An overview of durability model for timber structure decay under Indonesian climate

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Abstract. The problem of wood durability is closely related to the degradation mechanism that can be distinguished into mechanical, physical, biological, and chemical degradation. The most affecting combination of degradation in modelling the durability of wood structures is a combination of mechanical and biological. The durability model of wood structure reviewed was based on a model developed by CSIRO (Commonwealth Scientific and Industrial Research Organization), Australia. Parameters taken into account in the model included physical wood, climate, coating paint, thickness, width, connection, and geometry parameters. The model predicted a decay rate for timber installed in-ground and timber above-ground. The results of this study were expected to provide a preliminary description of the behavior of the durability of wood structures based on several parameters adapted based on environmental conditions in Indonesia.

Keywords: durability model, timber structures, degradation mechanism

1. Introduction
Durability is the main problem when using timber as the primary construction material. This durability issue will rise as the degradation mechanisms occur. There are various degradation mechanisms in timber structures, namely mechanical, physical, chemical, and biological degradation. By far, the combination of biological and mechanical degradation is essential in modelling the service life of timber structures. In this regard, the mechanical load subjected to timber structures determines the mechanical degradation. Gerhards and Link [1] used a damage model to describe the strength development of timber under long-term loads. Another utilization of the damage model has been developed by Van de Kuilen [2] to describe the long-term behavior of timber joints. These two models purely represent the strength development aspect of time.

In reality, the timber structures are subjected to various load types. One of them is the biological attack. The attack can be from decay fungi and termites. Due to this attack, the cross section of timber structures suffers from partial loss. The decay model is generated to compute the effective cross-section. Then, the remaining part is assumed to have its original strength. Zabel and Morrell Zabel and Morrell have proposed the decay fungi mechanism [3]. The concept is based on the moisture content absorbed by the wall of the cell as such; it is easily accessible to the decay fungi, which then proceeds to decay the wood rapidly. As various sophisticated concepts adopted in timber engineering, durability aspect begins to attract attention internationally, such as from the Australian Building Codes Board [4] and International Standard Organization [5].
FWPA (Forest and Wood Products Australia) funded an extensive Australian project titled ‘Design for Durability’. As a part of the project, several manuals have been produced, including manual no. 3 [6] and manual no. 4 [7]. Further, the service life design code for timber structures is proposed by Nguyen et al. [8]. It is drafted based on the 20-year data obtained by exposing 4000 small fair timber specimens in 11 sites around Australia. It is also enhanced by not less than 1500 tiny pieces of data gained from investigating existing timber constructions.

The hydrothermal model of building physics that incorporates an empirical model for wood decay development has been studied by Viitanen et al. [9]. This model is a base for assessing the durability and service life of timber products and a preliminary European risk level map of timber decay. The hydrothermal analysis with the decay process is studied for durability assessment of building envelopes by Saito et al. [10]. It enables evaluation of the long-term performance of building envelopes concerning both durability and drying potential. Kutnik [11] discusses the trends and challenges on the European standards on durability and performance of wood. He describes changes in European standard during the past ten years considering current vital issues, such as material resistance, moisture risk, and adaptation of existing regulations. The simulations of hydrothermal-corrosion model, which predicted the corrosion of steel and galvanized steel fasteners inserted into untreated and protective wood and exposed outdoors, have been carried out by Zelinka [12]. The results are compared to a one-year field test.

The research on the durability of timber structures is still rare in Indonesia. Therefore, the internationally recognized model will be adopted. This paper will take on a service life prediction model developed in [8]. It is chosen by geographical proximity consideration, which may influence several parameters, among others: temperature, moisture, degradation mechanisms, wood species, etc. The simulations will incorporate various durability classes of Indonesian timber species.

2. Methods

The durability model for timber structures decay was based on the model developed by CSIRO (Commonwealth Scientific and Industrial Research Organization), Australia funded by FWPA (Forest and Wood Products Australia). The model was considered for two conditions: 1. Decay in ground contact, 2. Decay above ground. The durability model for these two conditions was taken from manual no. 3 [6] and manual no. 4 [7] of Design for Durability.

The durability model consisted of fundamental equations, namely decay depth, lag, and rate equations. Each equation incorporated several important parameters to predict total durability values. Below are the descriptions of the basic equations and their related parameters.

2.1. Decay model basic equations

The model used to express decay depth over time consisted of two parts. The first part stated the value of decay depth for the time before and right at the initiation of decay, and the second part indicated the amount of decay depth for the time after the start of deterioration. This model was distinguished by two parameters, a decay lag, $t_{lag}$ (years) and a decay rate, $r$ (mm/year). Those two parameters were aimed to indicate median statistical values. For any given amount of decay depth at the initiation time ($d_0$), decay lag ($t_{lag}$), and decay rate ($r$), the decay depth after $t$ years of installation, $d(t)$ (mm), could be written as follows.

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

(1)

where:

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

(2)
This model can be schematically illustrated in figure 1.

\[
c = \frac{d_0}{t_{d_0}^2}
\]

The experimental facts or expert judgment were required for the value of \(d_0\). A value of 5 mm for \(d_0\) could be taken as both of those requirements were not available. For this model, the decay lag and the decay rate were considered to be related by the following formulation.

\[
t_{\text{lag}} = \begin{cases} 
5.5r^{-0.95} & \text{for Decay in ground contact} \\
8.5r^{-0.85} & \text{for Decay above ground}
\end{cases}
\]

The only parameter needed to be predicted in \(t_{\text{lag}}\) calculation was \(r\). The decay rate \(r\) in equation (4) was calculated by multiplying several affecting parameters, such as material, construction, and environmental factors. The value of \(r\) could be differentiated into the following two conditions, namely, decay in ground contact and decay above ground. The equations read as follow.

\[
r(k) = \begin{cases} 
r_{\text{untreated}} = k_{\text{wood}}k_{\text{climate}} & \text{for Decay in ground contact} \\
r = k_{\text{wood}}k_{\text{climate}}k_{\text{construction}} & \text{for Decay above ground}
\end{cases}
\]

where \(k_{\text{wood}}\), \(k_{\text{climate}}\), \(k_{\text{construction}}\) were parameters concerning the timber species, climate condition in the observed place, and the construction types which were used. It is noticeable that all these parameters would automatically influence the time lag \(t_{\text{lag}}\) as designated by equation (4).

2.2. The wood parameter

The wood parameter \(k_{\text{wood}}\) was determined by the timber species used. Further, the wood within a timber log was differentiated into core wood, outer heartwood, and sapwood. Figure 2 illustrates this differentiation. It was assumed that the radius of core wood and the thickness of outer heartwood were equal. For convenience and practicality, four Indonesian timber species, which represented four durability classes, were considered in this study. The timber’s trade names, botanical names, and durability classes are given in table 1.
Table 1. Natural durability classification.

| Trade Name  | Botanical Name            | Durability Class |
|-------------|---------------------------|------------------|
| Belian (Ulin)| *Eusideroxylon zwageri*  | 1                |
| Bangkirai   | *Shorea laevis*           | 2                |
| Keruing     | *Dipterocarpus spp*       | 3                |
| Meranti     | *Shorea spp*              | 4                |

The wood considered in the model was heartwood. Various wood parameters for heartwood in condition related to decay in ground contact could be seen in equation (6), whereas decay above ground and equation was in equation (7). The wood parameters were given according to their class of durability.

\[
k_{\text{wood, heart}} = \begin{cases} 
0.23 & \text{for class 1} \\
0.48 & \text{for class 2} \\
0.76 & \text{for class 3} \\
1.36 & \text{for class 4} 
\end{cases}
\text{for decay in ground contact} \tag{6}
\]

\[
k_{\text{wood, heart}} = \begin{cases} 
0.50 & \text{for class 1} \\
0.62 & \text{for class 2} \\
1.14 & \text{for class 3} \\
2.20 & \text{for class 4} 
\end{cases}
\text{for decay above ground} \tag{7}
\]

2.3. The climate parameter

The climatic disparity in a region influences the relative vulnerability of a location to fungal decay. The climate parameter \(k_{\text{climate}}\) would be differentiated into four major hazard zones denoted by alphabet A till D. Zone D was the most hazardous zone. The \(k_{\text{climate}}\) value of each adjacent area for a condition related to decay in ground contact and decay above ground is given in table 2.

Table 2. The climate parameter values of respective hazard zones.

| Hazard Zone | \(k_{\text{climate}}\) | decay in ground | decay above ground |
|-------------|-------------------------|-----------------|--------------------|
| A           | 0.5                     | 0.40            |
| B           | 1.5                     | 0.50            |
| C           | 2.5                     | 0.65            |
| D           | 3.0                     | 0.75            |

2.4. The construction parameter

There are several factors involving in the calculation of construction parameters. These factors, among others, are the thickness parameter \(k_t\), width parameter \(k_w\), painting parameter \(k_p\), connection parameter \(k_n\), and geometry parameter \(k_g\). The construction parameter is given as equation (8).

\[
k_{\text{construction}} = k_t k_w k_p k_n k_g \tag{8}
\]

The thickness parameter \(k_t\) was calculated as the consideration of the occurring moisture drying effect in timber. This effect of drying depends on the member thickness. The thicker the member, the longer the moisture will remain in the member. The thickness parameter \(k_t\) takes into account the effects of drying in the transverse direction to timber grain. It also takes into account the surface element contact.
or non-contact with other elements. A non-contact element will tend to dry if it is sufficiently thin rapidly. Equation (9) gives the values of \( k_t \) for non-contact surface of an element of thickness \( t \). For surfaces in contact with other elements, \( k_t = 1.0 \).

\[
\begin{cases}
  1 & \text{for } t \geq 20 \text{ mm} \\
  0.5 & \text{for } t \leq 10 \text{ mm} \\
  0.05t & \text{otherwise}
\end{cases}
\]  

The width parameter \( k_w \) was determined as the consideration of the occurring drying restraint on the decaying surface. This effect of drying depends on the specimen width in the cross-grain direction. The wider the width, the more restraints on the wood surface during drying are. More restraints mean larger and deeper checks on the surface and therefore tend to gain severe decay. The width parameter also takes into account the surface element contact or non-contact with other elements. Equation (10) gives the value of \( k_w \) for the non-contact surface of an element of width \( t \). For contact surfaces, \( k_w = 1.0 \).

\[
\begin{cases}
  1 & \text{for } w \leq 50 \text{ mm} \\
  1.5 & \text{for } w \geq 200 \text{ mm} \\
  \frac{w}{300} + \frac{5}{6} & \text{otherwise}
\end{cases}
\]  

The painting parameter \( k_p \) was calculated as the consideration of the occurring water inhibition over a decay zone. This effect of water inhibition results in more water trapped in the timber and consequently encourages decay. Equation (11) gives the value of \( k_p \) for painted wood. The painting parameters are given according to their class of durability. For unpainted wood \( k_p = 1.0 \).

\[
\begin{cases}
  3.5 & \text{for class 1} \\
  2.0 & \text{for class 2} \\
  1.5 & \text{for class 3} \\
  1.1 & \text{for class 4}
\end{cases}
\]  

The connection parameter \( k_n \) was determined as the consideration of the connector presence on the decaying surface. The connector often made with a gap to its hole to allow expansion. This gap would act as a path of moisture entry to boost the decay progress. Equation (12) gives the value of \( k_n \) for the presence or the absence of the connector.

\[
\begin{cases}
  2.0 & \text{if there is connector} \\
  1.0 & \text{if there is no connector}
\end{cases}
\]  

The geometry parameter \( k_g \) was a composite function of several other parameters. It included the factors, such as the embedment of the decaying surface, the material in contact with the decaying surface, the directional orientation of the decaying surface, grain orientation and the gap size of butt joints. Equation (13) expresses the geometry parameter.

\[
k_g = k_{g1}k_{g2}
\]  

where: \( k_{g1} \) is contact factor, and \( k_{g2} \) is position factor.

The contact factor \( k_{g1} \) was determined depending on whether the assessed surface was in contact with other structural members or not. Equation (14) expresses the value of contact factors. The description of contact factors can be illustrated in figure 3.
This study considered that the member had a non-contact surface and a vertical orientation. The position factor \(k_{g2}\) for vertical member depended on the direction of the decay-assessed surface. Equation (15) gave the values of \(k_{g2}\) for six different positions. An illustration of the position factor for the non-contact surface in vertical member can be seen in figure 4.

### 3. Discussion

Several numerical simulations were conducted to illustrate the development of decay depth in time. The simulations were carried out for four scenarios, which were plotted into four graphs (Figure 5 to Figure 8). The first graph (figure 5) showed the relation between decay depth \((d)\) and time \((t)\) for timber installed in-ground. It incorporated various wood parameters for several durability class, namely class 1 till class 4. The durability class refered to each wood species: Belian, Bangkirai, Keruing, and Meranti, respectively. The graph was also simulated for the most hazardous zone with the highest value of \(k_{\text{climate}}\). From the simulation, it was obtained that the lowest rate of decay \((r)\) = 0.69 mm/year for class 1 durability and the highest is 4.08 mm/year for class 4 durability. The decay lag \((t_{\text{lag}})\) = 7.824 years for Belian and 1.446 years for Meranti. The first part of the graph had a quadratic curve following the formula \(d = ct^2\). Meanwhile, the second part of the graph had a linear curve based on the formula \((t-t_{\text{lag}})r\). The chart simulated the time \((t)\) for 30 years resulting the highest value of \(d\) equal to 116.499 mm for Meranti and the lowest value equal to 15.301 mm for Belian. It was noticeable that the decay rate would reach the center of any structural element made from Meranti wood that has a diameter of around 20 cm in 30 years.

Figure 6 demonstrated the relationship between decay depth \((d)\) and time \((t)\) for timber above ground. It included a various wood parameter for several durability class, namely class 1 till class 4. The durability class related to each wood species: Belian, Bangkirai, Keruing, and Meranti, respectively. The graph was also modelled for the most hazardous zone with the highest value of \(k_{\text{climate}}\). From the

\[
k_{g1} = \begin{cases} 
0.3 & \text{non-contact} \\
0.6 & \text{flat contact} \\
1 & \text{embedded contact}
\end{cases}
\]  
\(14\)
plotting, it was obtained that the lowest rate of decay \( r = 1.01 \text{ mm/year} \) for class 1 durability and the highest was 4.46 mm/year for class 4 durability. The decay lag \( t_{lag} = 8.411 \text{ years} \) for Belian and 2.387 years for Meranti. The first part of the graph had a quadratic curve following the formula \( d = c t^2 \). Meanwhile, the second part of the graph had a linear curve based on the formula \( (t-t_{lag}) r \). The graph simulated the time \( t \) for 30 years resulting in the highest value of \( d \) equal to 123.015 mm for Meranti and the lowest value equal to 21.859 mm for Belian. It was noticeable that the decay rate would reach the center of any structural element made from Meranti wood that has a diameter of around 20 cm in 30 years.

The third graph (figure 7) showed the relation between decay depth \( d \) and time \( t \) for timber installed in-ground. It incorporated various wood parameters for several zones, namely Zone A till Zone D. The durability class was referred as the most durable wood species, Belian, which was categorized as class 1 durability. The graph was therefore simulated for the most durable class with the highest value of \( k_{\text{wood}} \). From the simulation, it was obtained that the lowest rate of decay \( r = 0.12 \text{ mm/year} \) for Zone A and the highest was 0.69 mm/year for Zone D. The decay lag \( t_{lag} = 42.942 \text{ years} \) for Hazard Zone A and 7.824 years for Hazard Zone D. The first part of the graph had a quadratic curve following the formula \( d = c t^2 \). Meanwhile, the second part of the graph had a linear curve based on the formula \( (t-t_{lag}) r \). The graph simulated the time \( t \) for 30 years resulting the highest value of \( d \) equal to 15.301 mm for Decay Hazard Zone D and the lowest value equal to 0.595 mm for Decay Hazard Zone A. It was noticeable that the decay rate would reach 1/7 way to achieve the center of any structural element made from Belian wood that has a diameter of around 20 cm in 30 years.

Figure 8 demonstrated the relationship between decay depth \( d \) and time \( t \) for timber above ground. It included various wood parameters for several zones, namely Zone A till Zone D. The durability class related to the most durable wood species, Belian, which is categorized as class 1 durability. The graph was therefore simulated for the most durable class with the highest value of \( k_{\text{wood}} \). From the plotting, it was obtained that the lowest rate of decay \( r = 0.54 \text{ mm/year} \) for Zone A and the highest was 1.01 mm/year for Zone D. The decay lag \( t_{lag} = 14.351 \text{ years} \) for Hazard Zone A and 8.411 years for Hazard Zone D. The first part of the graph had a quadratic curve following the formula \( d = c t^2 \). Meanwhile, the second part of the graph had a linear curve based on the formula \( (t-t_{lag}) r \). The graph simulated the time \( t \) for 30 years resulting the highest value of \( d \) equal to 21.859 mm for Decay Hazard Zone D and the lowest value equal to 8.450 mm for Decay Hazard Zone A. It was noticeable that the decay rate would reach 1/5 way to achieve the center of any structural element made from Belian wood that has a diameter of around 20 cm in 30 years.

![Figure 5. Decay depth (d) vs. time (t) for timber installed in-ground with different durability class in the most hazardous zone.](image)

![Figure 6. Decay depth (d) vs. time (t) for timber above ground with different durability class in the most hazardous zone.](image)
4. Conclusion
Some numerical simulations were carried out to demonstrate the decay rate of timber installed in-ground and timber above ground. These simulations incorporated various durability classes of Indonesian timber species, such as Belian, Bangkirai, Keruing, and Meranti, which were taken as samples. A variety of decay hazard zones were also taken into account in the simulations. The decay rate increased from 0.69 mm/year to 4.08 mm/year as the timber durability class decreased. The tlag parameter increased from 1.446 years to 7.824 years as the timber durability class increased. For t equal to 30 years, the decay depth decreased from 116.499 mm to 15.301 mm as the timber durability class increased. These results were valid for both various durability classes and different hazard decay zones. There were still chances to incorporate the Indonesian climate-related variables and make some adjustment for the possible condition in Indonesia. The structural degradations and typical degradation mechanisms, which were suitable for Indonesian environment, were also considerable.

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