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Research Paper

Service Life Analysis of Timber Structures in The Indonesian Coastal Environment

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ABSTRACT: *Indonesia is an archipelagic country that has the second-longest coastline in the world. Approximately 70% of the total population of this tropical climate country lives on the coastline. The fishermen's villages are typical in these areas. They are usually made of timber. The marine wood borer is a famous organism responsible for deteriorated timber structures. Knowing the service life of the coastal timber structures and infrastructures is essential to determine the repair or replacement actions and related preventive measures. The goal is to reduce the billions of dollars in loss per year. The service life analysis shows Belian is the most durable tropical wood species for marine borer attack decay. It deteriorated only 1.2 cm for above-ground structures and 9 cm for the condition under the marine borer attack for 20 years under the Indonesian climate. The wood durability class 1 and 2 is sufficient for above-ground structures. Meanwhile, the structures under marine borer attack require wood durability class 1.*

KEYWORDS: *Service Life, Timber Structures, Coastal Environment*

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I. INTRODUCTION

Nearly 50% of the world's population settled in areas within 100 km of the coastline [1]. The reason is that coastal areas benefit social and economic development for people, particularly in less developed coastal and islands [2]. Indonesia, a tropical country, has 16,056 islands and the second-longest coastline in the world after Canada. The coastline length of this archipelagic country is approximately 95,181 km [3]. Approximately 187.2 million Indonesian people, around 70% of the total population, live on the coastlines [4]. The coastal area may contain ecosystems, for instance, mangroves. This ecosystem protects from coastal hazards like surges, floods, and erosion [5] and the habitat of commercial fish [6]. This conducive environment makes traditional fishermen’s settlements flourish along the Indonesian coastline.

The fishermen's settlement in Indonesia usually has primary means and facilities [7]. This area's most common structures and facilities are timber houses, fishing ports, fish landing places, jetties, and fish markets. The building structures are commonly made of timber to maintain their light weight. A lightweight building is essential in this area of low bearing capacity. Timber deteriorates fast when it is not adequately treated. Marine organisms threaten their durability in the marine environment. Marine organisms like wood-borer activity are a source of considerable damage to maritime wooden structures. Wood-borer is responsible for billions of dollars of loss per year to coastal structures, such as piers, jetties, wharves, fishing, and aquaculture equipment [8], [9], [10]. Information on a structure's expected remaining service life is vital in deciding whether the structural members should be repaired or replaced. The possible degradation mechanism in timber structures, such as mechanical, physical, chemical, and biological degradations, is crucial. It is beneficial in determining repair actions and preventive measures.

Numerous research studies on the service life of timber structures, such as Van de Kuilen [11], combined the model of durability with the strength model, and Viitanen et al. [12] offered the building hygrothermal physics model. Meanwhile, Nofal & Kumaran [13] suggested the model of the hygrothermal model with damage functions. Also, Zelinka, Derome, & Glass [14] recommended a model of metal fastener corrosion embedded in solid, and Saito, Fukuda, & Sawachi [15] integrated hygrothermal analysis with a decay model. Wang, Leicester, & Nguyen [16] and MacKenzie, Wang, Leicester, Foliente, & Nguyen [17] extensively shared Australian long-term laboratory research and field experience. Bornemann, Brischke, & Alfredsen [18] proposed a dose-response model, and Kutnik, Suttie, & Brischke [19] presented European Standardization on wood durability and preservation. Meyer-Veltrup, Brischke, Niklewski, & Hansson [20] coupled the factorization approach with the dose-response model, and Prabowo & Hilmy [21] studied the Australian decay model inserting Indonesian tropical climate parameters.

Research on timber structures' service life in the tropical coastal environment still lacks, especially in Indonesia. Therefore, it is advantageous to adopt the service life model developed by Nguyen et al. [22], [23], [24]. This model is considered due to the geographic closeness between Indonesia and Australia. It opens an opportunity to share some similar parameters involved. However, adjusting to the unique Indonesian environment is still required.

II. METHODOLOGY

The durability of timber structures will be calculated by employing two models. They are the decay above-ground model based on Wang, Leicester, & Nguyen [16] and MacKenzie, Wang, Leicester, Foliente, & Nguyen [17] and the marine borer attack model based on Nguyen et al. [22], [23], [24]. The coastal environment in the studied areas is taken from the research by Diba et al. [25]. Belian, Bangkirai, Keruing, and Meranti are the tropical wood species chosen. Both models, the decay above-ground model, and the marine borer attack model, are simulated for 20 years. It is done to gain insight into the durability level of these Indonesian tropical wood species.

2.1 Coastal environment

The site studied was Mempawah coastal area. Mempawah is one of the regencies on the west coast of Kalimantan Island, Indonesia. It is located between 0°44' North Latitude to 00°0,4' South Latitude and from 108°24' to 109°21,5' East Longitude (Figure 1). Mempawah has low land, hills, and swampy coastal beaches. Slopes of 0 - 8 % dominate its area, and its altitude is 0 - 200 m above mean sea level. Mangrove forests flourish on these swampy coastal beaches. Two primary mangrove forests exist in Mempawah: Mempawah Mangrove Park and Polaria Mangrove Park. The coastal environment properties of these two parks are characterized by the water's physical and chemical properties (Table 1). It is based on the work of Diba et al. [25].

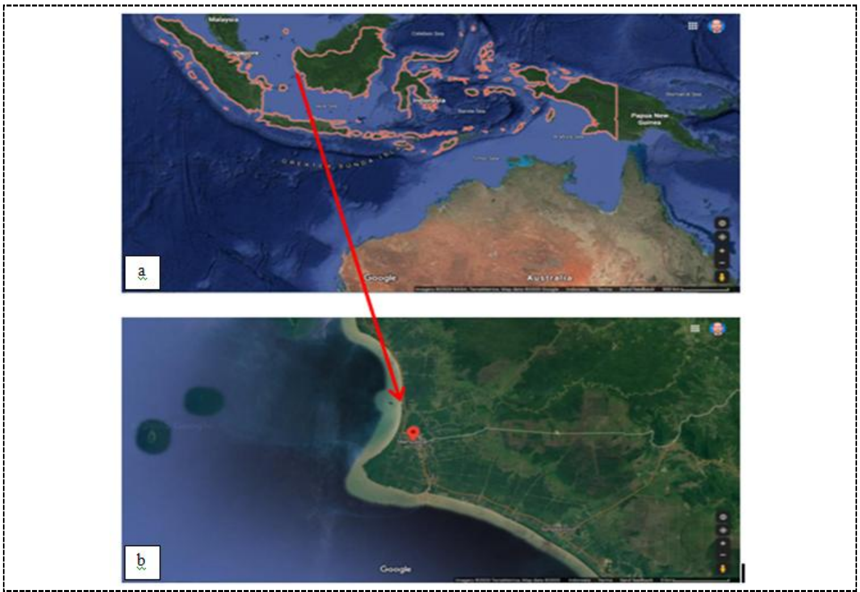

Figure1: Research location: a. Indonesian map, b. Mempawah coastal area

Table 1 Water physical and chemical properties

Water physical and chemical parameters	Location	
	Mempawah Mangrove Park	Polaria Mangrove Park
Temperature (°C)	28.06 ± 0.23	28.00 ± 0.22
pH	7.31 ± 0.03	8.34 ± 0.07
Salinity (%)	10.50 ± 0.35	6.55 ± 0.15
Dissolved oxygen (mg/L)	4.74 ± 0.10	5.59 ± 0.14
Biological Oxygen Demand (BOD) (mg/L)	8.47 ± 0.15	4.74 ± 0.07
Chemical Oxygen Demand (COD) (mg/L)	600.00 ± 0.20	512.30 ± 0.14

2.2 Marine wood borer species in Mempawah coastal area

Marine wood borer is a famous organism responsible for the wood deterioration in a coastal environment. The identification of marine wood borer species in the Mempawah coastal area here was carried out by Diba et al. [25]. The species of marine wood borer found in the observed area can be seen in Table 2.

Table 2 Marine wood borer in the observed area

Place	The tree vegetation	Marine borer species
Mempawah Mangrove Park	Rhizophora mucronata, Candelia candel, Avicennia marina, Bruguiera xylindrica	Teredo pocalifer
Polaria Mangrove Park	Rhizophora mucronata tree, Bruguiera xylindrica, Avicennia marina, Sonneratia ovata, Nypa fruticans. Avicennia officinalis, and Sonneratia alba	Neoteredo reynei, Teredo pocalifer, Teredo navalis, Teredo tritubulata, Teredo calmani, Teredo medilobata

2.3 The durability model

The model of timber durability is based on two models: the decay above-ground model and the marine borer attack model. The decay above-ground model referred to Wang et al. [16] and MacKenzie et al. [17]. The model of the marine borer attack was taken from Nguyen et al. [22], [23], [24]. The decay above ground is used to model the upper structures of the building. Meanwhile, the marine borer attack model predicts timber deterioration in the building's sub-structures. The illustration of the model used for respective building structures can be shown in Figure 2.

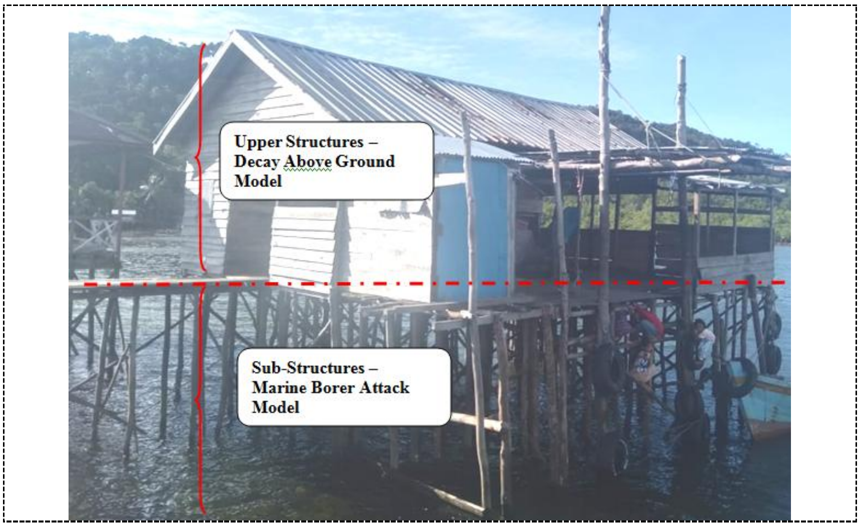

Figure2: Building structure decay modeling

The predicted model for decay above ground formulated in equation (1) consists of two terms the first deals with decay depth at the time before and right at decay initiation. The latter term is related to decay depth at the time after deterioration started. The main parameters involved in this model are the decay lag (t_{lag}) expressed in years and the decay rate (r) expressed in mm/year. The decay depth equation and its involving parameters are presented in equation (1) until equation (5).

$$d(t) = \begin{cases} ct^2 & \text{if} \quad t \le t_{d_0} \\ (t - t_{lag})r & \text{if} \quad t > t_{d_0} \end{cases} \tag{1}$$

$$t_{d_0} = t_{lag} + \frac{d_0}{r} \tag{2}$$

$$c = \frac{d_0}{t_{d_0}{}^2} \tag{3}$$

$$t_{lag} = 8.5r^{-0.85} \tag{4}$$

$$r = k_{\text{wood}} k_{\text{climate}} k_{\text{p}} k_{t} k_{\text{w}} k_{\text{n}} k_{\text{g}} \tag{5}$$

Where d(t) = decay depth after t years of installation, d(0) = decay depth at the initiation time, k_{wood} = wood parameter, $k_{climate}$ = climate parameter, k_p = paint parameter; kt = thickness parameter; k_w = width parameter; k_n = fastener parameter; and k_g = geometry parameter. The decay model is illustrated in figure 3.

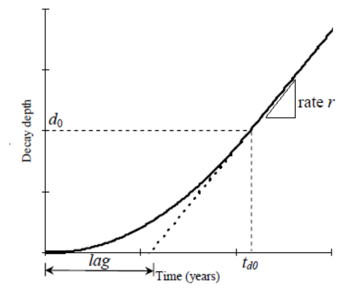

Figure3: Decay depth model, d(t) vs. t

The marine borer attack model is expressed in equation (6). First, the equation calculates the decay depth when the time lag is more than or equal to the observed time. Second, the decay depth is estimated for the time lag less than the observed time. The marine borer attack model and its related parameters can be formulated in equation (6) until equation (8). The illustration of the model can be seen in Figure 4.

$$d(t) = \begin{cases} 0 & \text{if} \quad t \le t_{lag} \\ (t - t_{lag})r & \text{if} \quad t > t_{lag} \end{cases} \tag{6}$$

$$t_{lag} = \begin{cases} 0 & \text{if} \quad r \ge 20 \\ 2.0 - 0.1r & \text{if} \quad t < 20 \end{cases} \tag{7}$$

$$r = k_{\text{wood}} k_{\text{water}} k_{\text{environment}} k_{\text{construction}} \tag{8}$$

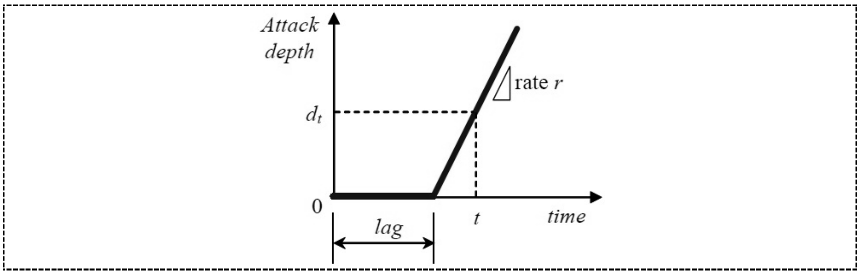

Figure4: Decay depth model, d(t) vs. t

2.4 The timber class and type of wood

The k_{wood} constant is considered by the wood type and timber durability class. The calculation will be carried out for hardwood. The type of timber will be chosen from Indonesian tropical wood. The wood species chosen represents four timber durability classes. The timber's trade names, botanical names, durability classes, and k_{wood} constants for related building structures' positions will be given in Table 3.

Table 3 k_{wood} constants

Type of Wood (Trade Name)	Botanical Name	Durability Class	k_{wood}		
			Above Ground	Hazard Coastal Zone	
				A to C	D to G
Belian (Ulin)	*Eusideroxylon zwageri*	1	0.50	1.1	1.3
Bangkirai	*Shorea laevis*	2	0.62	1.7	5.2
Keruing	*Dipterocarpus spp*	3	1.14	3.4	8.8
Meranti	*Shorea spp*	4	2.20	17.0	25.0

2.5 The hazard zone

The building location's vulnerability determines the climate parameter for the decay above-ground model to fungal decay. The $k_{climate}$ constant were divided into four primary hazard zone denoted by alphabet A to D. Zone A is the minor hazardous zone. The hazard zone for the corresponding $k_{climate}$ value is shown in table 4.

The hazard zone for the marine borer attack model depends on the k_{water} parameter found in equation (9). The formula was given by Knox [26]. T is the water temperature of the coastal hazard zone. The examples of the relation between the coastal hazard zone and the k_{water} parameter are given in table 5.

Table 4 The value of $k_{climate}$

Above-ground Decay Hazard Zone	kclimate
A	0.40
B	0.50
C	0.65
D	0.75

Table 5 The value of $_{kwater}$

Hazard coastal zone	Water temperature for the zone (°C)	k_{water}
A	15	0.7
B	17	0.9
C	19	1.2
D	21	1.6
E	23	2.0
F	28	3.0
G	28	3.8

2.6 The environment factor

The environment factor depends on two parameters: salinity parameter and wave parameter. The salinity parameter depends on the salinity of the seawater. It is classified into three classes having different salinity (Table 6). The wave parameter depends on whether the water is exposed to or sheltered from solid currents or surf (Table 7). The environmental factor is used for the marine borer attack model. It is expressed in equation (10).

$$k_{environment} = k_{\mathrm{salt}} k_{\mathrm{wave}} \tag{10}$$

Table 6 The value of k_{salt}

Salinity Class	Salinity (ppt)	k_{salt}	
		Zone A to D	Zone E to G
1	1-10	0.7	1.0
2	11-25	0.8	1.0
3	26-35	1.0	1.0

Table 7 The value of k_{wave}

Shelter	k_{wave}
Sheltered from strong current or surf (e.g., behind breakwaters, harbor, river, etc.)	1.0
Exposed to strong current and/or surf	0.6

2.7 The construction parameter

The construction parameter related to the decay above-ground model can be formulated as equation (11). The factors involved are the thickness parameter kt, width parameter k_w, painting parameter k_p, connection parameter k_n, and geometry parameter k_g. The value for each parameter involved is given in equation (12) to equation (18).

$$k_{construction} = k_t k_w k_p k_n k_g \tag{11}$$

$$k_t = \begin{cases} 1 & \text{for t} \geq 20 \text{ mm} \\ 0.5 & \text{for t} \leq 10 \text{ mm} \\ 0.05t & \text{otherwise} \end{cases} \tag{12}$$

$$k_w = \begin{cases} 1 & \text{for w} \leq \text{ 50 mm} \\ 1.5 & \text{for w } \geq \text{ 200 mm} \\ \dfrac{w}{300} + \dfrac{5}{6} & \text{otherwise} \end{cases} \tag{13}$$

$$k_p = \begin{cases} 3.5 & \text{for class 1} \\ 2.0 & \text{for class 2} \\ 1.5 & \text{for class 3} \\ 1.1 & \text{for class 4} \end{cases} \tag{14}$$

$$k_n = \begin{cases} 2.0 & \text{if there is connector} \\ 1.0 & \text{if there is no connector} \end{cases} \tag{15}$$

$$k_g = k_{g1} k_{g2} \tag{16}$$

$$k_{g1} = \begin{cases} 0.3 & \text{non-contact} \\ 0.6 & \text{flat contact} \\ 1 & \text{embedded contact} \end{cases} \tag{17}$$

$$k_{g2} = \begin{cases} 6 & \textit{Top flat} \\ 5 & \textit{Top sloping} \\ 2 & \textit{North} \\ 2 & \textit{West} \\ 1.5 & \textit{South} \\ 1.5 & \textit{East} \end{cases} \tag{18}$$

The construction parameter for the marine borer attack model is given by equation (19). The influencing factors are the protection parameter $k_{protect}$, the contact parameter $k_{contact}$, and the knot parameter k_{knot}. The protection parameter depends on the type of protective measure. The contact parameter depends on if there is a contact surface with other timber members. The knot parameter depends on if there are big knots with or without protective plates. The value of parameters affecting the construction parameters is in Table 8 until Table 10.

$$k_{construction} = k_{\text{protect}} k_{\text{contact}} k_{\text{knot}} \tag{19}$$

Table 8 The value of $k_{protect}$

Protection measure	$k_{protect}$
Floating collar/plastic wrap in the tidal zone	0.5
None	1.0

Table 9 The value of $k_{contact}$

Contact	$k_{contact}$
Contact with other timber members (e.g., Xbrace) in the tidal zone	2.0
None	1.0

Table 10 The value of k_{knot}

Knot presence	k_{knot}
Having knots without protective plate	2.0
Having knots with protective plate	1.0
None	1.0

III. RESULTS AND DISCUSSIONS

The calculations of decay depth d(t) were conducted to obtain information about the development of decay depth over time. The calculations were carried out using the decay above-ground model and the marine borer attack model. The results were plotted into two graphs, which were in Figure 5 and Figure 6.

The decay above-ground model takes k_{wood} constant from four Indonesian tropical wood species: Belian, Bangkirai, Keruing, and Meranti. These wood species belong to durability class 1, 2, 3, and 4, respectively. The k_{wood} constants are 0.5; 0.62; 1.14; and 2.20. The $k_{climate}$ constant is at 0.75 for Zone D, which is the most hazardous zone for the above-ground condition. The construction parameter $k_{construction}$ takes the values of several parameters, namely k_t, k_w, k_p, k_n, and k_g. The dimension of the structural component observed is assumed to be 150 mm x 150 mm. The kt is 1 for element thickness (t) more than or equal to 20 mm. The kw is 1.3. For painted wood, k_p is taken at 3.5. It is assumed that there is no connector, so the k_n is 2.0. The contact factor and position factors are taken at 0.3 and 2, respectively.

Figure 5 simulates the decay depth, d(t), versus the time (t) for 20 years. The decay rate (r) for Belian, Bangkirai, Keruing, and Meranti in 20 years is 1.05; 1.30; 2.39; and 4.62 mm/year. The decay lags (tlag) are 8.155; 6.792; 4.047; and 2.315 years. The graph consists of two parts. The first part is the quadratic curve following the formula $d=ct^2$. The second is the linear curve plotting the equation $(t-t_{lag})r$. The decay depth of Belian, Bangkirai, Keruing, and Meranti for 20 years are 12.438; 17.197; 38.191; and 81.707 mm.

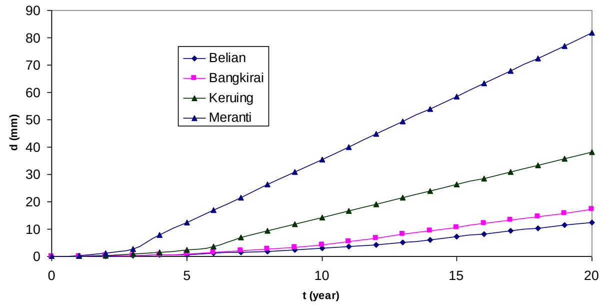

Figure5: Decay depth d(t) vs. time (t) for above-ground decay model for different durability classes of tropical wood species

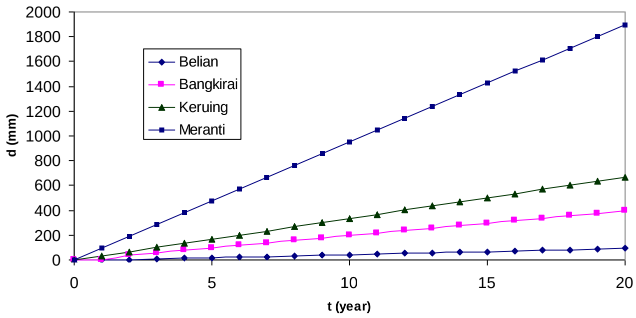

Figure6: Decay depth d(t) vs. time (t) for marine borer attack model for different durability classes of tropical wood species

The marine borer attack model takes k_{water} constant of 3.8 for water temperature 28°C and hazard coastal zone G. The k_{wood} is taken from four different Indonesian wood species: Belian, Bangkirai, Keruing, and Meranti. These wood species belong to durability class 1,2,3 and 4, respectively. The k_{wood} constants are 1.3; 5.2; 8.8; and 25.0 for hazard coastal zone G. The k_{salt} constant is 1.0 for salinity class 1 with salinity between 1 to 10 ppt for hazard coastal zone G. The k_{wave} constant is 1.0 for the condition of the building sheltered from strong current or surf. The $k_{protect}$ constant is 1.0 for no protection on the structures in the tidal zone. Meanwhile, the $k_{contact}$ constant is 1.0 for no contact with other timber members in the tidal zone. The k_{knot} constant is 1.0 for not having knots.

Figure 6 simulates the decay depth, d(t), versus the time (t) for 20 years. The decay rate (r) for Belian, Bangkirai, Keruing, and Meranti in 20 years is 4.94; 19.76; 33.44; and 95.00 mm/year. The decay lags (t_{lag}) are 1.506; 0.024; 0; and 0 years. The graph consists of two parts. The first part is a constant curve following the formula d(t) = 0. The second is the linear curve plotting the equation $(t-t_{lag})r$. The decay depth of Belian, Bangkirai, Keruing, and Meranti for 20 years are 91.360; 394.726; 668.800; and 1900.000 mm.

IV. CONCLUSIONS

The numerical simulations were conducted to illustrate the decay rate of timber for two conditions: decay above-ground and marine borer attack decay. These simulations considered the durability classes of Indonesian tropical timber species, Belian, Bangkirai, Keruing, and Meranti, for durability classes 1,2,3 and 4, respectively. The hazard zone for the two models, decay above-ground and marine borer attack decay, is classified as the most hazardous zone. The lowest decay rate (r) is 1.05 years for the decay above-ground model and 4.94 years for the marine borer attack model. Both values are from Belian species.

The highest decay lag (t_{lag}) is 8.155 years for the decay above-ground model and 1.506 years for the marine borer attack model. These values are from Belian species. The lowest decay depth d(t) for 20 years is

12.438 mm for the decay above-ground model and 91.360 mm for the marine borer attack model. These two decay depths are also from Belian species.

The calculations show that Belian is the most durable wood species. It deteriorated only 1.2 cm for above-ground structures and 9 cm for the condition under the marine borer attack for 20 years. The wood durability class 1 and 2 is sufficient for above-ground structures. Meanwhile, the structures under marine borer attack require wood durability class 1.

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