Forest&Wood Products Australia
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PROJECT NUMBER: PN07.1052

August 2007

Manual 9 – Models for timber produced in building envelope

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USP2007/046

MANUAL NO. 9

Service Life Models for Timber Structures Protected in Building Envelope

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April 2008

This report has been prepared for Forest & Wood Products Australia (FWPA).

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Acknowledgments

This Manual is one of a series of Manuals that have been produced as part of a project titled 'Design for Durability'. The authors are deeply indebted to the Forest and Wood Products Australia for their funding and collaboration in this project over the past 10 years. The authors would especially like to thank Colin MacKenzie (Timber Queensland) for the major role that he has played in managing and guiding this project to completion. Thanks are also due to Ivan Cole (CSIRO), and Wayne Ganther (CSIRO) for contributing extensive data and expertise to the development of the models described in this Manual. Finally our thanks go to Greg Foliente, Craig Seath, Sandra Roberts and numerous other CSIRO personnel for their assistance and contribution to this project

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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 predicting the service life of all types of timber construction located anywhere in Australia. A part of this project was to develop prediction models for the service life of timber components, including timber members and metal fasteners within a building envelope.

This Manual presents the development of service life models for timber elements protected in building envelop, including roof spaces, walls, and subfloors. The attack mechanisms considered are decay of timber members (Part A), corrosion of fasteners' part that is exposed to air (Part B), and corrosion of fasteners' part that is embedded in timber (Part C).

As the models are primarily based on expert opinions with very limited data, they are presented here for implementation to the Timberlife software, which is developed for educational purpose.

PART A

Decay Model for Timber Protected in Building Envelope

PART A – Contents

Decay Model for Timber Protected in Building Envelope

1. Timber Decay Model

A schematic illustration of the progress of a decay pattern assumed in the model is shown in Figure 1.1. It comprises essentially of a time-lag (*lag*) followed by a steady decay rate (*r*). The decay depth of timber after *t* years is given as:

$$d_t = \begin{cases} 0 & \text{if } t \le lag \\ (t - lag)r & \text{if } t > lag \end{cases} \tag{1.1}$$

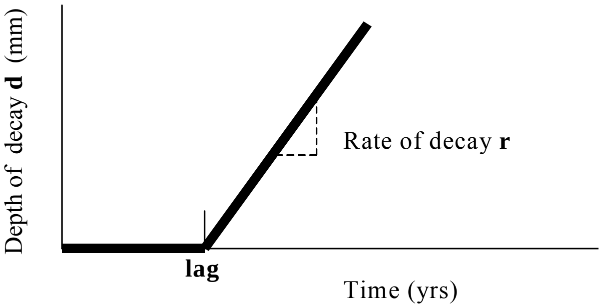

Figure 1.1 *Idealised decay-time relationship.*

The rate of decay is taken to be given by

$$r = k_{wood}\, k_{geometry}\, k_{climate} \tag{1.2}$$

where k_{wood} is related to the species of timber used, the zone of the tree from which it has been taken and the type of preservative. The term $k_{geometry}$ is related to the orientation and configuration of the structural element.

Using the mean annual value of time of wetness t_{wet}, which is the time that the timber is wetted by liquid water, as the climate indicator of decay rate, a climate factor $k_{climate}$ can be chosen as

$$k_{climate} = \begin{cases} 0.15 t_{wet}^{0.5} & \text{if } t_{wet} \text{ is in days/yrs;} \\ 0.03 t_{wet}^{0.4} & \text{if } t_{wet} \text{ is in hrs/yrs.} \end{cases} \tag{1.3}$$

For structures fully exposed to weather, $t_{wet} = t_{rain}$, where t_{rain} is the mean annual time of rainfall, which can be computed using weather data from Bureau of Meteorology (BOM). Refer Manual No. 1 (Wang and Leicester, 2008) for BOM data used for the project.

The idealized lag time is taken to be related to the rate of decay by the equation

$$lag = 8.5r^{-0.85} \tag{1.4}$$

The model for decay in building envelope is to be developed based on the decay model in exposed structures. Refer to the Manual No.4 (Wang et.al. 2008) for details of the model equations, hazard map and timber classification for application.

In the following sections, the model parameters, particularly t_{wet} will be determined for calculation of decay rate in microclimates of building envelop, including roof-space, wall cavity, and subfloor. The lag then can be estimated by Eq.(1.3), except the case for decay of the stud in the walls, where an additional lag is added (see Section 3.2.2).

2. Model Parameters for Roof-space

2.1 Time of wetness

It is assumed that leakage in the roof-space occurs when rain water, driven by strong wind speed of more than 4m/s, enters through the gaps between the ridge cap and the roof sheeting.

The annual time of wetness of timber (hrs/year) at the decay spots is then estimated as

$$t_{wet} = \sum_{i}^{N} (\alpha t_{rain,\ V \geq 4m/s} - t_{delay})_i \quad \text{with } (\alpha t_{rain,\ V \geq 4m/s} - t_{delay})_i > 0 \tag{2.1}$$

where:

- N is the number of occasions of rain during one year, i signifies the i^{th} occasion of rain
- $t_{rain,\ V \geq 4m/s}$ is the time of rain during which the wind speed is equal or more than 4m/s in one occasion of rain.
- t_{delay} is the time needed for the leaking water travelling from the ridge cap to the decay spots in each occasion of rain. This time is set as 0.2 hour (12 min).
- α is the wind direction adjustment factor. For a gable house,
    - $\alpha = 1.0$, if the wind direction is within the range from –45° to +45° to the direction perpendicular to the ridge
    - $\alpha = 0.2$, if the wind direction is within the range from –45° to +45° to the direction parallel to the ridge

2.2 Other parameters

Wood parameter k_{wood} (Wang, et.al. 2008)

Durability Class*	k_{wood}	
	Outer heartwood	Untreated sapwood
Class 1	0.5	6.52
Class 2	0.62	
Class 3	1.14	
Class 4	2.20	

** See Manual No.4 (Wang et.al. 2008)*

Assume flat contact geometry at decay spots, then (Wang, et.al. 2008)
$k_{geometry} = 0.6$

2.3 Failure criteria

For serviceability, decay depth = 2 mm
For replacement, decay depth = 10 mm

3. Model Parameters for Wall

3.1 Model Parameters for Decay of Panels

3.1.1 Time of wetness

It is assumed that leakage in the wall occurs when rain water, driven by strong wind speed, hits and enters through cracks in the external skin of the wall, as depicted in Fig. 3.1.1.

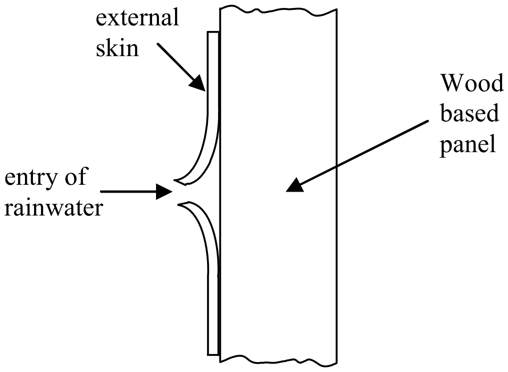

Figure 3.1.1 *Entry of rainwater via a crack in the external skin.*

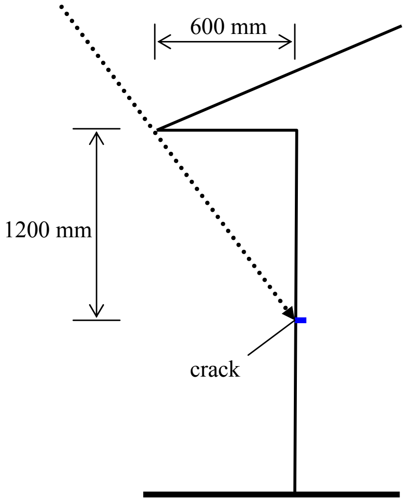

Figure 3.1.2 *Wind driven rain drops on a wall with an eave.*

For simplicity, it is assumed that the crack is at the mid-height of the wall, and dimension of the eave as shown in Figure 3.1.2. The dominant size of rain drops is assumed to be 1 mm in diameter.

The annual time of wetness of timber at the decay spots on the panel is then estimated as

$$t_{wet} = \sum_{i}^{N} (t_{raindrop,crack} - t_{drying})_i \quad \text{with } (t_{raindrop,crack} - t_{drying})_i > 0 \tag{3.1.1}$$

where:

- N is the number of occasions of rain during one year, i signifies the i^{th} occasion of rain
- $t_{raindrop,crack}$ is the time of rain during which the rain drops hits the crack on the wall being considered in each occasion of rain.
- t_{drying} is the adjustment time to take into account the extent of ventilation of the wall,
  - t_{drying} = 1.0 hour for cavity wall with both ends open and $S_{house} > 25$
  - t_{drying} = 0.2 hour (12 min) for cavity wall with both ends open and $S_{house} \leq 25$
  - t_{drying} = 0.0 hour for cavity wall with both ends close
  - t_{drying} = 0.0 hour for non-cavity wall
- S_{house} is the whole house ventilation score, determined by a score system presented in Section 5.1.

3.1.2 Other parameters

Material factor k_{wood} depends on material of the panel,

- k_{wood} = 13.4 for OSB (assume decay rate is twice that of plywood)
- k_{wood} = 6.52 for untreated plywood (assume decay rate is the same as that of sapwood)
- k_{wood} = 0.0 for fibre cement sheet (no decay)

Assume geometry at decay spots is similar to that of L-joint, then (Wang, et.al. 2008) $k_{geometry}$.= 1.0

3.1.3 Failure criteria for panels

For replacement, decay depth = 2/3 thickness. In Timberlife, decay depth = 10 because the thickness is 15mm.

3.2 Model Parameters for Decay of Studs

3.2.1 Time of wetness

The annual time of wetness of timber at the decay spots on the stud is then estimated as

$$t_{wet} = \sum_{i}^{N} (t_{raindrop,crack} - t_{drying})_i \quad \text{with } (t_{raindrop,crack} - t_{drying})_i > 0 \tag{3.2.1}$$

where:

- N is the number of occasions of rain during one year, i signifies the i^{th} occasion of rain
- $t_{raindrop,crack}$ is the time of rain during which the rain drops hits the crack on the wall being considered in each occasion of rain.

- t_{drying} is the adjustment time to take into account the extent of ventilation of the wall,
  - $t_{drying} = \infty$ for cavity wall. In other words, stud does not decay in this case.
  - $t_{drying} = 0.5$ hour for non-cavity wall with vapour barrier
  - $t_{drying} = 0.0$ hour for non-cavity wall without vapour barrier

3.2.2 Other parameters

Wood parameter k_{wood} (Wang, et.al. 2008)

Durability Class*	k_{wood}	
	Outer heartwood	Untreated sapwood
Class 1	0.5	6.52
Class 2	0.62	
Class 3	1.14	
Class 4	2.20	

** See Manual No.4 (Wang et.al. 2008)*

Assume flat contact geometry at decay spots, then (Wang, et.al. 2008)
$k_{geometry} = 0.6$

IMPORTANT: In this case, an additional lag time is added to the basic lag calculated by Eq.(1.3). This additional lag is an estimate of the time that takes the panel to degrade to the extent that the leaking water can easily get through the panel to wet the stud. The total lag is then determined by Eq.(3.2.2), in which the 1st term is the additional lag, and the 2nd term is the basic lag by Eq.(1.4)

$$lag = 3\beta\left(\frac{t_{rain,\ Melbourne}}{t_{rain}}\right) + 8.5r^{-0.85} \qquad (3.2.2)$$

where $t_{rain,Melbourne}$ (≈ 450) is the annual time of rain in Melbourne; t_{rain} is the annual time of rain at the location of the house under study; β is the adjustment factor taking into account the durability of the panel's material. The factor β is determined as follows,

- β = 1.0 for OSB
- β = 2.0 for untreated plywood

3.2.3 Failure criteria

For replacement, decay depth = 10 mm

4. Model Parameters for Subfloor

4.1 Time of wetness

It is assumed that leakage in the subfloor occurs when ‘living’ water leaks through cracks or construction gaps in the floor, often in the bathroom, laundry room or kitchen. The annual time of wetness of timber (hrs/year) at the decay spots in the subfloor is then estimated as

$$\begin{aligned} &t_{wet} = 365\ (t_{leakage} - t_{drying}) \\ &\text{with } (t_{leakage} - t_{drying}) > 0 \end{aligned} \tag{4.1}$$

where:

- $t_{leakage}$ is the time of leakage per day (hrs/day), classified into 3 levels as follows,
  - No leakage, then $t_{leakage} = 0$ (no problem)
  - Minor leakage, then $t_{leakage} = 1$ hour
  - Medium leakage, then $t_{leakage} = 6$ hours
  - Major leakage, then $t_{leakage} = 24$ hours

- t_{drying} is the adjustment time to take into account various factors. The procedure to determine t_{drying} is presented in Section 4.4.

4.2 Other parameters

Wood parameter k_{wood} (Wang, et.al. 2008)

Durability Class*	k_{wood}	
	Outer heartwood	Untreated sapwood
Class 1	0.5	6.52
Class 2	0.62	
Class 3	1.14	
Class 4	2.20	

** See Manual No.4 (Wang et.al. 2008)*

Assume flat contact geometry at decay spots, then (Wang, et.al. 2008)
$k_{geometry} = 0.6$

4.3 Failure criteria

For serviceability, decay depth = 2 mm
For replacement, decay depth = 10 mm

4.4 Procedure to determine adjustment time t_{drying}

Using the expert opinion procedure:

$$t_{drying} = t_{drying,mean} \prod_{i=1}^{n} (1 + k_i a_i) \qquad (4.4.1)$$

For a typical subfloor, $t_{drying,mean}$ = 3.34. The factors a_i and k_i are determined as in Table 4.4.1. Derivation and/or determination of these parameters are in Appendix A.

***Table 4.4.1** Determining a_i and k_i for subfloor to estimate t_{drying}*

i	Parameters	Options			a_i
		High risk $k_i = +1$	Medium risk $k_i = 0$	Low risk $k_i = -1$	
1	Subfloor ventilation	No vent	Standard	Large	-0.446
2	Whole house ventilation(1)	$S_{\text{house}} < 15$	$S_{\text{house}} = 15 - 30$	$S_{\text{house}} > 30$	-0.167
3	Annual local external wind speed (2)	<2 m/s	2 to 5 m/s	> 5 m/s	-0.223
4	Annual external temperature	<15°C	15 – 25°C	>25°C	-0.223
5	Soil type	Loam	Sand	Clay	-0.111
6	Water table depth	≤ 3m	–	> 3m	-0.223
7	Membrane	No	–	Yes	-0.223

(1) Procedure for whole house ventilation score, S_{house}, is presented in Section 5.1.
(2) Procedure for local external wind speed is presented in Section 5.2.

5. Supporting Procedures

5.1 Score system for whole house ventilation – S_{house}

Table 5.1.1 *Score system for whole house ventilation*

Roof ventilation	Options	Score
Sarking	Yes	0
	No	12
Eave ventilation	Yes	5
	No	0
Gable ventilation	Yes	10
	No	0
Ceiling ventilation	Yes	3
	No	0
Wall cavity	Yes, ends open	5
	Yes, ends close	1
	No	0
Subfloor ventilation	Large	15
	Standard	10
	No	0
	Total	S_{house}

5.2 Local External Wind speed

The local external wind speed used is at the height of the eave of 3m, which can be estimated as (ASHRAE, 2005)

$$V_{H=3m} = C_s C_{H=3m} V_{met} \tag{5.2.1}$$

where

V_{met} = wind speed measured at nearest BOM station
C_s = shelter factor depending on site classification as in Table 5.2.1
$C_{H=3m}$ = terrain and height adjustment coefficient, determined by Eq.(5.2.2)

$$C_{H=3m} = \left(\frac{270}{10.0}\right)^{0.14}\left(\frac{3.0}{\delta}\right)^{a} \tag{5.2.2}$$

where the constants a and δ depending on the local terrain category are taken from Table 5.2.2.

Table 5.2.1 *Shelter factor C_s (ASHRAE, 2005)*

Shelter class	C_s	Description of local shelter
1.	1.0	No obstructions or local shielding
2.	0.9	Typical shelter for an isolated rural house
3.	0.7	Typical shelter caused by other buildings across the street from the building under study
4.	0.5	Typical shelter for urban buildings on larger lots where sheltering obstacles are more than one building height away
5.	0.3	Typical shelter produced by buildings or other structures that are immediately adjacent (closer than one house height): e.g. neighbouring houses on the same side of the street, trees, bushes, etc.

Table 5.2.2. *Atmospheric boundary layer parameters (ASHRAE, 2005)*

Terrain category	Description	Exponent a	Layer thickness δ (m)
1	Large city centres, in which at least 50% of buildings are higher than 21 *m*, over a distance of at least 2000 *m* or 10 times the height of the structure upwind, whichever is greater	0.33	460
2	Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger, over a distance of at least 2000 *m* or 10 times the height of the structure upwind, whichever is greater	0.22	370
3	Open terrain with scattered obstructions having heights generally less than 10 *m*, including flat open country typical of **meteorological station** surroundings	0.14	270
4	Flat, unobstructed areas exposed to wind flowing over water for at least 1.6 *km*, over a distance of 500 *m* or 10 times the height of the structure inland, whichever is greater	0.10	210

References

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APPENDIX A

Using the expert opinion procedure (Leicester et.al., 2004a):

$$t_{drying} = t_{drying,mean} \prod_{i=1}^{n} (1 + k_i a_i) \qquad \text{(A1)}$$

where $i = 1$ to n is the number of parameters affecting the t_{drying}; a_{i} is constant depending on the importance rating of the i^{th} parameter. The factors k_i take the following values

- For a low risk option of the i^{th} paramete: $k_i = -1$
- For a medium risk option of the i^{th} parameter: $k_i = 0$
- For a high risk option of the i^{th} parameter: $k_i = +1$

Definitions of risk options for the influencing parameters are as in Table A1. Values of the important factor I_i of the parameters are also shown. These definitions and value are set based on expert opinions. In addition, the following parameters are estimated:

- $t_{\mathrm{average}}(H)$: Average or typical t_{drying} when all the parameters are at high risk values
- $t_{\mathrm{average}}(L)$: Average or typical t_{drying} when all the parameters are at low risk values

These 2 parameters are estimated as shown in Table A2, based on knowledge gained from a building envelope microclimate measurement program reported in Cole et.al. (2001), Ganther et.al. (2001), Leicester et.al. (2004b), and expert opinions via private communications with the authors during the course of the project.

The flowing equations approximate the relationship between the model and the data from expert opinions

$$t_{average}(H) = t_{drying,mean} \prod_{i=1}^{n} (1 + jI_i) \qquad \text{(A2)}$$

$$t_{average}(L) = t_{drying,mean} \prod_{i=1}^{n} (1 - jI_i) \qquad \text{(A3)}$$

where j is a constant that relates to the bias of the choice of the set of the importance ratings for the parameters. The constant j can be solved from the following equation (A4), which is the ratio of Eq. (A2) and Eq. (A3)

$$\frac{t_{average}(H)}{t_{average}(L)} = \frac{\prod_{i=1}^{n}(1+jI_i)}{\prod_{i=1}^{n}(1-jI_i)} \tag{A4}$$

Then the constant a_i can be obtained as

$$a_i = j\, I_i \tag{A5}$$

The mean value $t_{drying,mean}$ is then given by

$$t_{drying,mean} = \frac{t_{average}(H)}{\prod_{i=1}^{n}(1+jI_i)} = \frac{t_{average}(H)}{\prod_{i=1}^{n}(1+a_i)} \tag{A6}$$

Using data given in Tables A1 and A2, we have $j = -0.0557$, and $t_{drying,mean} = 3.34$.

Table A1 *Risk options and importance ratings for parameters affecting t_{drying} in subfloor*

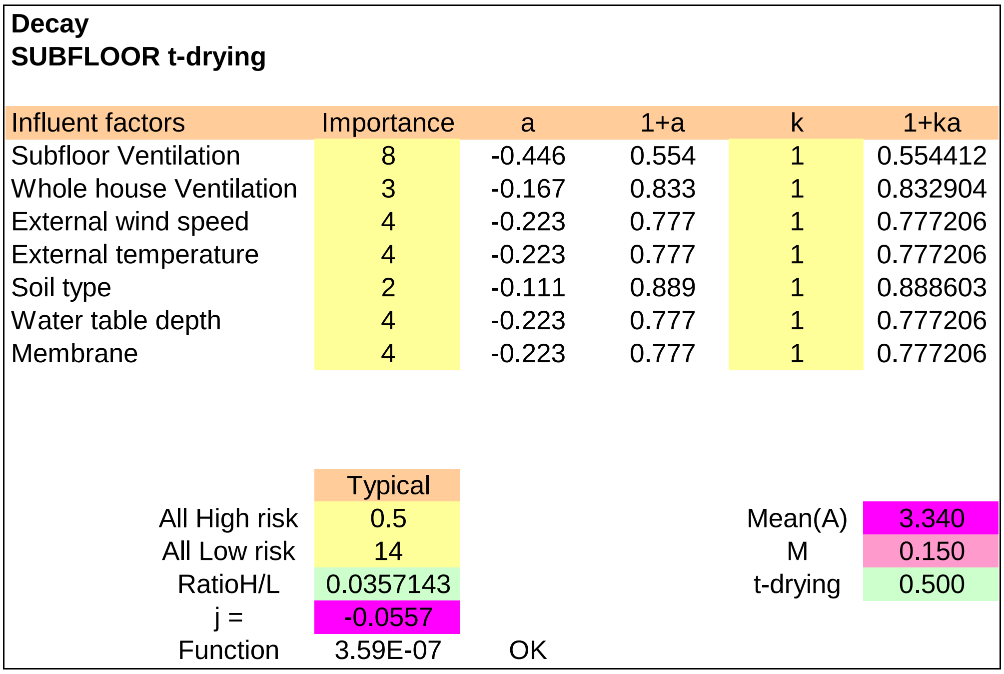
i	Parameters	Risk options			Importance rating I_i
		High risk $k_i = +1$	Medium risk $k_i = 0$	Low risk $k_i = -1$	
1	Subfloor ventilation	No vent	Standard	Large	8
2	Whole house ventilation(1)	$S_{house} < 15$	$S_{house} = 15 - 30$	$S_{house} > 30$	3
3	Annual local external wind speed (2)	< 2 m/s	2 to 5 m/s	> 5 m/s	4
4	Annual external temperature	< 15°C	15 – 25°C	> 25°C	4
5	Soil type	Loam	Sand	Clay	2
6	Water table depth	≤ 3m	–	> 3m	4
7	Membrane	No	–	Yes	4

(1) Procedure for whole house ventilation score, S_{house}, is presented in Section 5.1.
(2) Procedure for local external wind speed is presented in Section 5.2.

Table A2 *Average or typical t_{drying} when all the parameters are at high or low risk values*

Criteria	Estimated time (hrs) (Typical value)
All parameters set at high risk option (i.e. all $k = +1$)	0.5
All parameters set at low risk option (i.e. all $k = -1$)	14

An Excel spreadsheet was made for the procedure. A snapshot of the spreadsheet is also provided below.



Decay
SUBFLOOR t-drying

Influent factors	Importance	a	1+a	k	1+ka
Subfloor Ventilation	8	-0.446	0.554	1	0.554412
Whole house Ventilation	3	-0.167	0.833	1	0.832904
External wind speed	4	-0.223	0.777	1	0.777206
External temperature	4	-0.223	0.777	1	0.777206
Soil type	2	-0.111	0.889	1	0.888603
Water table depth	4	-0.223	0.777	1	0.777206
Membrane	4	-0.223	0.777	1	0.777206

	Typical				
All High risk	0.5			Mean(A)	3.340
All Low risk	14			M	0.150
RatioH/L	0.0357143			t-drying	0.500
j =	-0.0557				
Function	3.59E-07	OK			

PART B

Atmospheric Corrosion Model for Metal Fasteners in Building Envelope

PART B – Contents

Atmospheric Corrosion model for Metal Fasteners in Building Envelope

1. Atmospheric Corrosion Model

1.1. Model for Metal Fasteners Exposed Outdoor

Since the model for fasteners in building envelope is to be developed based on the model for fasteners exposed outdoor, the model equations for fasteners exposed outdoor will be presented in this section. For details of the model development, refer Manual No. 5 of atmospheric corrosion of fasteners (Nguyen, et.al. 2008).

1.1.1 Corrosion of Zinc

The corrosion depth of zinc over time, c_z (μm), is determined by the following power-law equation,

$$c_z = c_{0,z} t^{0.6} \tag{1.1.1.1}$$

where t (year) is the time in service; $c_{0,z}$ is the basic corrosion depth dependent on the presence of pollution agents. For unpolluted zinc, the basic corrosion depth, $c_{0,z}$, is estimated by

$$c_{0,z} = 0.025\, t_{\mathrm{wet}}^{0.6} S_{\mathrm{air}}^{0.5} + 0.006 t_{wet}^{0.2} P_{air} \tag{1.1.1.2}$$

where t_{wet} is time of wetness, which is defined as the percentage of time in a year when the relative humidity is above 80% and the temperature above 0°C. S_{air} (mg/m^2/day) is salt concentration in the air (airborne salinity). $\mathrm{P_{air}}$ is pollution of air in terms of level of airborne $\mathrm{SO_x}$ (μg/m^3)

1.1.2 Corrosion of Steel

The corrosion depth of steel over time, c_s (μm), is determined by the following power-law equation,

$$c_s = c_{0,s} t^{0.8} \tag{1.1.2.1}$$

where t (year) is the time in service; $c_{0,\mathrm{s}}$ is the basic corrosion depth dependent on the presence of pollution agents. The basic corrosion depth of polluted steel, $c_{0,\mathrm{s,poll}}$, is estimated by

$$c_{0,s} = 0.5 t_{wet}^{0.8} S_{air}^{0.5} + 0.1 t_{wet}^{0.5} P_{air} \tag{1.1.2.2}$$

where t_{wet} is time of wetness, which is defined as the percentage of time in a year when the relative humidity is above 80% and the temperature above 0°C. S_{air} (mg/m^2/day) is salt concentration in the air (airborne salinity). $\mathrm{P_{air}}$ is pollution of air in terms of level of airborne $\mathrm{SO_x}$ (μg/m^3)

1.1.3 Airborne Salinity

The salinity at a site, denoted by S_{air} (mg/m^2 per day), is estimated from the following equation,

$$S_{\mathrm{air}} = \max\begin{cases}\alpha_{\exp}\alpha_{\mathrm{micro}}\left[\alpha_{\mathrm{coast}}\beta_{\mathrm{coast}}\left(0.9e^{-10L_{coast}}+0.1e^{-L_{coast}}\right)+\alpha_{\mathrm{ocean}}e^{-0.02L_{\mathrm{coast}}}\right]\\ 1.0\end{cases} \tag{1.1.3.1}$$

in which L_{coast} is the distance to the coast in kilometres; the parameters α_{coast} and α_{ocean} take into account the effect of coastal zonation (Table 1.1.3.1); β_{coast} the effect of coastal exposure (Table 1.1.3.2); $\alpha_{\exp}$ the effect of site exposure (Table 1.1.3.3); and α_{micro} the effect of local shelter factors (Table 1.1.3.4).

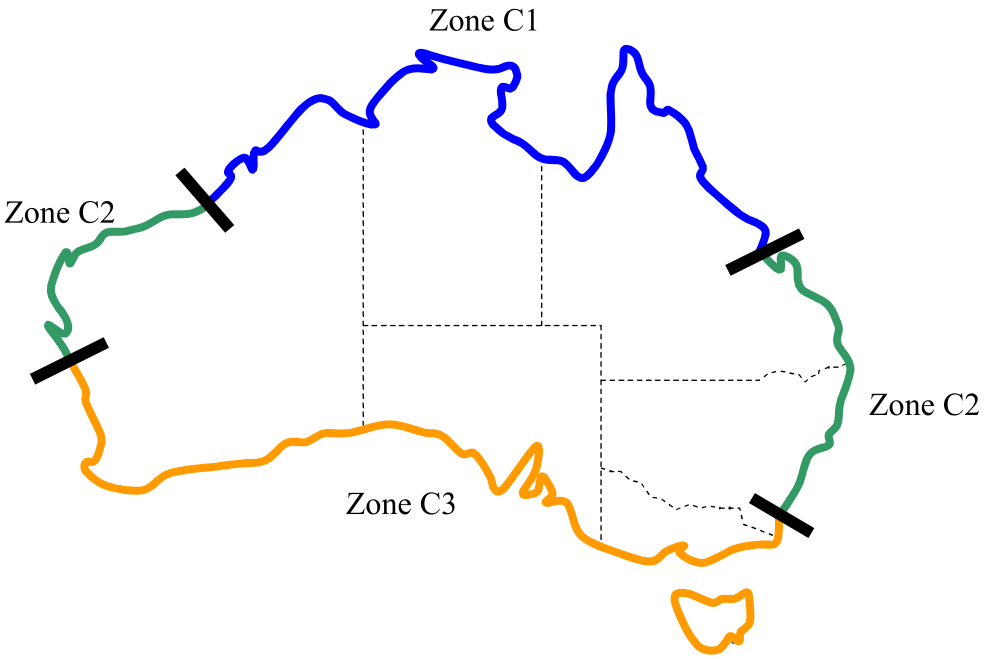


***Figure 1.1.3.1** Definition of coastal zones.*

***Table 1.1.3.1** Factors for the generation of airborne salt*

Coastal zone*	Zone factors	
	α_{coast}	α_{ocean}
C_1	50	2
C_2	150	6
C_3	500	20
* See Fig. 1.3.1		

***Table 1.1.3.2** Factors for airborne salt related to coastal exposure*

Coastal exposure condition*	β_{coast}
Closed bay	0.05
Partially closed bay	0.10
Open bay	0.35
Open surf	1.00
*See Fig. 1.1.3.2	

Table 1.1.3.3 *Factor for site classification*

Site classification	α_{exp}
Open to sea	2.00
Urban (suburbs)	0.50
Urban (city centre)	0.25
Other sites	1.00

Table 1.1.3.4 *Factor for local shelter (rain protection)*

Local Shelter	α_{micro}
Sheltered from rain	2.0
Exposed to rain	1.0

The coastal exposure condition is dependent on the opening angle, θ (degrees), and the radius, R (km), of the bay. By using an exposure factor for the idealised bay, α_{bay}, calculated as follows for given θ and R,

$$\alpha_{\text{bay}}^{2} = \left(\frac{\theta}{85}\right)^{2} + \left(\frac{R}{20}\right)^{2} \qquad (1.1.3.2)$$

then the coastal exposure condition is determined by the α_{bay} value:

$$\text{Coastal exposure condition} = \begin{cases} \text{Closed bay,} & \text{if } \alpha_{bay} < 1; \\ \text{Partially closed bay,} & \text{if } 1 \le \alpha_{bay} < 1.5; \\ \text{Open bay,} & \text{if } 1.5 \le \alpha_{bay} < 2.5; \\ \text{Open surf,} & \text{if } \alpha_{bay} \ge 2.5. \end{cases} \qquad (1.1.3.3)$$

The definition of Eq. (1.1.3.3) is schematically shown in Fig. 1.1.3.2.

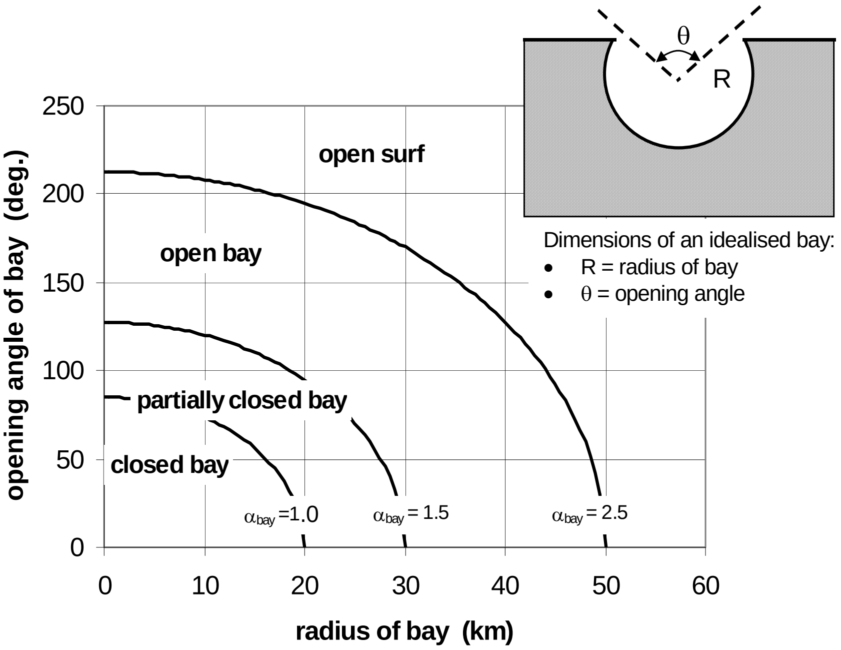


Figure 1.1.3.2 *Definition of coastal exposure condition.*

1.1.4 Airborne Pollution

An estimate of the pollution parameter, P_{air}, which is the pollution of air in terms of level of airborne SO_x ($\mu g/m^3$), can be made by,

$$P_{\mathrm{air}} = \frac{\alpha_{\mathrm{indus}}}{L_{indus} + 1} \qquad (1.1.4.1)$$

where L_{indus} (km) the distance to the nearest industrial complex; α_{indus} is defined in Table 1.1.4.1.

Table 1.1.4.1 *Industrial exposure factor*

Industry Type	Industrial exposure factor α_{indus}
Heavy industry (steel works, petrochemical)	110.0
Moderate industry (paper mills, large manufacturing)	22.0
Light industry (assembly plants)	5.5

1.1.5 Climate Related Parameters – Time of Wetness (t_{wet})

The climate factor considered in the computation of corrosion depth is the time-of-wetness, t_{wet} (%), the percentage of time in a year when the relative humidity is above 80% and the temperature above 0°C. For practical purposes, t_{wet} may be estimated by

$$t_{wet} = 0.22 D_{rain} \qquad (1.1.5.1)$$

where D_{rain} is the number of rain days per year, D_{rain} (days/year), for which a rain day is defined as a day on which there is at least 0.2 mm of rain. For practical purposes, D_{rain} for sites near the coast may take the representative values in Table 1.1.5.1, depending on the hazard zones defined in Figure 1.1.5.1. For an inland site, D_{rain} be estimated by

Error! Objects cannot be created from editing field codes. (1.1.5.2)

where L_{coast} is distance to the nearest coast (km); $D_{rain\text{-}inland}$ = 30 days/year is the representative value of D_{rain} for inland locations at about 1000 km or more from the coast.

Table 1.1.5.1 *Hazard zones and corresponding coastal zones and numbers of rain days*

Hazard Zone	Coastal type zone (Figure 1.3.1)	Representative D_{rain} (No. of rain days / year)
A	C1	70
B	C2	40
C	C1	100
D	C2	130
E	C3	130

***Figure 1.1.5.1**. Hazard Zones related to atmospheric corrosion*
(Zone E has the greatest hazard)

1.2. Model for Metal Fasteners in Building Envelope

The model equations for fasteners in building envelope take the same forms as those for fasteners outdoor, ie. Eqs (1.1.1.1), (1.1.1.2) for zinc, and Eqs (1.1.2.1), (1.1.2.2) for steel, with modified parameters as follows,

- S_{air} is determined depending on various factors as presented in Section 1.3.
- P_{air} is determined depending on various factors as presented in Section 1.4.
- t_{wet} is determined depending on various factors as presented in Section 1.5.

1.3. Salinity of Air in Building Envelope

The salinity of air in building envelope, $S_{air,\text{indoors}}$, is related to the salinity of air outside the building $S_{air,\text{outdoors}}$, by the following equation

$$S_{\text{air,indoors}} = \alpha\, S_{\text{air,outdoors}} \qquad (1.3.1)$$

where α is given as

$$\alpha = \alpha_{\text{mean}} \prod_{i=1}^{n} (1 + k_i a_i) \qquad (1.3.2)$$

The salinity of air outside $S_{\text{air,outdoors}}$ is estimated in Section 1.1.3.

1.3.1 Subfloor S_{air}

For a typical subfloor, $\alpha_{\text{mean}} = 0.253$. The factors a_i and k_i are determined as in Table 1.3.1.1. Derivation and/or determination of these parameters are in Appendix A.

Table 1.3.1.1 *Determining a_i and k_i for subfloor to estimate S_{air}*

i	Parameters	Risk level			a_i
		High risk $k_i = +1$	Medium risk $k_i = 0$	Low risk $k_i = -1$	
1	Subfloor ventilation	Large	Standard	No vent	0.843
2	Whole house ventilation$^{(1)}$	$S_{\text{house}} > 30$	$S_{\text{house}} = 15 – 30$	$S_{\text{house}} < 15$	0.316
3	Annual local external wind speed $^{(2)}$	> 5 m/s	2 to 5 m/s	<2 m/s	0.632

(1) Procedure for whole house ventilation score, S_{house}, is presented in Section 2.1.
(2) Procedure for local external wind speed is presented in Section 2.2.

1.3.2 Wall Cavity S_{air}

For a typical wall, $\alpha_{\text{mean}} = 0.207$. The factors a_i and k_i are determined as in Table 1.3.2.1. Derivation and/or determination of these parameters are in Appendix A.

Table 1.3.2.1 *Determining a_i and k_i for wall to estimate S_{air}*

i	Parameters	Risk level			a_i
		High risk $k_i = +1$	Medium risk $k_i = 0$	Low risk $k_i = -1$	
1	Wall ventilation	Cavity, ends open	Cavity, ends close	Non-cavity	0.752
2	Whole house ventilation$^{(1)}$	$S_{\text{house}} > 30$	$S_{\text{house}} = 15 - 30$	$S_{\text{house}} < 15$	0.282
3	Annual local external wind speed $^{(2)}$	> 5 m/s	2 to 5 m/s	<2 m/s	0.376
4	Orientation of wall to sea	Facing direction to sea	Other directions	Facing opposite direction to sea	0.564

(1) Procedure for whole house ventilation score, S_{house}, is presented in Section 2.1.
(2) Procedure for local external wind speed is presented in Section 2.2.

1.3.3 Roof space S_{air}

For a typical roof space, $\alpha_{\text{mean}} = 0.253$. The factors a_i and k_i are determined as in Table 1.3.3.1. Derivation and/or determination of these parameters are in Appendix A.

Table 1.3.3.1 *Determining a_i and k_i for roof space to estimate S_{air}*

i	Parameters	Risk level			a_i
		High risk $k_i = +1$	Medium risk $k_i = 0$	Low risk $k_i = -1$	
1	Roof ventilation$^{(3)}$	$S_{\text{roof}} > 20$	$S_{\text{roof}} = 10 - 19$	$S_{\text{roof}} < 10$	0.843
2	Whole house ventilation$^{(1)}$	$S_{\text{house}} > 30$	$S_{\text{house}} = 15 - 30$	$S_{\text{house}} < 15$	0.316
3	Annual local external wind speed $^{(2)}$	> 5 m/s	2 to 5 m/s	<2 m/s	0.632

(1) Procedure for whole house ventilation score, S_{house}, is presented in Section 2.1.
(2) Procedure for local external wind speed is presented in Section 2.2.
(3) Roof ventilation score S_{roof} is determined by Table 1.3.3.2.

Table 1.3.3.2 *Score system for roof ventilation to estimate S_{air}*

Roof ventilation	**Options**	**Score**
Sarking	Yes	0
	No	12
Eave ventilation	Yes	5
	No	0
Gable ventilation	Yes	10
	No	0
Ceiling ventilation	Yes	3
	No	0
Wall cavity	Yes, ends open	5
	Yes, ends close	0
	No	0
	Total	S_{roof}

1.4. Pollution of Air in Building Envelope

In the absence of direct measurements of pollution in the air within the building envelope, the pollution of air in building envelope, $P_{air,\mathrm{indoors}}$, is assumed to be related to the pollution of air outside the building $P_{air,\mathrm{outdoors}}$, in the same way as for salinity in the air by the following equation

$$P_{\mathrm{air,indoors}} = \alpha\, P_{\mathrm{air,outdoors}} \qquad (1.4.1)$$

where the parameter α is determined as for air salinity in Section 1.3. The pollution of air outside building envelope, $P_{air,outdoors}$ is estimated in Section 1.1.4.

1.5. Time of Wetness in Building Envelope

The time-of-wetness of timber located within a building envelope, $t_{\mathrm{wet,indoors}}$, is related to the standard time-of-wetness of timber located outside the building $t_{\mathrm{wet,outdoors}}$, by

$$t_{\mathrm{wet,indoors}} = \beta\, t_{\mathrm{wet,outdoors}} \qquad (1.5.1)$$

where β is given as

$$\beta = \beta_{\mathrm{mean}} \prod_{i=1}^{n} (1 + k_i a_i) \qquad (1.5.2)$$

The standard time-of-wetness of timber located outside the building $t_{\mathrm{wet,outdoors}}$ is estimated in Section 1.1.5.

1.5.1 Subfloor t_{wet}

For a typical subfloor, $\beta_{\mathrm{mean}} = 1.18$. The factors a_i and k_i are determined as in Table 1.5.1.1. Derivation and/or determination of these parameters are in Appendix B.

Table 1.5.1.1 *Determining a_i and k_i for subfloor to estimate t_{wet}*

i	Parameters	Risk level High risk $k_i = +1$	 Medium risk $k_i = 0$	 Low risk $k_i = -1$	a_i
1	Subfloor ventilation	No vent	Standard	Large	0.220
2	Whole house ventilation$^{(1)}$	$S_{\mathrm{house}} < 15$	$S_{\mathrm{house}} = 15 - 30$	$S_{\mathrm{house}} > 30$	0.083
3	Annual local external wind speed$^{(2)}$	<2 m/s	2 to 5 m/s	> 5 m/s	0.110
4	Annual external temperature	<15°C	15 – 25°C	>25°C	0.110
5	Soil type	Loam	Sand	Clay	0.055
6	Water table depth	1m	–	5m	0.110
7	Membrane	No	–	Yes	0.110

(1) Procedure for whole house ventilation score, S_{house}, is presented in Section 2.1.

(2) Procedure for local external wind speed is presented in Section 2.2.

1.5.2 Wall Cavity t_{wet}

For a typical wall, $\beta_{mean} = 0.73$. The factors a_i and k_i are determined as in Table 1.5.2.1. Derivation and/or determination of these parameters are in Appendix B.

Table 1.5.2.1 *Determining a_i and k_i for wall to estimate t_{wet}*

i	Parameters	Risk level			a_i
		High risk $k_i = +1$	Medium risk $k_i = 0$	Low risk $k_i = -1$	
1	Wall Ventilation	Non-cavity	Cavity, ends close	Cavity, ends open	0.374
2	Whole house ventilation(1)	$S_{house} < 15$	$S_{house} = 15 - 30$	$S_{house} > 30$	0.140
3	Annual local external wind speed(2)	<2 m/s	2 to 5 m/s	> 5 m/s	0.187
4	Annual external temperature	<15°C	15 – 25°C	>25°C	0.187
5	Orientation of wall to sun	South	East/West	North	0.234

(1) Procedure for whole house ventilation score, S_{house}, is presented in Section 2.1.

(2) Procedure for local external wind speed is presented in Section 2.2.

1.5.3 Roof space t_{wet}

For a typical roof space, $\beta_{mean} = 0.51$. The factors a_i and k_i are determined as in Table 1.5.3.1. Derivation and/or determination of these parameters are in Appendix B.

Table 1.5.3.1 *Determining a_i and k_i for roof space to estimate t_{wet}*

i	Parameters	Risk level			a_i
		High risk $k_i = +1$	Medium risk $k_i = 0$	Low risk $k_i = -1$	
1	Roof ventilation(3)	$S_{roof} < 10$	$S_{roof} = 10 - 19$	$S_{roof} > 20$	0.537
2	Whole house ventilation(1)	$S_{house} < 15$	$S_{house} = 15 - 30$	$S_{house} > 30$	0.201
3	Annual local external wind speed (2)	<2 m/s	2 to 5 m/s	> 5 m/s	0.268
4	Annual external temperature	<15°C	15 – 25°C	>25°C	0.268

(1) Procedure for whole house ventilation score, S_{house}, is presented in Section 2.1.

(2) Procedure for local external wind speed is presented in Section 2.2.

(3) Roof ventilation score S_{roof} is determined by Table 1.5.3.2.

Table 1.5.3.2 *Score system for roof ventilation to estimate* t_{wet}

Roof ventilation	**Options**	**Score**
Sarking	Yes	0
	No	12
Eave ventilation	Yes	5
	No	0
Gable ventilation	Yes	10
	No	0
Ceiling ventilation	Yes	-3
	No	0
Wall cavity	Yes, ends open	5
	Yes, ends close	0
	No	0
	Total	S_{roof}

2. EXTRA PROCEDURES

2.1 Score system for whole house ventilation – S_{house}

Table 2.1.1 *Score system for whole house ventilation*

Roof ventilation	Options	Score
Sarking	Yes	0
	No	12
Eave ventilation	Yes	5
	No	0
Gable ventilation	Yes	10
	No	0
Ceiling ventilation	Yes	3
	No	0
Wall cavity	Yes, ends open	5
	Yes, ends close	1
	No	0
Subfloor ventilation	Large	15
	Standard	10
	No	0
	Total	S_{house}

2.2 Local External Wind speed

The local external wind speed used is at the height of eave of 3m, which can be estimated as (ASHRAE, 2005)

$$V_{H=3m} = C_s C_{H=3m} V_{met} \tag{2.2.1}$$

where

V_{met} = wind speed measured at the nearest BOM station (Wang & Leicester 2008)
C_s = shelter factor depending on site classification as in Table 2.2.1.
$C_{H=3m}$ = terrain and height adjustment coefficient, determined by Eq.(2.2.2)

$$C_{H=3m} = \left(\frac{270}{10.0}\right)^{0.14} \left(\frac{3.0}{\delta}\right)^{a} \tag{2.2.2}$$

where the constants a, δ depending on the local terrain category are taken from Table 2.2.2.

Table 2.2.1. *Shelter factor C_s (ASHRAE, 2005)*

Site classification	Shelter factor C_s
Open to sea	1
Urban (suburbs)	0.7
Urban (city centre)	0.4
Other site	0.9

Table 2.2.2. *Atmospheric boundary layer parameters (ASHRAE, 2005)*

Terrain category	Description	Exponent a	Layer thickness δ (m)
1	Large city centres, in which at least 50% of buildings are higher than 21 *m*, over a distance of at least 2000 *m* or 10 times the height of the structure upwind, whichever is greater	0.33	460
2	Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger, over a distance of at least 2000 *m* or 10 times the height of the structure upwind, whichever is greater	0.22	370
3	Open terrain with scattered obstructions having heights generally less than 10 *m*, including flat open country typical of **meteorological station** surroundings	0.14	270
4	Flat, unobstructed areas exposed to wind flowing over water for at least 1.6 *km*, over a distance of 500 *m* or 10 times the height of the structure inland, whichever is greater	0.10	210

References

ASHRAE (2005), *ASHRAE Handbook – Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

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APPENDIX A

Derivation for Salinity of Air in Building Envelope

Using the expert opinion procedure (Leicester et.al., 2004a):

$$\alpha = \alpha_{mean} \prod_{i=1}^{n} (1 + k_i a_i) \tag{A1}$$

where i = 1 to n is the number of parameters affecting α; a_i is constant depending on the importance rating of the i^{th} parameter. The factors k_i take the following values

- For a low risk option of the i^{th} paramete: $k_i = -1$
- For a medium risk option of the i^{th} parameter: $k_i = 0$
- For a high risk option of the i^{th} parameter: $k_i = +1$

Definitions of risk options for the influencing parameters are as in Tables A1.1, A1.2, and A1.3 for Subfloor, wall cavity, and roof-space, respectively. Values of the important factor I_i of the parameters are also set. In addition, the following parameters are estimated:

- $\alpha_{\text{average}}(H)$: Average or typical α when all the parameters are at high risk values
- $\alpha_{\text{average}}(L)$: Average or typical α when all the parameters are at low risk values

These 2 parameters are estimated as shown in Tables A2.1, A2.2, and A2.3 for Subfloor, wall cavity, and roof-space, respectively.

These values of the parameters are set based on knowledge gained from a building envelope microclimate and airborne salinity measurement program reported in Cole et.al. (1996, 2001), Ganther et.al. (2001, 2002), Leicester et.al. (2004b), and expert opinions through private communications with the authors during the course of the project.

The flowing equations approximate the relationship between the model and the data

$$\alpha_{average}(H) = \alpha_{mean} \prod_{i=1}^{n} (1 + jI_i) \tag{A2}$$

$$\alpha_{average}(L) = \alpha_{mean} \prod_{i=1}^{n} (1 - jI_i) \tag{A3}$$

where j is a constant that relates to the bias of the choice of the set of the importance ratings for the parameters. The constant j can be solved from the following equation (A4), which is the ratio of Eq. (A2) and Eq. (A3).

$$\frac{\alpha_{average}(H)}{\alpha_{average}(L)} = \frac{\prod_{i=1}^{n}(1+jI_i)}{\prod_{i=1}^{n}(1-jI_i)} \tag{A4}$$

Then the constant a_i can be obtained as

$$a_i = j\, I_i \tag{A5}$$

The mean value $t_{drying,mean}$ is then given by

$$\alpha_{mean} = \frac{\alpha_{average}(H)}{\prod_{i=1}^{n}(1+jI_i)} = \frac{\alpha_{average}(H)}{\prod_{i=1}^{n}(1+a_i)} \tag{A6}$$

Using data given in Tables A1 and A2, we have

- For sub-floor: j = 0.1053, and $\alpha_{mean} = 0.253$
- For wall-cavity: j = 0.0940, and $\alpha_{mean} = 0.207$
- For roof-space: j = 0.1053, and $\alpha_{mean} = 0.253$

Table A1.1 *Risk options and importance ratings for parameters affecting S_{air} in subfloor*

i	Parameters	Risk level			Importance rating I_i
		High risk $k_i = +1$	Medium risk $k_i = 0$	Low risk $k_i = -1$	
1	Subfloor ventilation	Large	Standard	No vent	8
2	Whole house ventilation$^{(1)}$	$S_{house} > 30$	$S_{house} = 15 - 30$	$S_{house} < 15$	3
3	Annual local external wind speed $^{(2)}$	> 5 m/s	2 to 5 m/s	<2 m/s	6

(1) Procedure for whole house ventilation score, S_{house}, is presented in Section 1.6.

(2) Procedure for local external wind speed is presented in Section 1.7.

Table A1.2 *Risk options and importance ratings for parameters affecting S_{air} in wall cavity*

i	Parameters	Risk level			Importance rating I_i
		High risk $k_i = +1$	Medium risk $k_i = 0$	Low risk $k_i = -1$	
1	Wall ventilation	Cavity, ends open	Cavity, ends close	Non-cavity	8
2	Whole house ventilation$^{(1)}$	$S_{house} > 30$	$S_{house} = 15 - 30$	$S_{house} < 15$	3
3	Annual local external wind speed $^{(2)}$	> 5 m/s	2 to 5 m/s	<2 m/s	4
4	Orientation of wall to sea	Facing direction to sea	Other directions	Facing opposite direction to sea	6

(1) Procedure for whole house ventilation score, S_{house}, is presented in Section 1.6.

(2) Procedure for local external wind speed is presented in Section 1.7.

Table A1.3 *Risk options and importance ratings for parameters affecting S_{air} in roof-space*

i	Parameters	Risk level			Importance rating I_i
		High risk $k_i = +1$	Medium risk $k_i = 0$	Low risk $k_i = -1$	
1	Roof ventilation$^{(3)}$	$S_{roof} > 20$	$S_{roof} = 10 – 19$	$S_{roof} < 10$	8
2	Whole house ventilation$^{(1)}$	$S_{house} > 30$	$S_{house} = 15 – 30$	$S_{house} < 15$	3
3	Annual local external wind speed$^{(2)}$	> 5 m/s	2 to 5 m/s	<2 m/s	6

(1) Procedure for whole house ventilation score, S_{house}, is presented in Section 1.6.

(2) Procedure for local external wind speed is presented in Section 1.7.

(3) Roof ventilation score S_{roof} is determined by Table 1.3.3.2.

Table A2.1 *Average or typical α for sub-floor*

Criteria	Estimated α (Typical value)
All parameters set at high risk option (i.e. all $k = +1$)	1.0
All parameters set at low risk option (i.e. all $k = -1$)	0.01

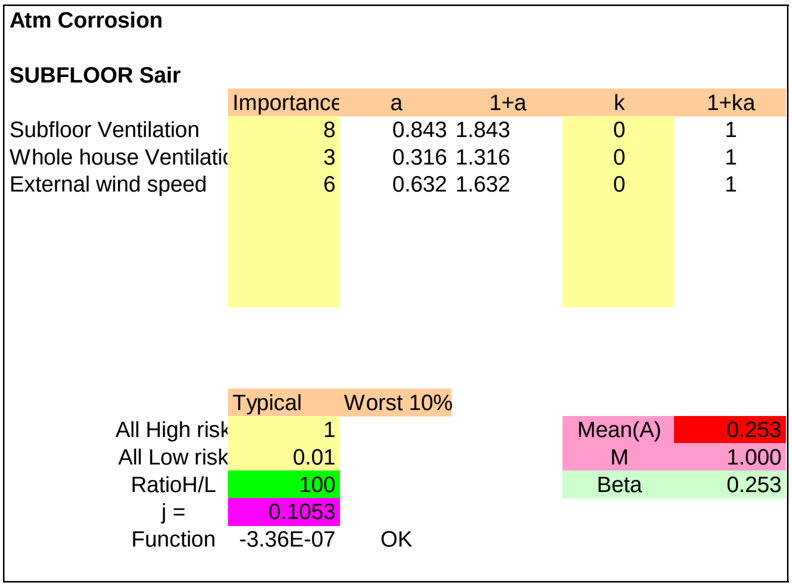
Table A2.2 *Average or typical α for wall cavity*

Criteria	Estimated α (Typical value)
All parameters set at high risk option (i.e. all $k = +1$)	1.0
All parameters set at low risk option (i.e. all $k = -1$)	0.01

Table A2.3 *Average or typical α for roof-space*

Criteria	Estimated α (Typical value)
All parameters set at high risk option (i.e. all $k = +1$)	1.0
All parameters set at low risk option (i.e. all $k = -1$)	0.01

An Excel spreadsheet was made for the procedure. Snapshots of the spreadsheet are provided below.

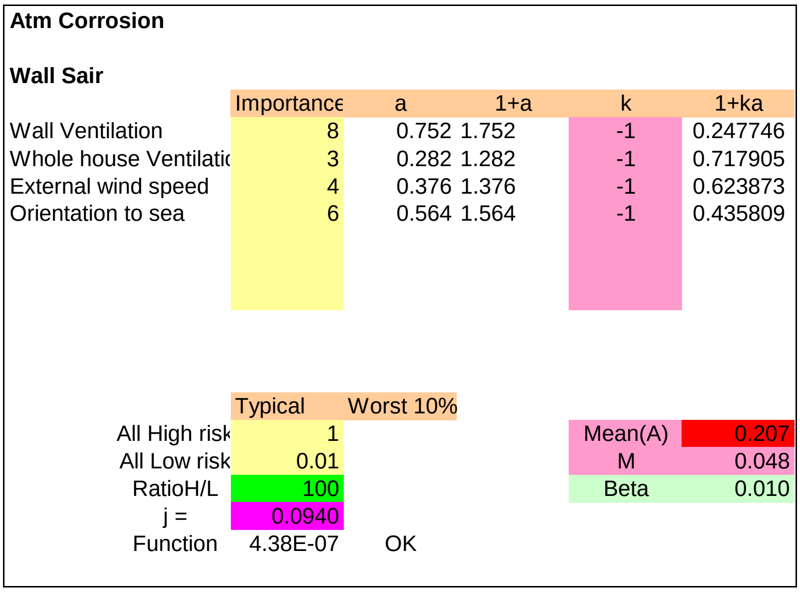


Atm Corrosion

SUBFLOOR Sair

	Importance	a	1+a	k	1+ka
Subfloor Ventilation	8	0.843	1.843	0	1
Whole house Ventilatio	3	0.316	1.316	0	1
External wind speed	6	0.632	1.632	0	1

	Typical	Worst 10%			
All High risk	1			Mean(A)	0.253
All Low risk	0.01			M	1.000
RatioH/L	100			Beta	0.253
j =	0.1053				
Function	-3.36E-07	OK			

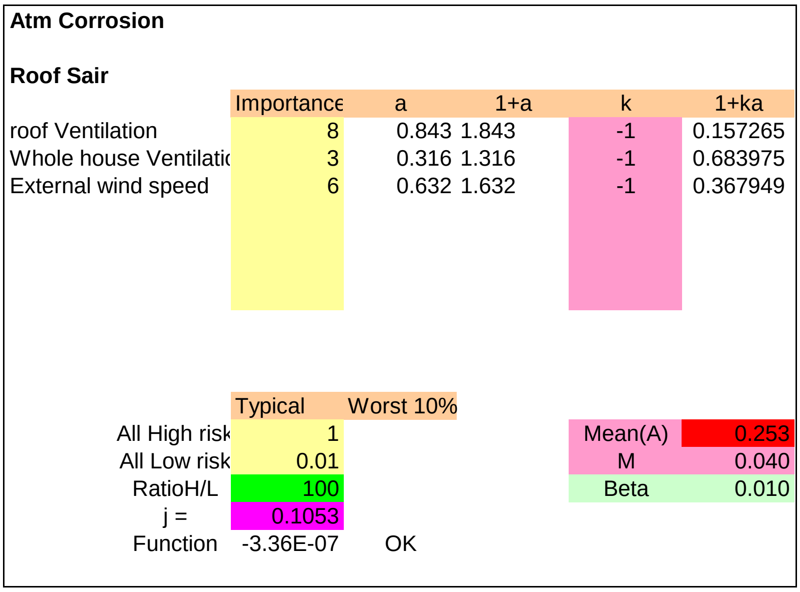


Atm Corrosion

Wall Sair

	Importance	a	1+a	k	1+ka
Wall Ventilation	8	0.752	1.752	-1	0.247746
Whole house Ventilatio	3	0.282	1.282	-1	0.717905
External wind speed	4	0.376	1.376	-1	0.623873
Orientation to sea	6	0.564	1.564	-1	0.435809

	Typical	Worst 10%			
All High risk	1			Mean(A)	0.207
All Low risk	0.01			M	0.048
RatioH/L	100			Beta	0.010
j =	0.0940				
Function	4.38E-07	OK			



Atm Corrosion

Roof Sair

	Importance	a	1+a	k	1+ka
roof Ventilation	8	0.843	1.843	-1	0.157265
Whole house Ventilatio	3	0.316	1.316	-1	0.683975
External wind speed	6	0.632	1.632	-1	0.367949

	Typical	Worst 10%			
All High risk	1			Mean(A)	0.253
All Low risk	0.01			M	0.040
RatioH/L	100			Beta	0.010
j =	0.1053				
Function	-3.36E-07	OK			

APPENDIX B

Derivation for Time of Wetness in Building Envelope

Using the expert opinion procedure (Leicester et.al., 2004a):

$$\beta = \beta_{mean} \prod_{i=1}^{n} (1 + k_i a_i) \tag{B1}$$

where i = 1 to n is the number of parameters affecting β; a_i is constant depending on the importance rating of the i^{th} parameter. The factors k_i take the following values

- For a low risk option of the i^{th} paramete: $k_i = -1$
- For a medium risk option of the i^{th} parameter: $k_i = 0$
- For a high risk option of the i^{th} parameter: $k_i = +1$

Definitions of risk options for the influencing parameters are as in Tables B1.1, B1.2, and B1.3 for Subfloor, wall cavity, and roof-space, respectively. Values of the important factor I_i of the parameters are also set. In addition, the following parameters are estimated:

- $\beta_{\text{average}}(H)$: Average or typical α when all the parameters are at high risk values
- $\beta_{\text{average}}(L)$: Average or typical α when all the parameters are at low risk values

These 2 parameters are estimated as shown in Tables B2.1, B2.2, and B2.3 for Subfloor, wall cavity, and roof-space, respectively.

These values of the parameters are set based on knowledge gained from a building envelope microclimate measurement program outlined in Cole et.al. (2001), and Ganther et.al. (2001), Leicester et.al. (2004b), and expert opinions through private communications with the authors during the course of the project.

The flowing equations approximate the relationship between the model and the data:

$$\beta_{average}(H) = \beta_{mean} \prod_{i=1}^{n} (1 + jI_i) \tag{B2}$$

$$\beta_{average}(L) = \beta_{mean} \prod_{i=1}^{n} (1 - jI_i) \tag{B3}$$

where j is a constant that relates to the bias of the choice of the set of the importance ratings for the parameters. The constant j can be solved from the following equation (B4), which is the ratio of Eq. (B2) and Eq. (B3).

$$\frac{\beta_{average}(H)}{\beta_{average}(L)} = \frac{\prod_{i=1}^{n} (1 + jI_i)}{\prod_{i=1}^{n} (1 - jI_i)} \tag{B4}$$

Then the constant a_i can be obtained as

$$a_i = j\, I_i \tag{B5}$$

The mean value $t_{drying,mean}$ is then given by

$$\beta_{mean} = \frac{\beta_{average}(H)}{\prod_{i=1}^{n}(1+jI_i)} = \frac{\beta_{average}(H)}{\prod_{i=1}^{n}(1+a_i)} \tag{B6}$$

Using data given in Tables B1 and B2, we have

- For subfloor: j = 0.0276, and $\alpha_{mean} = 1.180$
- For wall-cavity: j = 0.0468, and $\alpha_{mean} = 0.734$
- For roof-space: j = 0.0671, and $\alpha_{mean} = 0.505$

Table B1.1 *Risk options and importance ratings for parameters affecting t_{wet} in subfloor*

i	Parameters	Risk level			Importance rating I_i
		High risk $k_i = +1$	Medium risk $k_i = 0$	Low risk $k_i = -1$	
1	Subfloor ventilation	No vent	Standard	Large	0.220
2	Whole house ventilation$^{(1)}$	$S_{\text{house}} < 15$	$S_{\text{house}} = 15 – 30$	$S_{\text{house}} > 30$	0.083
3	Annual local external wind speed$^{(2)}$	<2 m/s	2 to 5 m/s	> 5 m/s	0.110
4	Annual external temperature	<15°C	15 – 25°C	>25°C	0.110
5	Soil type	Loam	Sand	Clay	0.055
6	Water table depth	1m	–	5m	0.110
7	Membrane	No	–	Yes	0.110

(1) Procedure for whole house ventilation score, S_{house}, is presented in Section 1.6.
(2) Procedure for local external wind speed is presented in Section 1.7.

Table B1.2 *Risk options and importance ratings for parameters affecting t_{wet} in wall cavity*

i	Parameters	Risk level			Importance rating I_i
		High risk $k_i = +1$	Medium risk $k_i = 0$	Low risk $k_i = -1$	
1	Wall Ventilation	Non-cavity	Cavity, ends close	Cavity, ends open	0.374
2	Whole house ventilation$^{(1)}$	$S_{\text{house}} < 15$	$S_{\text{house}} = 15 – 30$	$S_{\text{house}} > 30$	0.140
3	Annual local external wind speed$^{(2)}$	<2 m/s	2 to 5 m/s	> 5 m/s	0.187
4	Annual external temperature	<15°C	15 – 25°C	>25°C	0.187
5	Orientation of wall to sun	South	East/West	North	0.234

(1) Procedure for whole house ventilation score, S_{house}, is presented in Section 1.6.
(2) Procedure for local external wind speed is presented in Section 1.7.

***Table B1.3** Risk options and importance ratings for parameters affecting t_{wet} in roof-space*

i	Parameters	Risk level			Importance rating I_i
		High risk $k_i = +1$	Medium risk $k_i = 0$	Low risk $k_i = -1$	
1	Roof ventilation$^{(3)}$	$S_{\text{roof}} < 10$	$S_{\text{roof}} = 10 – 19$	$S_{\text{roof}} > 20$	0.537
2	Whole house ventilation$^{(1)}$	$S_{\text{house}} < 15$	$S_{\text{house}} = 15 – 30$	$S_{\text{house}} > 30$	0.201
3	Annual local external wind speed$^{(2)}$	<2 m/s	2 to 5 m/s	> 5 m/s	0.268
4	Annual external temperature	<15°C	15 – 25°C	>25°C	0.268

(1) Procedure for whole house ventilation score, S_{house}, is presented in Section 1.6.

(2) Procedure for local external wind speed is presented in Section 1.7.

(3) Roof ventilation score S_{roof} is determined by Table 1.3.3.2.

***Table B2.1** Average or typical β for sub-floor*

Criteria	Estimated β (Typical value)
All parameters set at high risk option (i.e. all $k = +1$)	2.5
All parameters set at low risk option (i.e. all $k = -1$)	0.5

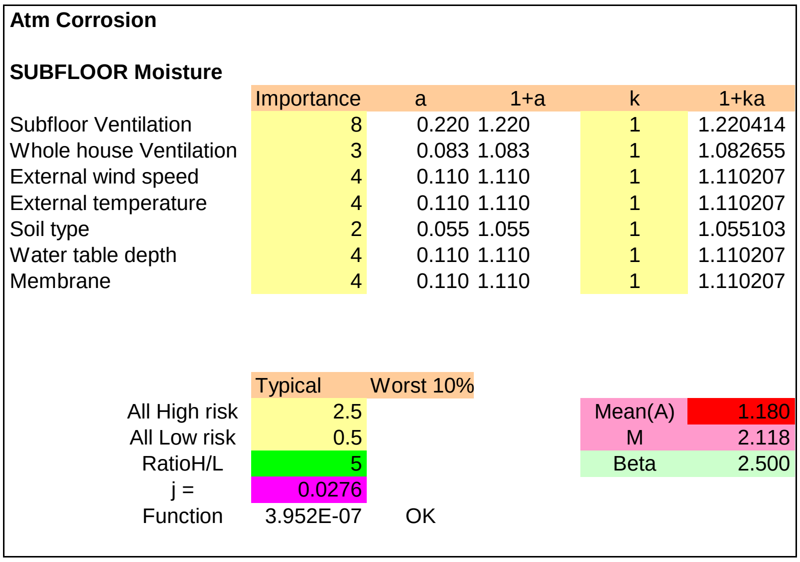
***Table B2.2** Average or typical β for wall cavity*

Criteria	Estimated β (Typical value)
All parameters set at high risk option (i.e. all $k = +1$)	2.0
All parameters set at low risk option (i.e. all $k = -1$)	0.2

***Table B2.3** Average or typical β for roof-space*

Criteria	Estimated β (Typical value)
All parameters set at high risk option (i.e. all $k = +1$)	1.5
All parameters set at low risk option (i.e. all $k = -1$)	0.1

An Excel spreadsheet was made for the procedure. Snapshots of the spreadsheet are also provided below.

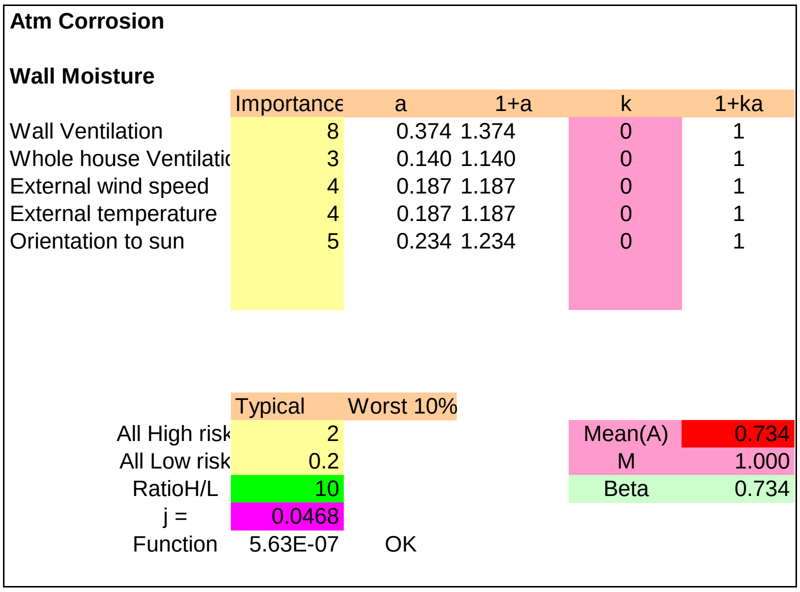


Atm Corrosion

SUBFLOOR Moisture

	Importance	a	1+a	k	1+ka
Subfloor Ventilation	8	0.220	1.220	1	1.220414
Whole house Ventilation	3	0.083	1.083	1	1.082655
External wind speed	4	0.110	1.110	1	1.110207
External temperature	4	0.110	1.110	1	1.110207
Soil type	2	0.055	1.055	1	1.055103
Water table depth	4	0.110	1.110	1	1.110207
Membrane	4	0.110	1.110	1	1.110207

	Typical	Worst 10%		
All High risk	2.5		Mean(A)	1.180
All Low risk	0.5		M	2.118
RatioH/L	5		Beta	2.500
j =	0.0276			
Function	3.952E-07	OK		

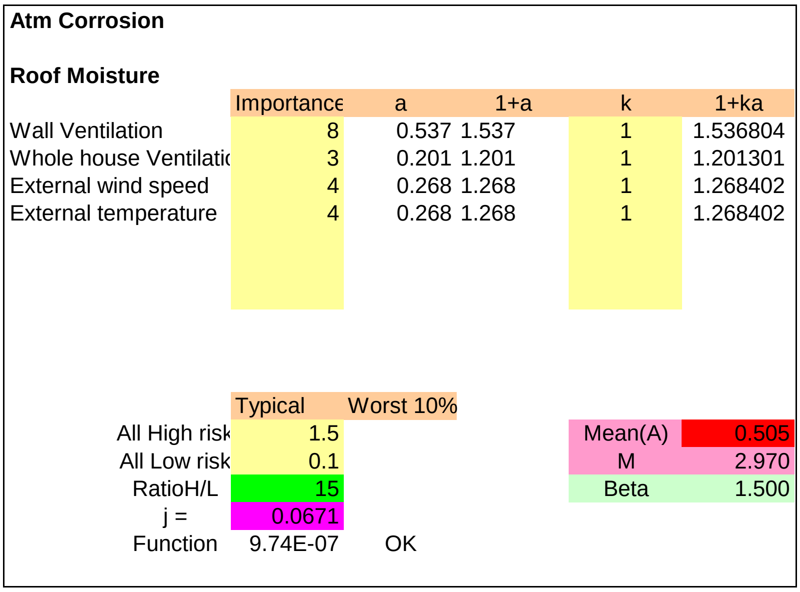


Atm Corrosion

Wall Moisture

	Importance	a	1+a	k	1+ka
Wall Ventilation	8	0.374	1.374	0	1
Whole house Ventilatic	3	0.140	1.140	0	1
External wind speed	4	0.187	1.187	0	1
External temperature	4	0.187	1.187	0	1
Orientation to sun	5	0.234	1.234	0	1

	Typical	Worst 10%		
All High risk	2		Mean(A)	0.734
All Low risk	0.2		M	1.000
RatioH/L	10		Beta	0.734
j =	0.0468			
Function	5.63E-07	OK		



Atm Corrosion

Roof Moisture

	Importance	a	1+a	k	1+ka
Wall Ventilation	8	0.537	1.537	1	1.536804
Whole house Ventilatic	3	0.201	1.201	1	1.201301
External wind speed	4	0.268	1.268	1	1.268402
External temperature	4	0.268	1.268	1	1.268402

	Typical	Worst 10%		
All High risk	1.5		Mean(A)	0.505
All Low risk	0.1		M	2.970
RatioH/L	15		Beta	1.500
j =	0.0671			
Function	9.74E-07	OK		

PART C

Embedded Corrosion Model for Metal Fasteners in Building Envelope

PART C – Contents

Embedded Corrosion model for Metal Fasteners in Building Envelope

1. HAZARD ZONES & CLIMATE ZONES
    - 1.1 Hazard zones
    - 1.2 Climate zones

2. MATERIAL GROUPING

3. MODEL EQUATIONS

4. MOISTURE CONTENT OF TIMBER
    - 4.1 Subfloor
    - 4.2 Roof-space
    - 4.3 Wall Cavity

5. CORROSION DEPTH

REFERENCES

1. Hazard and Climate Zones

The model for fasteners in building envelope is to be developed based on the model for fasteners in exposed structures. For details of the model development, refer the model manual of embedded corrosion of exposed fasteners (Manual No. 6, Nguyen, et.al. 2007).

1.1 Hazard Zones

For practical purpose, 3 hazard zones, namely A, B and C; are created as shown in Fig. 1.1.1. The $SEMC_{mean}$ values for the 3 hazard zones are in Table 1.1.1. Refer to Manual No. 6, Nguyen, et.al. (2008) for more details.

Figure 1.1.1. Hazard zone map based on $SEMC_{mean}$

Table 1.1.1 $SEMC_{mean}$ values for the 3 hazard zones

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

1.2 Climate Zones

There are 2 climate zones:

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

2. Material Grouping

The acidity classification of timber is presented in Table 2.1. Refer to Manual No. 6 (Nguyen, et.al. 2008) for more details.

Table 2.1 Timber Acidity classification

Standard Australia index	Trade name	Botanical name	Type	Density	Design 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 River	Backhousia bancroftii	H	950	-	2
-	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

3. Base Model Equations

The model for fasteners in building envelope is to be developed based on the model for fasteners in exposed structures. For details of the model development, refer the model manual of embedded corrosion of exposed fasteners (Manual No. 6, Nguyen, et.al. 2007).

The base models for corrosion of metals embedded in untreated and treated timber at moisture content M for 120 days are shown in Figures (3.1) and (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 the case of connectors embedded in untreated wood, at constant moisture content over 120 days, the following equations are proposed;

$$f_{120}(M) = \begin{cases} 0 & \text{if } M \le M_0; \\ 0.2\, C_{120}(M - M_0) & \text{if } M_0 < M < (M_0{+}5\%); \\ C_{120} & M \le (M_0{+}5\%) \end{cases} \tag{3.1}$$

where M (%) is moisture content, C_{120} (μm) is the depth of corrosion. The function is illustrated in Figure 3.1. Table 3.1 gives parameters of the model.

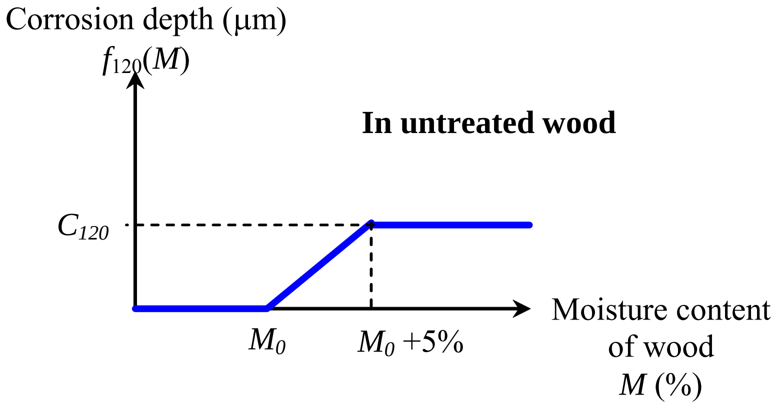


Figure 3.1. *Base model of embedded corrosion in untreated wood.*

Table 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

For the case of connectors embedded in CCA treated wood, at constant moisture content over 120 days, the following equations are used

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

$$f_{120}(M) = \begin{cases} 0 & \text{if } M \le M_0; \\ 0.7\ (M - M_0) & \text{if } M > M_0; \end{cases} \tag{3.2}$$

where M is moisture content. The function is illustrated in Figure 3.2.

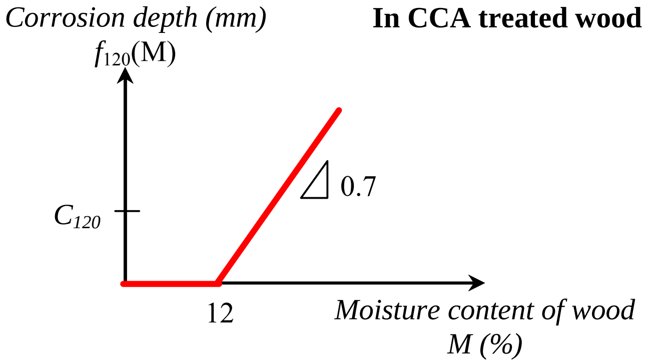


Figure 3.2. *Base model of embedded corrosion in CCA-treated wood.*

4. Timber Moisture Contents

The model for fasteners in building envelope is to be developed based on the model for fasteners in exposed structures. For details of the model development, refer the model manual of embedded corrosion of exposed fasteners (Manual No. 6, Nguyen, et.al. 2008).

Before the corrosion depth for an embedded fastener can be computed using the base model, the moisture content of the timber, appropriate to the climate and microclimate must first be calculated.

The mean seasonal moisture contents of a piece of timber for one year are estimated by:

$$TM_{mean} = exp[1.9 + 0.05\ SEMC_{mean}] \tag{4.1}$$

where the mean surface equilibrium moisture content, $SEMC_{mean}$, is given in Table 4.1.

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

$$BTM_{\text{mean}} = TM_{\text{mean}} + \Delta_{\text{enviroment}} \tag{4.2}$$

$$BTM_{\max} = BTM_{\text{mean}} + 0.1\ D\ TM_{\text{mean}} \tag{4.3}$$

where the damping factor *(D)*, is given in Tables 4.2, depending on microclimate. The estimation procedure for $\Delta_{\text{environment}}$ also depends on the microclimates to be considered, as presented in the followings.

4.1 Subfloor

$$\Delta_{\text{enviroment}} = \Delta_{\text{microclimate}} + \Delta_{\text{SFvent}} + \Delta_{\text{soil}} \tag{4.4}$$

The microclimate factor ($\Delta_{\text{microclimate}}$) is given in Tables 4.2. This table is the part for building envelope components from the general model presented in Cole et.al. (2001). The adjustment factor for subfloor ventilation (Δ_{SFvent}) depends on the extent of ventilation of the subfloor. The values for typical sub-floor ventilation scenarios are given in Table 4.3. The adjustment factor for moisture contribution from soil (Δ_{soil}) depends on the water table level and soil type. The values for typical soil scenarios are given in Table 4.4. Values of the factors are estimated using knowledge based on a building envelope microclimate and timber moisture content measurement program presented in Cole et.al. (1996a, 1996b, 1999, 2001), Ganther et.al. (2000, 2001), and expert opinions through private communications with the authors during the course of the project.

4.2 Roofspace

$$\Delta_{\text{enviroment}} = \Delta_{\text{microclimate}} + \Delta_{\text{RSvent}} \tag{4.5}$$

$$\Delta_{\text{RSvent}} = \Delta_{\text{sarking}} + \Delta_{\text{eave}} + \Delta_{\text{gable}} + \Delta_{\text{ceiling}} \tag{4.6}$$

The microclimate factor ($\Delta_{\text{microclimate}}$) is given in Tables 4.2. This table is the part for building envelope components from the general model presented in Cole et.al. (2001).

The factor for roof space ventilation (Δ_{RSvent}) is for the extent of ventilation of the roofspace, which depends on various kind of vents used. Equation (4.6) is for a typical gable house with 4 kinds of vents in roof space, including roof sarking, eave vents, gable vents, and ceiling vents. The values for these typical ventilation factors are given in Table 4.5. Values of the factors are estimated using knowledge based on a building envelope microclimate and timber moisture content measurement program presented in Cole et.al. (1996a, 1996b, 1999, 2001), Ganther et.al. (2000, 2001), and expert opinions through private communications with the authors during the course of the project.

4.3 Wall Cavitiy

$$\Delta_{\text{enviroment}} = \Delta_{\text{microclimate}} + \Delta_{\text{WCvent}} \tag{4.7}$$

The microclimate factor ($\Delta_{\text{microclimate}}$) is given in Tables 4.2. This table is the part for building envelope components from the general model presented in Cole et.al. (2001).

The adjustment factor for wall cavity ventilation (Δ_{WCvent}) depends on the extent of ventilation of the wall cavities. The values for typical ventilation scenarios are given in Table 4.6. Values of the factors are estimated using knowledge based on a building envelope microclimate and timber moisture content measurement program presented in Cole et.al. (1996a, 1996b, 1999, 2001), Ganther et.al. (2000, 2001), Leicester et.al. (2004), and expert opinions through private communications with the authors during the course of the project.

Table 4.1 *Mean surface equilibrium moisture content*

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

Table 4.2 *Damping factor and microclimate factor*

Microclimate	D		$\Delta_{\text{microclimate}}$	
	Marine(1)	**Other**	**Marine**	**Other**
Sub-floor	2.0	0.8	2.5	0.9
Wall cavity	1.5	1.1	0.5	0.6
Roof space	2.0	1.3	-0.5	-3.8

(1) If distance to coast < 1km, then climate zone is 'Marine'; otherwise, climate zone is 'Other', ie. non-marine (see Section 1.2).

Table 4.3 *Subfloor ventilation factor Δ_{SFvent}*

Extent of Ventilation	Δ_{SFvent}	
	Marine	**Other**
None	4.0	1.5
Standard	0.0	0.0
Large	-1.0	-0.5

Table 4.4 *Soil moisture factor Δ_{soil}*

Membrane use and water table level	Δ_{soil}		
	Loam	**Sand**	**Clay**
Without membrane:			
1 m	1.5	1.0	0.5
5 m	0.2	0.1	0.0
With membrane installed:	0.0	0.0	0.0

Table 4.5 *Ventilation factors for roof space*

Options	$\Delta_{sarking}$ **Roof sarking**	Δ_{eave} **Eave vents**	Δ_{gable} **Gable vents**	$\Delta_{ceiling}$ **Ceiling vents**
Yes	0.0	0.0	0.0	0.0
No	-2.0	0.2	2.0	-1.5

Table 4.6 *Wall ventilation factor Δ_{WCvent}*

Wall configuration	Δ_{WCvent}		
	North wall	**East/west wall**	**South wall**
Wall with 19mm-wide cavity:			
* Opening at both ends	-1.5	0.0	1.5
* Not opening	0.5	2.0	3.5
Non-cavity wall	1.0	2.5	4.0

5. Corrosion Depths

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

$$c_o = \frac{1}{2}\left[f_{120}(BTM_{\max}) + 0.3 f_{120}(BTM_{\mathrm{mean}})\right] \tag{5.1}$$

where $f_{120}(M)$ is the corrosion depth of connectors embedded in untreated wood for 120 days, given in Eq.(3.1) as a function of timber moisture content M (%) estimated in Section 4.

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

$$c = c_o t^n \tag{5.2}$$

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

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

For zinc $$c_o = 1.3 f_{120}(BTM_{\mathrm{mean}}) \tag{5.3}$$

For steel $$c_o = 2.1 f_{120}(BTM_{\mathrm{mean}}) \tag{5.4}$$

where $f_{120}(M)$ is the corrosion depth of connectors embedded in CCA-treated wood for 120 days, given by Eq.(3.2).

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.

For details of the model development, refer the Manual No. 6 of embedded corrosion of fasteners (Nguyen, et.al. 2008).

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