In-Ground Decay Modeling of Historic Timber Foundations of Sultanate Mosque in Sambas, Indonesia

Uray Alif Wibawa, Herry Prabowo, Ari Fitriyanto

1 Department of Architecture, Politeknik Negeri Pontianak, Jl. Jenderal Ahmad Yani, Kota Pontianak 78124, Indonesia
2 Laboratory for Construction, Innovative Structures, and Building Physics, Politeknik Negeri Pontianak, Jl. Jenderal Ahmad Yani, Kota Pontianak 78124, Indonesia

*prabowoherry@yahoo.com

Abstract. Timber is a construction material easily degraded when exposed to the weather without any particular treatment. The deterioration risk of timber structures increases over time. The historic buildings suffer the most severe deterioration after exposed to hundreds of years. The demand for preserving the heritage building as a legacy from the past is increasing nowadays. Thus, it is essential to know the building’s residual service life to determine the proper measures at the right time. It is required to decide when the responsible party should do a replacement or repair action on the main building elements. The simulation of decay depth on the Sambas Sultanate Palace showed that the timber foundations had not faced severe deterioration problems. The occurring decay depth is 25.940 mm (in 135 years), and the initiation of decay occurred in 22 years after the mosque was built. It has not reached the center of the foundation cross-section yet. Thus, it is concluded that the building is in excellent stability and safety condition.

1. Introduction

Indonesia is the biggest archipelagic country comprised of thousands of islands and hundreds of tribes. It has a rich cultural heritage. All tribes have their own unique timber houses passed from generation to generation. Besides houses, typical historic buildings are Sultanate Palaces and Old Mosques. It is vital to preserving heritage buildings as a legacy from the past. Sambas Sultanate Mosque is one of the historic timber buildings currently still in function. It is located in the city of Sambas, West Kalimantan Province, Indonesia. The building was first built around 1708 until 1732 by Sultan Umar Aqamaddin I. Later, the mosque was renovated and extended in by Sultan Muhammad Sjahfuddin II on October 10th, 1885.

Timber is easily degraded when exposed to the weather without any particular treatment. Its durability as a construction material is related to degradation mechanisms that occurred. Mechanical, physical, chemical, and biological degradations are the possible mechanisms that threaten the building’s service life. It is essential to gain insight into the building’s residual service life because it is beneficial to determine the right time to repair or replace the building’s structural elements.

Several researchers have studied the issue of timber structures' service life. Van de Kuilen [1] studied the combination of durability models with strength models, Viitanen et al. [2] proposed a hygrothermal model of building physics, and Nofal & Kumaran [3] offered a structural and hygrothermal model with damage functions. Zelinka, Derome, & Glass [4] suggested corrosion of metal fasteners embedded in solid wood model and Saito, Fukuda, & Sawachi [5] recommend integral hygrothermal analysis with the decaying process model. Wang, Leicester, & Nguyen [6] and MacKenzie, Wang, Leicester, Foliente, & Nguyen [7] showed an extensive and long-term field and
laboratory research and experience in Australia. Bornemann, Brischke, & Alfredsen [8] presented a
dose-response performance model, and Kutnik, Suttie, & Brischke [9] showed European
Standardization on wood durability and preservation. Meyer-Veltrup, Brischke, Niklewski, & Hansson
[10] suggested a factorization approach based on the dose-response model and Prabowo & Hilmy [11]
incorporated Indonesian tropical climate parameters into the Australian decay model.
There is a small number of timber structures durability research in Indonesia. Due to this limitation,
it is decided to utilize the durability model studied by MacKenzie, Wang, Leicester, Foliente, &
Nguyen [7]. The territorial proximity between Indonesia and Australia is one of the considerations of
adopting this model. Timber durability class and species of local timber will be incorporated regarding
the Indonesian tropical climate issues. Temperature, relative humidity, and degradation mechanism are
parameters concerned.

2. Methodology
The durability of timber structures will be modeled by employing a model established by the
Australian CSIRO (Commonwealth Scientific and Industrial Research Organisation) [7]. The model
takes into account the decay in-ground condition to model the timber foundation of the building. The
macro-climate data of the city of Sambas were taken from the local weather station. Meanwhile, upper
parts of timber foundations were measured to obtain their hygro-thermal data. The dimension of the
building and the type of foundations were described.

2.1. Decay depth formulation
The formula of decay depth expressed in equation (1) consists of two main terms. The first term deals
with the decay depth value for the time before and right at the initiation of decay. The second one is
related to the amount of decay depth for the time after the start of deterioration.

The parameters involved in the equation are a decay lag (tlag) expressed in years and a decay rate
(r) expressed in mm/year. The decay depth formulation and its related parameters can be seen in
equation (1) until equation (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. The decay model is
illustrated in figure 1.

\[
d(t) = \begin{cases} 
  ct^2 & \text{if } t \leq t_{d0} \\
  (t - t_{lag})r & \text{if } t > t_{d0} 
\end{cases} 
\]  

(1)

\[
t_{d0} = t_{lag} + \frac{d_0}{r} 
\]  

(2)

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

(3)

\[
t_{lag} = 5.5r^{-0.95} 
\]  

(4)

\[
r = k_{wood}k_{climate} 
\]  

(5)

**Figure 1.** Decay depth model, d(t) vs. t.
2.2. Local weather data
Relative humidity (RH) and temperature (T) are served as the local weather data. They are based on climate data recorded by Paloh Climatological Station, Sambas Regency, Indonesia. The data obtained from July 2004 until July 2019 [12]. The weather data, RH and T, are then graphed in figure 2 and figure 3.

![Figure 2. Relative humidity in July (2004-2019).](image1)

![Figure 3. Temperature in July (2004-2019).](image2)

2.3. The building foundation
The foundations of the building are made of timber. The timber species is locally called Belian (ulin) (Botanical name: *Eusideroxylon zwageri*). This species is reputable for its durability against the weather. This kind of timber foundation system is locally known as Tiang Tongkat Foundation.

This old traditional foundation is made by using a square timber pile. The cross-section of the pile is ranging from 10 cm x 10 to 20 cm x 20 cm. The length of the pile varied from 100 cm to 380 cm. To be easily driven into the ground, the bottom end of the pile is sharpened. Then, one or two pairs of horizontal timber beams are attached to the pile at the distance 50 cm to 100 cm from the top end of the pile. It can be seen in figure 4.

The building plan dimension is 22 m x 22 m. Its main structural elements are made of Belian. The main room, porch, and tower are the main parts of the building. The building plan and the front view are in figure 5.

![Figure 4. Tiang tongkat foundation.](image3)
The hygro-thermal measurements
The relative humidity and temperature measurements of the timber foundations are carried out using the humidity–temperature digital instrument (YK-2001TM type, Lutron, Taiwan), Figure 6. It is done based on ASTM F2420-05 [13]. The measuring time is in the morning (8 am until 10 am), noon (from 11.30 am to 1.30 pm), and in the afternoon (from 4 pm to 6 pm). It is carried out in July 2020. The results are plotted in figure 7 until figure 8.

3. Results and discussions
The calculation of the timber foundation’s decay depth has been done to predict the service life of the building's foundation. It is assumed that the initiation of decay depth is 5 mm deep under the foundation elements’ surface. The parameters inserted into the decay formulation are $k_{\text{wood}} = 0.46$ (ulin species in-ground), $k_{\text{climate}} = 0.5$ (the least hazardous zone).
Figure 9 depicted the increase of decay depth, \( d(t) \) over time \( t \) during the building's whole service life (135 years). The resulted curve show a decay rate \( (r) = 0.23 \) mm/year. The decay lag \( (\text{tlag}) \) read 22.219 years, which means that the initiation of decay occurred around 22 years after it was built. The first portion of the graph simulates a parabolic curve based on the equation \( dt = ct^2 \). On the other hand, the second portion of the graph shows a linear curve following the equation \( (t-\text{tlag})r \).

Figure 10 simulates the decay depth, \( d(t) \) versus the time \( t \) for 100 years. It is plotted to show the initiation of tlag more comprehensively. It can be noticed that after 100 years that the decay depth reach 17.890 mm, and after 135 years, it reach 25.940 mm.

![Figure 9. d(t) vs. t during service life.](image1)

![Figure 10. d(t) vs. t at tlag](image2)

### 4. Conclusions

The prediction of historic building service life is essential in determining any measurement relating to the repair and replacement of the main building elements. A straightforward and practical formulation of the predicted service life is mainly needed. The numerical prediction of decay depth for Sambas Sultanate Mosque showed that the timber foundations had not faced severe deterioration problems. Due to the decay depth that has not reached the center of the timber foundations' cross-section yet. The occurring decay depth is 25.940 mm (in 135 years), and the initiation of decay occurred in 22 years after the mosque was built. There is also an effort to strengthen the foundation of the building by adding concrete slabs at the foundation. It is the part in contact with the ground. It certainly will increase the bearing capacity of the foundation and the stability and safety as well.

### Acknowledgments

Authors wish to acknowledge financial support from DIPA Polnep fiscal year 2020. The assistance or encouragements from colleagues and extraordinary works by technical staff are also gratefully acknowledged.

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