Ironbark, red (broad-leaved)	Eucalyptus fibrosa	E	1116	-	3
327	Ironbark, red (narrow-leaved)	Eucalyptus crebra	E	1046	4.0	3
336	Ironwood Cooktown	Erythrophleum chlorostgchys	H	1220	-	2
340	Jam, raspberry	Acacia acuminata	H	1038	-	2
341	Jarrah	Eucalyptus marginata	E	823	3.3	3
-	Kapur	Dryobalanops spp.	H	750	3.3	3
344	Karri	Eucalyptus diversicolor	E	905	4.2	2
	Keruing	Dipterocarpus spp.	H	750	5.1	1
173	Kwila	Intsia bijuga	H	825	-	2
-	Mahogany, Philippine, red, dark	Shorea spp.	H	650	-	2
-	Mahogany, Philippine, red, light	Shorea, Pentacme, Parashorea spp.	H	550	-	2
384	Mahogany, red	Eucalyptus resinifera	E	955	3.0	3
391	Mahogany, white	Eucalyptus acmenoides	E	993	3.5	3
391	Mahogany, white	Eucalyptus umbra	E	887	-	3
387	Mahonany, southern	Eucalyptus botryoides	E	919	-	3
411	Mallet, brown	Eucalyptus astringens	E	974	-	3
432	Marri	Corymbia Calophylla	E	855		3
-	Meranti, red, dark	Shorea spp.	H	650	3.9	3
-	Meranti, red, light	Shorea spp.	H	400	5.0	2
226	Mersawa (Garawa)	Anisoptera thyrifera	H	630	4.5	2
434	Messmate	Eucalyptus obliqua	E	722	3.2	3
435	Messmate, Gympie	Eucalyptus cloeziana	E	996	-	3
458	Oak, bull	Allocasuarina luehmannii	H	1050	-	2
240	Oak, white, American	Quercus alba	H	750	-	2
509	Peppermint, black	Eucalyptus amygdalina	E	753	-	3
510	Peppermint, broad leaved	Eucalyptus dives	E	811	-	3
512	Peppermint, narrow leaved	Eucalyptus radiata	E	822	3.2	3
515	Peppermint, river	Eucalyptus elata	E	804	-	3
529	Pine, black	Prumnopitys amara	S	500	-	2
533	Pine, caribbean	Pinus caribaea	S	550	3.9	3
534	Pine, celery-top	Phyllocladus asplenifolius	S	646	-	2
545	Pine, hoop	Araucaria cunninghamii	S	550	5.2	1
546	Pine, Huon	Lagarostrobos franklinii	S	520	4.6	2
548	Pine, kauri	Agathis robusta	S	503	-	2
549	Pine, King William	Athrotaxis selaginoides	S	400	-	2
559	Pine, radiata	Pinus radiata	S	540	4.8	2
561	Pine, slash	Pinus elliotii	S	650	-	2
-	Ramin	Gonystylus spp.	H	650	5.2	1
326	Redwood	Sequoia sempervirens	S	400	-	2
332	Rosewood, New Guinea	Pterocarpus indicus	H	577	-	2
635	Satinay	Syncarpia hillii	H	838	-	2
668	Stringybark, Blackdown	Eucalyptus sphaerocarpa	E	1000	-	3
671	Stringybark, brown	Eucalyptus capitellata	E	838	-	3

676	Stringybark, red	Eucalyptus macrorhyncha	E	899	-	3
680	Stringybark, white	Eucalyptus eugenioides	E	856	-	3
681	Stringybark, yellow	Eucalyptus muelleriana	E	884	4	3
688	Tallowwood	Eucalyptus microcorys	E	990	3.5	3
-	Taun	Pometia pinnata	H	700	-	2
369	Teak, Burmese	Tectona grandis	H	600	4.5	2
713	Tingle, red	Eucalyptus jacksonii	E	772	-	3
714	Tingle, yellow	Eucalyptus guilfoylei	E	900	-	3
720	Tuart	Eucalyptus gomphocephala	E	1036	-	3
723	Turpentine	Syncarpia glomulifera	H	945	3.5	3
747	Wandoo	Eucalyptus wandoo	E	1099	-	3
774	Woolybutt	Eucalyptus longifolia	E	1068	-	3
780	Yate	Eucalyptus cornuta	E	1100	-	3
788	Yertchuk	Eucalyptus consideniana	E	939	-	3

2.4 Model Equations of Embedded Corrosion

The initial model for embedded corrosion was presented in Appendix C, which was developed based on a test program of nail's embedded corrosion in 120 days provided by Cole et.al. (internal communication & lab reports). In 2002, based on some expert opinions from Mackenzie (2000), we modified the model, particularly with reduced 120-day corrosion for metal embedded in acidity class 3 timber. The modified model in 2002 is presented in Appendix D.

The final model presented in this section is made with some further simplifications and modifications to the earlier versions of the model. The simplifications and modifications are based on

- revisiting 120-day corrosion data
- calibrating to BRANZ test data (Kear et.al. 2006)
- calibrating to 2-year embedded corrosion of nail in-service

Summary of the tests and fittings of the model prediction to the tests' data are presented in Chapter 3.

2.4.1 The Base Model of Embedded corrosion in untreated wood

The corrosion depth of connectors embedded in untreated wood subjected to 120-day corrosion, $f_{120}(M)$, is:

$$f_{120}(M) = 0 \qquad \text{if } M < M_o \qquad (2.4.1.1)$$

$$f_{120}(M) = 0.2\, C_{120}\, (M - M_o) \qquad \text{if } M_o < M < (M_o + 5\%) \qquad (2.4.1.2)$$

$$f_{120}(M) = C_{120} \qquad \text{if } M \geq (M_o + 5) \qquad (2.4.1.3)$$

where M is moisture content. The function is illustrated in Figure 2.4.1.1. Table 2.4.1.1 gives parameters of the model. Compared to the model in 2002 (Appendix D), the following revisions have been made, based on a review of data from nails embedded in timber for 120 days and checks with other sources of data (see Chapter 3):

- A ramp has put into f_{120} function from M_0 to (M_0 +5%)
- Parameter M_0 for steel in softwood is reduced from 20% to 15%

- Parameters C120 are refined and can be estimated from wood pH by the following linear functions
  - For zinc in hardwood,
    $C_{120} = 5.0(7.0 - \text{pH}) - 5.5$ (2.4.1.4)
  - For zinc in softwood,
    $C_{120} = (7.0 - \text{pH}) + 2.5$ (2.4.1.5)
  - For steel in hardwood,
    $C_{120} = 6.0\,(7.0 - \text{pH}) - 7.0$ (2.4.1.6)
  - For steel in softwood,
    $C_{120} = 4.0\,(7.0 - \text{pH}) - 4.0$ (2.4.1.7)

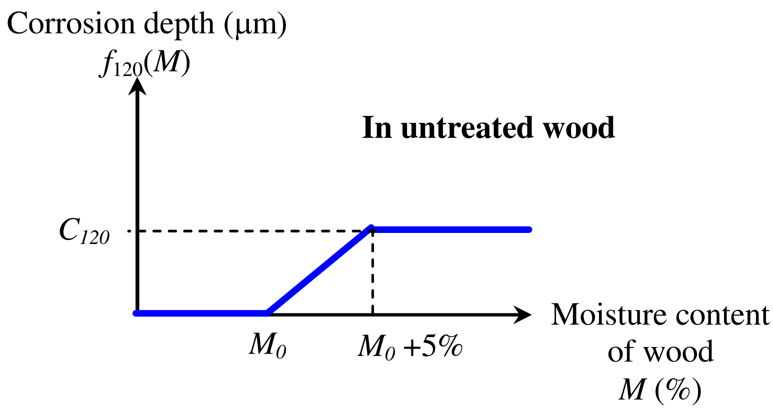


Figure 2.4.1.1. Base model of embedded corrosion in untreated wood.

Table 2.4.1.1 Parameters of the corrosion model of embedded fasteners in untreated wood

Material	Wood type	C_{120}			M_0 (%)
		Acidity class 1	Acidity class 2	Acidity class 3	
Zinc	Hardwood	2.0	7.0	12.0	10
	Softwood	4.0	5.0	6.0	15
Steel	Hardwood	2.0	8.0	14.0	15
	Softwood	2.0	6.0	10.0	15

2.4.2 The Base Model of Embedded Corrosion in CCA treated wood

The base model, ie. the model for 120-day corrosion, for both steel and zinc connectors embedded in CCA treated wood is given by:

$f_{120}(M) = 0$ if $M < 12$ (2.4.2.1)

$f_{120}(M) = 0.7\,(M\text{-}12)$ if $M \geq 12$ (2.4.2.2)

where M is moisture content. The function is illustrated in Figure 2.4.2.1. Compared to the 2002's model (Appendix D), the following revision are made

- The same base model are used for steel and zinc
- Wood moisture content threshold of the onset of corrosion is revised to 12%

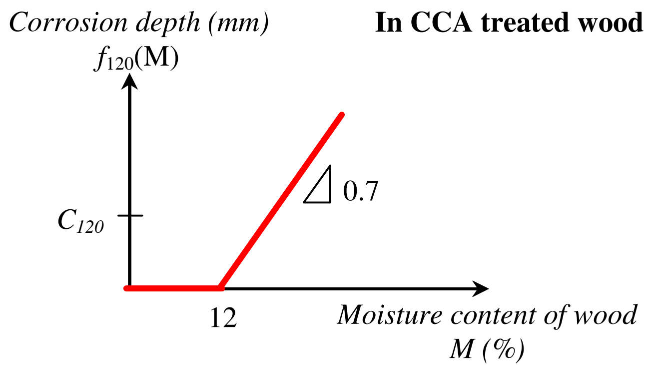


Figure 2.4.2.1. Base model of embedded corrosion in CCA-treated wood.

The revision was made to reflect the findings of BRANZ study (Kear et.al. 2006), where steel corrosion was found consistently higher than zinc corrosion after one year embedded in CCA-treated wood. The base models used in 2002's model (Appendix D), however, contradicted to this observation. Revisiting the 120-day corrosion data (see Section 3.3), we see that corrosion of both zinc and steel are more or less at the same rate at 120 days. We therefore made the revision, ie. using the same base model of zinc and steel in CCA-treated wood. The fitting of the revised base model to the 120-day data is presented in Section 3.3.

2.4.3 Corrosion Depth

The corrosion depth, c, over the period t years is given by

$$c = c_o\, t^n \qquad (2.4.3.1)$$

where c_o is the corrosion rate (μm/year), or more precisely, the corrosion depth for the first year. For fasteners embedded in untreated wood, n= 0.5 for zinc and n = 0.6 for steel. For fasteners embedded in CCA-treated wood, n= 0.6 for zinc and n= 1.0 for steel. This revised long-term effect of CCA-treated wood is based on the understanding that the corrosion product does not reduce much the corrosion progress caused by chemical agent of CCA in the treated wood, as it does in untreated wood, particularly for steel.

From the check with data of 2-year corrosion of embedded nail in timber joint exposed to in-service condition presented in Section 3.1, we found that the 2002's model very much over-predicted the mean measured corrosion (and actually predicted reasonably the worst 10-percentile of the measured corrosion). The 2002's model prediction appeared to be about twice the mean measured corrosion. For better match with reality, we decided to reduce the corrosion rate by a factor of 2. The corrosion rate c_o the becomes

For the case of untreated wood:

$$c_o = \frac{1}{2}\left[f_{120}(BTM_{max}) + 0.3 f_{120}(BTM_{mean})\right] \qquad (2.4.3.2)$$

For the case of treated wood:

- For zinc $c_o = 1.3 f_{120}(BTM_{mean})$ (2.4.3.3)
- For steel $c_o = 2.1 f_{120}(BTM_{mean})$ (2.4.3.4)

where f_{120} is defined by Eqs. (2.4.1.1) and (2.4.1.2) for untreated wood case and Eqs.(2.4.2.1) to (2.4.2.2) for CCA treated wood case. It is noted that the corrosion rate of steel is revised to be approximately 1.6 times the corrosion for zinc. This factor of 1.6 can be derived from equation (2.4.3.1), and is also supported by BRANZ tests data, as presented in Section 3.2. The modification for steel corrosion model in treated wood are based on the conclusion of the BRANZ study, where the zinc coatings were consistently shown to be more durable than mild steel in all tests. This behaviour, however, was not observed clearly in the 120-day embedded test as plotted in Figures 3.3.5 and 3.3.6. This was may be due to the duration of test, which was not long enough for the protective effects of zinc corrosion product to work.

2.5 Design Corrosion Depths

2.5.1 Coefficient of variation

The coefficient of variation of corrosion depths, V_c, is determined from the model predictions and measurements of corrosion depths given in the fittings/checks in Chapter 3. From the comparision of the corrosion depths that resulted from the measurement (c_m) with the model-prediction corrosion depths (c_p), log-normal distributions are assumed for the uncertainties of the predicted and measured corrosion depths over time. This leads to the coefficient of variation of the corrosion depth, denoted by V_c, evaluated as follows (Ang & Tang, 2006),

$$V_c = \sqrt{e^{\sigma^2} - 1} \tag{2.5.1.1}$$

in which

$$\sigma^2 = \frac{1}{n-2} \sum \left(\ln c_m - \ln c_p \right)^2 \tag{2.5.1.2}$$

where c_m is the measured corrosion depth, c_p is the predicted corrosion depth, and n is the number of data points. The values of V_c thus obtained from the checks with 2-year embedded nails *individual* data in Chapter 3. The results are listed in Table 2.5.1.1,

Table 2.5.1.1. Coefficient V_c for embedded corrosion model

Data Group	V_c
Marine sites – all steel and zinc	2.6
Non-marine sites – all steel and zinc	1.9
All data, both zinc and steel	2.0

For the Engineering Code, the coefficient V_c for the whole model is set to be 2.0.

2.5.2 Design Corrosion Depths

The design depth of embedded corrosion, c_{design} will be given by

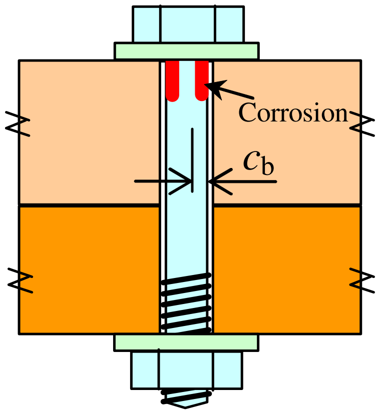
$$c_{design} = c\left(1 + \alpha V_c\right) \qquad (2.5.2.1)$$

where

- c is the mean depth of the loss in fastener cross-section due to embedded corrosion, computed by equations given in Section 2.4.3.
- V_c is the coefficient of variation of c, presented in Section 2.5.1.
- α is specified parameter related to the target reliability level.
    - $\alpha = 0.8$ for normal consequence of failure elements.
    - $\alpha = 0.4$ for low consequence of failure elements.

From the design depth of embedded corrosion, the residual cross-section is estimated; from which engineers compute the acceptable design load capacity by normal AS1720.1 procedure. Refer Manual No.2 (Leicester et.al. 2008) for the derivation of the design corrosion depth.

2.6 Corrosion of Bolts



It is known that bolted joints can form a very special case of embedded fastener, because they are often placed in oversized holes pre-drilled into the timber, thus allowing moisture/water, salt and oxygen to enter, a situation that does not occur with other fasteners. To provide some sort of indication of the corrosion of bolts, an assumption is made that the worst corrosion occurs near the neck of the bolt, and this is either due to the embedded corrosion mechanism that is enhanced by water ingress into the bolt's hole; or due to atmospheric corrosion that is enhanced if the connector is near a beach. The procedures are as follows,

- To compute the corrosion depth due to the embedded corrosion, follow all the steps in the procedure presented in Chapter 1. To consider the enhancing effect by water ingress into the bolt's hole, the rain factor Δ_{rain} given in Table 1.4.2 is multiplied with a factor of 1.5.
- To compute of the corrosion depth due to atmospheric corrosion that is enhanced if the connector is near a beach, see Section 5.4 in Manual No. 5 (Nguyen et.al. 2008a).

The corrosion depth c_b near the neck of the bolt is taken to be the higher of these two computed corrosion values.

It is noted that from calculation results, the corrosion at bolt's necks/shanks appeared to be governed by atmospheric corrosion in most cases. Details of the computed corrosion depth due to atmospheric corrosion that is enhanced if the connector is near a beach are presented in Section 5.4 of Manual 5 (Nguyen et.al. 2008a).

3. Data Fittings

3.1 Fittings & calibration with data of 2-year embedded nails exposed to in-service conditions

The check and calibration of the model is made using data of corrosion on embedded nails, which were derived from the results of 2-year exposure of nail joints at various locations in 8 houses in VIC, NSW, and QLD (Cole et.al., 1996a, 1996b, 2001, Ganther et.al. , 2000, 2001).

All 8 houses were located in hazard zone C on the embedded corrosion hazard zone map. The data for Marine climate zone are from the two houses at Harbord (distance to coast = 0.6km) and Narrabeen (distance to coast = 0.1km). The data for Non-marine climate zone are from the rest, including the houses at Innisfail 1, Innisfail 2, Mt Buller, Naranderra, Pennant Hills, and The Gap 18. The nail joints were exposed to 4 microclimates, including outdoor/exterior, roof space, sub-floor, and wall cavities. Timbers tested are of many species/types, which are grouped into the following types:

- CCA treated pine: includes those described as ‘Treated pine’, ‘H3’, ‘H5’
- LOSP treated pine
- Eucalypts: Mountain Ash, Spotted Gum
- Hardwood: Brush Box
- Softwood: Radiata Pine, Douglas Fir
- Plywood

The nail joint test specimens consisted of pieces of the timbers 35 mm wide x 20 mm deep x 200 mm long. Each piece had the ends sealed with epoxy resin which was cured before assembly. There were 4 types of commonly available nails used in the test; hot dip galvanised 41 mm long, zinc plated 31 mm long, blue processed nails 40 mm long and uncoated bright nails 30 mm long with square copper nails used in some exposures. Processed nails are bright nails covered with a light polymeric film. The details on nail dimensions are given in Table 3.1.1. The test specimens were constructed by nailing two pieces of each wood along its length on the 35 mm flat with 3 samples of each type of nail. The separation between each nail was at least 15 mm, allowing 12 nails per wood type, arranged in two offset lines. Figure 3.1.1 shows the typical nail joint specimen exposed to in-service conditions.

Figure 3.1.1. *Exposed nail joint specimens on façade (left) and in subfloor (right)*

Table 3.1.1. *Nail dimensions*

Nail type	Section type	Shank length (mm)	Diameter (mm)	Coating thickness (μm)	Shank surface area
Copper	square	29.59	1.94	--	237
Copper, long	square	51.30	2.55	--	523
Hot dipped	round	39.3	2.40	111	296
Zinc Plate	round	30.34	1.49	23	142
Process	round	40.6	1.90		242
Bright	round	28.5	1.94	--	190
Bright, long	round	39.28	1.95	--	244

The test specimens were exposed for 2 years (or as close to 2 years as practical). Specimens exposed on the facade of buildings were in general placed approximately 0.4-0.8 metres below the eaves so that they were sheltered from both direct sunlight and direct rain. If it was not possible to expose specimens under eaves an artificial shelter was constructed. Specimens exposed in the sub-floor were generally exposed in a position a significant distance (more than 2 m) away from any wall and were hung on wire from the floor joists so that they were midway between joist and earth. Specimens exposed in wall cavities were placed in the cavity above the sub-floor and thus were in general less than 0.5 m from the bottom of the cavity.

After exposure the nail joint specimens were returned to the laboratory and the nails were extracted, assessed for extent of corrosion. The corrosion product was removed by cleaning in acid to determine mass loss of the nails in g/year/m^2. One-year-corrosion depth on the nail shank then can be estimated as follows,

$$\textit{One year corrosion depth}\ [\mu\text{m/year}] = \frac{\textit{Mass loss}\ [\text{g/year/m}^2]}{\textit{Density}\ [\text{g/m}^2/\mu\text{m}]}$$

where the density of zinc is 7.1 g/cm^3 (7.1 g/m^2/μm), density of steel is 7.7 g/cm^3 (7.7 g/m^2/μm).

3.1.1 Predictions using the 2002's model

Figure 3.1.1.1 presents the checks, where the predictions were made by 2002's model in Appendix D. As the result, the predictions overestimate the mean measurement.

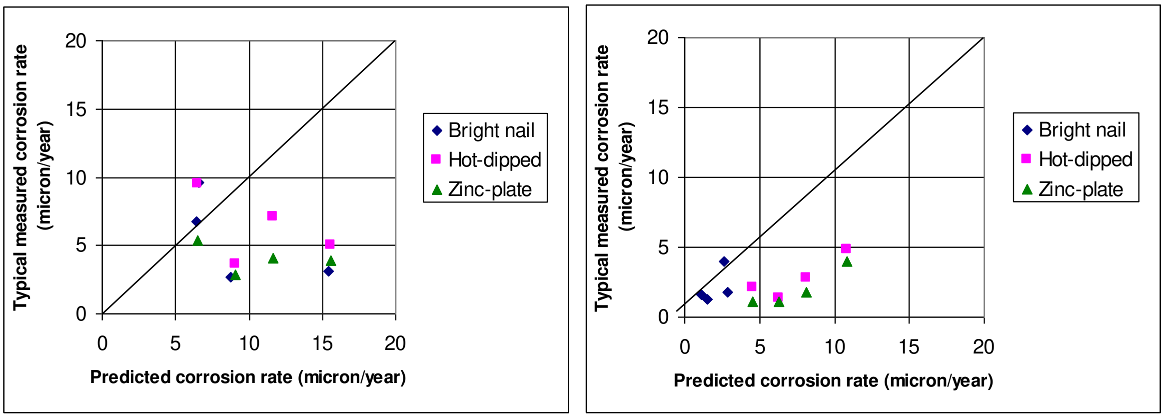
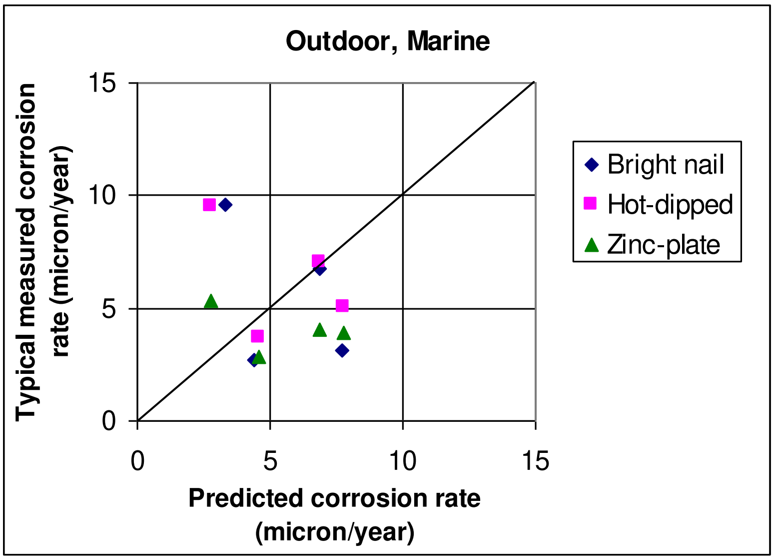


Figure 3.1.1.1 Checks with 2-year embedded nails data outdoor using 2002's model . Left: Marine sites, Right: Non-marine sites

3.1.2 Predictions of the nail corrosion in joints exposed outdoor using the current model

Figure 3.1.2.1 presents the checks, where the prediction were made by the final model in Chapter 1, i.e. with the reduced factor of 2 for the corrosion rate and revised corrosion rate for steel in CCA-treated timber, as explained in Chapter 2. As the result, the predictions reasonably agree with the mean measurements. Note that the measured data are group-average data.

Figure 3.1.2.2 presents the same checks, but using individual measured data. This comparison between prediction and measurement data is used to estimate the coefficient of variation as presented in Section 2.5.1. The data are in Table 3.1.2.1 and 3.1.2.2 (Cole, private communication and internal reports).



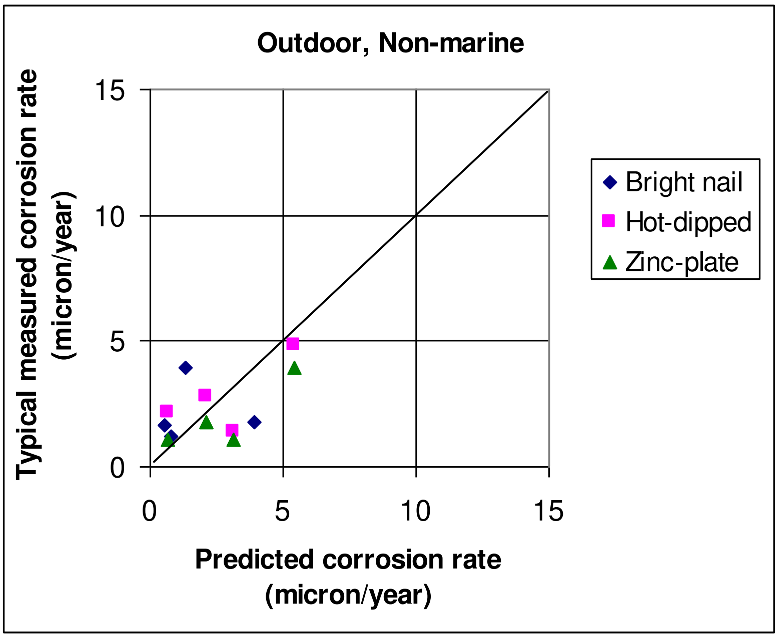
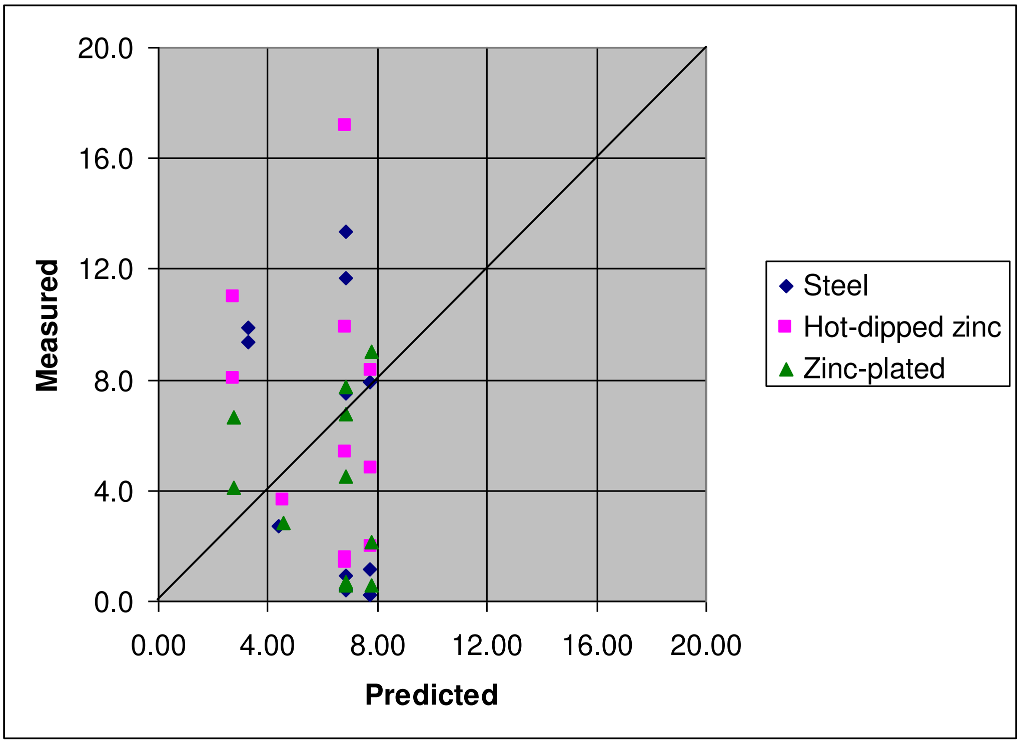


Figure 3.1.2.1 Checks with outdoor 2-year embedded nails group-averaged data using the current model . Top: Marine sites, Bottom: Non-marine sites



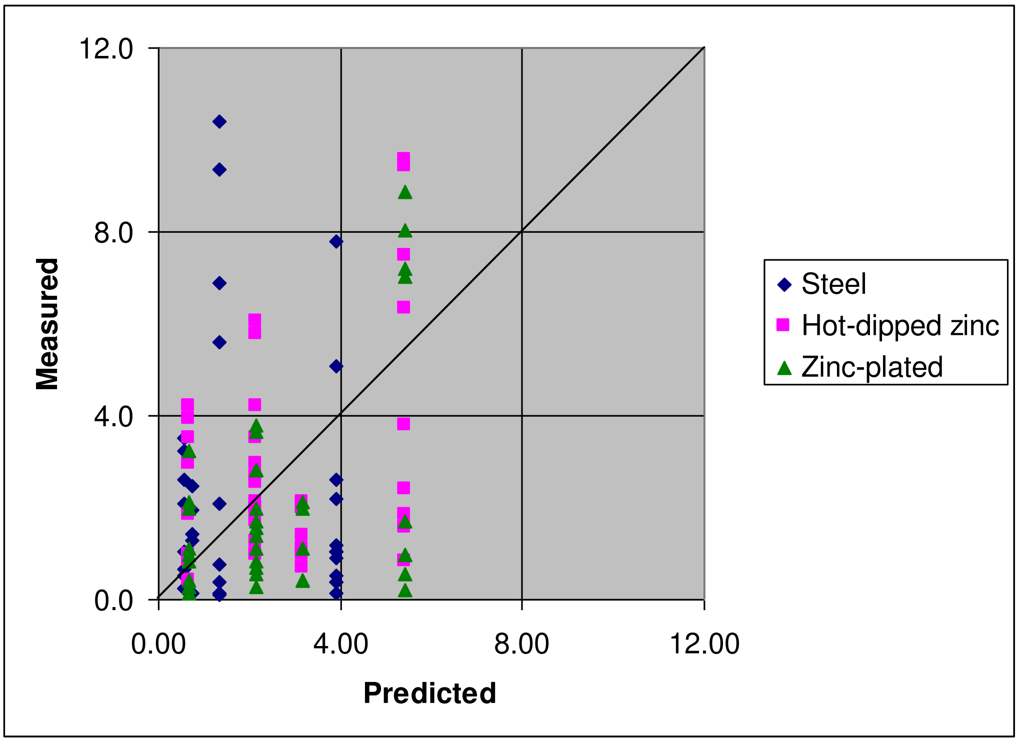


Figure 3.1.2.2 Checks with *outdoor* 2-year embedded nails individual data using the current model. Top: Marine sites, Bottom: Non-marine sites

Table 3.1.2.1 Check with individual data of 2-year embedded nails *outdoor* – Marine sites

Site	SEMC mean	SEMC max	Hazard Zone	Climate zone	Nail	Timber	Wood Type	MassLoss $g/m^2/yr$	1-year Corrosion Depth (micron)	Prediction 2007
Harbord	15.41	16.227	C	Marine	bright	H3	CCA	3	0.4	6.84
Narrabeen	15.454	16.284	C	Marine	bright	H3	CCA	58	7.5	6.84
Harbord	15.41	16.227	C	Marine	bright	H5	CCA	7	0.9	6.84
Narrabeen	15.454	16.284	C	Marine	bright	H5	CCA	103	13.4	6.84
Narrabeen	15.454	16.284	C	Marine	bright	Treated Pine	CCA	90	11.7	6.84
Harbord	15.41	16.227	C	Marine	bright	Mountain Ash	E	2	0.3	7.69
Narrabeen	15.454	16.284	C	Marine	bright	Mountain Ash	E	61	7.9	7.69
Narrabeen	15.454	16.284	C	Marine	bright	Spotted Gum	E	9	1.2	7.69
Narrabeen	15.454	16.284	C	Marine	bright	Brush Box	H	21	2.7	4.40
Narrabeen	15.454	16.284	C	Marine	bright	Douglas Fir	S	76	9.9	3.30
Narrabeen	15.454	16.284	C	Marine	bright	Radiata Pine	S	72	9.4	3.30
Harbord	15.41	16.227	C	Marine	hot dip	H3	CCA	10	1.4	6.84
Narrabeen	15.454	16.284	C	Marine	hot dip	H3	CCA	38	5.4	6.84
Harbord	15.41	16.227	C	Marine	hot dip	H5	CCA	11	1.5	6.84
Narrabeen	15.454	16.284	C	Marine	hot dip	H5	CCA	70	9.9	6.84
Narrabeen	15.454	16.284	C	Marine	hot dip	Treated Pine	CCA	122	17.2	6.84
Harbord	15.41	16.227	C	Marine	hot dip	Mountain Ash	E	34	4.8	7.80
Narrabeen	15.454	16.284	C	Marine	hot dip	Mountain Ash	E	59	8.3	7.80
Narrabeen	15.454	16.284	C	Marine	hot dip	Spotted Gum	E	14	2.0	7.80
Narrabeen	15.454	16.284	C	Marine	hot dip	Brush Box	H	26	3.7	4.55
Narrabeen	15.454	16.284	C	Marine	hot dip	Douglas Fir	S	57	8.0	2.75
Narrabeen	15.454	16.284	C	Marine	hot dip	Radiata Pine	S	78	11.0	2.75
Harbord	15.41	16.227	C	Marine	zinc plate	H3	CCA	5	0.7	6.84
Narrabeen	15.454	16.284	C	Marine	zinc plate	H3	CCA	32	4.5	6.84
Harbord	15.41	16.227	C	Marine	zinc plate	H5	CCA	4	0.6	6.84
Narrabeen	15.454	16.284	C	Marine	zinc plate	H5	CCA	48	6.8	6.84
Narrabeen	15.454	16.284	C	Marine	zinc plate	Treated Pine	CCA	55	7.7	6.84
Harbord	15.41	16.227	C	Marine	zinc plate	Mountain Ash	E	15	2.1	7.80
Narrabeen	15.454	16.284	C	Marine	zinc plate	Mountain Ash	E	64	9.0	7.80
Narrabeen	15.454	16.284	C	Marine	zinc plate	Spotted Gum	E	4	0.6	7.80
Narrabeen	15.454	16.284	C	Marine	zinc plate	Brush Box	H	20	2.8	4.55
Narrabeen	15.454	16.284	C	Marine	zinc plate	Douglas Fir	S	29	4.1	2.75
Narrabeen	15.454	16.284	C	Marine	zinc plate	Radiata Pine	S	47	6.6	2.75

Table 3.1.2.2 Check with individual data of 2-year embedded nails *outdoor* – Non-Marine sites

Site	SEMC-mean	SEMC-max	Hazard Zone	Climate zone	Nail	Timber	Wood Type	Mass Loss g/m2/yr	Measured 1-year Corrosion Depth (μm)	Model-Prediction corrosion depth (μm)
Innisfail 1	17.3	18.4	C	Non-marine	bright	H3	CCA	3	0.4	3.90
Innisfail 2	17.3	18.4	C	Non-marine	bright	H3	CCA	20	2.6	3.90
Mt Buller	15.8	19.5	C	Non-marine	bright	H3	CCA	39	5.1	3.90
Naranderra	18.1	22.5	C	Non-marine	bright	H3	CCA	8	1.0	3.90
Pennant Hills	15.0	15.7	C	Non-marine	bright	H3	CCA	4	0.5	3.90
Innisfail 1	17.3	18.4	C	Non-marine	bright	H5	CCA	7	0.9	3.90
Innisfail 2	17.3	18.4	C	Non-marine	bright	H5	CCA	8	1.0	3.90
Mt Buller	15.8	19.5	C	Non-marine	bright	H5	CCA	17	2.2	3.90
Naranderra	18.1	22.5	C	Non-marine	bright	H5	CCA	3	0.4	3.90
Pennant Hills	15.0	15.7	C	Non-marine	bright	H5	CCA	8	1.0	3.90
Innisfail 1	17.3	18.4	C	Non-marine	bright	Treated Pine	CCA	9	1.2	3.90
Mt Buller	15.8	19.5	C	Non-marine	bright	Treated Pine	CCA	60	7.8	3.90
Naranderra	18.1	22.5	C	Non-marine	bright	Treated Pine	CCA	8	1.0	3.90
The Gap 18	15.3	16.0	C	Non-marine	bright	Treated Pine	CCA	1	0.1	3.90
Innisfail 1	17.3	18.4	C	Non-marine	bright	Mountain Ash	E	53	6.9	1.32
Innisfail 2	17.3	18.4	C	Non-marine	bright	Mountain Ash	E	72	9.4	1.32
Naranderra	18.1	22.5	C	Non-marine	bright	Mountain Ash	E	6	0.8	1.32
Pennant Hills	15.0	15.7	C	Non-marine	bright	Mountain Ash	E	1	0.1	1.32
Innisfail 1	17.3	18.4	C	Non-marine	bright	Spotted Gum	E	80	10.4	1.32
Innisfail 2	17.3	18.4	C	Non-marine	bright	Spotted Gum	E	43	5.6	1.32
Mt Buller	15.8	19.5	C	Non-marine	bright	Spotted Gum	E	16	2.1	1.32
Pennant Hills	15.0	15.7	C	Non-marine	bright	Spotted Gum	E	0.9	0.1	1.32
The Gap 18	15.3	16.0	C	Non-marine	bright	Spotted Gum	E	3	0.4	1.32
Innisfail 1	17.3	18.4	C	Non-marine	bright	Brush Box	H	11	1.4	0.75
Innisfail 2	17.3	18.4	C	Non-marine	bright	Brush Box	H	15	1.9	0.75
Mt Buller	15.8	19.5	C	Non-marine	bright	Brush Box	H	19	2.5	0.75
Naranderra	18.1	22.5	C	Non-marine	bright	Brush Box	H	1	0.1	0.75
Pennant Hills	15.0	15.7	C	Non-marine	bright	Brush Box	H	10	1.3	0.75
The Gap 18	15.3	16.0	C	Non-marine	bright	Brush Box	H	1	0.1	0.75
Innisfail 1	17.3	18.4	C	Non-marine	bright	Douglas Fir	S	8	1.0	0.57
Innisfail 2	17.3	18.4	C	Non-marine	bright	Douglas Fir	S	16	2.1	0.57
Mt Buller	15.8	19.5	C	Non-marine	bright	Douglas Fir	S	27	3.5	0.57
Naranderra	18.1	22.5	C	Non-marine	bright	Douglas Fir	S	2	0.3	0.57
Pennant Hills	15.0	15.7	C	Non-marine	bright	Douglas Fir	S	2	0.3	0.57
The Gap 18	15.3	16.0	C	Non-marine	bright	Douglas Fir	S	2	0.3	0.57
Innisfail 1	17.3	18.4	C	Non-marine	bright	Radiata Pine	S	27	3.5	0.57
Innisfail 2	17.3	18.4	C	Non-marine	bright	Radiata Pine	S	20	2.6	0.57
Mt Buller	15.8	19.5	C	Non-marine	bright	Radiata Pine	S	25	3.2	0.57
Naranderra	18.1	22.5	C	Non-marine	bright	Radiata Pine	S	5	0.6	0.57
The Gap 18	15.3	16.0	C	Non-marine	bright	Radiata Pine	S	4	0.5	0.57

Table 3.1.2.2 (cont) Check with individual data of 2-year embedded nails *outdoor* – Non-Marine sites

Site	SEMC-mean	SEMC-max	Hazard Zone	Climate zone	Nail	Timber	Wood Type	Mass Loss g/m2/yr	Measured 1-year Corrosion Depth (μm)	Model-Prediction corrosion depth (μm)
Innisfail 1	17.3	18.4	C	Non-marine	hot dip	H3	CCA	14	2.0	2.14
Innisfail 2	17.3	18.4	C	Non-marine	hot dip	H3	CCA	25	3.5	2.14
Mt Buller	15.8	19.5	C	Non-marine	hot dip	H3	CCA	41	5.8	2.14
Naranderra	18.1	22.5	C	Non-marine	hot dip	H3	CCA	14	2.0	2.14
Pennant Hills	15.0	15.7	C	Non-marine	hot dip	H3	CCA	12	1.7	2.14
Innisfail 1	17.3	18.4	C	Non-marine	hot dip	H5	CCA	21	3.0	2.14
Innisfail 2	17.3	18.4	C	Non-marine	hot dip	H5	CCA	19	2.7	2.14
Mt Buller	15.8	19.5	C	Non-marine	hot dip	H5	CCA	30	4.2	2.14
Naranderra	18.1	22.5	C	Non-marine	hot dip	H5	CCA	9	1.3	2.14
Pennant Hills	15.0	15.7	C	Non-marine	hot dip	H5	CCA	7	1.0	2.14
Innisfail 1	17.3	18.4	C	Non-marine	hot dip	Treated Pine	CCA	18	2.5	2.14
Mt Buller	15.8	19.5	C	Non-marine	hot dip	Treated Pine	CCA	43	6.1	2.14
Naranderra	18.1	22.5	C	Non-marine	hot dip	Treated Pine	CCA	15	2.1	2.14
The Gap 18	15.3	16.0	C	Non-marine	hot dip	Treated Pine	CCA	7	1.0	2.14
Innisfail 1	17.3	18.4	C	Non-marine	hot dip	Mountain Ash	E	45	6.3	5.42
Innisfail 2	17.3	18.4	C	Non-marine	hot dip	Mountain Ash	E	53	7.5	5.42
Naranderra	18.1	22.5	C	Non-marine	hot dip	Mountain Ash	E	13	1.8	5.42
Pennant Hills	15.0	15.7	C	Non-marine	hot dip	Mountain Ash	E	17	2.4	5.42
Innisfail 1	17.3	18.4	C	Non-marine	hot dip	Spotted Gum	E	68	9.6	5.42
Innisfail 2	17.3	18.4	C	Non-marine	hot dip	Spotted Gum	E	67	9.4	5.42
Mt Buller	15.8	19.5	C	Non-marine	hot dip	Spotted Gum	E	27	3.8	5.42
Pennant Hills	15.0	15.7	C	Non-marine	hot dip	Spotted Gum	E	5.9	0.8	5.42
The Gap 18	15.3	16.0	C	Non-marine	hot dip	Spotted Gum	E	11	1.5	5.42
Innisfail 1	17.3	18.4	C	Non-marine	hot dip	Brush Box	H	8	1.1	3.16
Innisfail 2	17.3	18.4	C	Non-marine	hot dip	Brush Box	H	15	2.1	3.16
Mt Buller	15.8	19.5	C	Non-marine	hot dip	Brush Box	H	7	1.0	3.16
Naranderra	18.1	22.5	C	Non-marine	hot dip	Brush Box	H	10	1.4	3.16
Pennant Hills	15.0	15.7	C	Non-marine	hot dip	Brush Box	H	14	2.0	3.16
The Gap 18	15.3	16.0	C	Non-marine	hot dip	Brush Box	H	5	0.7	3.16
Innisfail 1	17.3	18.4	C	Non-marine	hot dip	Douglas Fir	S	25	3.5	0.66
Innisfail 2	17.3	18.4	C	Non-marine	hot dip	Douglas Fir	S	21	3.0	0.66
Mt Buller	15.8	19.5	C	Non-marine	hot dip	Douglas Fir	S	21	3.0	0.66
Naranderra	18.1	22.5	C	Non-marine	hot dip	Douglas Fir	S	3	0.4	0.66
Pennant Hills	15.0	15.7	C	Non-marine	hot dip	Douglas Fir	S	6	0.8	0.66
The Gap 18	15.3	16.0	C	Non-marine	hot dip	Douglas Fir	S	7	1.0	0.66
Innisfail 1	17.3	18.4	C	Non-marine	hot dip	Radiata Pine	S	30	4.2	0.66
Innisfail 2	17.3	18.4	C	Non-marine	hot dip	Radiata Pine	S	28	3.9	0.66
Mt Buller	15.8	19.5	C	Non-marine	hot dip	Radiata Pine	S	13	1.8	0.66
Naranderra	18.1	22.5	C	Non-marine	hot dip	Radiata Pine	S	7	1.0	0.66
The Gap 18	15.3	16.0	C	Non-marine	hot dip	Radiata Pine	S	7	1.0	0.66

Table 3.1.2.2 (cont) Check with individual data of 2-year embedded nails *outdoor* – Non-Marine sites

Site	SEMC-mean	SEMC-max	Hazard Zone	Climate zone	Nail	Timber	Wood Type	Mass Loss g/m2/yr	Measured 1-year Corrosion Depth (μm)	Model-Prediction corrosion depth (μm)
Innisfail 1	17.3	18.4	C	Non-marine	zinc plate	H3	CCA	12	1.7	2.14
Innisfail 2	17.3	18.4	C	Non-marine	zinc plate	H3	CCA	11	1.5	2.14
Mt Buller	15.8	19.5	C	Non-marine	zinc plate	H3	CCA	27	3.8	2.14
Naranderra	18.1	22.5	C	Non-marine	zinc plate	H3	CCA	20	2.8	2.14
Pennant Hills	15.0	15.7	C	Non-marine	zinc plate	H3	CCA	5	0.7	2.14
Innisfail 1	17.3	18.4	C	Non-marine	zinc plate	H5	CCA	14	2.0	2.14
Innisfail 2	17.3	18.4	C	Non-marine	zinc plate	H5	CCA	11	1.5	2.14
Mt Buller	15.8	19.5	C	Non-marine	zinc plate	H5	CCA	20	2.8	2.14
Naranderra	18.1	22.5	C	Non-marine	zinc plate	H5	CCA	10	1.4	2.14
Pennant Hills	15.0	15.7	C	Non-marine	zinc plate	H5	CCA	2	0.3	2.14
Innisfail 1	17.3	18.4	C	Non-marine	zinc plate	Treated Pine	CCA	8	1.1	2.14
Mt Buller	15.8	19.5	C	Non-marine	zinc plate	Treated Pine	CCA	26	3.7	2.14
Naranderra	18.1	22.5	C	Non-marine	zinc plate	Treated Pine	CCA	6	0.8	2.14
The Gap 18	15.3	16.0	C	Non-marine	zinc plate	Treated Pine	CCA	4	0.6	2.14
Innisfail 1	17.3	18.4	C	Non-marine	zinc plate	Mountain Ash	E	57	8.0	5.42
Innisfail 2	17.3	18.4	C	Non-marine	zinc plate	Mountain Ash	E	63	8.9	5.42
Naranderra	18.1	22.5	C	Non-marine	zinc plate	Mountain Ash	E	7	1.0	5.42
Pennant Hills	15.0	15.7	C	Non-marine	zinc plate	Mountain Ash	E	4	0.6	5.42
Innisfail 1	17.3	18.4	C	Non-marine	zinc plate	Spotted Gum	E	51	7.2	5.42
Innisfail 2	17.3	18.4	C	Non-marine	zinc plate	Spotted Gum	E	50	7.0	5.42
Mt Buller	15.8	19.5	C	Non-marine	zinc plate	Spotted Gum	E	12	1.7	5.42
Pennant Hills	15.0	15.7	C	Non-marine	zinc plate	Spotted Gum	E	1.6	0.2	5.42
The Gap 18	15.3	16.0	C	Non-marine	zinc plate	Spotted Gum	E	7	1.0	5.42
Innisfail 1	17.3	18.4	C	Non-marine	zinc plate	Brush Box	H	14	2.0	3.16
Innisfail 2	17.3	18.4	C	Non-marine	zinc plate	Brush Box	H	15	2.1	3.16
Mt Buller	15.8	19.5	C	Non-marine	zinc plate	Brush Box	H	3	0.4	3.16
Naranderra	18.1	22.5	C	Non-marine	zinc plate	Brush Box	H	3	0.4	3.16
Pennant Hills	15.0	15.7	C	Non-marine	zinc plate	Brush Box	H	8	1.1	3.16
The Gap 18	15.3	16.0	C	Non-marine	zinc plate	Brush Box	H	3	0.4	3.16
Innisfail 1	17.3	18.4	C	Non-marine	zinc plate	Douglas Fir	S	6	0.8	0.66
Innisfail 2	17.3	18.4	C	Non-marine	zinc plate	Douglas Fir	S	7	1.0	0.66
Mt Buller	15.8	19.5	C	Non-marine	zinc plate	Douglas Fir	S	14	2.0	0.66
Naranderra	18.1	22.5	C	Non-marine	zinc plate	Douglas Fir	S	2	0.3	0.66
Pennant Hills	15.0	15.7	C	Non-marine	zinc plate	Douglas Fir	S	2	0.3	0.66
The Gap 18	15.3	16.0	C	Non-marine	zinc plate	Douglas Fir	S	2	0.3	0.66
Innisfail 1	17.3	18.4	C	Non-marine	zinc plate	Radiata Pine	S	15	2.1	0.66
Innisfail 2	17.3	18.4	C	Non-marine	zinc plate	Radiata Pine	S	8	1.1	0.66
Mt Buller	15.8	19.5	C	Non-marine	zinc plate	Radiata Pine	S	23	3.2	0.66
Naranderra	18.1	22.5	C	Non-marine	zinc plate	Radiata Pine	S	1	0.1	0.66
The Gap 18	15.3	16.0	C	Non-marine	zinc plate	Radiata Pine	S	3	0.42	0.66

3.1.3 Predictions of the nail corrosion in joints within building envelope using the current model

Figure 3.1.3.1 presents the checks between the measured corrosion rate of nail embedded in nail joints tested in building envelope parts, including roof space, subfloor and wall cavity, with the model prediction, which was made by the final model in Chapter 1. The purpose of this check is to justify the model parameter for building envelope parts (Appendix D) that are used in the score system (Section 4), which is used in Design Guide (Section 6).

Figure 3.1.3.1 is for the nails in roof-space; Figure 3.1.3.2 is for the nails in sub-floor; Figure 3.1.3.3 is for the nails in wall cavity.

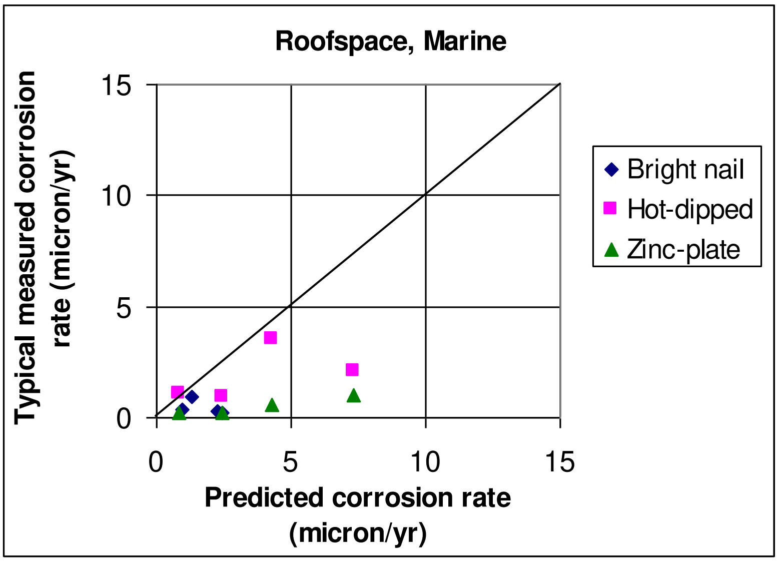


Figure 3.1.2.1 Checks with 2-year embedded nails in roof-space using the current model

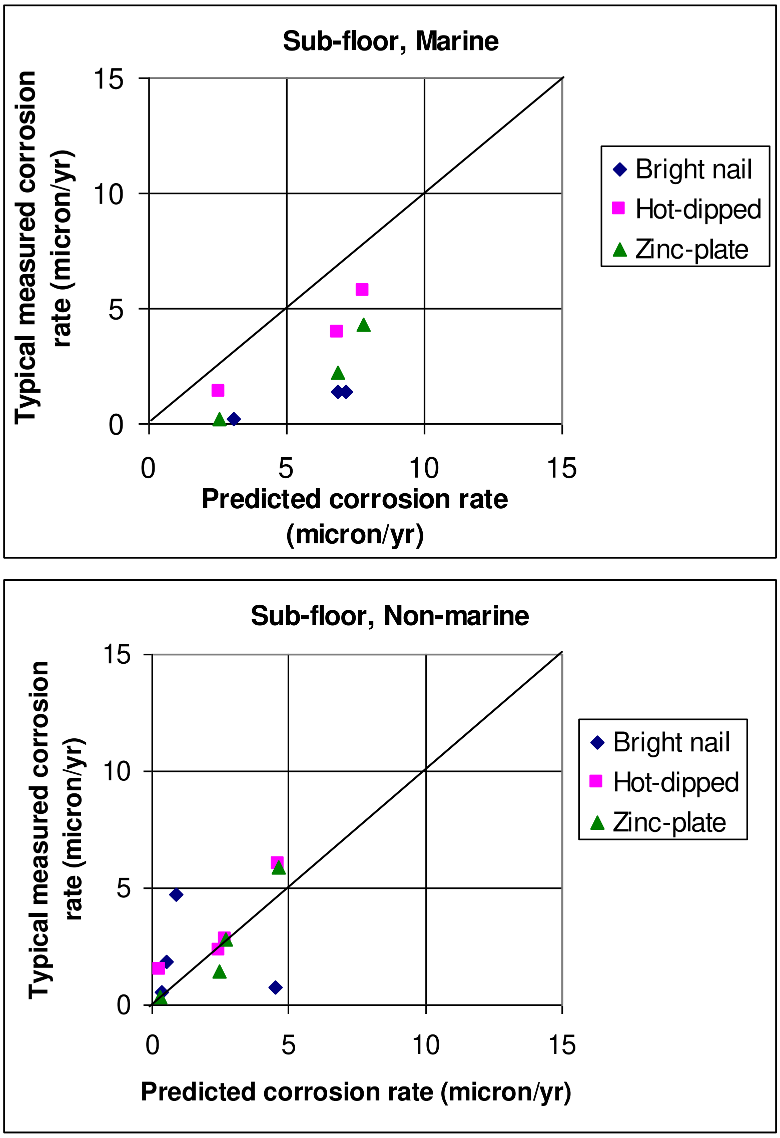


Figure 3.1.2.1 Checks with outdoor 2-year embedded nails in sub-floor using the current model . Top: Marine sites, Bottom: Non-marine sites

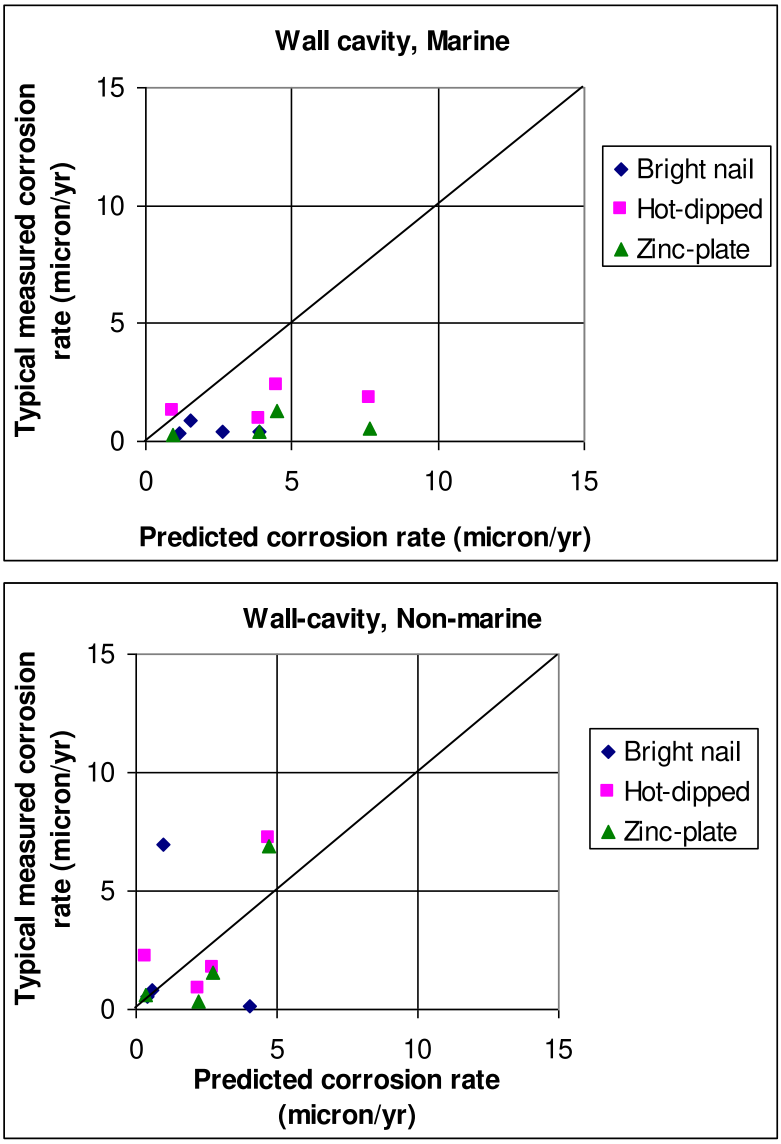


Figure 3.1.2.1 Checks with outdoor 2-year embedded nails in wall cavity using the current model . Top: Marine sites, Bottom: Non-marine sites

3.2 Fitting with data from BRANZ Study Report of Embedded Corrosion Tests

Table 3.2.1 presented the data from in a BRANZ study report by Kear et al. (2006). There were 2 tests, 'Sandwich test' and 'Panel Pin test', where corrosion of mild steel, hot-dipped-galvanised (HDG) steel, and stainless steel were measured after 12 months (sandwich test) or 14 months (panel pin test) embedded in untreated, CCA-treated, and other preservative-treated radiata pine timber. The tests were carried out in Lab conditioning rooms with constant temperature and humidity. The Sandwich test was carried at 21^{o}C and 98% of relative humidity. The Panel Pin tests were also carried out at 21^{o}C, but at 3 different levels of relative humidity, including 75%, 90% and 98%, which, as measured and reported in the study, correspond to average timber moisture contents of 10.5%, 17.9%, and 20.3%, respectively.

Only data for mild steel and HDG in untreated and CCA-treated timber, which are related to the model in this report, are presented in Table 3.2.1. The corrosion results were given in terms of corrosion rate (μm/year). Most of the results are determined from the plots in the BRANZ report, where only few numerical results were given. In Table 3.2.1, it is noted that the data from Panel Pin test at MC of 20.3% appeared to be inconsistent with the others. The test gave much higher corrosion rate than the sandwich test did, although they are both exposed to the same controlled condition, ie. at 21^{o}C and 98% of relative humidity. We think that at this condition with the configuration of the panel pin tests, it was possible that condensation could have occurred on the protruding part of the pin and then dripped or entered by capillary action into the pin hole, resulting in much higher local moisture content of timber around the pin, and hence higher corrosion rate. The setup of the sandwich test did not facilitate the condensation, and hence the test results are more reliable. In this section, we will use the sandwich test results and the panel pin test results at lower MC for calibration, and neglecting the panel pin test results at the highest MC of 20.3%.

Based on checking and calibrating the model with these data, the most important modification to the model is for steel corrosion in CCA-treated wood. As a conclusion of the BRANZ study, the zinc coatings were consistently shown to be more durable than mild steel in all tests. This behaviour, however, was not observed clearly in the 120-day embedded test as plotted in Figure C.4.3. To be consistent with the data observed, we re-develop the model for steel in CCA-treated wood as follows,

- The base model for 120-day corrosion of steel and zinc connectors embedded in CCA treated wood is revised to be the same, see Section 2.4.2. This was due to the duration of test, which was not long enough for the protective effect of zinc corrosion product to work.
- From Table 3.2.1, the ratio between average corrosion rate of steel and average corrosion rate of zinc in CCA-treated wood ranges from 1.2 to 2.0, with an average of 1.6. The equation for corrosion rate of steel in CCA-treated wood is then revised to be 1.6 times the corrosion rate of zinc, as presented in Section 2.4.4.
- This revision of steel corrosion rate in CCA-treated wood is also consistent with the equation for corrosion depth over time, Eq.(2.4.3.1), which is

$$c = c_o t^n \qquad (3.2.1)$$

where n=0.6 for zinc and n=1.0 for steel in treated wood. The corrosion rate is then

$$c_{o} = \frac{c}{t^{n}} \quad (3.2.2)$$

Consider the ratio between the corrosion rate of steel and the corrosion rate of zinc:

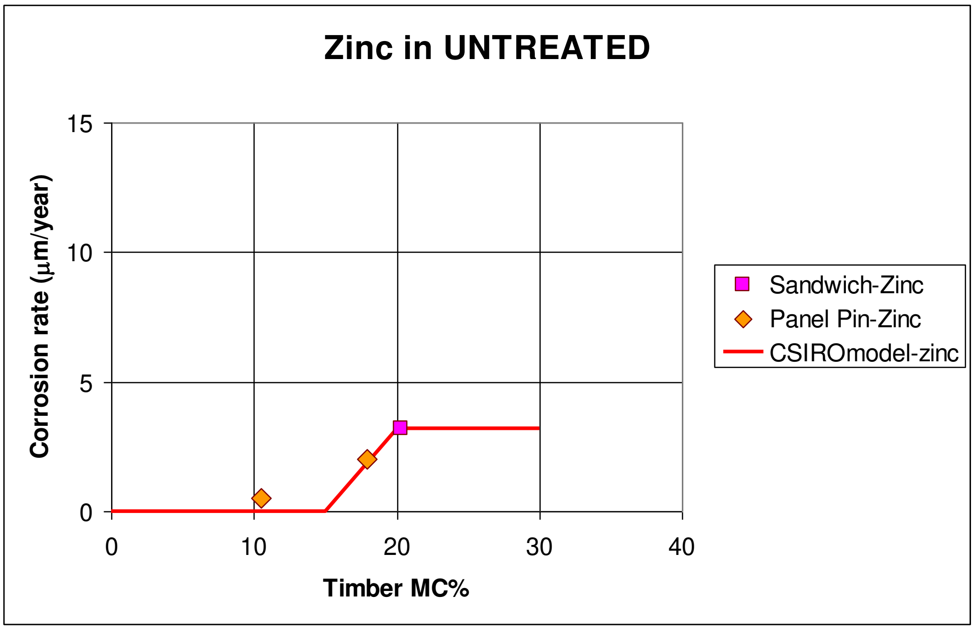
$$\frac{c_{0,steel}}{c_{0,zinc}} = \frac{c_{steel}}{c_{zinc}} \frac{t^{0.6}}{t^{1.0}} = \frac{c_{steel}}{c_{zinc}} t^{-0.4} \quad (3.3.3)$$

At t = 1/3 year, ie. 120 days, the corrosion of steel and zinc are the same, then

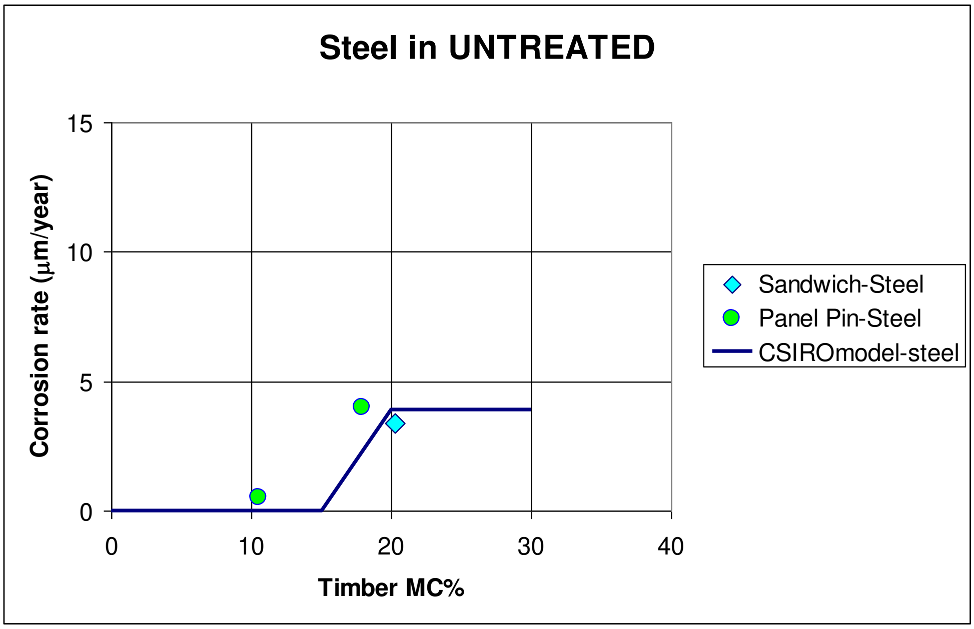
$$\frac{c_{0,steel}}{c_{0,zinc}} = \left(\frac{1}{3}\right)^{-0.4} \approx 1.6$$

The ratio is the same as the factor 1.6 obtained from the results of BRANZ test as presented above.

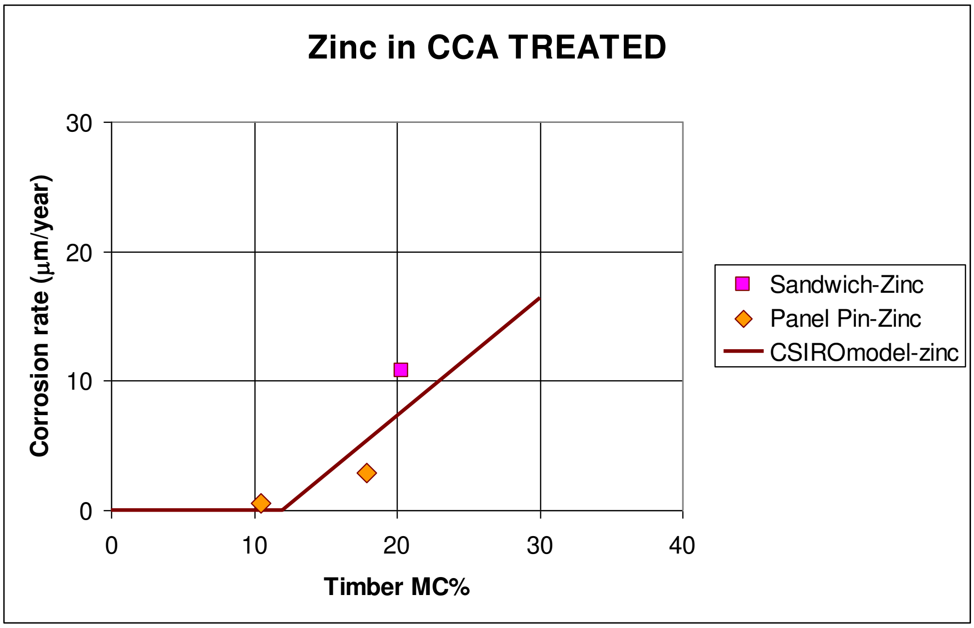
The comparisons of the model (Section 1) to BRANZ test data are in Figures 3.2.1 to 3.2.4, which show reasonable agreements.



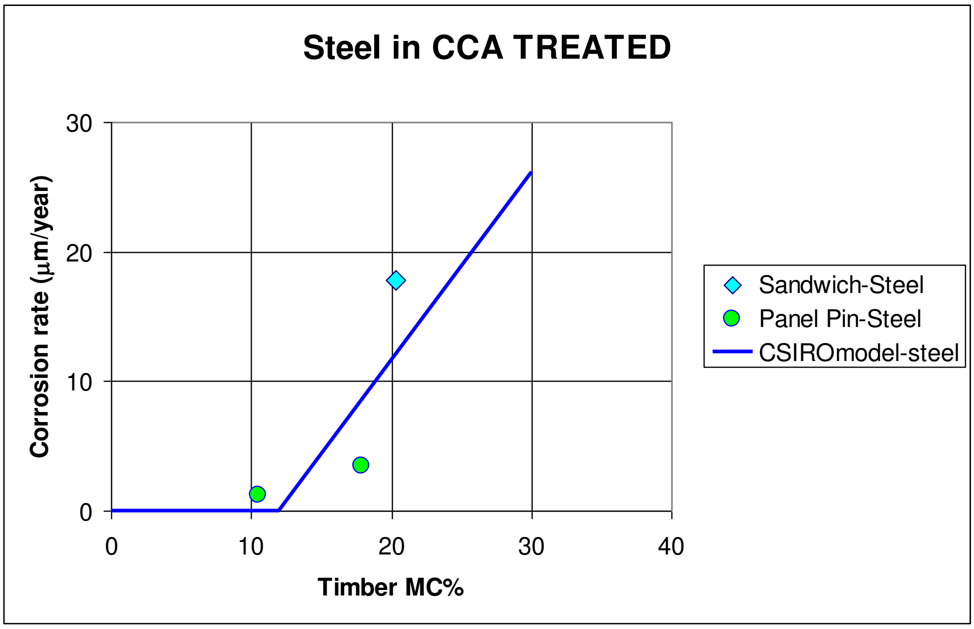
Figures 3.2.1 Comparison of the model prediction of corrosion rate (Eq.(1.5.1)) vs timber MC with BRANZ test data for zinc in untreated Radiata pine (Table 3.2.1)



Figures 3.2.2 Comparison of the model prediction of corrosion rate (Eq.(1.5.1)) vs timber MC with BRANZ test data of steel in untreated Radiata pine (Table 3.2.1)



Figures 3.2.3 Comparison of the model prediction of corrosion rate (Eq.(1.6.1)) vs Timber MC with BRANZ test data of zinc in treated Radiata pine (Table 3.2.1)



Figures 3.2.4 Comparison of the model prediction of corrosion rate (Eq.(1.6.2)) vs Timber MC with BRANZ test data of steel in treated Radiata pine (Table 3.2.1)

Table 3.2.1 Data of corrosion rate of metals from embedded tests in BRANZ Study Report (summarised from Kear et al. 2006)

BRANZ Tests	Timber MC %	STEEL corrosion rate (μm/y) - Mild steel specimens					ZINC corrosion rate (μm/y) - HDG steel speciemens				
		Untreated	CCA-treated				Untreated	CCA-treated			
			Avg.	H3.2	H4	H5		Avg.	H3.2	H4	H5
Sandwich Test	20.3%	3.4	17.8	13.2	17.2	23.0	3.2	10.8	11.0	10.9	10.4
Panel Pin Test	20.3%	20.0	66.0	73.0	64.0	61.0	16.0	17.0	10.7	19.0	21.4
	17.9%	4.0	3.5	2.2	4.2	4.1	2.0	2.9	1.2	2.0	5.4
	10.5%	0.5	1.2	1.1	1.1	1.3	0.5	0.6	0.6	0.3	0.8

3.3 Fitting with 120-day corrosion tests

This is a laboratory test where timber nail-joint specimens were put into conditioned chambers to investigate the dependency of embedded corrosion on timber moisture contents for various timber species and/or preservative treatments.

Chambers were established to give a range of constant relative humidity (RH) between 55% to 100% and a range of temperature (T) between 15°C to 25°C. Salt solutions were used to regulate RH. When $Ca(NO_3)_2.4H_2O$, $NaNO_2$, $NaNO_3$, KCl, $BaCl_2$ and K_2SO_4 salts and distilled water are used then constant RH of 55, 66, 86, 92, 96 and 100% are established. At a constant temperature of 20°C, the equilibrium Moisture Content (EMC) of the air is 11, 13, 16, 18, 20, 25, and 30%, respectively. The surface EMC (SEMC) of timber placed in these chambers can be assumed to reach the air EMC instantly. The air was circulated in the chambers to ensure that it is well mixed and that condition is uniform.

Timber nail-joint specimens were similar to that of the 2-year exposure test described in Section 3.1. Timber species were Meranti, Karri, Kauri, Red Ironbark, Oregon, Mountain Ash, Spotted Gum, BrushBox, Radiata Pine, treated Pine with LOSP, and CCA at H3 and H5 levels. Four types of nail were used, including bright steel, hot-dipped galvanised, zinc-plated, and copper.

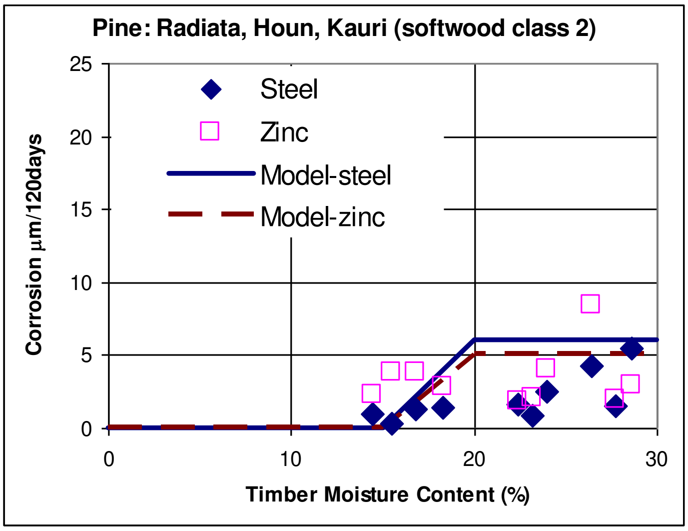
The timbers were put in the chambers, and be weighted once a week. Once their weights do not change for 3 weeks, they (the whole piece of timber) were considered to reach EMC. Two sticks of the same species were jointed by a series of nails to make the joint specimens. The nails were weighted prior to nailing. A minimum of 3 nails for each type will be used for each timber at each condition. The nail-joint specimens were then left in the chambers for 120 days.

After exposure the nail joint specimens were returned to the laboratory and the nails were extracted, assessed for extent of corrosion. The corrosion product was removed by cleaning in acid to determine mass loss of the nails in g/year/m^2. One-year-corrosion depth on the nail shank then can be estimated as follows,

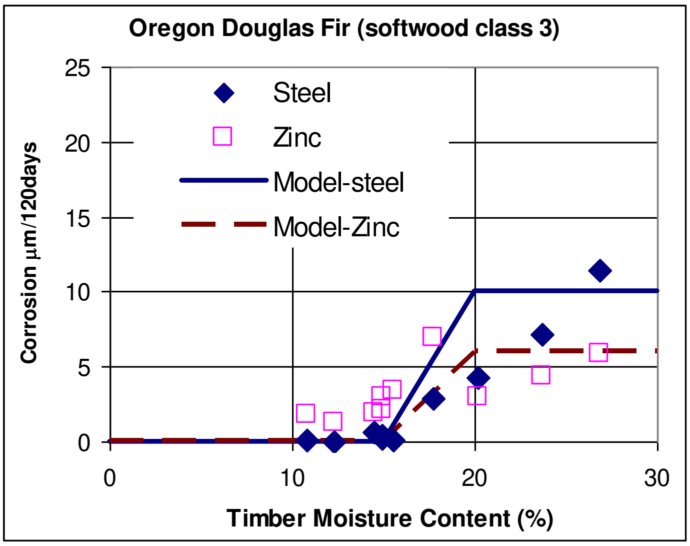
$$\textit{corrosion depth}\ [\mu\text{m/120days}] = \frac{\textit{Mass loss}\ [\text{g/120days/m}^2]}{\textit{Density}\ [\text{g/m}^2/\mu\text{m}]}$$

where the density of zinc is 7.1 g/cm^3 (7.1 g/m^2/μm), density of steel is 7.7 g/cm^3 (7.7 g/m^2/μm).

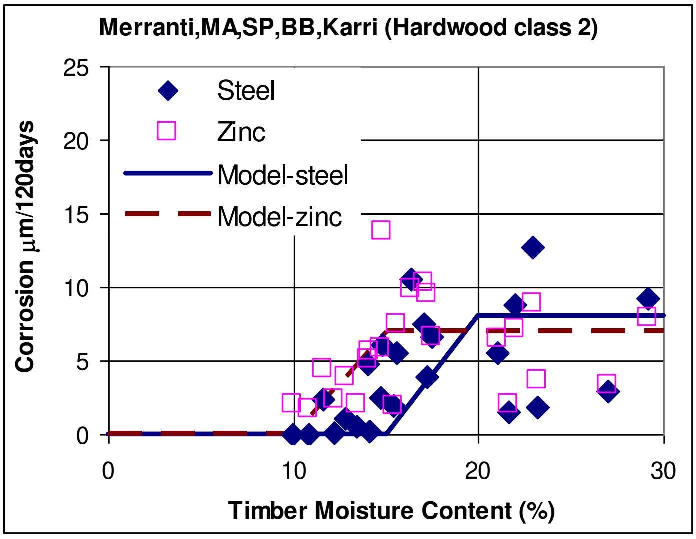
The data is presented in Table 3.3.1 (Cole, private communication and internal reports), which was the same as that used for the base model in 2000 (Appendix C). This section provides the final check of the data with the current model that has been revised considerably since 2000. Figures 3.3.1 to 3.3.6 show the check, which justifies the base models presented in Section 1.



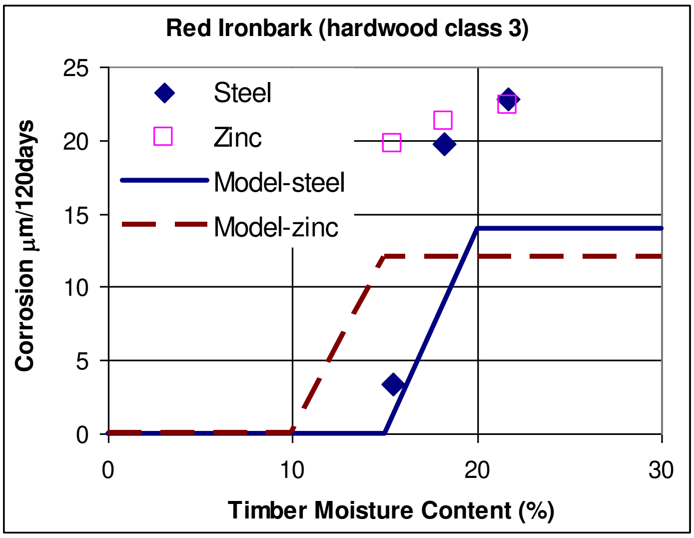
Figures 3.3.1 Check of the model with 120-day corrosion of nails in softwood class 2 timber. Data from Table 3.3.1. Model Equation is (1.5.2).



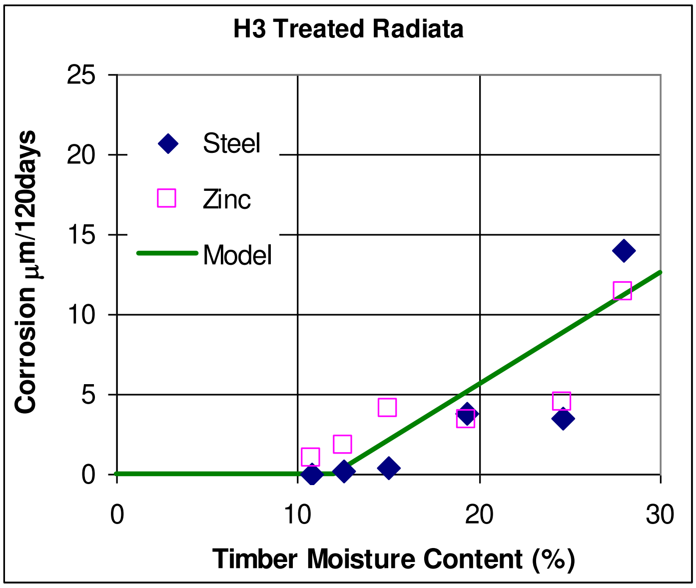
Figures 3.3.2 Check of the model with 120-day corrosion of nails in softwood class 3 timber. Data from Table 3.3.1. Model Equation is (1.5.2).



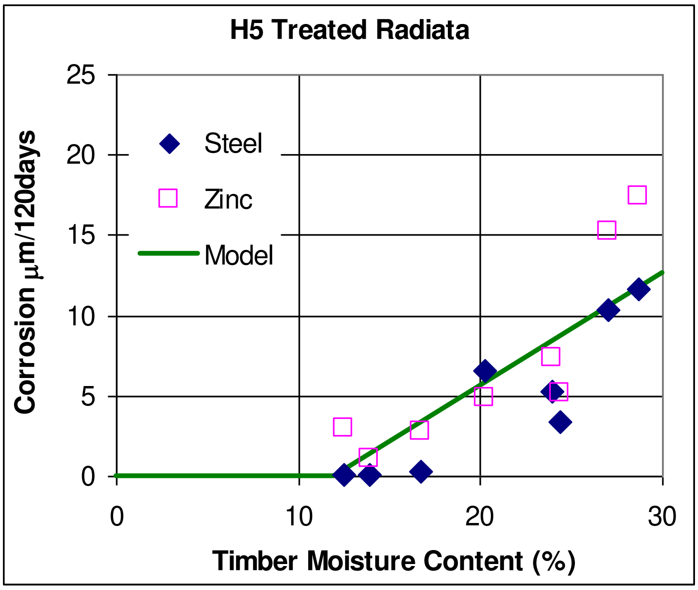
Figures 3.3.3 Check of the model with 120-day corrosion of nails in hardwood class 2 timber. Data from Table 3.3.1. Model Equation is (1.5.2).



Figures 3.3.4 Check of the model with 120-day corrosion of nails in hardwood class 3 timber. Data from Table 3.3.1. Model Equation is (1.5.2).



Figures 3.3.5 Check of the model with 120-day corrosion of nails in H3 CCA-treated Radiata pine. Data from Table 3.3.1. Model Equation is (1.6.3).



Figures 3.3.6 Check of the model with 120-day corrosion of nails in H5 CCA-treated Radiata pine. Data from Table 3.3.1. Model Equation is (1.6.3).

Table 3.3.1 Data of 120-day embedded nail corrosion

Timber	wood type	pH	EMC (%)	Bright nail mass loss (g/m2 per 120days)	Hot-dip galvanised nail mass loss (g/m2 per 120days)	Steel corrosion depth (micron/ 120days)	Zinc corrosion depth (micron/ 120days)
Oregon	Softwood	4.0	14.5	5	14	0.6	2.0
Oregon	Softwood	4.0	15.5	1	24	0.1	3.4
Oregon	Softwood	4.0	20.2	33	21	4.3	3.0
Douglas fir	Softwood	4.2	10.8	1	13	0.1	1.8
Douglas fir	Softwood	4.2	12.3	0.4	9	0.1	1.3
Douglas fir	Softwood	4.2	14.9	1.3	15	0.2	2.1
Douglas fir	Softwood	4.2	14.9	3.1	21	0.4	3.0
Douglas fir	Softwood	4.2	17.7	22	49	2.9	6.9
Douglas fir	Softwood	4.2	23.7	55	31	7.1	4.4
Douglas fir	Softwood	4.2	26.8	88	42	11.4	5.9
Radiata pine	Softwood	5.0	16.8	10	27	1.3	3.8
Radiata pine	Softwood	5.0	24.0	19	29	2.5	4.1
Radiata pine	Softwood	5.0	28.6	42	21	5.5	3.0
Radiata pine	Softwood	5.0	23.2-90%	7	15	0.9	2.1
Radiata pine	Softwood	5.0	27.7	12	14	1.6	2.0
Huon Pine	Softwood	4.5	14.4	8	16	1.0	2.3
Huon Pine	Softwood	4.5	18.3	11	20	1.4	2.8
Huon Pine	Softwood	4.5	26.4	33	60	4.3	8.5
Kauri	Softwood	5.1	15.5	2.9	27	0.4	3.8
Kauri	Softwood	5.1	22.4	12.5	13	1.6	1.8
Meranti	Hardwood	3.9	12.8	8	28	1.0	3.9
Meranti	Hardwood	3.9	15.4	15	14	1.9	2.0
Meranti	Hardwood	3.9	21.6	12	15	1.6	2.1
Brush box	Hardwood	4.4	14	37	36	4.8	5.1
Brush box	Hardwood	4.4	17.5	51	47	6.6	6.6
Brush box	Hardwood	4.4	21	43	46	5.6	6.5
Karri	Eucalyptus	4.0	15.6	43	53	5.6	7.5
Karri	Eucalyptus	4.0	16.3	81	70	10.5	9.9
Karri	Eucalyptus	4.0	22.9	98	63	12.7	8.9
Mountain Ash	Eucalyptus	4.5	10.8	0.2	12	0.0	1.7
Mountain Ash	Eucalyptus	4.5	12.2	1	17	0.1	2.4
Mountain Ash	Eucalyptus	4.5	14.1	2	40	0.3	5.6
Mountain Ash	Eucalyptus	4.5	14.8	47	98	6.1	13.8
Mountain Ash	Eucalyptus	4.5	17.0	58	73	7.5	10.3
Mountain Ash	Eucalyptus	4.5	22.0	68	51	8.8	7.2
Mountain Ash	Eucalyptus	4.5	29.1	71	56	9.2	7.9
Mountain Ash	Eucalyptus	4.5	27*-96%	23	24	3.0	3.4
Mountain Ash	Eucalyptus	4.5	23.2*-90%	14	26	1.8	3.7

Table 3.3.1 (cont) Data of 120-day embedded nail corrosion

Timber	**wood type**	**pH**	**EMC (%)**	**Bright nail mass loss (g/m2 per 120days)**	**Hot-dip galvanised nail mass loss (g/m2 per 120days)**	Steel corrosion depth (micron/ 120days)	Zinc corrosion depth (micron/ 120days)
Red Ironbark	Eucalyptus	4.1	15.4	26	140	3.4	19.7
Red Ironbark	Eucalyptus	4.1	18.2	152	151	19.7	21.3
Red Ironbark	Eucalyptus	4.1	21.7	176	159	22.9	22.4
Spotted gum	Eucalyptus	4.4	9.9	0	15	0.0	2.1
Spotted gum	Eucalyptus	4.4	11.6	18	32	2.3	4.5
Spotted gum	Eucalyptus	4.4	13.4	4	15	0.5	2.1
Spotted gum	Eucalyptus	4.4	14.7	19	42	2.5	5.9
Spotted gum	Eucalyptus	4.4	17.2	30	68	3.9	9.6
Spotted gum	Eucalyptus	4.4	30				
H3	Treated		10.8	0	7	0.0	1.0
H3	Treated		12.5	1.4	13	0.2	1.8
H3	Treated		15	3	29	0.4	4.1
H3	Treated		19.3	29	24	3.8	3.4
H3	Treated		28.0	108	81	14.0	11.4
H3	Treated		24.6*	27	32	3.5	4.5
H5	Treated		12.5	1	21	0.1	3.0
H5	Treated		13.9	1	8	0.1	1.1
H5	Treated		16.7	2	20	0.3	2.8
H5	Treated		20.2	51	35	6.6	4.9
H5	Treated		23.9	41	52	5.3	7.3
H5	Treated		28.7	90	124	11.7	17.5
H5*(8months)	Treated		24.4	26	37	3.4	5.2
H5 (8 months)	Treated		27	80	108	10.4	15.2
Treated pine	Treated		17.2	10	24	1.3	3.4
Treated pine	Treated		20.6	22	37	2.9	5.2
Treated pine	Treated		27.6	75	41	9.7	5.8
LOSP	Treated		10.4				
LOSP	Treated		12.2	1	23	0.1	3.2
LOSP	Treated		14.7	1	15	0.1	2.1
LOSP	Treated		16.6	11	23	1.4	3.2
LOSP	Treated		20.8	3	9	0.4	1.3
LOSP	Treated		23.2	11	16	1.4	2.3
LOSP	Treated		27.2	26	30	3.4	4.2

4. Hazard Score System

4.1 Definition of Hazard Scores

Table 4.1.1 gives the total hazard scores for various scenarios of the corrosion in embedded fasteners. Derivation of this table is presented in Appendix A. Components of building envelope, however, are included as they will be present in the Service Life Design Guide.

Table 4.1.1 Hazard scores for corrosion of embedded fasteners

Microclimate	Total scores for various microclimates					
	Zone A		Zone B		Zone C	
	Marine	Other	Marine	Other	Marine	Other
Subfloor	14	12	16	14	18	16
Wall cavity	12	12	14	14	16	16
Roof space	11	9	13	11	15	13
Outdoors for fasteners other than bolts						
Sheltered / partly sheltered(1)	19	12	22	15	25	18
Exposed vertical surface(2)	20	13	25	18	31	24
Exposed horizontal surface(3)	22	15	30	23	40	33
Outdoors bolts						
Sheltered / partly sheltered(1)	19	12	23	16	26	19
Exposed vertical surface(2)	21	14	27	20	35	28
Exposed horizontal surface(3)	24	17	35	28	49	42

(1) e.g. house cladding; (2)e.g. fencing; (3) e.g. decking

4.2 Definition of Hazard Class

For ease of application to service life prediction of various types of fastener, the selection of hazard class limit have been decided to have the same limits for steel and zinc, but to have different limits for types of wood. The definition of hazard classes and their boundaries in terms of the total scores for embedded corrosion of fasteners have been chosen as shown in Table 4.2.1 and illustrated in Figures 4.2.1 and 4.2.2 for zinc and steel fasteners, respectively. It is noted that there are some revision from the 2002's score system (Appendix E), including

- Untreated timber is divided into hardwood and softwood only
- Expand the range of the middle hazard rating for untreated wood to capture better the uncertainties around the 'jumping' step, now is revised as a ramp, of corrosion with moisture content.

Table 4.2.1 Definition of hazard ratings

Hazard score			**Hazard rating**
In untreated timber		**CCA-treated timber**	
Hardwoods	**Softwoods**		
<12	<14	<12	$HR1_{emb}$
12~19	14~22	12~17	$HR2_{emb}$
>19	>22	18~23	$HR3_{emb}$
na	na	24~30	$HR4_{emb}$
na	na	>30	$HR5_{emb}$

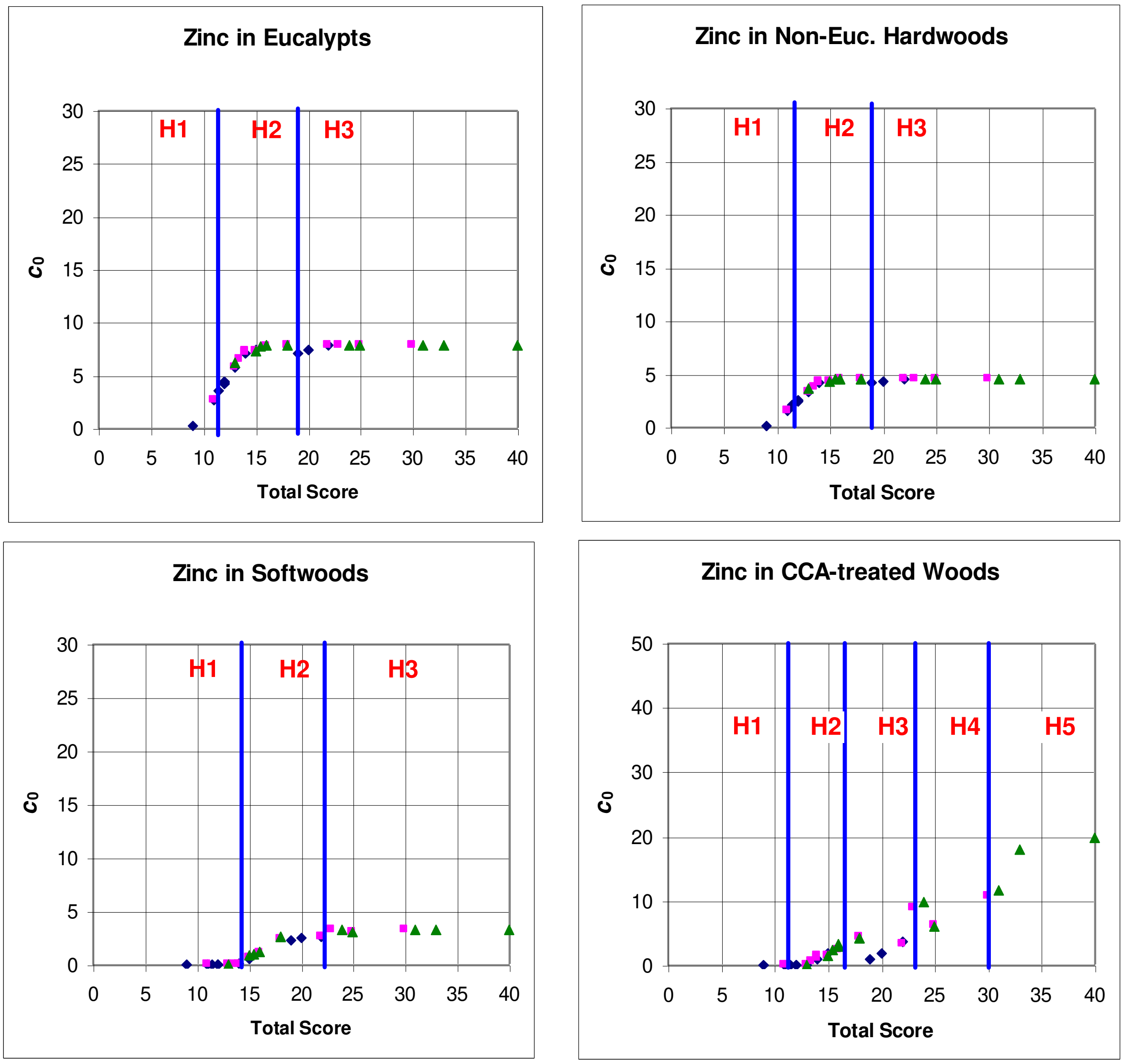


Figure 4.2.1. Hazard ratings for zinc fasteners embedded in different types of wood (Data from Appendix B)

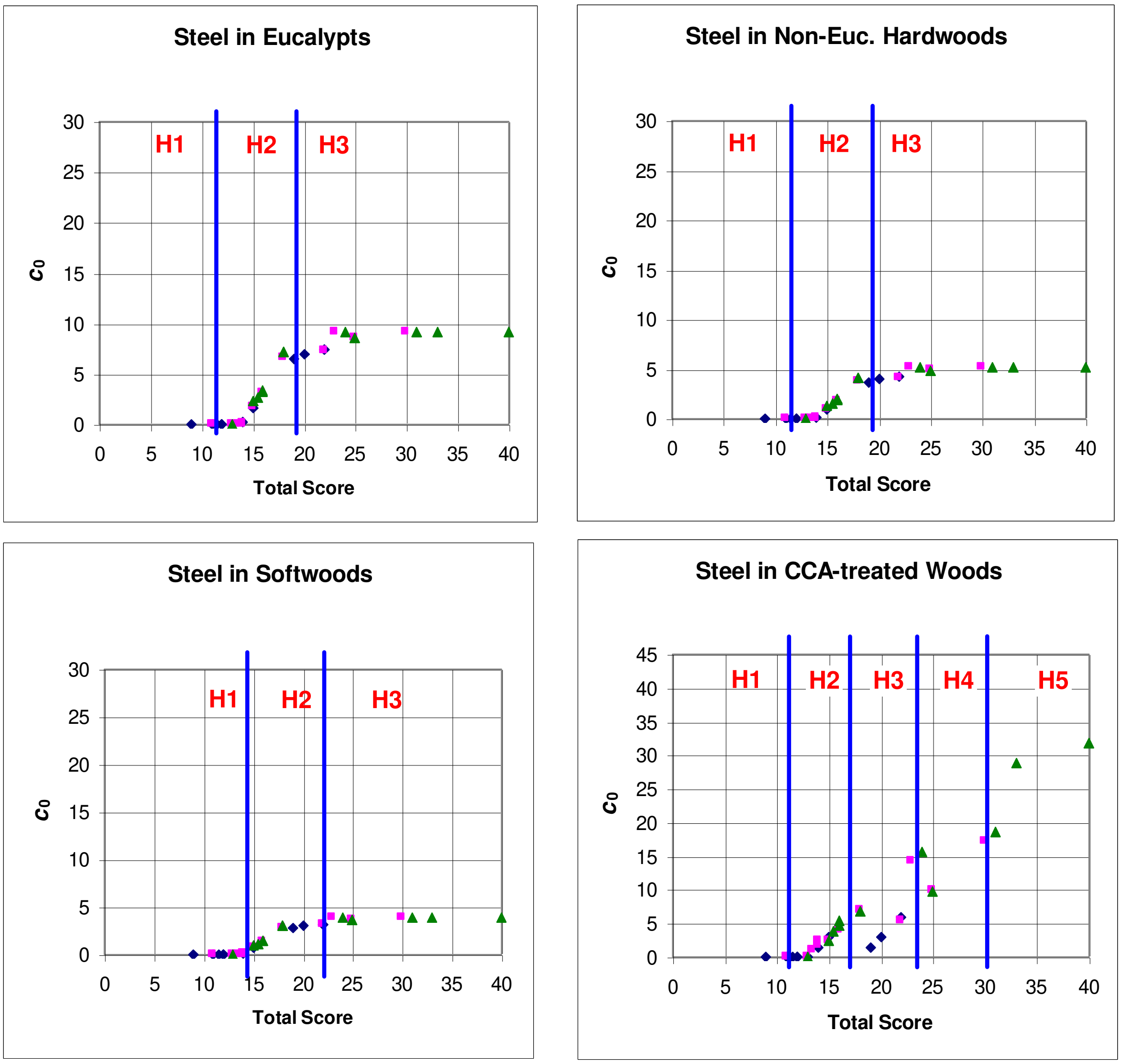


Figure 4.2.2. Hazard ratings for steel fasteners embedded in different types of wood (Data from Appendix B)

4.3 Derived c_0 values for the Score System

Based on the theoretical values of c_0 varying in each hazard class, representative values of c_0 for the classes are estimated and presented in Tables 4.3.1 and 4.3.2 for zinc and steel, respectively. Compared to the 2002 model, the assign c_0 values for hazard classes are reduced by a factor about 2, and then the c_0 values for steel in CCA treated timber are also revised to be about 1.6 times those for zinc, as the result from checks and calibration presented in Section 3.

Table 4.3.1 The first-year corrosion depth of embedded zinc fasteners

Hazard rating	c_0 - the first-year corrosion depth of zinc			
	Untreated timber			CCA-treated timber
	Acidity Class 1	Acidity Class 2	Acidity Class 3	
$HR1_{emb}$	0	0	0	0
$HR2_{emb}$	1.0	2.5	4.5	4.0
$HR3_{emb}$	2.0	4.5	8.0	10.0
$HR4_{emb}$	na	na	na	15.0
$HR5_{emb}$	na	na	na	20.0

Table 4.3.2 The first-year corrosion depth of embedded steel fasteners

Hazard rating	c_0 - the first-year corrosion depth of steel			
	Untreated timber			CCA-treated timber
	Acidity Class 1	Acidity Class 2	Acidity Class 3	
$HR1_{emb}$	0	0	0	0
$HR2_{emb}$	1.5	4.5	7.5	7.0
$HR3_{emb}$	3.0	6.0	10	15.0
$HR4_{emb}$	na	na	na	25.0
$HR5_{emb}$	na	na	na	32.0

4.4 Corrosion Depth

The corrosion depth, c, over the period t years is given by

$$c = c_o\, t^n \qquad (4.4.1)$$

where c_o is the corrosion rate (μm/year), or more precisely, the corrosion depth for the first year. For fasteners embedded in untreated wood, n= 0.5 for zinc and n = 0.6 for steel. For fasteners embedded in CCA-treated wood, n= 0.6 for zinc and n = 1.0 for steel.

4.5 Service life

The service-life life of a steel fastener is assumed to be the time at which all of the effective zinc coasting, if any, and 30% of the original strength in steel, is lost. The life of a zinc coating is assumed to be the time at which all of the effective zinc protection is lost. The fasteners under consideration are assumed to be subject to bending moment; therefore the decrease of fastener bending strength is proportional to the increase of corrosion depth. For conservative calculation, the initial diameter of screws is taken at the root (i.e. excluding the thread), and that of bolts is taken at the shank.

5. Equations for the Draft Engineering Code and TimberLife

5.1 Scope and Aplication

This Section provides the calculation procedures for the design corrosion depths on embedded parts of metal fasteners, which can be used to estimate the corrosion depths for metal fasteners used in any timber construction located anywhere in Australia.

5.2 Corrosion of Embedded Parts of Fasteners (Embedded Corrosion)

This Section provides the calculation procedures for the design corrosion depths on metal fasteners' parts that are tightly embedded in wood, such as the shank of nails, screws, and nailplate's teeth, as depicted in Figure 5.2.1.

The design corrosion depths is to be determined by

$$c_{design} = c\left(1+\alpha V_c\right) \qquad (5.2.1)$$

where

- c is the mean depth of the loss in fastener cross-section due to embedded corrosion for a chosen design life time. To evaluate the mean corrosion depths, the timber acidity class and hazard zone of the structure location are obtained from Section 5.2.1. Timber moisture content is estimated from Section 5.2.2. The mean corrosion depth is then estimated using the procedure in Section 5.2.3 for fasteners embedded in untreated wood, and Section 5.2.4 for fasteners embedded in CCA-treated wood.
- V_c is the coefficient of variation of c, and α is specified parameter related to the target reliability level. The values of these parameters are set in Section 5.2.5.

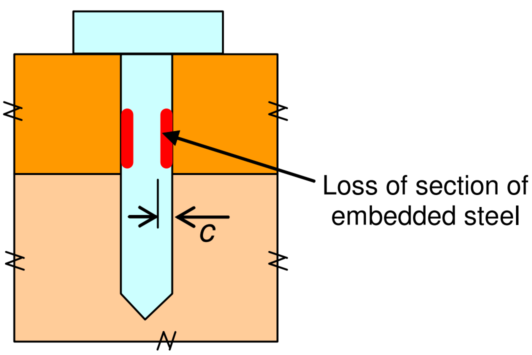


Figure 5.2. 1 Embedded corrosion depth

5.2.1 Timber Acidity Classification and Hazard zones

Durability classification of timber is listed in Table 3.1.1.

The hazard zone map is shown in Figure 5.2.1.1. Three hazard zones and their representative mean annual surface equilibrium moisture content $SEMC_{\text{mean}}$ and the boundary $SEMC_{\text{mean}}$ are in Table 5.2.1.1. Values of $SEMC_{mean}$ for major cities and towns in Australia are listed in Table 3.2.1.

Table 5.2.1.1 Effective $SEMC_{mean}$ values for the 3 hazard zones

Zone	$SEMC_{mean}$
A	9
B	12
C	15

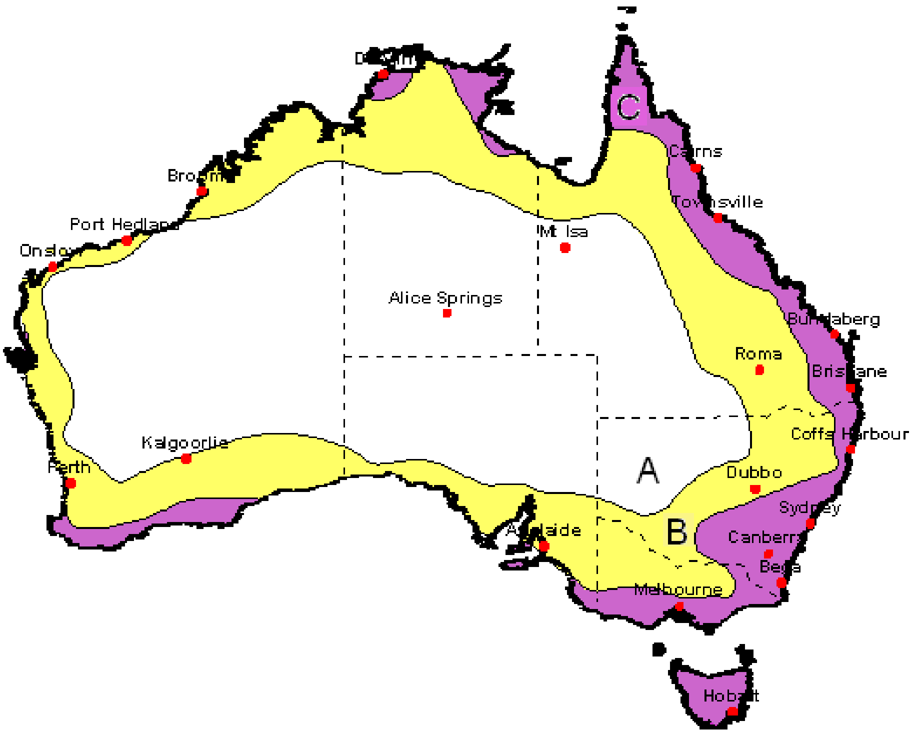


Figure 5.2.1.1 Embedded corrosion hazard zone map. Zone C is most hazardous.

5.2.2 Moisture Content of Timber

The mean annual surface equilibrium moisture content, $SEMC_{mean}$, is given in Table 5.2.1.1, depending on hazard zones. For a specific location, refer to Table 3.2.1, where the values of the $SEMC_{mean}$ of major cities and towns in Australia are listed. The mean seasonal moisture content of a piece of timber, TM_{mean} for one year is estimated as,

$$TM_{mean} = exp(1.9 + 0.05\ SEMC_{mean}) \qquad (5.2.2.1)$$

The mean and maximum seasonal moisture contents of timber in building, $BTM_{\max}$ and BTM_{mean}, are:

$$BTM_{\text{mean}} = TM_{\text{mean}} + \Delta_{\text{climate}} + \Delta_{\text{rain}} \qquad (5.2.2.2)$$

$$BTM_{\max} = BTM_{\text{mean}} + 0.1\ D\ TM_{\text{mean}} \qquad (5.2.2.3)$$

where the damping factor *(D)*, the adjustment factors for the climate (Δ_{climate}) are given in Tables 5.2.2.1. The adjustment factor for rain (Δ_{rain}) is given in Table 5.2.2.2.

Table 5.2.2.1 Damping factor and adjustment factor for climate

Climate zone	***D***	Δ_{climate}
Marine*	6.0	2.5
Other	2.0	0.5

* Marine: if the distance to coast < 1 km

Table 5.2.2.2 Adjustment factor Δ_{rain}

Outdoor (Facades)	Δ_{rain}		
	Hazard zone A	**Hazard zone B**	**Hazard zone C**
Sheltered / partly sheltered from rain	0	1	2
Vertical surface exposed to rain	1	4	8
Horizontal surface exposed to rain	3	9	17

5.2.3 Corrosion Depth of embedded fasteners in untreated wood

For the case of untreated wood, corrosion depth for the first year (mm), c_o is computed as follows,

$$c_o = \frac{1}{2}\left[f_{120}(BTM_{max}) + 0.3 f_{120}(BTM_{mean}) \right] \qquad (5.2.3.1)$$

where $f_{120}(M)$ is the corrosion depth of connectors embedded in untreated wood for 120 days, given as a function of timber moisture content M,

$$f_{120}(M) = \begin{cases} 0 & \text{if } M \le M_0; \\ 0.2\ C_{120}(M - M_0) & \text{if } M_0 < M < (M_0 + 5\%); \\ C_{120} & \text{if } M \ge (M_0 + 5\%) \end{cases} \qquad (5.2.3.2)$$

The function is illustrated in Figure 5.2.3.1. Values of C_{120} and M_0 are listed in Table 5.2.3.1 depending on the timber acidity class and timber type.

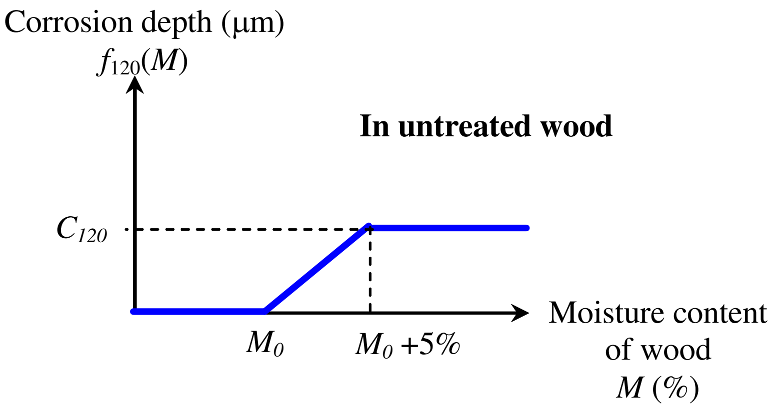


Figure 5.2.3.1. Base model of embedded corrosion in untreated wood.

Table 5.2.3.1 Parameters of the corrosion model of embedded fasteners in untreated wood

Material	Wood type	C_{120}			M_0 (%)
		Acidity class 1	Acidity class 2	Acidity class 3	
Zinc	Hardwood	2.0	7.0	12.0	10
	Softwood	4.0	5.0	6.0	15
Steel	Hardwood	2.0	8.0	14.0	15
	Softwood	2.0	6.0	10.0	15

The corrosion depth of embeeded fasteners in untreated wood, c, over the period t years is computed by

$$c = c_o\, t^n \qquad (5.2.3.3)$$

where n= 0.5 for zinc and n = 0.6 for steel.

5.2.4 Corrosion Depth of Embedded Fasteners in CCA treated wood

For the case of CCA-treated wood, corrosion depth for the first year (mm), c_o is computed as follows,

For Zinc $$c_o = 1.3 f_{120}(BTM_{mean}) \tag{5.2.4.1}$$

For steel $$c_o = 2.1 f_{120}(BTM_{mean}) \tag{5.2.4.2}$$

where $f_{120}(M)$ is the corrosion depth of connectors embedded in CCA-treated wood for 120 days, given by

$$f_{120}(M) = \begin{cases} 0 & \text{if } M \le M_0; \\ 0.7\ (M - M_0) & \text{if } M > M_0; \end{cases} \tag{5.2.4.3}$$

where M is moisture content, M_0 = 12%. The function is illustrated in Figure 5.2.4.1.

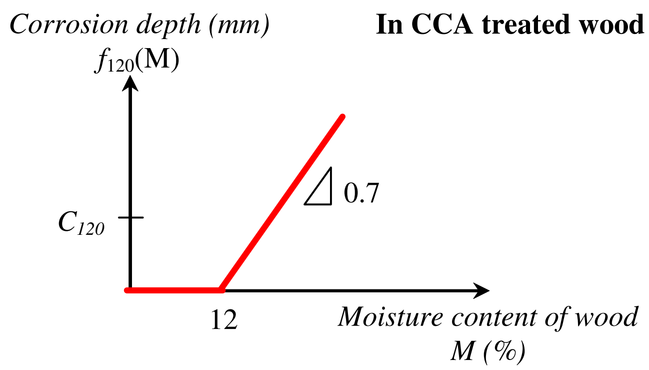


Figure 5.2.4.1. Base model of embedded corrosion in CCA-treated wood.

The corrosion depth of embedded fasteners in CCA-treated wood, c, over the period t years is computed by

$$c = c_o\, t^n \tag{5.2.4.4}$$

where n= 0.6 for zinc and n = 1.0 for steel.

5.2.5 Design Depth of Embedded Corrosion

The design depth of embedded corrosion, c_{design} will be given by

$$c_{design} = c\left(1 + \alpha V_c\right) \quad (5.2.5.1)$$

where

- c is the mean depth of the loss in fastener cross-section due to embedded corrosion, computed by Eq.(5.2.3.3) or Eq.(5.2.4.4) for a chosen design life time.
- V_c is the coefficient of variation of c. From available data, it is recommended that V_c = 2.0.
- α is specified parameter related to the target reliability level.
  - α = 0.8 for normal consequence of failure elements.
  - α = 0.4 for low consequence of failure elements.

From the design depth of embedded corrosion, the residual cross-section is estimated; from which engineers compute the acceptable design load capacity by normal AS1720.1 procedure.

5.3 Corrosion of Bolts

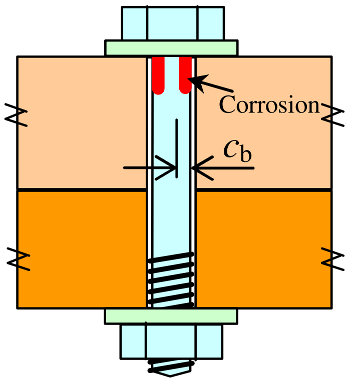


Figure 5.3.1 Depth of corrosion at the neck of the bolt

It is known that bolted joints can form a very special case of embedded fastener, because they are often placed in oversized holes pre-drilled into the timber, thus allowing moisture/water, salt and oxygen to enter, a situation that does not occur with other fasteners. To provide some sort of indication of the corrosion of bolts, an assumption is made that the worst corrosion occurs near the neck of the bolt, and this is either due to the embedded corrosion mechanism that is enhanced by water ingress into the bolt's hole; or due to atmospheric corrosion that is enhanced if the connector is near a beach. The procedures are as follows,

- To compute the corrosion depth due to the embedded corrosion, follow the procedure in Section 5.2, with a modification that the adjusted factor Δ_{rain} (Table 5.2.2.2) is multiplied by factor of 1.5 to take into account the increasing of timber moisture content due to water ingress into the bolt's holes.
- To compute of the corrosion depth due to atmospheric corrosion that is enhanced if the connector is near a beach, follow the procedure in Manual No.5.

The corrosion depth c_b near the neck of the bolt is taken to be the higher of these two computed corrosion values.

6. Equations for the Design Guide

6.1 Hazard Zones

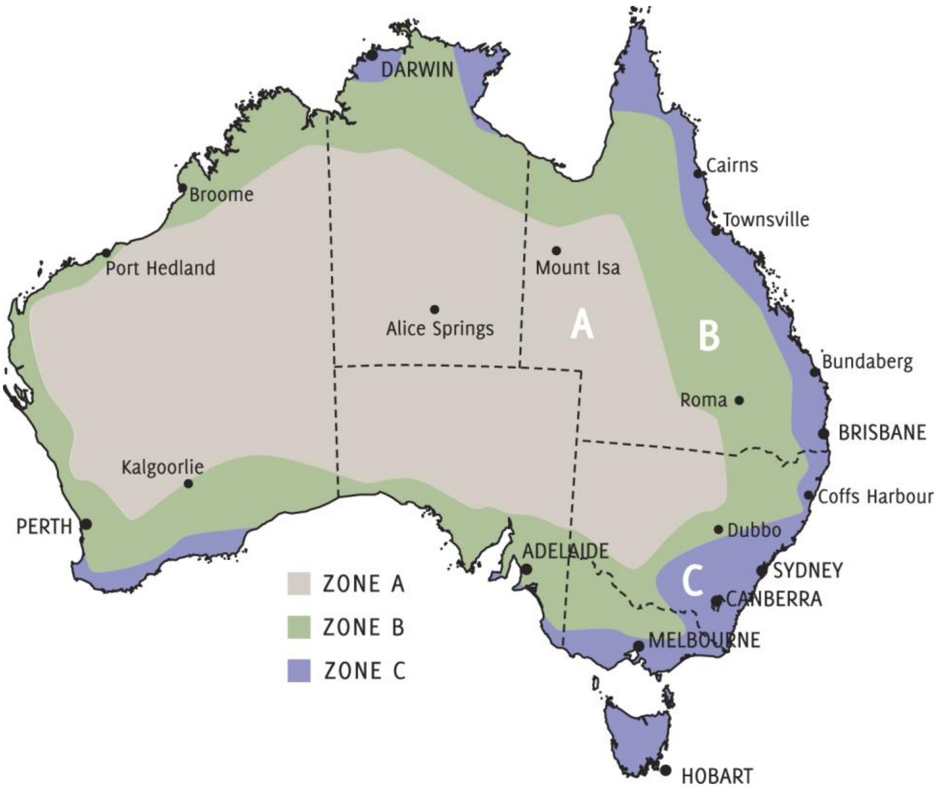


Figure 6.1.1. Hazard zone map

6.2 Climate Zones

- Marine: if the distance to coast < 1 km
- Other, ie. non-marine

6.3 Timber Acidity Classification

Timber acidity classification is in Table 6.3.3.

Table 6.3.3 Natural acidity Classification

Standard Australia index	Trade name	Botanical name	Type	Density	Measured pH	Natural acidity class
22	Ash, alpine	Eucalyptus delegatensis	E	650	3.6	3
25	Ash, Crow’s	Flindersia australis	H	950	5.1	1
30	Ash, mountain	Eucalyptus regnans	E	640	4.7	2
37	Ash, silvertop	Eucalyptus sieberi	E	862	3.5	3
-	Balau (selangan batu)	Shorea spp.	H	900	-	2
-	Bangkirai	Shorea laevifolia	H	850	-	2
65	Beech, myrtle	Nothofagus cunninghamii	H	705	-	2
-	Belian (ulin)	Eusideroxylon zwageri	H	1000	-	2
84	Blackbutt	Eucalyptus pilularis	E	884	3.6	3
86	Blackbutt, New England	Eucalyptus andrewsii	E	850	-	3
87	Blackbutt, WA	Eucalyptus patens	E	849	-	3
88	Blackwood	Acacia melanoxylon	H	650	-	2
97	Bloodwood, red	Corymbia gummifera	E	900	3.6	3
90	Bloodwood, white	Corymbia trachyphloia	E	1023	-	3
109	Bollywood	Litsea reticulata	S	532	3.9	3
121	Box, brush	Lophostemon confertus	H	900	4.5	2
126	Box, grey	Eucalyptus moluccana	E	1105	3.5	3
127	Box, grey, coast	Eucalyptus bosistoana	E	1110	3.4	3
134	Box, long leaved	Eucalyptus goniocalyx	E	873	-	3
138	Box, red	Eucalyptus polyanthemos	E	1064	-	3
144	Box, steel	Eucalyptus rummeryi	E	0	-	3
145	Box, swamp	Lophostemon suaveolens	H	850	-	2
150	Box, yellow	Eucalyptus melliodora	E	1075	-	3
148	Box,white	Eucalyptus albens	E	1112	-	3
162	Brigalow	Acacia harpophylla	H	1099	-	2
165	Brownbarrel	Eucalyptus fastigata	E	738	3.3	3
167	Bullich	Eucalyptus megacarpa	E	640	-	3
-	Calantas (kalantas)	Toona calantas	H	500	-	2
178	Candlebark	Eucalyptus rubida	E	750	-	3
73	Cedar, red, western	Thuja plicata	S	448	3.3	3
544	Cypress	Callitris glaucophylla	S	680	5.4	1
114	Fir, Douglas	Pseudotsuga menziesii	S	520	3.5	3
253	Gum, blue, southern	Eucalyptus globulus	E	900	-	3
254	Gum, blue, Sydney	Eucalyptus saligna	E	843	3.6	3
266	Gum, grey	Eucalyptus propinqua	E	1050	3.8	3
267	Gum, grey, mountain	Eucalyptus cypellocarpa	E	961	3.6	3
268	Gum, Maiden's	Eucalyptus maidenii	E	992	-	3
269	Gum, manna	Eucalyptus viminalis	E	814	-	3
272	Gum, mountain	Eucalyptus dalrympleana	E	700	-	3
281	Gum, red, forest	Eucalyptus tereticornis	E	737	4.2	2
281	Gum, red, river	Eucalyptus camaldulensis	E	913	-	3
284	Gum, rose	Eucalyptus grandis	E	753	5.1	1
286	Gum, salmon	Eucalyptus salmonophloia	E	1070	-	3
288	Gum, scribbly	Eucalyptus haemastoma	E	907	-	3
289	Gum, shining	Eucalyptus nitens	E	530	-	3
293	Gum, spotted	Corymbia maculata	E	988	4.5	2
294	Gum, sugar	Eucalyptus cladocalyx	E	1105	-	3
305	Gum, yellow	Eucalyptus leucoxylon	E	1008	-	3
310	Hardwood, Johnstone	Backhousia bancroftii	H	950	-	2

	River					
-	Hemlock, western	Tsuga heterophylla	S	500	4.9	2
322	Ironbark, grey	Eucalyptus paniculata	E	1110	4.0	3
325	Ironbark, red	Eucalyptus sideroxylon	E	1086	-	3
326	Ironbark, red (broad-leaved)	Eucalyptus fibrosa	E	1116	-	3
327	Ironbark, red (narrow-leaved)	Eucalyptus crebra	E	1046	4.0	3
336	Ironwood Cooktown	Erythrophleum chlorostgchys	H	1220	-	2
340	Jam, raspberry	Acacia acuminata	H	1038	-	2
341	Jarrah	Eucalyptus marginata	E	823	3.3	3
-	Kapur	Dryobalanops spp.	H	750	3.3	3
344	Karri	Eucalyptus diversicolor	E	905	4.2	2
	Keruing	Dipterocarpus spp.	H	750	5.1	1
173	Kwila	Intsia bijuga	H	825	-	2
-	Mahogany, Philippine, red, dark	Shorea spp.	H	650	-	2
-	Mahogany, Philippine, red, light	Shorea, Pentacme, Parashorea spp.	H	550	-	2
384	Mahogany, red	Eucalyptus resinifera	E	955	3.0	3
391	Mahogany, white	Eucalyptus acmenoides	E	993	3.5	3
391	Mahogany, white	Eucalyptus umbra	E	887	-	3
387	Mahonany, southern	Eucalyptus botryoides	E	919	-	3
411	Mallet, brown	Eucalyptus astringens	E	974	-	3
432	Marri	Corymbia Calophylla	E	855		3
-	Meranti, red, dark	Shorea spp.	H	650	3.9	3
-	Meranti, red, light	Shorea spp.	H	400	5.0	2
226	Mersawa (Garawa)	Anisoptera thyrifera	H	630	4.5	2
434	Messmate	Eucalyptus obliqua	E	722	3.2	3
435	Messmate, Gympie	Eucalyptus cloeziana	E	996	-	3
458	Oak, bull	Allocasuarina luehmannii	H	1050	-	2
240	Oak, white, American	Quercus alba	H	750	-	2
509	Peppermint, black	Eucalyptus amygdalina	E	753	-	3
510	Peppermint, broad leaved	Eucalyptus dives	E	811	-	3
512	Peppermint, narrow leaved	Eucalyptus radiata	E	822	3.2	3
515	Peppermint, river	Eucalyptus elata	E	804	-	3
529	Pine, black	Prumnopitys amara	S	500	-	2
533	Pine, caribbean	Pinus caribaea	S	550	3.9	3
534	Pine, celery-top	Phyllocladus asplenifolius	S	646	-	2
545	Pine, hoop	Araucaria cunninghamii	S	550	5.2	1
546	Pine, Huon	Lagarostrobos franklinii	S	520	4.6	2
548	Pine, kauri	Agathis robusta	S	503	-	2
549	Pine, King William	Athrotaxis selaginoides	S	400	-	2
559	Pine, radiata	Pinus radiata	S	540	4.8	2
561	Pine, slash	Pinus elliotii	S	650	-	2
-	Ramin	Gonystylus spp.	H	650	5.2	1
326	Redwood	Sequoia sempervirens	S	400	-	2
332	Rosewood, New Guinea	Pterocarpus indicus	H	577	-	2
635	Satinay	Syncarpia hillii	H	838	-	2
668	Stringybark, Blackdown	Eucalyptus sphaerocarpa	E	1000	-	3
671	Stringybark, brown	Eucalyptus capitellata	E	838	-	3

676	Stringybark, red	Eucalyptus macrorhyncha	E	899	-	3
680	Stringybark, white	Eucalyptus eugenioides	E	856	-	3
681	Stringybark, yellow	Eucalyptus muelleriana	E	884	4	3
688	Tallowwood	Eucalyptus microcorys	E	990	3.5	3
-	Taun	Pometia pinnata	H	700	-	2
369	Teak, Burmese	Tectona grandis	H	600	4.5	2
713	Tingle, red	Eucalyptus jacksonii	E	772	-	3
714	Tingle, yellow	Eucalyptus guilfoylei	E	900	-	3
720	Tuart	Eucalyptus gomphocephala	E	1036	-	3
723	Turpentine	Syncarpia glomulifera	H	945	3.5	3
747	Wandoo	Eucalyptus wandoo	E	1099	-	3
774	Woolybutt	Eucalyptus longifolia	E	1068	-	3
780	Yate	Eucalyptus cornuta	E	1100	-	3
788	Yertchuk	Eucalyptus consideniana	E	939	-	3

6.4 Total Hazard Scores

Table 6.4.1 gives the total hazard scores for various scenarios of the corrosion in embedded fasteners.

Table 6.4.1 Hazard scores for corrosion of embedded fasteners

Microclimates	Total Hazard scores					
	Zone A		Zone B		Zone C	
	Marine	Other	Marine	Other	Marine	Other
Subfloor	14	12	16	14	18	16
Wall cavity	12	12	14	14	16	16
Roof space	11	9	13	11	15	13
Outdoor:						
Sheltered / partly sheltered[(1)]	19	12	23	16	26	19
Vertical surface exposed to rain[(2)]	21	14	27	20	35	28
Horizontal surface exposed to rain[(3)]	24	17	35	28	49	42

(1) e.g. house cladding; (2) e.g. fencing, (3) e.g. decking

Note that for the Design Guide, where the Score System is used for estimating the corrosion:

- The building envelope parts (roofspace, subfloor and wall cavity) are included with the assumption that they are reasonably well ventilated.
- The total hazard scores used for outdoor were actually those derived for bolts. This is a conservative assumption as the total hazard scores for other fasteners are slightly lower than those for bolts.

6.5 Hazard Class

Table 6.5.1 Definition of hazard ratings for fasteners embedded in untreated timber

Hazard score		Hazard rating
Hardwoods	Softwoods	
<12	<14	$HR1_{emb}$
12~19	14~22	$HR2_{emb}$
>19	>22	$HR3_{emb}$

Table 6.5.2 Definition of hazard ratings for fasteners embedded in CCA-treated timber

Hazard score	Hazard rating
<12	$HR1_{emb}$
12~17	$HR2_{emb}$
18~23	$HR3_{emb}$
24~30	$HR4_{emb}$
>30	$HR5_{emb}$

6.6 Derived c_0 values

Representative values of c_0 for the classes are estimated and presented in Tables 6.6.1 and 6.6.2 for zinc and steel, respectively.

Table 6.6.1 The first-year corrosion depth of embedded zinc fasteners

Hazard rating	**c_0 - the first-year corrosion depth of zinc**			
	Untreated timber			**CCA-treated timber**
	Acidity Class 1	**Acidity Class 2**	**Acidity Class 3**	
$HR1_{emb}$	0	0	0	0
$HR2_{emb}$	1.0	2.5	4.5	4.0
$HR3_{emb}$	2.0	4.5	8.0	10.0
$HR4_{emb}$	na	na	na	15.0
$HR5_{emb}$	na	na	na	20.0

Table 6.6.2 The first-year corrosion depth of embedded steel fasteners

Hazard rating	**c_0 - the first-year corrosion depth of steel**			
	Untreated timber			**CCA-treated timber**
	Acidity Class 1	**Acidity Class 2**	**Acidity Class 3**	
$HR1_{emb}$	0	0	0	0
$HR2_{emb}$	1.5	4.5	7.5	7.0
$HR3_{emb}$	3.0	6.0	10	15.0
$HR4_{emb}$	na	na	na	25.0
$HR5_{emb}$	na	na	na	32.0

6.7 Corrosion Depth

The corrosion depth, c, over the period t years is given by

$$c = c_o\, t^n \tag{6.7.1}$$

where n= 0.5 for zinc and n = 0.6 for steel in untreated timber; n= 0.6 for zinc and n = 1.0 for steel in CCA-treated timber; c_o is corrosion depth for the first year (mm)

6.8 Service life

The service-life life of a steel fastener is assumed to be the time at which all of the effective zinc coasting, if any, and 30% of the original strength in steel, is lost. The life of a zinc coating is assumed to be the time at which all of the effective zinc protection is lost. The fasteners under consideration are assumed to be subject to bending moment; therefore the decrease of fastener bending strength is proportional to the increase of corrosion depth. For conservative calculation, the initial diameter of screws is taken at the root (i.e. excluding the thread), and that of bolts is taken at the shank.

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APPENDIX A

Derivation of Score System to Estimate Timber Moisture Content

This section presents the development of the score system based on the model equations in Appendix D for estimating the maximum moisture content of timber in buildings (BTM_{max}).

Further simplifications of the simplified theory presented in Appendix D are needed to establish a simple linear score system to predict the moisture content of wood, as follows. From Eqs. (D.4.3.1), (D.4.3.2), and (D.4.3.3), we get

$$TM_{max} = exp(2B)\ TM_{mean} \tag{A.1}$$

Consider the factor '$exp(2B)$' with B values from Table D.4.3.2

For hardwoods	B = 0.050	then	$exp(2B)$ = 1.105
For softwoods	B = 0.054	then	$exp(2B)$ = 1.114
For CCA-treated pine	B = 0.045	then	$exp(2B)$ = 1.094

It can be seen that the factor '$exp(2B)$' does not change much, and has the average of 1.1. Then approximately we have

$$TM_{max} = 1.1\ TM_{mean} \tag{A.2}$$

Using Eqs.(A.2) and (2.4.3.4), Eq.(D.4.3.5) can be divided into 4 terms as follows,

$$BTM_{\max} \doteq TM_{\text{mean}} + 0.1D(TM_{\text{mean}}) + \Delta_{\text{microclimate}} + \Delta_{\text{climate}} + \Delta_{\text{rain}} \tag{A.3}$$

The 1st term TM_{mean} depends mainly on hazard zone. Average values and variation range of TM_{mean} for untreated wood are listed in Table A.1, from which the score for hazard zones, $Score_{hazard\text{-}zone,}$ are set.

The 2nd term depends mainly on the damping parameter D. The total average value of TM_{mean} (calculated for all possible cases – see Appendix B) is 11.8. Therefore, the 2nd term can be approximated as 1.2D. The score for the effects of this 'damping term', $Score_{damping,}$ can be determined as shown in Table A.2, where D values are from Table D.4.3.3.

The 3rd and the 4th terms can be used together to establish the score for microclimate, $Score_{climate,}$ due to climate effects. The two terms $\Delta_{climate}$ and $\Delta_{microclimate}$ can be simply summed together to give the score.

The last term Δ_{rain} gives the score for rain effects, $Score_{rain}$, as given in Table A.4. Values of Δ_{rain} are from Table D.4.3.4. For bolts, as presented in Section 1.8, the scores are 1.5 times higher than those for other fasteners.

The total score is calculated as

$$Score_{total} = Score_{hazard\text{-}zone} + Score_{damping} + Score_{climate} + Score_{rain} \tag{A.4}$$

With the way to establish the score system as presented above, the total score $Score_{total}$ is also the estimate of the maximum moisture content of wood in building (BTM_{max}). Figure A.1 shows the total score $Score_{total}$ versus the BTM_{max} calculated by the timber moisture content model in Section 1.2.2 for all possible combinations of climates at different hazard and climate zones for different types of wood (see Appendix B). It can be seen that the score approximates the moisture content quite well. The errors between BTM_{max} and the total score are also shown in Table B.1, Appendix B. In all cases, the errors are quite small.

Table A.1 Scores for Hazard Zones determined from the term TM_{mean} in Eq. (A.3)

Hazard zones	Average of TM_{mean}	Variation range of TM_{mean}	$Score_{harzard\text{-}zone}$
A	9.8	9.6~9.9	9
B	11.4	11.3~11.5	11
C	13.3	13.3	13

Table A.2 Scores for microclimate determined by damping factor D

Microclimate	D (from Table D.4.3.3)		$Score_{damping} \approx 1.2\,D$	
	Marine	**Other**	**Marine**	**Other**
Sub-floor	2.0	1.0	2.5	1.5
Wall cavity	1.5	1.5	2.0	2.0
Roof space	2.0	2.0	2.5	2.5
Facades (Outdoor)	6.0	2.0	7.5	2.5

Table A.3 Scores for microclimate determined by climate adjusted factors

Microclimate	$Score_{climate} = \Delta_{climate} + \Delta_{microclimate}$	
	Marine	**Other**
Sub-floor	2.5	1.5
Wall cavity	0.5	1.0
Roof space	-0.5	-2.5
Outdoor:	2.5	0.5

Table A.4 Scores for the effect of rain determined by the rain adjustment factor

Outdoor (Facades) Microclimate	***Score*$_{rain}$ = Δ_{rain}**		
	Hazard zone A	**Hazard zone B**	**Hazard zone C**
For fasteners other than bolts			
Sheltered / partly sheltered from rain	0	1	2
Vertical surface exposed to rain	1	4	8
Horizontal surface exposed to rain	3	9	17
For bolts			
Sheltered / partly sheltered from rain	0	1.5	3
Vertical surface exposed to rain	1.5	6	12
Horizontal surface exposed to rain	4.5	13.5	25.5

Table A.5 Total scores for corrosion of embedded fasteners calculated by Eq.(A.4)

Microclimate	**Total scores for various microclimates**					
	Zone A		**Zone B**		**Zone C**	
	Marine	Other	Marine	Other	Marine	Other
Subfloor	14	12	16	14	18	16
Wall cavity	12	12	14	14	16	16
Roof space	11	9	13	11	15	13
Outdoors for fasteners other than bolts						
Sheltered / partly sheltered	19	12	22	15	25	18
Exposed vertical surface	20	13	25	18	31	24
Exposed horizontal surface	22	15	30	23	40	33
Outdoors bolts						
Sheltered / partly sheltered	19	12	23	16	26	19
Exposed vertical surface	21	14	27	20	35	28
Exposed horizontal surface	24	17	35	28	49	42

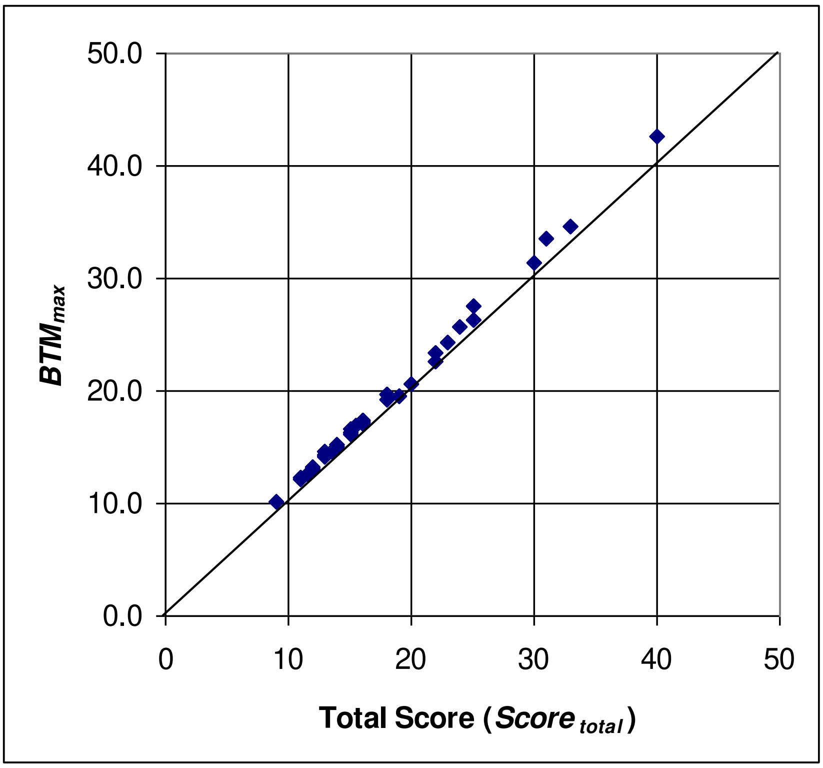


Figure A.1. Maximum moisture content of timber in buildings (BTM_{max}) versus total score ($Score_{total}$) – Data is from Table B.1, Appendix B.

APPENDIX B

MOISTURE CONTENTS & FIRST-YEAR CORROSION DEPTHS FOR THEORETICAL CORROSION SCENARIOS

Table B.1 presents the calculation of timber moisture contents and the first-year corrosion depths for all possible corrosion scenarios, which are made by combinations of different microclimates with different hazard and climate zones for different types of wood in the Timber Moisture content model in Section 1.2.2.

The total score determined by Eq.(A.4) to estimate the maximum moisture content of timber in building as present in Section 4 is also provided. The error of the estimation is computed as

$$error = \left(\frac{Total\ score - BTM_{\max}}{BTM_{\max}} \right) \times 100 \qquad (\%) \qquad \text{(C.1)}$$

Table B.1 Calculation of moisture contents and the first-year corrosion depths of all theoretical corrosion scenarios

Hazard Zone	SEMC mean	SEMC max	Δ rain	Wood type	A	B	C_{120}	M_0	Micro-climate	Climate Zone	D	Δ climate	Δ micro	TM_{mean}	TM_{max}	BTM_{mean}	BTM_{max}	Total score	Error* %
A	9	11	0	E	1.9	0.05	14	15	Subfloor	Marine	2.0	2.0	0.5	10.49	11.59	12.99	15.19	14	-7.8
A	9	11	0	E	1.9	0.05	14	15	Subfloor	Other	1.0	0.0	1.5	10.49	11.59	11.99	13.09	12	-8.3
A	9	11	0	E	1.9	0.05	14	15	Wall	Marine	1.5	2.0	-1.5	10.49	11.59	10.99	12.64	11.5	-9.0
A	9	11	0	E	1.9	0.05	14	15	Wall	Other	1.5	0.0	1.0	10.49	11.59	11.49	13.14	12	-8.7
A	9	11	0	E	1.9	0.05	14	15	Roof	Marine	2.0	2.0	-2.5	10.49	11.59	9.99	12.19	11	-9.8
A	9	11	0	E	1.9	0.05	14	15	Roof	Other	2.0	0.0	-2.5	10.49	11.59	7.99	10.19	9	-11.7
A	9	11	0	E	1.9	0.05	14	15	Outdoor no rain	Marine	6.0	2.0	0.5	10.49	11.59	12.99	19.60	19	-3.1
A	9	11	0	E	1.9	0.05	14	15	Outdoor no rain	Other	2.0	0.0	0.5	10.49	11.59	10.99	13.19	12	-9.0
A	9	11	1	E	1.9	0.05	14	15	Outdoor+rainV	Marine	6.0	2.0	0.5	10.49	11.59	13.99	20.60	20	-2.9
A	9	11	1	E	1.9	0.05	14	15	Outdoor+rainV	Other	2.0	0.0	0.5	10.49	11.59	11.99	14.19	13	-8.4
A	9	11	3	E	1.9	0.05	14	15	Outdoor+rainH	Marine	6.0	2.0	0.5	10.49	11.59	15.99	22.60	22	-2.7
A	9	11	3	E	1.9	0.05	14	15	Outdoor+rainH	Other	2.0	0.0	0.5	10.49	11.59	13.99	16.19	15	-7.4
A	9	11	0	H	1.9	0.05	8	15	Subfloor	Marine	2.0	2.0	0.5	10.49	11.59	12.99	15.19	14	-7.8
A	9	11	0	H	1.9	0.05	8	15	Subfloor	Other	1.0	0.0	1.5	10.49	11.59	11.99	13.09	12	-8.3
A	9	11	0	H	1.9	0.05	8	15	Wall	Marine	1.5	2.0	-1.5	10.49	11.59	10.99	12.64	11.5	-9.0
A	9	11	0	H	1.9	0.05	8	15	Wall	Other	1.5	0.0	1.0	10.49	11.59	11.49	13.14	12	-8.7
A	9	11	0	H	1.9	0.05	8	15	Roof	Marine	2.0	2.0	-2.5	10.49	11.59	9.99	12.19	11	-9.8
A	9	11	0	H	1.9	0.05	8	15	Roof	Other	2.0	0.0	-2.5	10.49	11.59	7.99	10.19	9	-11.7
A	9	11	0	H	1.9	0.05	8	15	Outdoor no rain	Marine	6.0	2.0	0.5	10.49	11.59	12.99	19.60	19	-3.1
A	9	11	0	H	1.9	0.05	8	15	Outdoor no rain	Other	2.0	0.0	0.5	10.49	11.59	10.99	13.19	12	-9.0
A	9	11	1	H	1.9	0.05	8	15	Outdoor+rainV	Marine	6.0	2.0	0.5	10.49	11.59	13.99	20.60	20	-2.9
A	9	11	1	H	1.9	0.05	8	15	Outdoor+rainV	Other	2.0	0.0	0.5	10.49	11.59	11.99	14.19	13	-8.4
A	9	11	3	H	1.9	0.05	8	15	Outdoor+rainH	Marine	6.0	2.0	0.5	10.49	11.59	15.99	22.60	22	-2.7
A	9	11	3	H	1.9	0.05	8	15	Outdoor+rainH	Other	2.0	0.0	0.5	10.49	11.59	13.99	16.19	15	-7.4
A	9	11	0	S	1.9	0.05	6	15	Subfloor	Marine	2.0	2.0	0.5	10.49	11.59	12.99	15.19	14	-7.8
A	9	11	0	S	1.9	0.05	6	15	Subfloor	Other	1.0	0.0	1.5	10.49	11.59	11.99	13.09	12	-8.3
A	9	11	0	S	1.9	0.05	6	15	Wall	Marine	1.5	2.0	-1.5	10.49	11.59	10.99	12.64	11.5	-9.0
A	9	11	0	S	1.9	0.05	6	15	Wall	Other	1.5	0.0	1.0	10.49	11.59	11.49	13.14	12	-8.7
A	9	11	0	S	1.9	0.05	6	15	Roof	Marine	2.0	2.0	-2.5	10.49	11.59	9.99	12.19	11	-9.8
A	9	11	0	S	1.9	0.05	6	15	Roof	Other	2.0	0.0	-2.5	10.49	11.59	7.99	10.19	9	-11.7
A	9	11	0	S	1.9	0.05	6	15	Outdoor no rain	Marine	6.0	2.0	0.5	10.49	11.59	12.99	19.60	19	-3.1
A	9	11	0	S	1.9	0.05	6	15	Outdoor no rain	Other	2.0	0.0	0.5	10.49	11.59	10.99	13.19	12	-9.0
A	9	11	1	S	1.9	0.05	6	15	Outdoor+rainV	Marine	6.0	2.0	0.5	10.49	11.59	13.99	20.60	20	-2.9
A	9	11	1	S	1.9	0.05	6	15	Outdoor+rainV	Other	2.0	0.0	0.5	10.49	11.59	11.99	14.19	13	-8.4
A	9	11	3	S	1.9	0.05	6	15	Outdoor+rainH	Marine	6.0	2.0	0.5	10.49	11.59	15.99	22.60	22	-2.7
A	9	11	3	S	1.9	0.05	6	15	Outdoor+rainH	Other	2.0	0.0	0.5	10.49	11.59	13.99	16.19	15	-7.4
A	9	11	0	CCA	1.9	0.05	0	12	Subfloor	Marine	2.0	2.0	0.5	10.49	11.59	12.99	15.19	14	-7.8
A	9	11	0	CCA	1.9	0.05	0	12	Subfloor	Other	1.0	0.0	1.5	10.49	11.59	11.99	13.09	12	-8.3
A	9	11	0	CCA	1.9	0.05	0	12	Wall	Marine	1.5	2.0	-1.5	10.49	11.59	10.99	12.64	11.5	-9.0
A	9	11	0	CCA	1.9	0.05	0	12	Wall	Other	1.5	0.0	1.0	10.49	11.59	11.49	13.14	12	-8.7
A	9	11	0	CCA	1.9	0.05	0	12	Roof	Marine	2.0	2.0	-2.5	10.49	11.59	9.99	12.19	11	-9.8
A	9	11	0	CCA	1.9	0.05	0	12	Roof	Other	2.0	0.0	-2.5	10.49	11.59	7.99	10.19	9	-11.7
A	9	11	0	CCA	1.9	0.05	0	12	Outdoor no rain	Marine	6.0	2.0	0.5	10.49	11.59	12.99	19.60	19	-3.1
A	9	11	0	CCA	1.9	0.05	0	12	Outdoor no rain	Other	2.0	0.0	0.5	10.49	11.59	10.99	13.19	12	-9.0
A	9	11	1	CCA	1.9	0.05	0	12	Outdoor+rainV	Marine	6.0	2.0	0.5	10.49	11.59	13.99	20.60	20	-2.9
A	9	11	1	CCA	1.9	0.05	0	12	Outdoor+rainV	Other	2.0	0.0	0.5	10.49	11.59	11.99	14.19	13	-8.4
A	9	11	3	CCA	1.9	0.05	0	12	Outdoor+rainH	Marine	6.0	2.0	0.5	10.49	11.59	15.99	22.60	22	-2.7
A	9	11	3	CCA	1.9	0.05	0	12	Outdoor+rainH	Other	2.0	0.0	0.5	10.49	11.59	13.99	16.19	15	-7.4

Hazard Zone	SEMC mean	SEMC max	Δ rain	Wood type	A	B	C_{120}	M_0	Micro-climate	Climate Zone	D	Δ climate	Δ micro	TM_{mean}	TM_{max}	BTM_{mean}	BTM_{max}	Total score	Error* %
B	12	14	0	E	1.9	0.05	14	15	Subfloor	Marine	2.0	2.0	0.5	12.18	13.46	14.68	17.24	16	-7.2
B	12	14	0	E	1.9	0.05	14	15	Subfloor	Other	1.0	0.0	1.5	12.18	13.46	13.68	14.96	14	-6.4
B	12	14	0	E	1.9	0.05	14	15	Wall	Marine	1.5	2.0	-1.5	12.18	13.46	12.68	14.60	13.5	-7.6
B	12	14	0	E	1.9	0.05	14	15	Wall	Other	1.5	0.0	1.0	12.18	13.46	13.18	15.10	14	-7.3
B	12	14	0	E	1.9	0.05	14	15	Roof	Marine	2.0	2.0	-2.5	12.18	13.46	11.68	14.24	13	-8.7
B	12	14	0	E	1.9	0.05	14	15	Roof	Other	2.0	0.0	-2.5	12.18	13.46	9.68	12.24	11	-10.2
B	12	14	1	E	1.9	0.05	14	15	Outdoor no rain	Marine	6.0	2.0	0.5	12.18	13.46	15.68	23.37	22	-5.9
B	12	14	1	E	1.9	0.05	14	15	Outdoor no rain	Other	2.0	0.0	0.5	12.18	13.46	13.68	16.24	15	-7.7
B	12	14	4	E	1.9	0.05	14	15	Outdoor+rainV	Marine	6.0	2.0	0.5	12.18	13.46	18.68	26.37	25	-5.2
B	12	14	4	E	1.9	0.05	14	15	Outdoor+rainV	Other	2.0	0.0	0.5	12.18	13.46	16.68	19.24	18	-6.5
B	12	14	9	E	1.9	0.05	14	15	Outdoor+rainH	Marine	6.0	2.0	0.5	12.18	13.46	23.68	31.37	30	-4.4
B	12	14	9	E	1.9	0.05	14	15	Outdoor+rainH	Other	2.0	0.0	0.5	12.18	13.46	21.68	24.24	23	-5.1
B	12	14	0	H	1.9	0.05	8	15	Subfloor	Marine	2.0	2.0	0.5	12.18	13.46	14.68	17.24	16	-7.2
B	12	14	0	H	1.9	0.05	8	15	Subfloor	Other	1.0	0.0	1.5	12.18	13.46	13.68	14.96	14	-6.4
B	12	14	0	H	1.9	0.05	8	15	Wall	Marine	1.5	2.0	-1.5	12.18	13.46	12.68	14.60	13.5	-7.6
B	12	14	0	H	1.9	0.05	8	15	Wall	Other	1.5	0.0	1.0	12.18	13.46	13.18	15.10	14	-7.3
B	12	14	0	H	1.9	0.05	8	15	Roof	Marine	2.0	2.0	-2.5	12.18	13.46	11.68	14.24	13	-8.7
B	12	14	0	H	1.9	0.05	8	15	Roof	Other	2.0	0.0	-2.5	12.18	13.46	9.68	12.24	11	-10.2
B	12	14	1	H	1.9	0.05	8	15	Outdoor no rain	Marine	6.0	2.0	0.5	12.18	13.46	15.68	23.37	22	-5.9
B	12	14	1	H	1.9	0.05	8	15	Outdoor no rain	Other	2.0	0.0	0.5	12.18	13.46	13.68	16.24	15	-7.7
B	12	14	4	H	1.9	0.05	8	15	Outdoor+rainV	Marine	6.0	2.0	0.5	12.18	13.46	18.68	26.37	25	-5.2
B	12	14	4	H	1.9	0.05	8	15	Outdoor+rainV	Other	2.0	0.0	0.5	12.18	13.46	16.68	19.24	18	-6.5
B	12	14	9	H	1.9	0.05	8	15	Outdoor+rainH	Marine	6.0	2.0	0.5	12.18	13.46	23.68	31.37	30	-4.4
B	12	14	9	H	1.9	0.05	8	15	Outdoor+rainH	Other	2.0	0.0	0.5	12.18	13.46	21.68	24.24	23	-5.1
B	12	14	0	S	1.9	0.05	6	15	Subfloor	Marine	2.0	2.0	0.5	12.18	13.46	14.68	17.24	16	-7.2
B	12	14	0	S	1.9	0.05	6	15	Subfloor	Other	1.0	0.0	1.5	12.18	13.46	13.68	14.96	14	-6.4
B	12	14	0	S	1.9	0.05	6	15	Wall	Marine	1.5	2.0	-1.5	12.18	13.46	12.68	14.60	13.5	-7.6
B	12	14	0	S	1.9	0.05	6	15	Wall	Other	1.5	0.0	1.0	12.18	13.46	13.18	15.10	14	-7.3
B	12	14	0	S	1.9	0.05	6	15	Roof	Marine	2.0	2.0	-2.5	12.18	13.46	11.68	14.24	13	-8.7
B	12	14	0	S	1.9	0.05	6	15	Roof	Other	2.0	0.0	-2.5	12.18	13.46	9.68	12.24	11	-10.2
B	12	14	1	S	1.9	0.05	6	15	Outdoor no rain	Marine	6.0	2.0	0.5	12.18	13.46	15.68	23.37	22	-5.9
B	12	14	1	S	1.9	0.05	6	15	Outdoor no rain	Other	2.0	0.0	0.5	12.18	13.46	13.68	16.24	15	-7.7
B	12	14	4	S	1.9	0.05	6	15	Outdoor+rainV	Marine	6.0	2.0	0.5	12.18	13.46	18.68	26.37	25	-5.2
B	12	14	4	S	1.9	0.05	6	15	Outdoor+rainV	Other	2.0	0.0	0.5	12.18	13.46	16.68	19.24	18	-6.5
B	12	14	9	S	1.9	0.05	6	15	Outdoor+rainH	Marine	6.0	2.0	0.5	12.18	13.46	23.68	31.37	30	-4.4
B	12	14	9	S	1.9	0.05	6	15	Outdoor+rainH	Other	2.0	0.0	0.5	12.18	13.46	21.68	24.24	23	-5.1
B	12	14	0	CCA	1.9	0.05	0	12	Subfloor	Marine	2.0	2.0	0.5	12.18	13.46	14.68	17.24	16	-7.2
B	12	14	0	CCA	1.9	0.05	0	12	Subfloor	Other	1.0	0.0	1.5	12.18	13.46	13.68	14.96	14	-6.4
B	12	14	0	CCA	1.9	0.05	0	12	Wall	Marine	1.5	2.0	-1.5	12.18	13.46	12.68	14.60	13.5	-7.6
B	12	14	0	CCA	1.9	0.05	0	12	Wall	Other	1.5	0.0	1.0	12.18	13.46	13.18	15.10	14	-7.3
B	12	14	0	CCA	1.9	0.05	0	12	Roof	Marine	2.0	2.0	-2.5	12.18	13.46	11.68	14.24	13	-8.7
B	12	14	0	CCA	1.9	0.05	0	12	Roof	Other	2.0	0.0	-2.5	12.18	13.46	9.68	12.24	11	-10.2
B	12	14	1	CCA	1.9	0.05	0	12	Outdoor no rain	Marine	6.0	2.0	0.5	12.18	13.46	15.68	23.37	22	-5.9
B	12	14	1	CCA	1.9	0.05	0	12	Outdoor no rain	Other	2.0	0.0	0.5	12.18	13.46	13.68	16.24	15	-7.7
B	12	14	4	CCA	1.9	0.05	0	12	Outdoor+rainV	Marine	6.0	2.0	0.5	12.18	13.46	18.68	26.37	25	-5.2
B	12	14	4	CCA	1.9	0.05	0	12	Outdoor+rainV	Other	2.0	0.0	0.5	12.18	13.46	16.68	19.24	18	-6.5
B	12	14	9	CCA	1.9	0.05	0	12	Outdoor+rainH	Marine	6.0	2.0	0.5	12.18	13.46	23.68	31.37	30	-4.4
B	12	14	9	CCA	1.9	0.05	0	12	Outdoor+rainH	Other	2.0	0.0	0.5	12.18	13.46	21.68	24.24	23	-5.1

Hazard Zone	SEMC mean	SEMC max	Δ rain	Wood type	A	B	C_{120}	M_0	Micro-climate	Climate Zone	D	Δ climate	Δ micro	TM_{mean}	TM_{max}	BTM_{mean}	BTM_{max}	Total score	Error* %
C	15	17	0	E	1.9	0.05	14	15	Subfloor	Marine	2.0	2.0	0.5	14.15	15.64	16.65	19.63	18	-8.3
C	15	17	0	E	1.9	0.05	14	15	Subfloor	Other	1.0	0.0	1.5	14.15	15.64	15.65	17.14	16	-6.7
C	15	17	0	E	1.9	0.05	14	15	Wall	Marine	1.5	2.0	-1.5	14.15	15.64	14.65	16.89	15.5	-8.2
C	15	17	0	E	1.9	0.05	14	15	Wall	Other	1.5	0.0	1.0	14.15	15.64	15.15	17.39	16	-8.0
C	15	17	0	E	1.9	0.05	14	15	Roof	Marine	2.0	2.0	-2.5	14.15	15.64	13.65	16.63	15	-9.8
C	15	17	0	E	1.9	0.05	14	15	Roof	Other	2.0	0.0	-2.5	14.15	15.64	11.65	14.63	13	-11.1
C	15	17	2	E	1.9	0.05	14	15	Outdoor no rain	Marine	6.0	2.0	0.5	14.15	15.64	18.65	27.59	25	-9.4
C	15	17	2	E	1.9	0.05	14	15	Outdoor no rain	Other	2.0	0.0	0.5	14.15	15.64	16.65	19.63	18	-8.3
C	15	17	8	E	1.9	0.05	14	15	Outdoor+rainV	Marine	6.0	2.0	0.5	14.15	15.64	24.65	33.59	31	-7.7
C	15	17	8	E	1.9	0.05	14	15	Outdoor+rainV	Other	2.0	0.0	0.5	14.15	15.64	22.65	25.63	24	-6.4
C	15	17	17	E	1.9	0.05	14	15	Outdoor+rainH	Marine	6.0	2.0	0.5	14.15	15.64	33.65	42.59	40	-6.1
C	15	17	17	E	1.9	0.05	14	15	Outdoor+rainH	Other	2.0	0.0	0.5	14.15	15.64	31.65	34.63	33	-4.7
C	15	17	0	H	1.9	0.05	8	15	Subfloor	Marine	2.0	2.0	0.5	14.15	15.64	16.65	19.63	18	-8.3
C	15	17	0	H	1.9	0.05	8	15	Subfloor	Other	1.0	0.0	1.5	14.15	15.64	15.65	17.14	16	-6.7
C	15	17	0	H	1.9	0.05	8	15	Wall	Marine	1.5	2.0	-1.5	14.15	15.64	14.65	16.89	15.5	-8.2
C	15	17	0	H	1.9	0.05	8	15	Wall	Other	1.5	0.0	1.0	14.15	15.64	15.15	17.39	16	-8.0
C	15	17	0	H	1.9	0.05	8	15	Roof	Marine	2.0	2.0	-2.5	14.15	15.64	13.65	16.63	15	-9.8
C	15	17	0	H	1.9	0.05	8	15	Roof	Other	2.0	0.0	-2.5	14.15	15.64	11.65	14.63	13	-11.1
C	15	17	2	H	1.9	0.05	8	15	Outdoor no rain	Marine	6.0	2.0	0.5	14.15	15.64	18.65	27.59	25	-9.4
C	15	17	2	H	1.9	0.05	8	15	Outdoor no rain	Other	2.0	0.0	0.5	14.15	15.64	16.65	19.63	18	-8.3
C	15	17	8	H	1.9	0.05	8	15	Outdoor+rainV	Marine	6.0	2.0	0.5	14.15	15.64	24.65	33.59	31	-7.7
C	15	17	8	H	1.9	0.05	8	15	Outdoor+rainV	Other	2.0	0.0	0.5	14.15	15.64	22.65	25.63	24	-6.4
C	15	17	17	H	1.9	0.05	8	15	Outdoor+rainH	Marine	6.0	2.0	0.5	14.15	15.64	33.65	42.59	40	-6.1
C	15	17	17	H	1.9	0.05	8	15	Outdoor+rainH	Other	2.0	0.0	0.5	14.15	15.64	31.65	34.63	33	-4.7
C	15	17	0	S	1.9	0.05	6	15	Subfloor	Marine	2.0	2.0	0.5	14.15	15.64	16.65	19.63	18	-8.3
C	15	17	0	S	1.9	0.05	6	15	Subfloor	Other	1.0	0.0	1.5	14.15	15.64	15.65	17.14	16	-6.7
C	15	17	0	S	1.9	0.05	6	15	Wall	Marine	1.5	2.0	-1.5	14.15	15.64	14.65	16.89	15.5	-8.2
C	15	17	0	S	1.9	0.05	6	15	Wall	Other	1.5	0.0	1.0	14.15	15.64	15.15	17.39	16	-8.0
C	15	17	0	S	1.9	0.05	6	15	Roof	Marine	2.0	2.0	-2.5	14.15	15.64	13.65	16.63	15	-9.8
C	15	17	0	S	1.9	0.05	6	15	Roof	Other	2.0	0.0	-2.5	14.15	15.64	11.65	14.63	13	-11.1
C	15	17	2	S	1.9	0.05	6	15	Outdoor no rain	Marine	6.0	2.0	0.5	14.15	15.64	18.65	27.59	25	-9.4
C	15	17	2	S	1.9	0.05	6	15	Outdoor no rain	Other	2.0	0.0	0.5	14.15	15.64	16.65	19.63	18	-8.3
C	15	17	8	S	1.9	0.05	6	15	Outdoor+rainV	Marine	6.0	2.0	0.5	14.15	15.64	24.65	33.59	31	-7.7
C	15	17	8	S	1.9	0.05	6	15	Outdoor+rainV	Other	2.0	0.0	0.5	14.15	15.64	22.65	25.63	24	-6.4
C	15	17	17	S	1.9	0.05	6	15	Outdoor+rainH	Marine	6.0	2.0	0.5	14.15	15.64	33.65	42.59	40	-6.1
C	15	17	17	S	1.9	0.05	6	15	Outdoor+rainH	Other	2.0	0.0	0.5	14.15	15.64	31.65	34.63	33	-4.7
C	15	17	0	CCA	1.9	0.05	0	12	Subfloor	Marine	2.0	2.0	0.5	14.15	15.64	16.65	19.63	18	-8.3
C	15	17	0	CCA	1.9	0.05	0	12	Subfloor	Other	1.0	0.0	1.5	14.15	15.64	15.65	17.14	16	-6.7
C	15	17	0	CCA	1.9	0.05	0	12	Wall	Marine	1.5	2.0	-1.5	14.15	15.64	14.65	16.89	15.5	-8.2
C	15	17	0	CCA	1.9	0.05	0	12	Wall	Other	1.5	0.0	1.0	14.15	15.64	15.15	17.39	16	-8.0
C	15	17	0	CCA	1.9	0.05	0	12	Roof	Marine	2.0	2.0	-2.5	14.15	15.64	13.65	16.63	15	-9.8
C	15	17	0	CCA	1.9	0.05	0	12	Roof	Other	2.0	0.0	-2.5	14.15	15.64	11.65	14.63	13	-11.1
C	15	17	2	CCA	1.9	0.05	0	12	Outdoor no rain	Marine	6.0	2.0	0.5	14.15	15.64	18.65	27.59	25	-9.4
C	15	17	2	CCA	1.9	0.05	0	12	Outdoor no rain	Other	2.0	0.0	0.5	14.15	15.64	16.65	19.63	18	-8.3
C	15	17	8	CCA	1.9	0.05	0	12	Outdoor+rainV	Marine	6.0	2.0	0.5	14.15	15.64	24.65	33.59	31	-7.7
C	15	17	8	CCA	1.9	0.05	0	12	Outdoor+rainV	Other	2.0	0.0	0.5	14.15	15.64	22.65	25.63	24	-6.4
C	15	17	17	CCA	1.9	0.05	0	12	Outdoor+rainH	Marine	6.0	2.0	0.5	14.15	15.64	33.65	42.59	40	-6.1
C	15	17	17	CCA	1.9	0.05	0	12	Outdoor+rainH	Other	2.0	0.0	0.5	14.15	15.64	31.65	34.63	33	-4.7

Appendix C:. Model Equations 2000

C.1. Introduction

This section presents the early version of the model (Cole, private communication / internal reports) for corrosion of both hot-dipped zinc and bright steel fasteners, which are embedded in untreated and CCA-treated timbers. The model for embedded corrosion uses wood acidity as a starting point. Seasonal moisture content of the wood is used as the corroding parameter indicator.

C.2 Timber Acidity

In this model it will be assumed that the corrosion of untreated timber is related to the acidity of timber, defined as (7− pH), where pH is the acidity of free water in contact with the wood. This is a new concept, and is introduced to make the design procedure more widely applicable. Acidity is used as the basis of the corrosion model since it is the most easily accessible parameter for corrosion of metal in contact with wood. It can be readily measured, and in fact measured values are available for a large number of timber species.

A collection of acidity values derived from BCE measurements and reports by Davis (1994) and Bootle (1983) are reported in Table C.2.1. It should be borne in mind that although the measurement of wood acidity is quick, simple and straightforward it does show considerable variability from piece to piece, and within the same piece of timber.

Table C.2.1. Reported pH values of timber species

Common Name	Botanical Name	BCE	Bootle	Davis	Suggested Design pH
Alder, brown	*Caldcluvia paniculosa*		5.0		5.0
Ash, Alpine	*Eucalyptus delegatensis*		3.6		3.6
Ash, Crow's	*Flindersia australis*		5.1		5.1
Ash, English	*Fraxinus excelsoir*		3.5-5.3		4.0
Ash, Silver	*Flindersia bourjotiana*		5.1		5.1
Ash, Silvertop	*Eucalyptus sieberi*		3.5		3.5
Ash, mountain	*Eucalyptus regnans*	4.7			4.7
Balsa	*Ochroma pyramidale*		5.4-7.2		6.0
Baltic, red	*Pinus sylvestris*		4.3-4.6		4.5
Baltic, white			4.0-5.0		4.5
Bangalay				3.56	3.6
Bean, black	*Castanospermum australe*		3.8-5.2		4.2
Beech	*Fagus* spp?			4.5-5.9	5.0
Beech, European	*Fagus sylvatica*		4.5-6.1		5.0

Common Name	Botanical Name	BCE	Bootle	Davis	Suggested Design pH
Beech, negrohead	*Nothofagus moorei*		4.6-5.1		5.0
Beech, silky	*Citronella moorie*		5.7		5.7
Beech, white	*Gmelina dairympleana*		4.6-5.0		4.8
Birch, white	*Schizomeria ovata*		3.9-4.9		4.2
Blackbutt	*Eucalyptus pilularis*	4.69	3.4	3.12-3.25	3.6
Bloodwood, red	*Eucalyptus gummifera*		3.6		3.6
Bollywood	*Cinnamomum baileyanum*		3.9		3.9
Box, grey	*Eucalyptus microcarpa*		3.5		3.5
Coastal grey box	*Eucalyptus bosistoana*			3.43	3.4
Brownbarrel	*Eucalyptus fastigata*		3.3		3.3
Brush box	*Tristania conferta*	4.6	3.9-4.6	4.55	4.5
Carabeen, yellow	*Sloanea woollsii*		4.4		4.4
P. Caribae	*Pinus caribaea*	5.31			5.3
Cedar, red, western	*Thuja plicata*		2.9-4.0	2.9-4.7	3.3
Chestnut	*Castanea sativa*		3.6		3.6
Coachwood	*Ceratopetalum apetalum*		5.0		5.0
Cypress	*Cupressus macrocarpa*	5.35			5.4
Elm	*Ulmus* spp		6.0-7.2	6.0-7.2	6.2
Fir, Douglas	*Pseudotsuga menziesii*	4.0	3.1-4.4		3.5
Douglas Fir, Oregon Pine	*Pseudotsuga menziesii*			3.1-4.4	3.5
Geronggang			2.6		2.6
Gum, grey	*Eucalyptus canaliculata*		3.8		3.8
Forest red gum	*Eucalyptus blakelyi*	4.96	3.7		4.2
Rose gum	*Eucalyptus grandis*	5.12			5.1
Mountain grey gum	*Eucalyptus cypellocarpa*			3.57	3.6
Sydney Blue gum	*Eucalyptus saligna*		3.6-4.2	3.65-3.80	3.6
Flooded gum	*Eucalyptus rudis*			3.84	3.8
Spotted gum	*Eucalyptus citriodora*	4.5	46-5.0	4.25-4.68	4.5
Hemlock, western	*Tsuga heterophylla*		4.8-5.4		4.9
Hickory	*Carya* spp		5.2		5.2
Iroko	*Chlorophora excelsa*		5.2-7.2		5.5
Red ironbark	*Eucalyptus crebra*	5.06	3.7	3.66	4.0
		4.1			4.0
Grey ironbark	*Eucalyptus drepanophylla*	5.82	3.7	4.88	4.0
Jarrah	*Eucalyptus marginata*		3.0-3.7	3.0-3.7	3.3
Jelutong	*Dyera costulata*		4.6	4.65	4.6
Kapur (Camphorwood)	*Cinnamomum oliveri*		3.2-3.7		3.3
Karri	*Eucalyptus diversicolor*	4.3	4.1	4.05	4.2
Kauri	*Agathis vitiensis*	5.2			5.2
Kempas			3.6-4.6		4.0
Keruing	*Dipterocarpus genus*		5.1		5.1
Larch, European	*Larix decidua*		4.0		4.0
Lignum vitae	*Guaiacum officinale*			3.6	3.6
LOSP		4.6			4.6
Mahogany, African	*Khaya ivorensis*		4.5-5.1		4.7
Mahogany, brush	*Geissois benthamii*		5.1		5.1
Mahogany, red	*Eucalyptus pellita*		2.4-3.4		3.0
Mahogany, rose	*Dysoxylum fraseranum*		4.0		4.0
Mahogany, white	*Eucalyptus acmenoides*		3.9	3.24	3.5
Cuban mahogany	*Swietenia* spp			2.75	2.7

Common Name	**Botanical Name**	**BCE**	**Bootle**	**Davis**	**Suggested Design pH**
(sapwood)					
(heartwood)				3.85	3.8
Maple, rose	*Cryptocarya erythroxylon*		5.5		5.5
Maple, sugar Queensland?	*Flindersia brayleyana*		5.0-5.8		5.4
Meranti	*Shorea* spp	3.9			3.9
Meranti, red, light	*Shorea* spp		4.3-6.1	5.2	5.0
Meranti, red, dark (sapwood)	*Shorea* spp		3.9-5.3	5.4	5.0
(heartwood)				3.85	3.9
Mercau Merbau?	*Pometia acuminata*		4.3		4.3
Mersawa	*Anisoptera* sp		4.3-4.6		4.5
Messmate	*Eucalyptus obliqua*		3.2		3.2
Oak, European	*Quercus ilex*		3.3-5.2		4.0
Oak, Japanese	*Quercus mongolica*		3.2-4.7		3.8
Southern Silky Oak	*Grevilla robusta*			4.95	4.9
Oregon	*Pseudotsuga taxifolia*	3.9			3.9
Peppermint	*Eucalyptus radiata*			3.15	3.2
Pine, cypress, white	*Callitris columellaris*		5.7		5.7
Pine, hoop	*Araucaria cunninghamii*		5.2		5.2
Pine, maritime	*Pinus pinaster*		3.8	3.8	3.8
Pine, radiata	*Pinus radiata*	5.0	4.0-4.8		4.8
Pine, Huon	*Dacrydium franklinii*	4.6			4.6
Pine, caribbean	*Pinus caribaea*			3.9	3.9
Pine, scots	*Pinus sylvestris*			4.3-4.6	4.5
Poplar	*Populus* spp		4.6-5.6		5.0
Ramin			5.2	5.25	5.2
Sacau (Fiji)		5.58			5.6
Sapote	*Calocarpus sapota*		5.3-4.6		5.0
Sassafras	*Daphnandra dielsii*		5.5		5.5
Seraya, white	*Shorea* spp		5.0-5.5		5.3
Spruce, Sitka	*Oicea sitchensis*		3.4-5.5		4.0
Sycamore	*Acer pseudoplatanus*		4.3-6.0		5.0
Tallowwood	*Eucalyptus microcorys*		3.6-3.8	3.55-3.56	3.5
Teak	*Tectona grandis*		4.5		4.5
Turpentine	*Syncarpia glomulifera*		3.6-3.9	3.21	3.5
Yellow stringybark	*Eucalyptus muellerana*	4.73		3.62	4.0
Yellowwood	*Flindersia xanthoxyla*		4.9-5.2		5.0

H3, CCA treated Radiata pine		4.8			na
H5, CCA treated Radiata pine		4.9			na

C.3. Corrosion Model

C.3.1 The Base Corrosion Model

The base models was developed based on corrosion data of metals embedded in untreated and treated timber at moisture content M for 120 days (Cole, internal reports – see Section 3.3). The base models are shown in Figures (C.3.1) and (C.3.2) respectively. Specifically, the metals herein refer to hot dipped galvanised zinc and bright steel. The corrosion depth at 120 days, denoted as $f_{120}(M)$ on the vertical axis is a function of the moisture content of the timber. For untreated wood, under constant conditions, the corrosion is defined by a threshold moisture content M_o. For values of $M < M_o$, $f_{120}(M) = 0$; For values of $M \geq M_o$, $f_{120}(M) = C_{120}$. For treated wood, the corrosion depth is defined by a threshold moisture content M_o, and a value of $f_{120}(M)$ that increase with the moisture content of the timber, M.

C.3.2 Parameters for Untreated Wood

For the case of connectors embedded in untreated wood, at constant moisture content over 120 days, the following equations are proposed; C_{120}, in μm is the depth of corrosion.
The corrosion model for connectors embedded in untreated wood subjected to 120 days corrosion is then:

$$f_{120}(M) = 0 \qquad \text{if } M < M_o \qquad \text{(C.3.1)}$$
$$f_{120}(M) = C_{120} \qquad \text{if } M \geq M_o \qquad \text{(C.3.2)}$$

where M_o and C_{120} are defined as follows by equations (C.3.3) to (C.3.10).

- For zinc in hardwood, $C_{120} = 0.150 \exp\{1.62\ (7-\text{pH})\}$ (C.3.3)
- For zinc in softwood, $C_{120} = 3.19 \exp\{0.179\ (7-\text{pH})\}$ (C.3.4)
- For steel in hardwood, $C_{120} = 0.120 \exp\{1.74\ (7-\text{pH})\}$ (C.3.5)
- For steel in softwood, $C_{120} = 0.280 \exp\{1.19\ (7-\text{pH})\}$ (C.3.6)

Where the value of pH used are given in Table C.2.1. The moisture threshold parameters M_o (%) are set as follows:

- For zinc in hardwood, $M_o = 10$ (C.3.7)
- For zinc in softwood, $M_o = 15$ (C.3.8)
- For steel in hardwood, $M_o = 15$ (C.3.9)
- For steel in softwood, $M_o = 20$ (C.3.10)

The fit of the proposed model with the test data for various species is shown in Section C.4. It is seen that the fit is reasonably good except for the case of Meranti species.

C.3.3 Parameters for CCA-Treated Wood

The model for of zinc connectors embedded in CCA treated wood is given by:

$$f_{120}(M) = 0 \qquad \text{if } M < M_o \qquad \text{(C.3.11)}$$
$$f_{120}(M) = 0.7\ (M\text{-}10) \qquad \text{if } M \geq M_o \qquad \text{(C.3.12)}$$

where $M_o = 10$

The model for of steel connectors embedded in CCA treated wood is given by:

$f_{120}(M) = 0$ if $M < M_o$ (C.3.13)

$f_{120}(M) = 0.7\ (M\text{-}13)$ if $M \geq M_o$ (C.3.14)

where $M_o = 13$

C.3.4 Moisture Content of Timber

Before the corrosion depth for an embedded fastener can be computed using the base models, the moisture content of the timber, appropriate to the climate and microclimate must first be calculated. A model for moisture content of timber was developed based on a test program presented in Cole et.al., 1996a, 1999, Ganther et.al. , 2000.

Initially, the surface equilibrium moisture content (*SEMC*) for a given temperature and humidity is calculated according to Bramhall's equation as follows:

$$SEMC = \frac{\log_e\left[\dfrac{\log_e(H/100) - 0.0251}{17.884 + 0.0002362(T+273)^2 - 0.1432(T+273)}\right]}{0.92 \times \log_e\left[1.0327 - 0.000674(T+273)\right]} \quad \text{(C.3.15)}$$

where

T = the dry bulb temperature (C°)
H = relative humidity (%)

The *SEMC* should be calculated every three hours, using data from a nearby Bureau of Meteorology station. The three hourly data should then be averaged for each of the four seasons, beginning with summer (i.e. December to February) to obtain values for each of the four seasons, $SEMC_{season}$ (i.e. $SEMC_{summer}$, $SEMC_{autumn}$, $SEMC_{winter}$, $SEMC_{spring}$). We assume that the seasonal value of *SEMC* penetrates reasonably deep into the timber. From these four values, we can compute $SEMC_{mean}$, the mean annual value of the four seasonal moisture contents, and $SEMC_{max}$, the maximum seasonal *SEMC*. Both of these values are required in the embedded corrosion procedure, and can be derived from Bureau of Meteorology station data. Alternatively, values of $SEMC_{mean}$ can be obtained from published maps in a variety of sources, including some Australian Standards. A map of $SEMC_{mean}$ for Australia is shown in Figure C.3.3. If maps of $SEMC_{max}$ are not available, then for practical purposes, $SEMC_{max}$ can be computed directly from Bureau of Meteorology data or approximated as ($SEMC_{mean}$ + 2) %. From these values, the moisture content of the timber can be calculated for various exposure conditions. Let us define the following notation for the moisture content in a piece of timber:

TM – the seasonal value of moisture content in a piece of timber
TM_{max} – the maximum value out of the four TM values for one year

*TM*mean – the mean annual value of the four TM values for one year

The moisture content for a season of the exposed timber, TM_{season}, can be calculated using the following:

$$TM_{season} = \exp\left[A + B\ SEMC_{season}\right] \quad (C.3.16)$$

where *A* and *B* are given in Table C.3.2. *TM* is then calculated for each of the seasons, using the seasonal *SEMC* values and subsequently TM_{max} and TM_{mean} are calculated. Finally, these values are used to calculate the maximum and mean values of the moisture content in the timber *within the building* of interest, by adjusting for the microclimate in the following manner.

Let us define the following notation for timber inside a building:

BTM – the seasonal value of moisture content of timber in a building
BTM_{max} – the maximum value out of the four BTM values for one year
BTM_{mean} – the mean annual value of the four BTM values for one year.

The moisture content of the timber in the building, *BTM*, can be calculated using the following:

$$BTM_{max} = TM_{mean} + D\left[TM_{max} - TM_{mean}\right] + \Delta_{microclimate} + \Delta_{climate} \quad (C.3.17)$$

$$BTM_{mean} = TM_{mean} + \Delta_{microclimate} + \Delta_{climate} \quad (C.3.18)$$

The damping factor (*D*) and the adjustment factors for the climate ($\Delta_{climate}$) and the microclimate ($\Delta_{microclimate}$) are given in Tables C.3.3 and C.3.4.

In Tables C.3.3 and C.3.4, the damping, climate and microclimate depend on a climate zone classification of the building location. To derive this zone classification, the building location is first defined in terms of a climate type according to Figure C.3.4, and then the step-by-step procedure specified in Table C.3.5 is used to derive the climate zone.

C.3.5 Computation of Corrosion Depth

Now that the moisture content of the timber for the appropriate climate and microclimate has been calculated, the corrosion depth, over a period of time can be computed.

The corrosion depth, *c*, over the period t years is given by

$$c = c_o\, t^n \quad (C.3.19)$$

where n= 0.5 for zinc and n = 0.6 for steel; c_o is corrosion depth for the first year.

For the case of untreated wood:

$$c_o = f_{120}(BTM_{max}) + 0.3 f_{120}(BTM_{mean}) \quad (C.3.20)$$

For the case of CCA-treated wood:

$$c_o = 2.5 f_{120}(BTM_{mean}) \qquad (C.3.21)$$

where f_{120} is defined by equations (C.3.1) to (C.3.14). The form of Eqs. (C.3.19) to (C.3.21) is developed in Cole (internal reports).

Table C.3.2. Moisture content parameters *A* and *B*

Moisture Content Parameter	**Hardwoods**	**Softwoods**	**CCA Treated Pine**
A	1.84	1.78	2
B	0.05	0.054	0.045

Table C.3.3. Damping factor used in calculation of *BTM*

Climate Zone	**Damping, *D***			
	Sub-Floor	**Wall-cavity**	**Roof-space**	**Facades**
TROPICAL	1.5	1.5	1.5	1
SUB-TROPICAL	1	1.5	2	1.5
TEMPERATE	1	1.5	2	3
INLAND	0.5	0.6	0.6	1
ALPINE	0.2	0.6	0.6	1
MARINE	2	1.5	2	6

Table C.3.4. Climate and Micro-climate adjustment factors used in calculation of *BTM*

Climate Zone	$\Delta_{climate}$	$\Delta_{microclimate}$			
		Sub-Floor	**Wall-cavity**	**Roof-space**	**Facades**
TROPICAL	0	1.5	2	-4.5	0.5
SUB-TROPICAL	0	0.5	0.5	-5.0	0.5
TEMPERATE	0	0.5	0.5	-4.5	0.5
INLAND	0	0.5	0.5	-2.5	0.5
ALPINE	1	1.5	-0.5	-2.5	0.5
MARINE	2	0.5	-1.5	-2.5	0.5

Table C.3.5. Definition of Climate Zone

Step 1. First: determine the climate type from the map in Figure C.3.4.
Step 2. Check if in MARINE Zone If the distance to the coast < 1km then zone = MARINE
Step 3. Check if in ALPINE Zone If the distance to the coast >1km If climate type is temperate and elevation > 700m then zone = ALPINE If climate type is tropical and elevation > 300m then zone = ALPINE If climate type is sub-tropical and elevation > 250m then zone = ALPINE
Step 4. Check if in INLAND Zone If the distance to the coast > 100 km If climate type is sub-tropical–arid then zone = INLAND If climate type is temperate –arid then zone = INLAND
Step 5. If not MARINE, ALPINE or INLAND, then: If climate type is tropical then zone = TROPICAL If climate type is sub-tropical then zone = SUBTROPICAL If climate type is temperate then zone = TEMPERATE

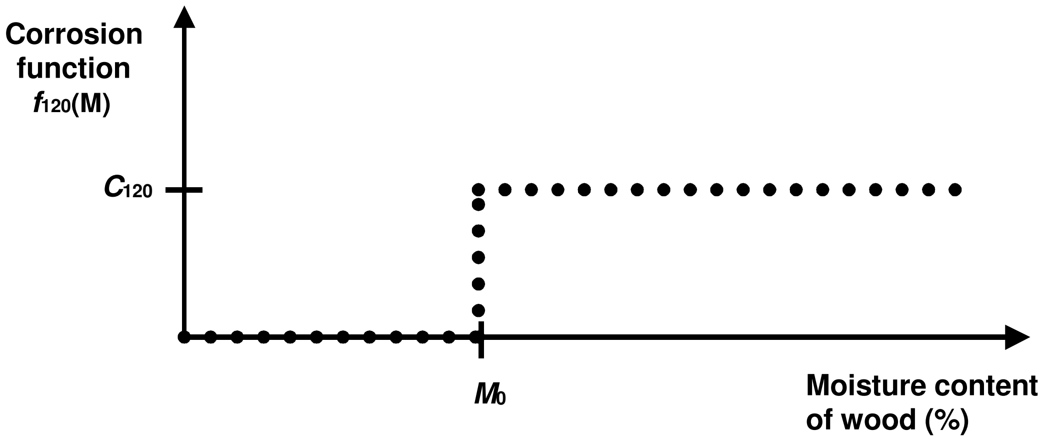


Figure C.3.1. Corrosion function $f_{120}(M)$ for timber embedded in untreated wood.

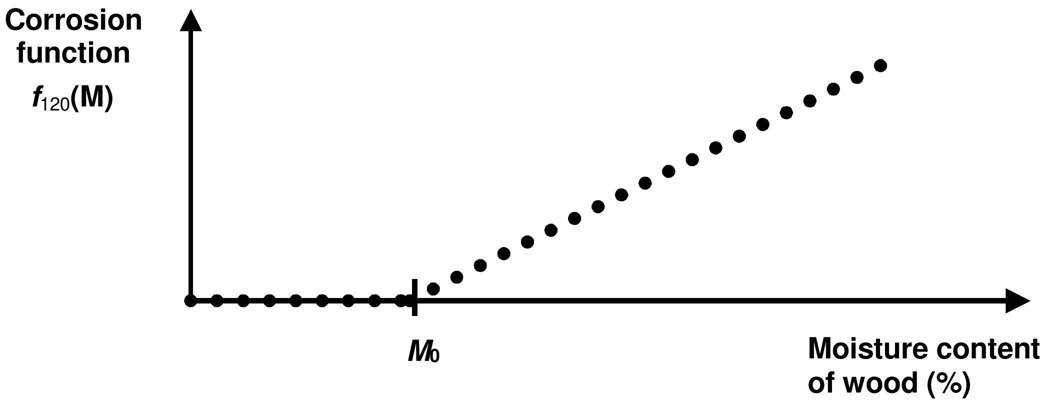


Figure C.3.2. Corrosion function $f_{120}(M)$ for timber embedded in CCA treated wood.

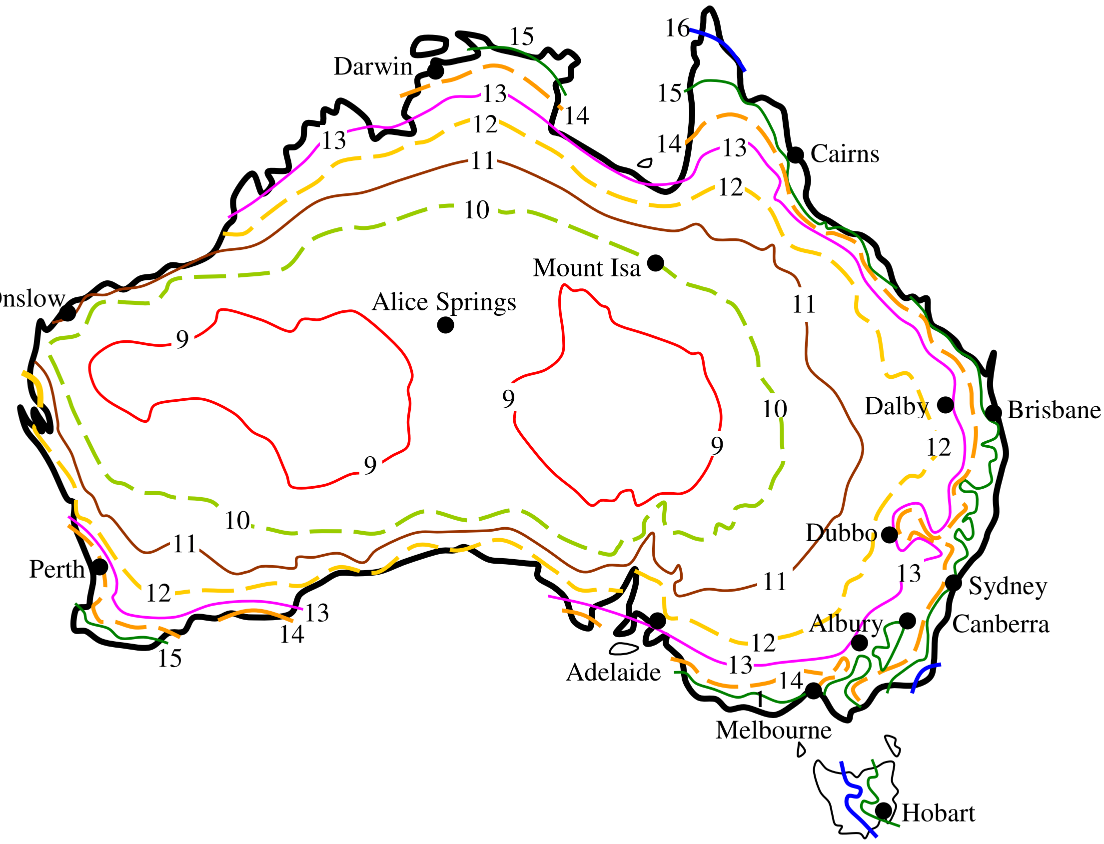


Figure 1.3.3. Annual mean surface moisture content of timber outdoors.

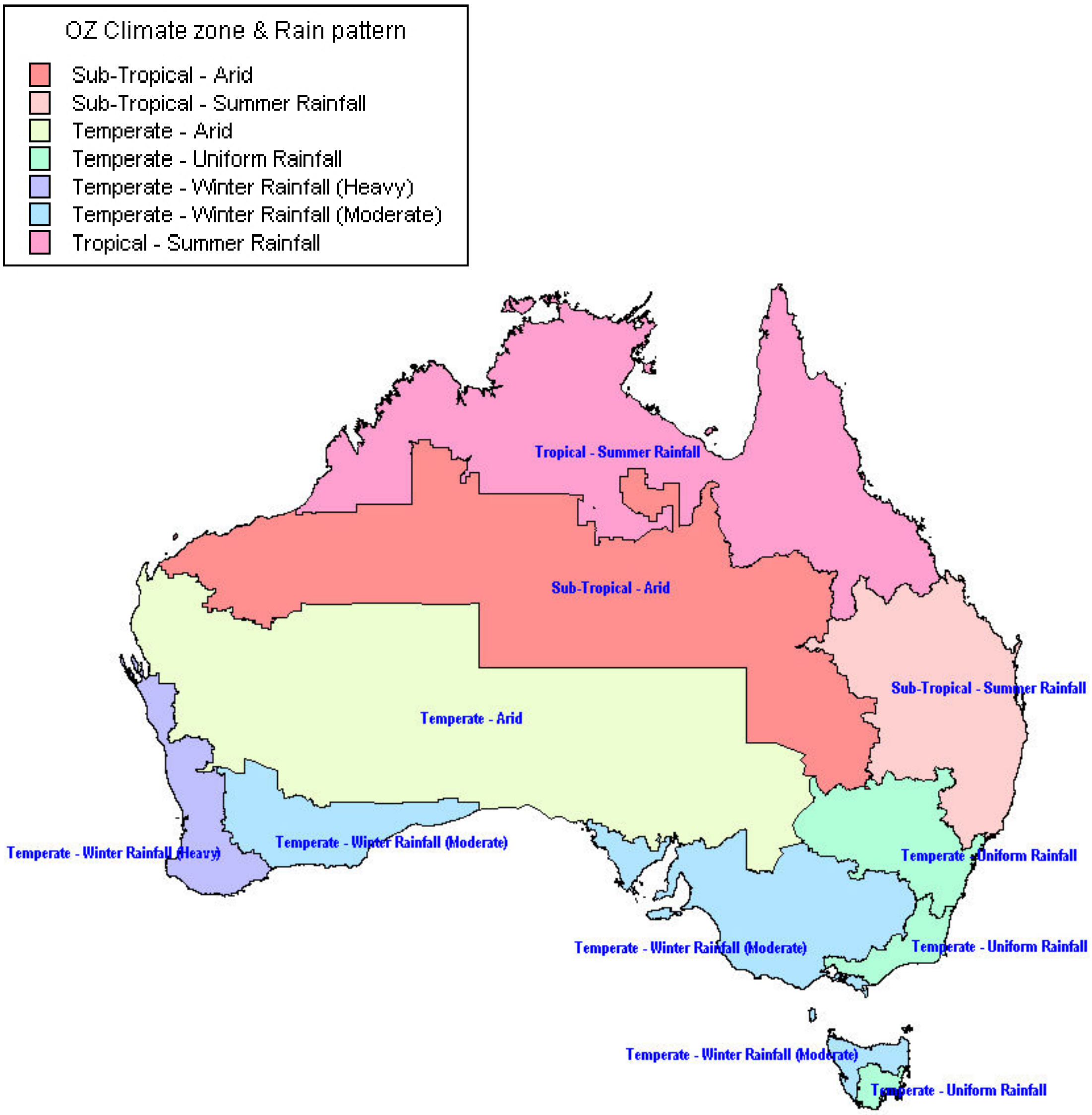


Figure C.3.4. Climate Type, used to derive Climate Zone by the procedure in Table C.3.5

C.4 Data from nails embedded in timber for 120 days under constant moisture content

The data on nails embedded in timber for 120 days has been given in Section 3.3. This Section provides the fitting of the data with the early version of the model presnted in this appendix. The fitting function f_{120} in Section C.3 for the hot dipped galvanised zinc and for bright steel are compared with the measured data. Data is shown in Figure C.4.1 for nails embedded in hardwoods, in Figure C.4.2 for nails embedded in softwoods and in Figure C.4.3 for nails embedded in CCA treated timber. It is to be noted that the model predictions are reasonably good for all cases except for the case of Meranti timber. This may be due to the fact that Meranti is the trade name given to a mixture of more than 50 tropical species of timber, and that quite different species may have been used in the measurements of acidity and the nail corrosion rate. Data is in Table 3.3.1.

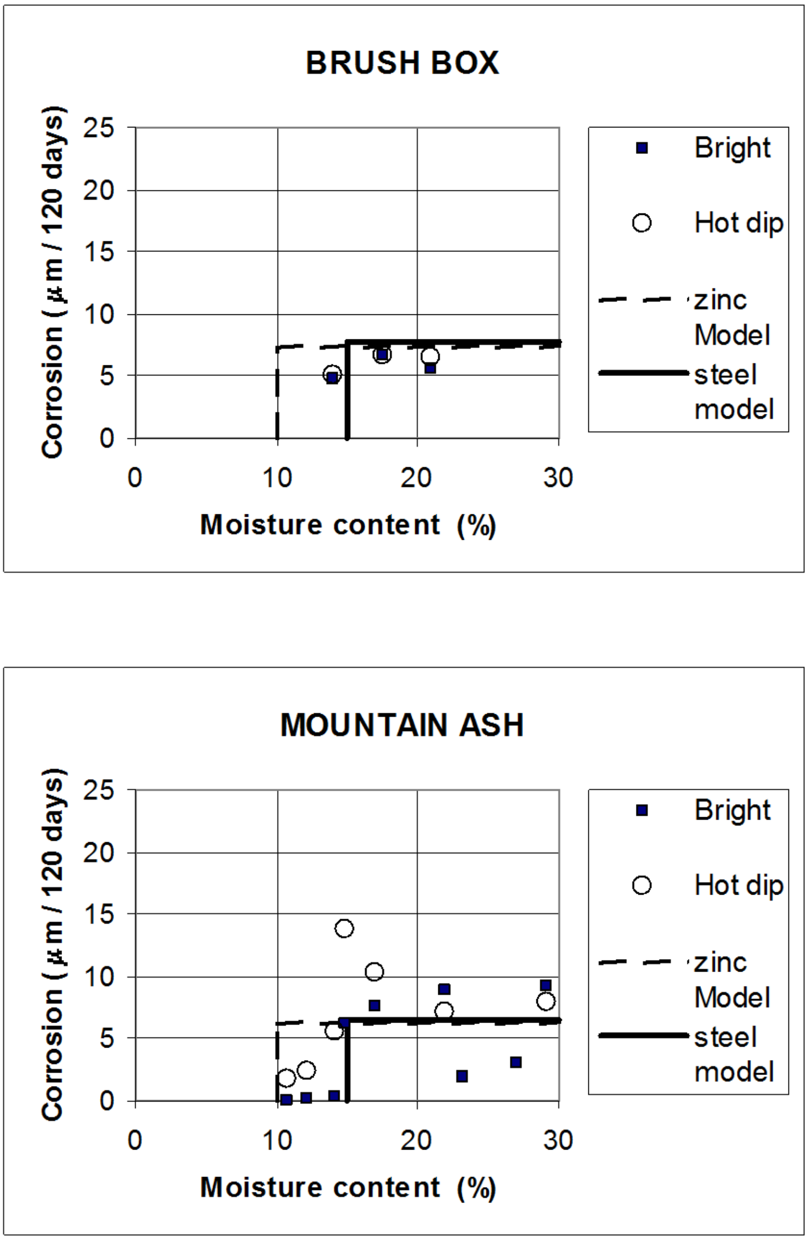
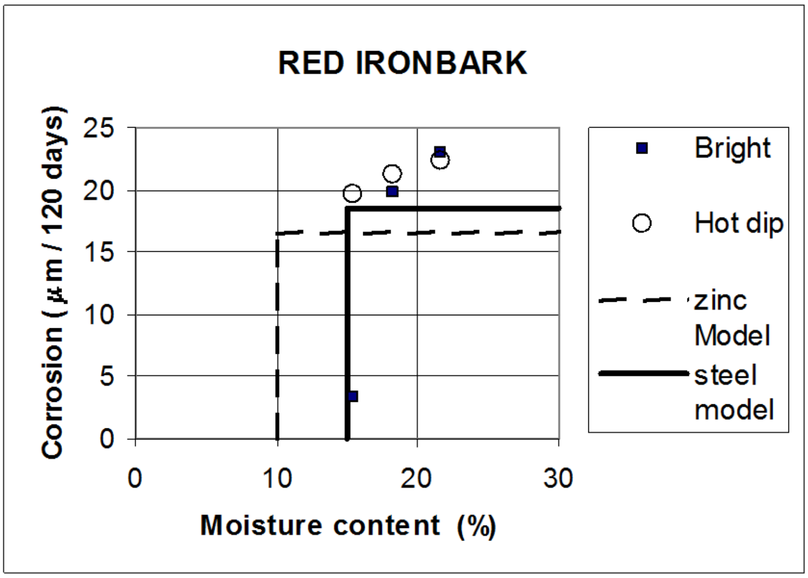


Figure C.4.1. *Comparison of corrosion model for embedded metal, with test data for hardwoods.*



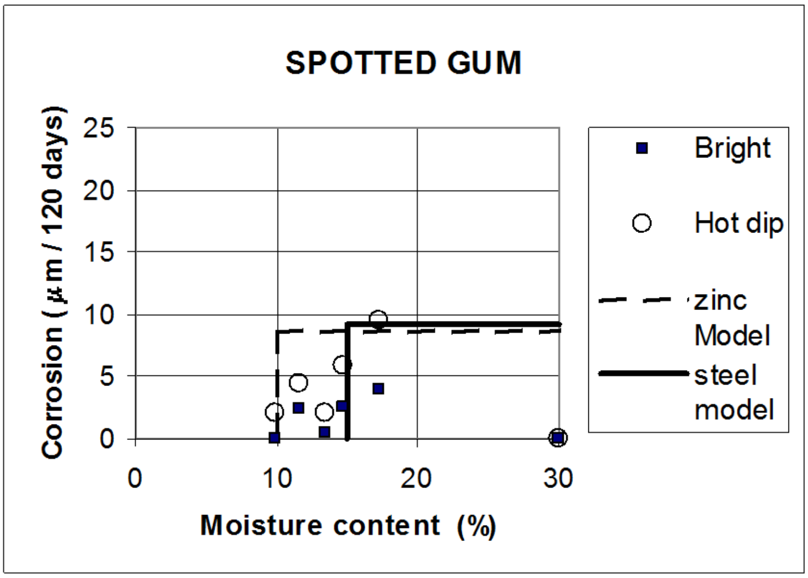
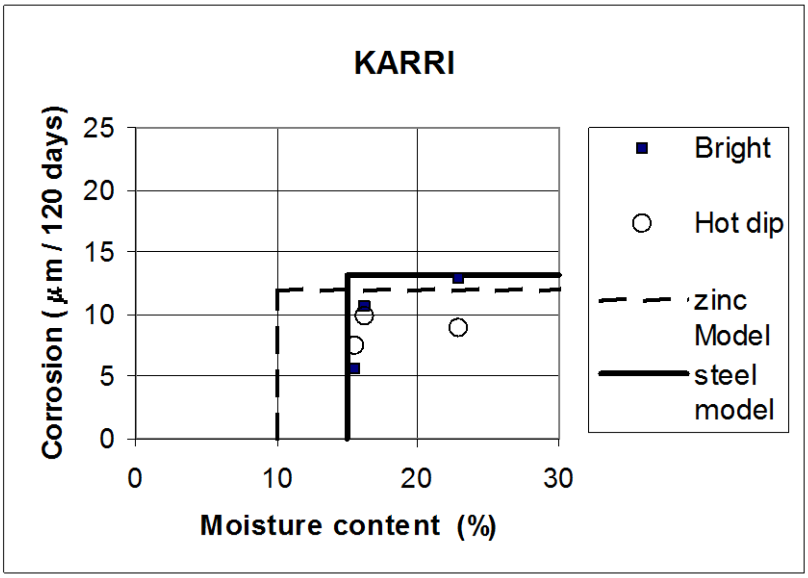


Figure C.4.1 (cont) *Comparison of corrosion model for embedded metal, with test data for hardwoods.*



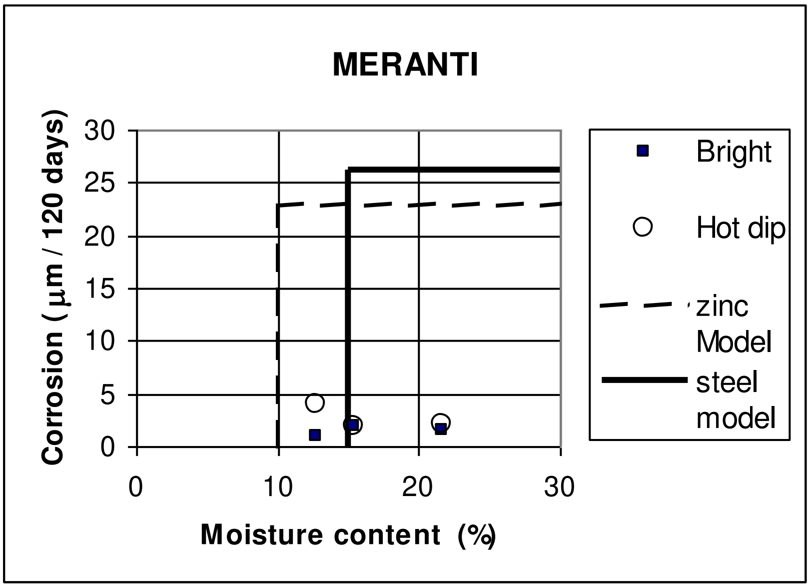


Figure C.4.1 (cont) *Comparison of corrosion model for embedded metal, with test data for hardwoods.*

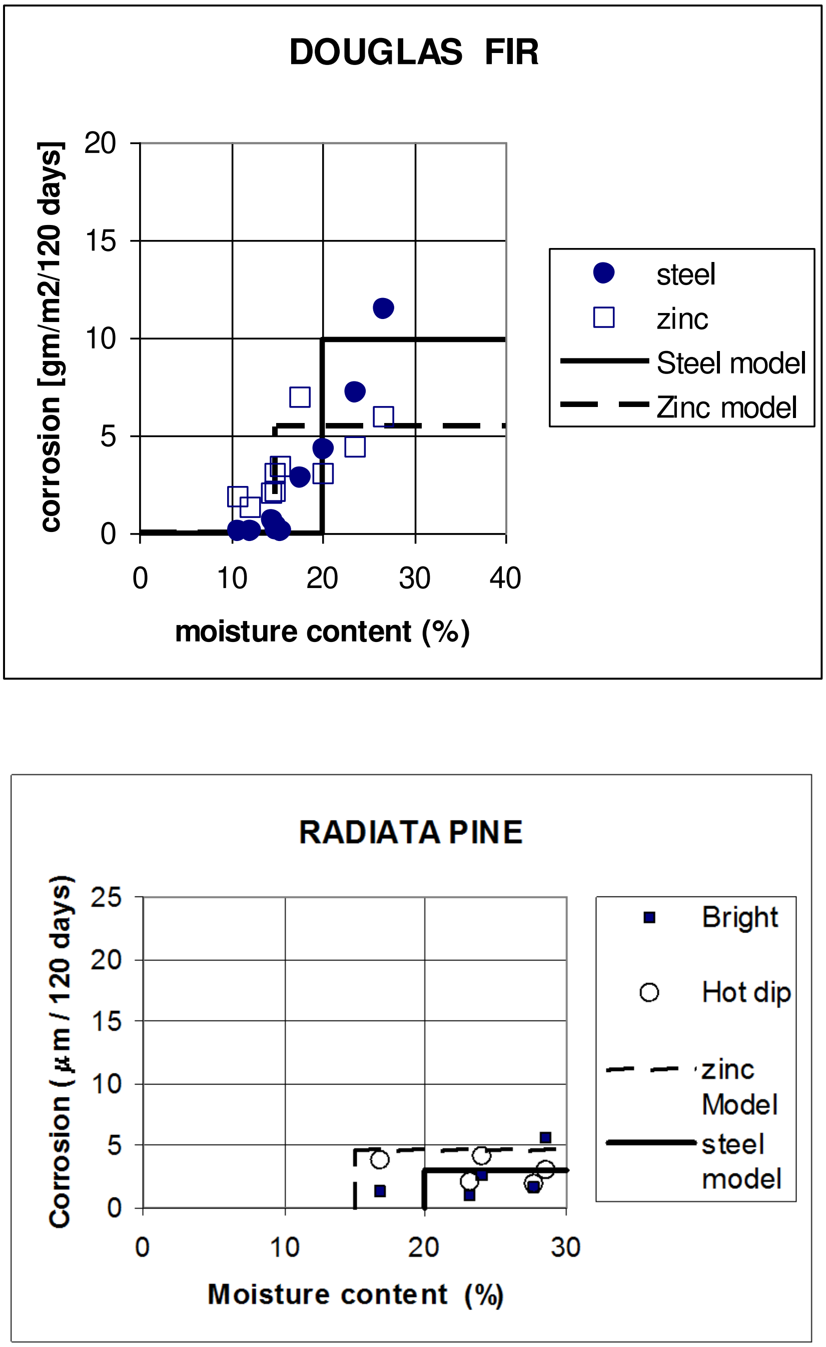
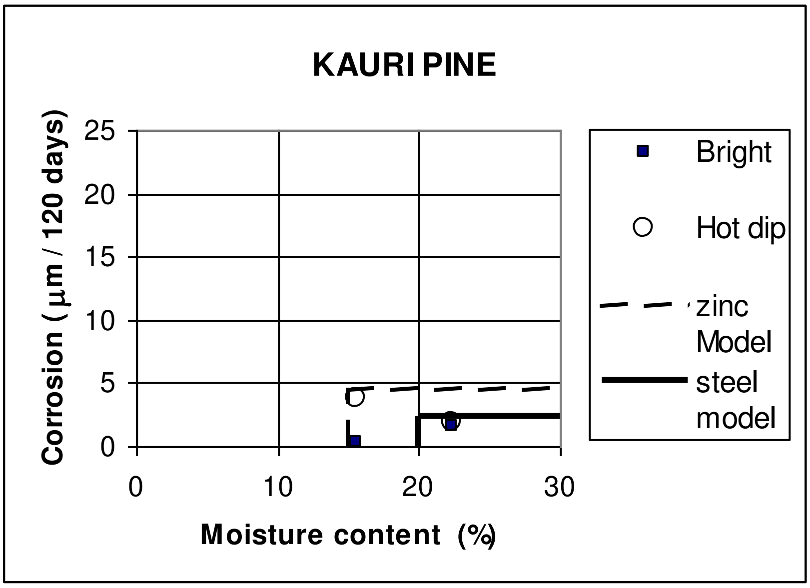


Figure C.4.2 *Comparison of corrosion model for embedded metal, with test data for softwood timber.*



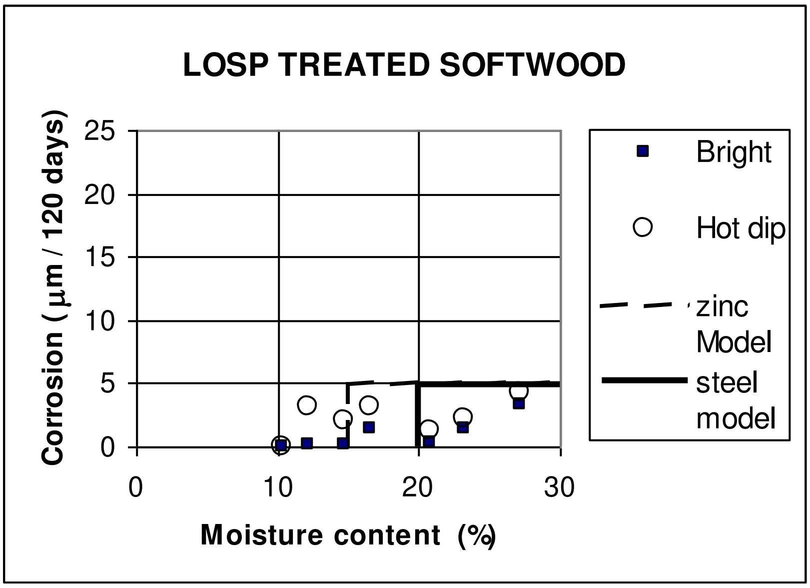


Figure C.4.2 (cont) *Comparison of corrosion model for embedded metal, with test data for softwood timber.*

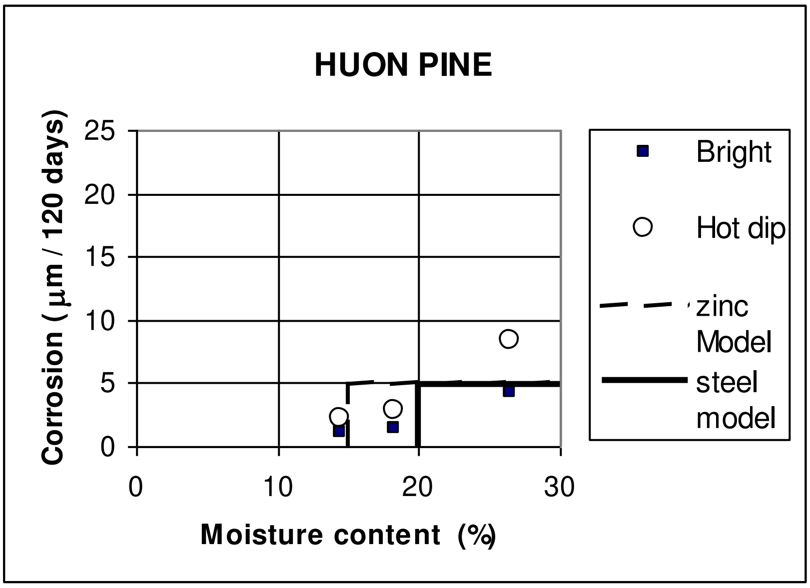
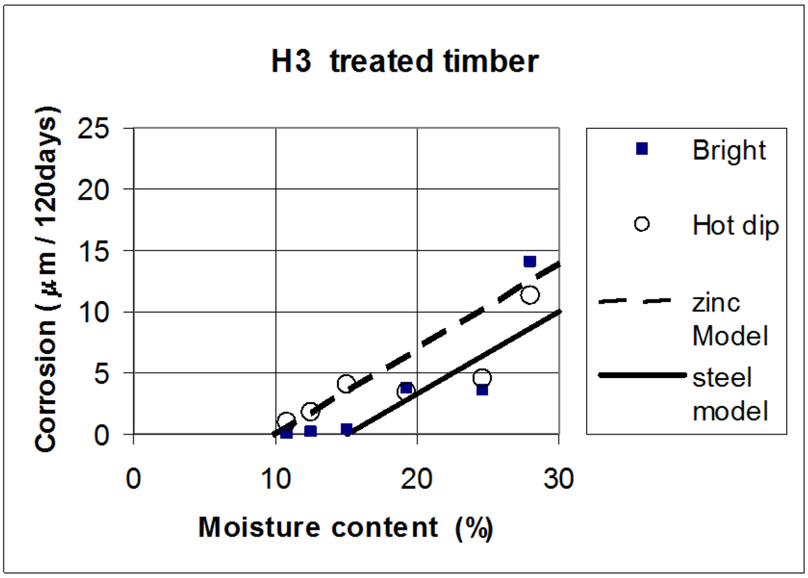


Figure C.4.2 (cont) *Comparison of corrosion model for embedded metal, with test data for softwood timber.*



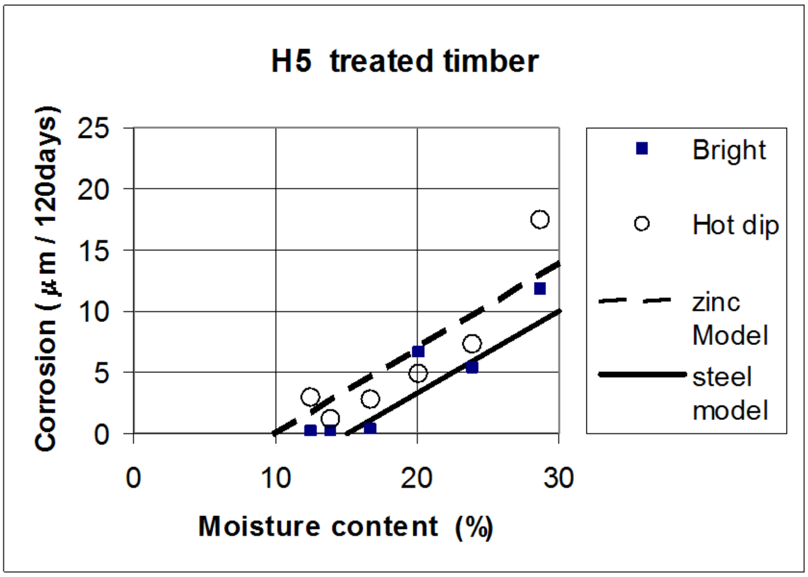


Figure C.4.3 *Comparison of corrosion model for embedded metal,with test data for CCA treated Radiata pine.*

Appendix D:. Model Equations 2002

D.1 Hazard Zones

To simplify the calculation procedure, 3 hazard zones, namely A, B and C; are created as shown in Fig. D.1.1. This original map - similar to the SEMC map in Fig. C.3.3 - is plotted from the $SEMC_{mean}$ data of the Bureau of Meteorology (BOM). However, there has been an adjustment in the $SEMC_{mean}$ data due to the simplification of the climate zones. The adjustment has been made to the tropical areas, which have latitudes less than 23° S. The $SEMC_{mean}$ data in the tropical areas has been increased 1% to compensate for using the simplified values of $\Delta_{microclimate}$ for climate zone 'other', ie. non-marine, as in Table D.4.3.3. This will be defined as the effective SEMC. The simplified climate zonation is presented in the next section.

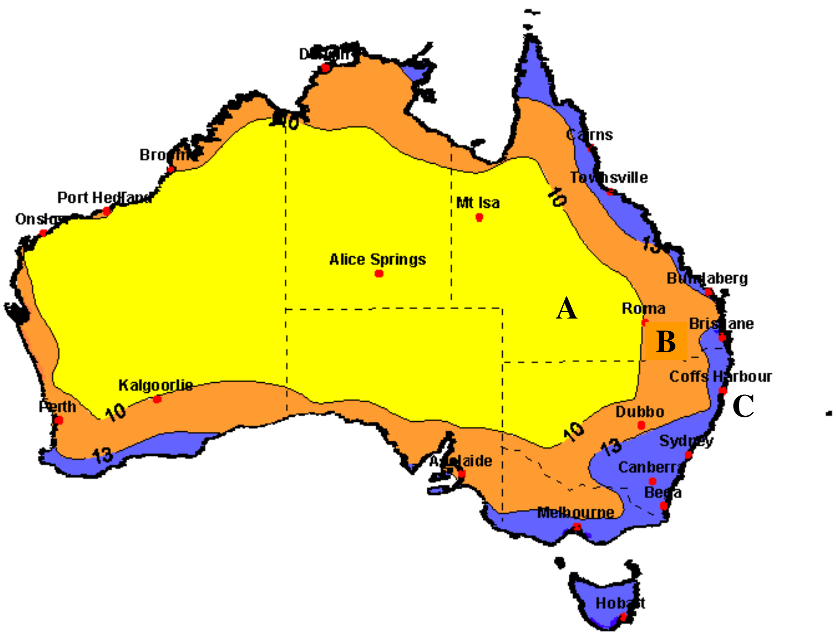


Figure D.1.1. 'Original' hazard zone map based on $SEMC_{mean.}$

Furthermore, expert opinions (MacKenzie, private communication) suggested that zone C should not be cut out along the coast near Brisbane. Figure D.1.2 is the modified map currently used in the Compendium. The modification was made by adjusting the effective $SEMC_{mean}$ at Gympie (BOM data point C62) from 12.38% to 13%. The boundary and the zone effective $SEMC_{mean}$ values are in Table D.1.1.

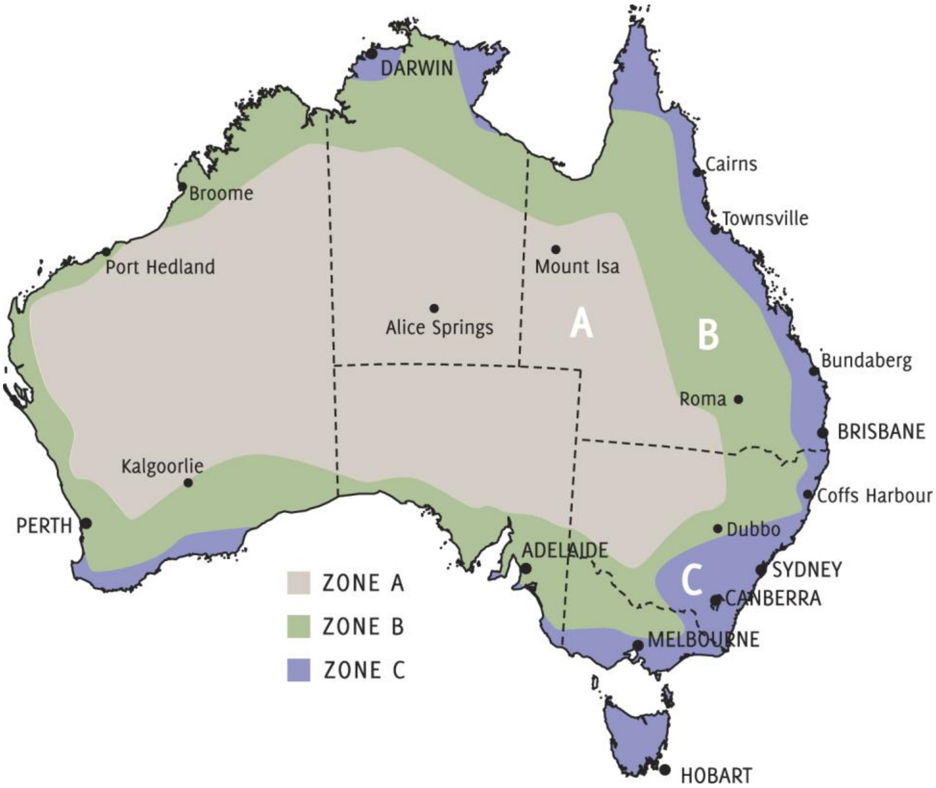


Figure D.1.2. Modified Hazard zone map based on effective $SEMC_{mean}$ - currently used in the Compendium.

Table D.1.1 Effective $SEMC_{mean}$ values for the 3 hazard zones

Zone	**Zone effective $SEMC_{mean}$**	**Effective $SEMC_{mean}$ used for boundary**
A	9	
		10
B	12	
		13
C	15	

D.2 Climate Zones

The climate zonation procedure with 6 zones as presented in Table 1.3.5 is simplified by defining only 2 climate zones:

- Marine: if the distance to coast < 1 km
- Other, ie. non-marine

D.3 Material Grouping

See Section 2.3.2 for timber classification based on acidity.

D.4 Simplified Theory Equations

This section provides the simplified version of the theoretical equations in Appendix C to be used for the calculation in the 2002's Compendium (Leicester et.al. 2002).

D.4.1 The Base Model of Embedded corrosion in untreated wood

The corrosion depth of connectors embedded in untreated wood subjected to 120-day corrosion, $f_{120}(M)$, is:

$$f_{120}(M) = 0 \quad \text{if } M < M_o \qquad \text{(D.4.1.1)}$$
$$f_{120}(M) = C_{120} \quad \text{if } M \geq M_o \qquad \text{(D.4.1.2)}$$

where M is moisture content. The function is illustrated in Figure D.4.1.1. Table D.4.1.1 gives parameters of the model calculated by Eqs.(1.3.3) to (1.3.10), using representative pH values in Table D.3.2.

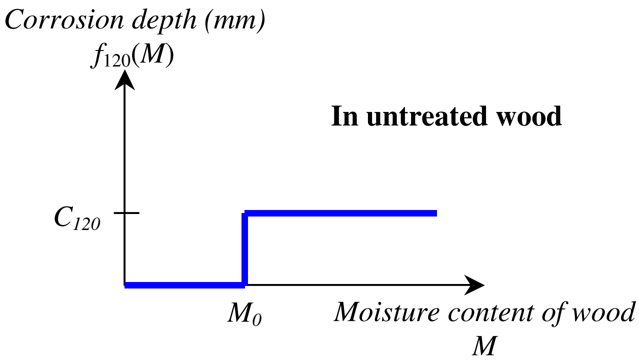


Figure D.4.1.1. Base model of embedded corrosion in untreated wood.

Table D.4.1.1 Parameters of the corrosion model of embedded fasteners in untreated wood

Parameter	pH	Zinc connector		Steel connector	
		Hardwood	Softwood	Hardwood	Softwood
C_{120}					
Acidity class 1	5.5	1.7	4.2	1.6	1.7
Acidity class 2	4.5	8.6	5.0	9.3	5.5
Acidity class 3	3.5	12.5*	6.0	16*	13*
M_0 (%)		10	15	15	20

(*) Values adjusted to the available measured data. The values calculated from Eqs. (1.3.3), (1.3.5) and (1.3.6) are unacceptable high (43.5, 53.0, and 18.0, respectively), where the assigned pH of 3.5 for acidity class 3 species appear to be out of valid range of the equations.

D.4.2 The Base Model of Embedded Corrosion in CCA treated wood

The model for of zinc connectors embedded in CCA treated wood is given by:

$$f_{120}(M) = 0 \quad \text{if } M < 10 \qquad \text{(D.4.2.1)}$$
$$f_{120}(M) = 0.7\,(M\text{-}10) \quad \text{if } M \geq 10 \qquad \text{(D.4.2.2)}$$

The model for of steel connectors embedded in CCA treated wood is given by:

$$f_{120}(M) = 0 \quad \text{if } M < 13 \qquad \text{(D.4.2.3)}$$

$$f_{120}(M) = 0.7\,(M\text{-}13) \qquad \text{if } M \geq 13 \qquad \text{(D.4.2.4)}$$

where M is moisture content. The function is illustrated in Figure D.4.2.1.

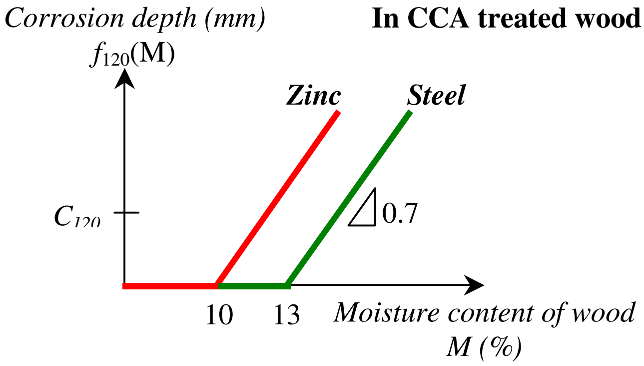


Figure D.4.2.1. Base model of embedded corrosion in CCA-treated wood.

D.4.3 Moisture Content of Timber

The surface equilibrium moisture content (*SEMC*) for a given temperature and humidity is calculated according to Bramhall's equation as follows:

$$SEMC = \frac{\log_e\left[\dfrac{\log_e(H/100) - 0.0251}{17.884 + 0.0002362(T+273)^2 - 0.1432(T+273)}\right]}{0.92 \times \log_e\left[1.0327 - 0.000674(T+273)\right]} \qquad \text{(D.4.3.0)}$$

where

T = the dry bulb temperature (C°)
H = relative humidity (%)

The *SEMC* can be calculated with time, using data from a nearby Bureau of Meteorology station, and then be averaged to obtain $SEMC_{\text{mean}}$, the mean annual value of the *surface* moisture contents. From Eq.(1.3.16), the maximum and the mean seasonal moisture contents of a piece of timber for one year are:

$$TM_{mean} = exp[A + B\, SEMC_{mean}] \qquad \text{(D.4.3.1)}$$
$$TM_{max} = exp[A + B\, SEMC_{max}] \qquad \text{(D.4.3.2)}$$
$$SEMC_{max} = SEMC_{mean} + 2 \qquad \text{(D.4.3.3)}$$

Where TM_{max} = the maximum value out of the four *TM* seasonal values of moisture content in a piece of timber for one year, TM_{mean} = the mean annual value of timber moisture content. The mean surface equilibrium moisture content, $SEMC_{mean}$, can be computed from BOM data using the procedure above with Eq.(D.4.3.0); or taken the representative value given in Table D.4.3.1. The moisture content parameters A and B are provided in Table D.4.3.2.

The maximum and mean seasonal moisture contents of timber *in building*, BTM_{max} and BTM_{mean}, are:

$$BTM_{\text{mean}} = TM_{\text{mean}} + \Delta_{\text{microclimate}} + \Delta_{\text{climate}} + \Delta_{\text{rain}} \qquad \text{(D.4.3.4)}$$

$$BTM_{\max} = BTM_{\text{mean}} + D\left[TM_{\max} - TM_{\text{mean}}\right] \qquad \text{(D.4.3.5)}$$

where the damping factor *(D)*, the adjustment factors for the climate (Δ_{climate}) and microclimate ($\Delta_{\text{microclimate}}$) are given in Tables D.4.3.3. Values in Table D.4.3.3 are based on simplifying Tables 1.3.3 and 1.3.4, noting the adjustment for $SEMC_{\text{mean}}$ of 1% for all areas above 23˚ S, i.e. roughly for all 'tropical' areas as defined in Fig.1.3.4.

The adjustment factor for rain (Δ_{rain}) is given in Table D.4.3.4, and used only for outdoor structures (facades), which is divided into 3 types: structures sheltered or partly sheltered from rain (such as house cladding), vertical structures exposed to rain (such as fencing), and horizontal structures exposed to rain (such as decking). Values of this factor are resulted from the reality checks with expert opinions as presented in Section D.5. For other microclimates, including sub-floor, wall cavity, and roof space, $\Delta_{\text{rain}} = 0$.

For determining the above factors, it is necessary to know the Hazard zone and Climate zone of the structure. The Hazard zonation and map are presented in Section D.1, and the Climate zonation is presented in Section D.2

Table D.4.3.1 Mean surface equilibrium moisture content

Hazard zone	$SEMC_{mean}$
A	9
B	12
C	15

Table D.4.3.2 Moisture content parameters *A* and *B*

Moisture Content Parameter	**Hardwoods**	**Softwoods**	**CCA Treated Pine**
A	1.84	1.78	2.00
B	0.05	0.054	0.045

Table D.4.3.3 Damping factor and adjustment factor for climate and micro-climate

Microclimate	*D*		Δ_{climate}		$\Delta_{\text{microclimate}}$	
	Marine(1)	**Other**	**Marine**	**Other**	**Marine**	**Other**
Sub-floor	2.0	1.0	2.0	0	0.5	1.5
Wall cavity	1.5	1.5	2.0	0	-1.5	1.0
Roof space	2.0	2.0	2.0	0	-2.5	-2.5
Outdoor	6.0	2.0	2.0	0	0.5	0.5

(1) If distance to coast < 1km, then climate zone is 'Marine'; otherwise, climate zone is 'Other'

Table D.4.3.4 Adjustment factor Δ_{rain}

Outdoor (Facades) Microclimate	**Adjustment factor Δ_{rain}**		
	Hazard zone A	**Hazard zone B**	**Hazard zone C**
Sheltered / partly sheltered from rain	0	1	2
Vertical surface exposed to rain	1	4	8
Horizontal surface exposed to rain	3	9	17

D.4.4 Corrosion Depth

The corrosion depth, c, over the period t years is given by

$$c = c_o t^n \tag{D.4.4.1}$$

where n= 0.5 for zinc and n = 0.6 for steel; c_o is corrosion depth for the first year (mm) computed as follows,

For the case of untreated wood:

$$c_o = f_{120}(BTM_{max}) + 0.3 f_{120}(BTM_{mean}) \tag{D.4.4.2}$$

For the case of treated wood:

$$c_o = 2.5 f_{120}(BTM_{mean}) \tag{D.4.4.3}$$

where f_{120} is defined by Eqs. (D.4.1.1) and (D.4.1.2) for untreated wood case and Eqs.(D.4.2.1) to (D.4.2.4) for CCA treated wood case.

D.5 Modification due to Expert Opinions

The following facts provided by expert opinions (MacKenzie, 2002) have been considered to further extend and calibrate the score system for outdoor structures. They are:

- ‘A HDG (Hot-Dip Galvanised) nail in a treated pine deck exposed to rain in Brisbane would be expected to last about 15 years, on a fence we would expect 25 years. For plain bright nail, probably 5 years less’.
- ‘For plain nails in Hardwoods fencing up here (Brisbane) I would expect about 30 years and for HDG nails in exposed hardwood decking around 30 years’.
- ‘Plain nails punched, puttied and pained cladding on houses, hardwood or cypress cladding/frame > 100 years’
- ‘For treated pine cladding on houses fixed with HDG nails, would expect 50^+ years’

The extension and calibration of the score system were carried out for outdoor microclimate. The outdoor structures are divided into 3 groups: (1) Sheltered / partly sheltered to rain, (2) Exposed to rain - Vertical surface (e.g. fencing) and (3) Exposed to rain - Horizontal surface (e.g. decking). The target of the calibration was to match the computed service lives of the fasteners to the above facts provided by the expert opinions.

The extension and calibration were resulted in the introduction of the adjustment factor for rain, Δ_{rain}, to the theory equations, and its recommended values are listed in Table D.4.3.4.

Appendix E:. Hazard Score System 2002

E.1 Definition of Hazard Scores

Table E.1.1 gives the total hazard scores for various scenarios of the corrosion in embedded fasteners. Derivation of this table is presented in Appendix A.

Table E.1.1 Hazard scores for corrosion of embedded fasteners as used in the 2002 Compendium (Leicester et.al. 2002)

Microclimate[1]	**Total Hazard scores**					
	Zone A[2]		**Zone B**[2]		**Zone C**[2]	
	Marine[3]	Other	Marine	Other	Marine	Other
Subfloor	14	12	16	14	18	16
Wall cavity	12	12	14	14	16	16
Roof space	11	9	13	11	15	13
Outdoors						
Sheltered / partly sheltered[4]	19	12	22	15	25	18
Exposed vertical surface[5]	20	13	25	18	*31*	*24*
Exposed horizontal surface[6]	*22*	15	30	*23*	40	33

(1) For information on the building envelope, see Section 5.1 in the 2002 Compendium
(2) See hazard zone map in Figure D.1.2
(3) Climate zone is 'Marine' when distance to coast < 1km
(4) e.g. house cladding
(5) e.g. fencing
(6) e.g. decking

E.2 Definition of Hazard Class

For ease of application to service life prediction of various types of fastener, the selection of hazard class limit have been decided to have the same limits for steel and zinc, but to have different limits for types of wood. The definition of hazard classes and their boundaries in terms of the total scores for embedded corrosion of fasteners have been chosen as shown in Table E.2.1 and illustrated in Figures E.2.1 and E.2.2 for zinc and steel fasteners, respectively.

It is noted that to have the same hazard class limits for both zinc and steel fasteners embedded in untreated wood, the hazard class H3 acts as a 'buffer' class located near or right at the 'jumping steps' of the theoretical values of c_0. This is somewhat a compromising solution for practical uses, and justified because such sudden jumping steps of c_0 would not be true in reality.

Table E.2.1 Definition of hazard ratings

Hazard rating	Hazard score			
	In untreated timber			CCA-treated timber
	Eucalypts	Other hardwoods	Softwoods	
H1	na	na	na	<12
H2	<12	<12	<16	12~17
H3	12~15	12~15	16~20	18~23
H4	>15	>15	>20	24~30
H5	na	na	na	>30

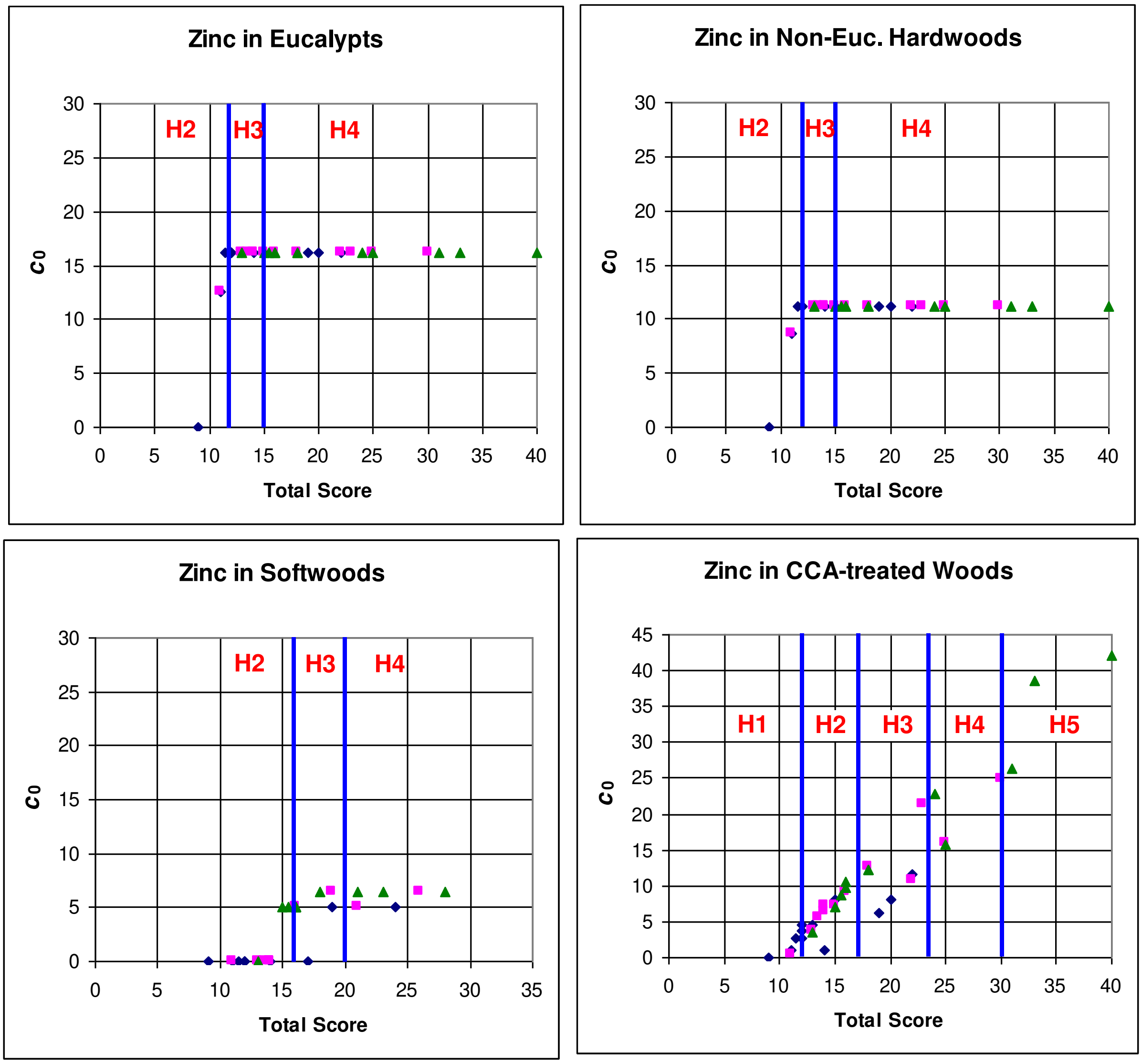


Figure E.2.1. Hazard ratings for zinc fasteners embedded in different types of wood

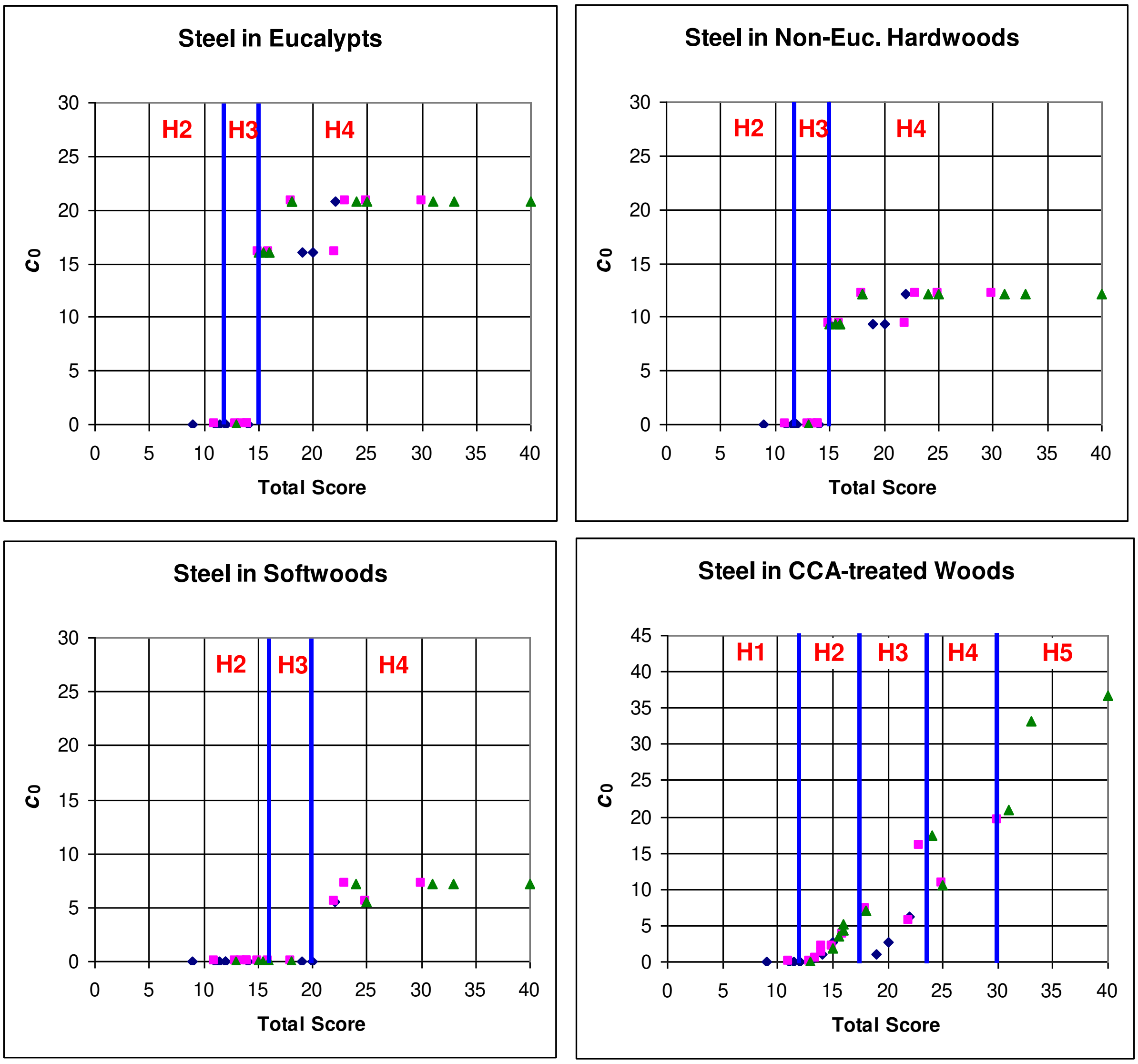


Figure E.2.2. Hazard ratings for steel fasteners embedded in different types of wood

E.3 Derived c_0 values for the 2002 Compendium (Leicester et.al. 2002)

Based on the theoretical values of c_0 varying in each hazard class, representative values of c_0 for the classes are assumed and presented in Tables E.3.1 and E.3.2 for zinc and steel, respectively.

Table E.3.1 The first-year corrosion depth of embedded zinc fasteners– as used in the Compendium (Leicester et.al. 2002)

Hazard rating	**c_0 - the first-year corrosion depth of zinc**		
	Untreated timber		**CCA-treated timber**
	Eucalypts	**Others**	
H1	na	na	0
H2	0	0	8
H3	12	4	20
H4	16	6	30
H5	na	na	40

Table E.3.2 The first-year corrosion depth of embedded steel fasteners – as used in the Compendium (Leicester et.al. 2002)

Hazard rating	**c_0 - the first-year corrosion depth of steel**		
	Untreated timber		**CCA-treated timber**
	Eucalypts	**Others**	
H1	na	na	0
H2	0	0	5
H3	15	7	15
H4	20	10	25
H5	na	na	35

E.5 Service life

The service-life life of a steel fastener is assumed to be the time at which all of the effective zinc coasting, if any, and 30% of the original strength in steel, is lost. The life of a zinc coating is assumed to be the time at which all of the effective zinc protection is lost. The fasteners under consideration are assumed to be subject to bending moment; therefore the decrease of fastener bending strength is proportional to the increase of corrosion depth. For conservative calculation, the initial diameter of screws is taken at the root (i.e. excluding the thread), and that of bolts is taken at the shank.