Case Studies in Construction Materials 6 (2017) 91–102

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Case study

Estimation the remaining service-lifetime of wooden structure of geothermal cooling tower

Effendi Tri Bahtiar[a,*], Naresworo Nugroho[a], Mohamad Miftah Rahman[a], Arinana[a], Rita Kartika Sari[a], Wilis Wirawan[b], Dede Hermawan[a]

[a] Faculty of Forestry, Bogor Agricultural University, Bogor 16001, Indonesia
[b] Star Energy Geothermal (Wayang Windu) Ltd, Pengalengan, West Java, Indonesia

ARTICLE INFO

Article history:
Received 29 February 2016
Received in revised form 7 December 2016
Accepted 5 January 2017
Available online 12 January 2017

Keywords:
Creep
Long-term strength and life-time
Wooden cooling tower
Geothermal power plant

ABSTRACT

Similar with other construction materials, wood strength is decreasing when applied by long term loading. Wooden cooling tower structure at Star Energy Geothermal (Wayang Windu) Ltd was built in 1998 and it should be evaluated to avoid sudden structural failure. Evaluation conducted through several steps: wood species identification, the physical and mechanical properties testing, and estimation for remaining service-lifetime by generating mathematical models derived from creep test and reduction of cross sectional area of the wood. Identification result that the wood are redwood (*Sequoia sempervirens*) and Douglas fir (*Pseudotsuga menziesii*). The wood density value has degraded from the surface until 0.25 cm depth. Strength characteristics of the wood have considerably decreased, but the allowable stress for bending, tension parallel to grain, and shear were still higher than NDS2005 requirements. The allowable stress for compression parallel to grain was slightly lower than NDS, while compression perpendicular to grain was much lower. Average modulus of elasticity reduces become lower than the value stated by the code, but the minimum value of modulus of elasticity (E_{min}) of redwood was still higher than the code value, while E_{min} of Douglas fir is slightly lower. Then, in accordance with those findings, the construction would not failure yet but the deformation and vibration will occur in higher rate than design planning. This research develops mathematical models for estimating the remaining service-lifetime of the wooden cooling tower structure in geothermal power plant based on the wood performance in resisting long term loading and its deterioration rate. The deterioration rate of wood member of cooling tower structure at Star Energy Geothermal (Wayang Windu) Ltd is 0.0147 cm depth per year, so equation for the residual service life estimation is $\frac{\sigma_{later}}{\sigma_{today}} = \frac{bh^2}{(b-0.0147T)(h-0.0147T)^2}$, and σ_{later} must be lower than allowable stress.

Abbreviations: AF&PA, American forest and paper association; ASTM, American society for testing and materials; Ltd, limited; MOE, modulus of elasticity; MOR, modulus of rupture; NDS, national design specification.

* Corresponding author.
E-mail address: bahtiar_et@yahoo.com (E.T. Bahtiar).

http://dx.doi.org/10.1016/j.cscm.2017.01.001
2214-5095/

Nomenclature

W	Weight
V	Volume
T	Time
y	Deflection
e	Natural number (2.718281828)
P	Load
K	Ratio between load and failure load
SR	Modulus of rupture
I	Moment of inertia
b	Width of beam section
h	Height of beam section
M	Bending moment
c	Distance from centroid to the outer surface of beam
f	Deterioration depth
Ft//	Tensile strength parallel to grain
Fs	Shear strength
$Fc_{\perp}$	Compressive strength perpendicular to grain
Fc//	Compressive strength parallel to grain
E	Modulus of elasticity

Greek Symbols

ρ	Weight density
σ	Stress

1. Introduction

Wood is most suitable material for huge cooling tower structure (more than 1000–1500 tons) because it has low thermal conductivity value (0.14 $Wm^{-1}K^{-1}$) [1], and high strength to density ratio. As construction material, wood is a good choice. Wood is composed by three main components elements; those are cellulose, hemicellulose, and lignin. The wood quality is very crucial and represented by the value of its density and stiffness that reflect to its strength elements[2]. Cooling tower designers generally prefer to use redwood (*Sequoia sempervirens*) or Douglas fir (*Pseudotsuga menzieesi*) than other wood species. Since long-term usage, wood quality deteriorate over time. Chemical, biological, and physical attacks [3], or their combinations cause wood deterioration. The cooling tower component degradation should be evaluated and considered in order to avoid the sudden failure of the structure. The material properties deterioration can be approximated by mechanical testing and physical-chemical properties degradation rate measurement. The approach was carried by measuring the allowable stress and then compared it with the National Design Specification (NDS) 2005 (AF&PA 2005) [4]. Creep testing was also conducted to elaborate long term load effect; followed by the deterioration rate to improve the accuracy and precision of estimation. The deterioration may reduce the dimension of cross section and lowered the second moment of area (*I*) of the member.

This study aims to measure the reduction of the allowable stress of wood component of geothermal cooling tower and estimate its remaining service-lifetime. The wood samples were taken from structural component of cooling tower at Star Energy Geothermal (Wayang Windu) Ltd that has been operated for 17 years.

2. Methodology

The research conducted at Forest Products Department Faculty of Forestry Bogor Agricultural University. The samples were cut from structural component of geothermal cooling tower that has not been replaced since the first operation of cooling tower (17 years ago).

2.1. Preparation materials and making test sample

First, the samples were aerated by fan until they reached air-dry moisture content. There were four samples with code M 12–13 (for wood M) and L 16–17 TD (L) with dimensions 9 cm × 9 cm × 180 cm and code J 14–15 (J) and P 14–15 (P) with dimensions 9 cm × 9 cm × 285 cm. Each sample was cut into two parts. Each section was further subdivided into samples for chemical, mechanical, and creep testing according to Fig. 1. Section A and D were prepared for tensile parallel to grain, bending, and creep samples, section B for density deterioration and shear parallel to grain samples, and section C for

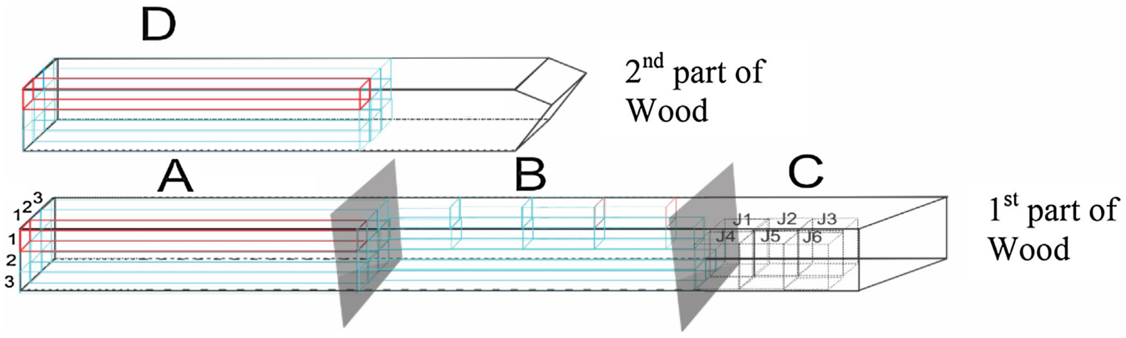

Fig. 1. Illustration sketch cutting wood samples.

compressive parallel to grain and compressive perpendicular to grain samples. Wood identification samples were cut from the tip of section B. Sample dimension for mechanical properties testing was accordance to ASTM D 143 [5]. The dimensions for creep, bending and tensile testing were 2.5 cm × 2.5 cm × 42 cm. Tensile samples were formed according to ASTM D143 [5]. Sample for compression parallel and perpendicular to grain were 2.5 cm × 2.5 cm × 10 cm. Shear testing required samples in 5 cm × 5 cm × 6 cm dimension and formed following ASTM D 143 [5].

2.2. Wood species identification

The wood identification began with microtome slides making. Before slicing, 1 cm × 1 cm ×1 cm cube wood were boiled in 80 °C water for a week. The slices were made in each transverse, radial, and tangential sections. Each slice was stained with safranin for 24 h, and then gradually washed in water and alcohol solution (10%, 20%, 30%, 50%, 60%, 80%, 90%, and absolute concentration). After washing in alcohol, the slice dipped into xylol until it becomes translucent. Each slice was glued to microscope glass slide. The glue was Canadian balsam that was also useful for preserving the slide samples.

The picture of each section was taken by microscope photograph with 10× and 40× magnification for microscopic identification. Macroscopic identification was also conducted by observing the wood block under loupe with 3× magnification as described by Schulze and Borner [6]. The anatomic characteristics of wood (resin canal, early wood – late wood transition, odor and color of heartwood, etc.) were noted and used for key identification. Softwood key chart which developed by Hoadley [7] was chosen as basic guide to identify the wood species (Fig. 2).

2.3. Measuring the depth of wood deterioration

The depth of wood deterioration was estimated by measuring the degradation of wood density at certain depths. The samples were weighed and the volume was measured, then it was shaved 10 times. Each shaves was 0.5 mm depth. After each shaved, the wood was re-weight and its volume was re-measured, in order to get the density at each specific depth. The density of each depth was calculated by formulae which reported by Bahtiar et al. [8,9]:

$$\rho_i = \frac{W_i - W_{i+1}}{V_i - V_{i+1}}$$

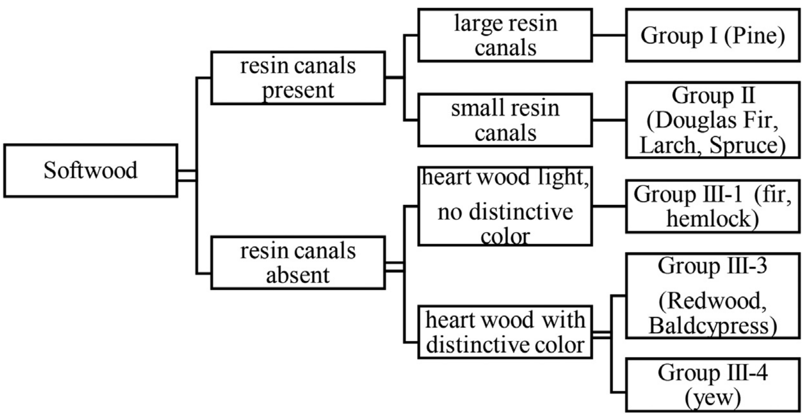

Fig. 2. Softwood identification keys [7].

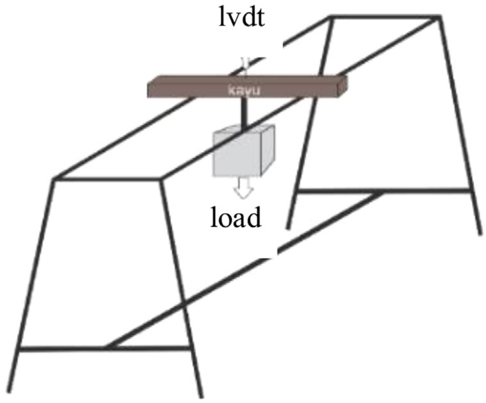

Fig. 3. Creep testing illustration.

Where: ρ_i = density at i-th depth, W = weight of the wood, V = volume of the wood, i = before i-th times shaved, $i + 1$ = after i-th times shaved.

The deterioration depth is appointed when the density at certain depth was coincided with the control. The control is the center of each wood sample because the outer layer protects it so that the inner layer may not deteriorate. The deterioration depth divided by the period of usage is deterioration rate.

2.4. Mechanical properties testing

The mechanical properties testing (compression parallel to grain, compression perpendicular to grain, tensile parallel to grain, shear parallel to grain, and static bending) were conducted according to ASTM D143 procedure [5]. The test was conducted in air-dry condition. The test results were processed become strength characteristics, that is the 5% lower percentile limit, and then the strength characteristics were reduced by adjustment factor in accordance with ASTM D2915 [10] to obtain its allowable stress.

2.5. Creep testing

Creep testing aims to approximate the strength of the wood due to a static long-term loading. Each sample was tested by center point bending as shown in Fig. 3 for approximately 10 days. Specimens for creep test and static bending test have similar dimensions and span length, that is 2.5 × 2.5 × 42 cm with 28 cm span. Then each creep test sample was loaded by a constant load. There were five load levels applied to the samples, namely 15.79 kgf; 20.05 kgf; 29.68 kgf; 40.03 kgf; 50.53 kgf; and 60.79 kgf. Static bending test using Universal Testing Machine (UTM) was done before creep testing to get the average value of deflection when failure (y_f), initial deflection (y_{inst}), maximum load ($P_{\max}$), and Modulus of Rupture (MOR, S_R). All of Linear Variable Displacement Transducers (LVDT) were tared (zeroed) when the targeted loads were reached, thus the LVDT did not measure the initial deflection (y_{inst}) but pure creep deflection only ($y_{cr} = y(t) - y_{inst}$). The deflections were recorded every 20 min then plotted on Cartesian diagram. Since the total deflection ($y(t)$) will be used for determining the residual service life-time, the plot of raw creep deflection (y_{cr}) was preferred and more useful than creep value ($y(t)/y_{inst}$) or relative creep value ($(y(t)-y_{inst})/y_{inst}$) plot. Simple linear regression with logarithm transformation was conducted to fit the deflection curve during creep testing.

The creep testing was conducted in normal room condition without any environmental treatments or controls. The temperature and relative humidity (RH) during creep testing were recorded every 20 min, and then sinusoidal equation [11,12] was conducted to fit the daily fluctuation of temperature and RH in the laboratory.

2.6. Calculation to estimate remaining service-Lifetime of wood

Remaining service life-time estimation was performed on four wood samples that come from the structural component of geothermal cooling tower. The cooling tower has operated for 17 years, and the samples were taken from the original structural component that were never replaced since the beginning. Estimation began by calculating the MOE, MOR, failure deflection, and initial deflection of mechanical bending test and deflection that occurs when the creep testing. Then these values would processed mathematically to obtain a model for calculating the remaining service-lifetime and consider the rate of deterioration. After measuring the static bending strength, creep testing was performed. The calculations for estimating the residual service lifetime was conducted based on method developed by Bahtiar et al. [8,9] to obtain a mathematical model for estimating the remaining service-lifetime of wood. Bahtiar et al. [8,9] method used raw creep deflection as a basic variable for estimating the residual service-lifetime, which was slightly different with FPL and Forintek model. FPL model used ratio of applied stress to the short-term strength ($\sigma_{(t)}$) as the basic variable, while Forintek model included damage threshold stress ratio (σ_0) below no damage is assumed to accumulate [13].

The creep deflections were recorded at every 20 min for 10 days then plotted on a Cartesian diagram as ordinate (y) and time of loading as absis (x), then they were fitted by linear regression with logarithm transformation with the model (Eq. (1)):

$$y = a\ln T + c \quad (1)$$

Where: y = deflection (cm), T = loading time (hours)

Based on static bending test results, the values of failure deflection (y_f) and initial deflection (y_{inst}) were measured. Failure deflection (y_f) is deflection when the samples were failure in static bending testing, while initial deflection (y_{inst}) is the deflection when the load value at static bending test is at the same value with fixed load of creep testing. The difference of failure deflection and initial deflection of each sample ($Y_i = y_f - y_{inst}$) is assumed as targeted deflection of creep loading to failure. Creep loading would reach the targeted deflection in T_i time long. T_i is calculated by Eq. (2).

$$T_i = \sqrt[a]{e^{(Y_i - c)}} \quad (2)$$

The value of the time length required to failure for each creep test sample (T_i) was plotted to the Cartesian diagram with the corresponding fixed load magnitude in creep testing (P). These points were approached by simple linear regression with logarithm or power transformation that can be assumed as magnitude of failure load at duration of loading specified by Eq. (3) for the logarithm and Eq. (4) for power transformation.

$$P = s\ln T + m \quad (3)$$

$$P = sT^m \quad (4)$$

Where: P = Failure load at creep testing (kg), T = Load Duration (years)

The ratio between the failure load value on a long-term loading (P) and the average value of failure load from static bending test ($P_{\max}$), is noted as K which can be defined with Eq. (5).

$$K = \frac{P}{P_{\max}} \quad (5)$$

The K value is equivalent to the ratio of maximum stress on long-term (σ) and Modulus of Rupture (S_R) of static bending test, so that Eq. (5) can be converted into Eq. (6).

$$K = \frac{P}{P_{\max}} = \frac{\sigma}{S_R} \quad \text{or} \quad \mathrm{P} = \frac{\sigma P_{\max}}{S_R} \quad (6)$$

Load duration to failure estimation can be derived from Eq. (6) by inserting static bending MOR (S_R) values and equations P in the form of Eq. (3) or (4) to obtain Eq. (7) for P based on logarithm transformations and Eq. (8) for power transformation.

$$T = \exp\left(\frac{\sigma P_{\max}}{sS_R} - \frac{m}{s}\right) \quad (7)$$

$$T = \sqrt[m]{\frac{\sigma P_{\max}}{sS_R}} \quad (8)$$

Eqs. (7) and (8) could be applied for estimating the remaining service-lifetime with a predetermined bending stress if there is not any dimensional deterioration. The equation does not consider the reduction of the effective cross section of the wood due to deterioration.

Wood is the object of physical, biological, and chemical attack, which reduce its effective dimension. Effective cross-sectional area is a factor that affected the wood strength that should be taken into consideration. A decrease in cross-sectional area lead to a decrease in moment of inertia (I) as a function of time. The moment of inertia at any future time can be predicted from Eq. (9) within assumption that the decay rate is linear during usage period (17 years).

$$I = \frac{\left(b - \frac{f}{17}T\right)\left(h - \frac{f}{17}T\right)^3}{12} \quad (9)$$

Where: I = moment of inertia (cm^4), b = width of beam section (cm), h = height of beam section (cm), T = loading period (years), f = deterioration depth (cm), T = loading period (years), f = deterioration depth (cm)

Thus, Eq. (10) determines the ratio of moment of inertia later by the moment of inertia today.

$$\frac{I_{later}}{I_{today}} = \frac{\left(b - \frac{f}{17}T\right)\left(h - \frac{f}{17}T\right)^3}{bh^3} \quad (10)$$

In general, Eq. (11) presents the bending stress:

$$\sigma = \frac{Mc}{I} \quad (11)$$

Therefore, equation for the bending stress ratio for bending stress at that time compared with the current value in accordance with dimensional deterioration only is:

$$\frac{\sigma_{later}}{\sigma_{today}} = \frac{bh^2}{\left(b - \frac{f}{17}T\right)\left(h - \frac{f}{17}T\right)^2} \quad (12)$$

Furthermore, Eq. (7) or (8) is combined with Eq. (12) to obtain the ratio of the later wood strength compared to today. The results were Eq. (13) for logarithm transformation and Eq. (14) for power transformation. Eq. (13) or (14) approximate the maximum bending stress that will be still acceptable for a certain period in the future.

$$\sigma = \frac{S_R}{P_{\max}}(s\ln T + m)\frac{\left(b - \frac{f}{17}T\right)\left(h - \frac{f}{17}T\right)^2}{bh^2} \quad (13)$$

$$\sigma = \frac{S_R}{P_{\max}} sT^m \frac{\left(b - \frac{f}{17}T\right)\left(h - \frac{f}{17}T\right)^2}{bh^2} \quad (14)$$

Eq. (13) or (14) can be used to approximate the remaining service-lifetime (T) of wooden structure to reach allowable stress required by NDS 2005. When the stress (σ) is lower than allowable stress, the structure will be collapse. The remaining service-lifetime is calculated by substituting the stress (σ) in Eq. (13) or (14) with bending allowable stress requirement (NDS 2005) [4], and solved for corresponding T.

3. Results and discussion

3.1. Wood identification

The wood species identification was conducted based on Hoadley key identification [7] for softwood. Observations of the wood anatomical structures indicated that the samples were Douglas fir (*Pseudotsuga menziesii*) and Redwood (*Sequoia sempervirens*). Wood J and P were Douglas fir, while wood L and M were Redwood (Fig. 4). These two wood species look almost similar: the texture was smooth, has clearly distinction of early wood and late wood. The main visible difference is the resin channels. Douglas fir has resin canal whereas there are no resin channels in Redwood [7].

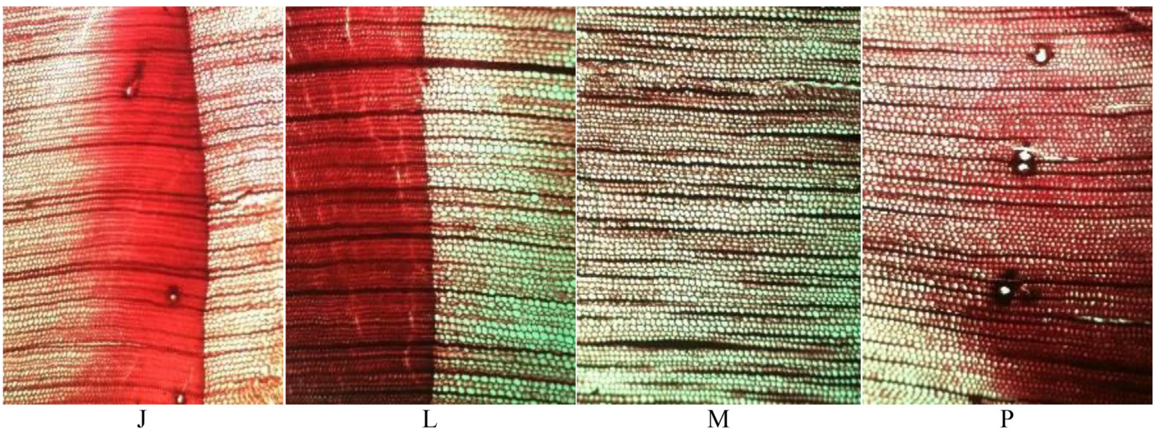

Fig. 4. Photos of the transverse section of the sample (40×).

3.2. Density degradation

The wood density was measured in air-dry conditions. The wood shaved each 0.5 mm from the surface. The volume and weight before and after shaved were measured. Deterioration depth was determined when the density was lower than control. Control was the inner side of the samples that assumed deterioration free. The measurement results can be seen in Fig. 5 that showed Douglas fir undergo the most severe density degradation with a depth of 0.25 cm from the surface (wood J). Up to the depth (0.25 cm), the density was lower than control. Center of sample was as the control. The lowest degradation of wood was 0.0 cm for wood L, followed by M and P with 0.2 cm and 0.18 cm of depth. The results showed decreasing density at each depth. This showed that the deterioration occurred, especially on the cell wall. For safety reason, in this study 0.25 cm was chosen as standard deterioration depth since it was the deepest deterioration depth. Since the wood has been applied for 17 years cooling tower operation, the degradation rate is 0.0147 cm/year.

The density degradation is mainly caused by cell wall thickness reduction during cooling tower operation. The degradation of wood cell wall during cooling tower operation was reported by Bahtiar et al. [8], which observed the cell wall thickness of redwood under Scanning Electron Microscope (SEM) photograph and found that the percentage of cell wall area compared to cross sectional area is degraded significantly during PT Indonesia Power's cooling tower operation in Kamojang West Java Indonesia. Some splits and shakes were found on the surface of redwood as the result of middle lamella exfoliation and secondary cell wall erosion [8]. Several environmental conditions (such as 1. water flow erosion and wind abrasion, 2. thermal and moisture content variation in each piece of wood may rise the internal stress, 3. UV radiation may affect to the chemical properties of cell wall) may responsible for this degradation. Erosion on the wood surface commonly occurs very slowly. William et al. [14], reported that wood surface erodes 6–12 mm depth for 100 years outdoor building application in temperate area, while Bahtiar et al. [8] reported that Redwood eroded 2.95 mm depth after 23 years cooling tower operation in geothermal power plant. High temperature may responsible for cellulose and hemicellulose degradation that reduce the wood strength and darken the surface color. UV changes the wood color become grayish brown. UV sunrays radiation also affect the wood cell by forming the free radicals that degrade the wood polymer [15]. Degradation caused by UV occurs in a very thin layer only, but its combination with wind abrasion and water erosion may results severe degradation.

Wood biodegradation is more often than abiotic degradation, but the specific condition in geothermal power plant obstructs the wood destroying organism growth rate, so that abiotic factor results more severe degradation than biotic. Sulphur content in the geothermal water is commonly very high, and its reaction results Sulphur dioxide (SO_2) which acts as antioxidant, antimicrobials, and poisonous to fungi. High content of H_2S in geothermal water makes it more acid so that the wood destroying organisms do not grow well.

3.3. The mechanical properties of wood

Some tests for measuring the mechanical properties of wood were conducted, namely: bending, compression parallel to grain, compression perpendicular to grain, tensile parallel to grain, and shear parallel to grain. The test were conducted based

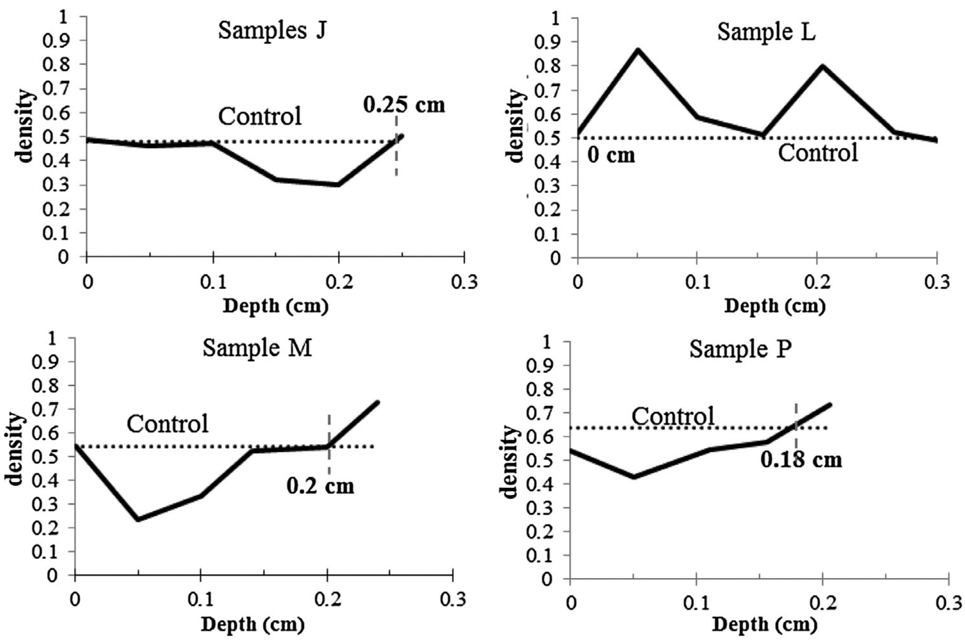

Fig. 5. The Density of wood a) J, b) L, c) M, and d) P at various depths [9].

Table 1
Mechanical test results of the samples compared to FPL [16].

Criteria	MOR	Ft//	Fs	Fc ⊥	Fc//	MOE
a. Douglas Fir						
Average Testing Result (kgf/cm^2)	509	603	88	25	233	47386
Number of samples	9	14	9	8	8	9
FPL (2010) strength value[a]) (kgf/cm^2)	918	1240	99	54	485	125425
b. Redwood						
Average Testing Result (kgf/cm^2)	367	694	79	24	183	47596
Number of samples	7	7	7	8	8	7
FPL (2010) strength value[b]) (kgf/cm^2)	704	747	66	49	432	93814

Note: MOR = Modulus of rupture, MOE = Modulus of elasticity, Fb = bending strength, Ft// = tensile strength parallel to grain, Fs = shear strength, Fc⊥ = compression perpendicular to grain, Fc// = compression parallel to grain.
[a] Douglas fir inferior north which grown in Northern USA with moisture content12%.
[b] Redwood Young-growth which grown in USA with moisture content 12%.

on ASTM D143 [5] using Universal Testing Machine (UTM) Instron type 3369. Mechanical test results showed that almost all of the strength decreased significantly when compared to Douglas fir and Redwood strength released by FPL [16] (Table 1). Strength degradation may be caused by wood deterioration as the result of chemical attack, biological attack, and/or physical decay due to the temperature fluctuation or rupture of the wood cells by crystallization of dissolved solids in the cooling water [3]. Since the wood density in the outer layer degrades significantly, the cross sectional area and second moment of area reduction is occurred so that the mechanical properties also decrease. The strength reduction should be considered since the rest strength could be lower than a half of the original value.

3.4. The allowable stress of wood

Allowable stress is the maximum stress that could be applied to the structural member so the construction is safe and will not be failure during its service-life. Allowable stress is the material strength characteristic multiplied by safety factor. Designers choose the allowable stress for reference design strength value to ensure that the service load applied to the structure do not exceed the elastic limit. Allowable stress of the wood is not the average strength value. The average value generate that there is 50% probability that the samples were lower than the average and would fail. Average mechanical testing result value must be processed become characteristic value that is 5% lower percentile limit, then reduced by the adjustment factor based on ASTM D2915 [10] in order to get the allowable stress. American Forest and Paper Association (AF&PA) published the National Design Specification (NDS) for complete guidance for designing wooden structures in Allowable Stress Design (ASD) and Load and Resistance Factor Design (LRFD) [4]. The allowable stress of several wood species is available in the NDS. The allowable stress of the samples compared to NDS 2005 [4] is in Table 2.

The Douglas fir test results showed that the allowable stress on bending was still higher than NDS 2005 requirement (Table 2). Redwood allowable stress on bending also had the same strength value. This value indicated that the structure was safe from bending load and would not fail in the near future. MOE of both timbers was much lower than the code, which generate a risk of greater deflection and vibration of the structure compared to the planned design. The lower value of MOE did not cause failure on the structure because the MOR was still higher than the code requirement. The compression stress perpendicular to grain of Redwood and Douglas fir had been severely reduced; the rest of the strength was only about a quarter of the allowable stress. However, the low value of compression stress perpendicular to grain can increase due to the densification mechanism. Compression strength parallel to grain of Douglas fir and Redwood were lower than NDS 2005 so that connections location that receiving compression load were need to be re-evaluated carefully.

Table 2
Allowable **s**tress of samples compared to NDS 2005 for dimensions smaller than 12.7 × 12.7 cm.

Criteria	Fb	Ft//	Fs	Fc⊥	Fc//	MOE	
						E	E_{min}
a. Douglas fir							
Testing results (kgf/cm^2)	136	74	32	10	74	47386	36984
NDS 2005 value (kgf/cm^2)	112	67	12	44	77	112491	40778
b. Redwood							
Testing results (kgf/cm^2)	136	217	25	10	72	47596	37400
NDS 2005 value (kgf/cm^2)	98	67	10	46	84	91399	33044

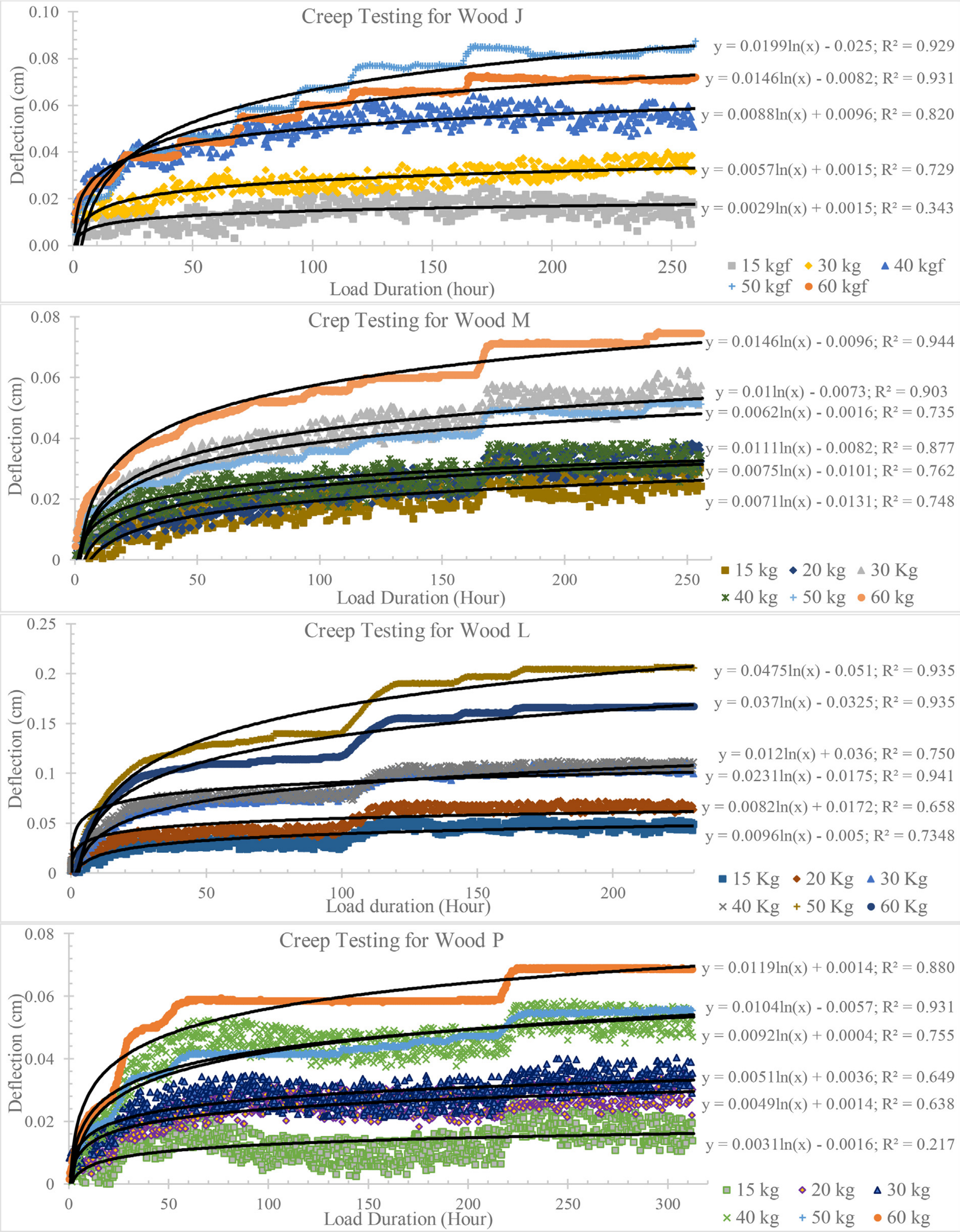

Fig. 6. Deflection vs. load duration of creep test curve.

3.5. Creep testing

Creep testing was conducted to approximate the maximum long-term load that can be applied to the wood safely. Wood has a lower ability to resist long term loading than short-term one. The test results for the creep of samples are presented in Fig. 6. These graphs show that the creep deflections (y_{cr}) increase with the loading time even though the amount of loading is constant. Creep deflection (y_{cr}) is also greater at any heavier load.

As seen on Fig. 6, there is daily variation of creep deflection because of temperature and RH fluctuation. Bahtiar et al. [11] also reported this phenomenon for wooden component of residential house in Bogor. The temperature and humidity in the laboratory during creep testing period were recorded every 20 min and the sinusoidal equation [11,12] were conducted to fit the daily temperature and RH fluctuation. As expected, the best-fit sinusoidal equation for the temperature and RH fluctuation during this creep testing was not significantly different compared to Bahtiar's report [11] since both creep testing was conducted in the same room without any environmental modification. The temperature and RH fluctuation affect to creep deflection so that there is sinusoidal pattern on the creep deflection following the daily cycle changes in temperature and humidity.

3.6. Remaining service-lifetime of wood

Creep deflection equation of the curve at each increment of time can be fitted with a simple linear regression with logarithm transformation. The deflection limit to failure can be used for approximating the time to failure of the structural member as developed in Forintek and FPL models. In FPL model, ratio of applied stress to the short-term stress is proposed as basic variable to estimate the residual service-lifetime, while Forintek model also consider the damage threshold stress ratio below no damage is assumed to accumulate [13]. In this study, raw creep deflections and deflection value to failure are chosen as basic variable for estimating the residual service-lifetime. This approach produces equations that can be used to predict the time required to achieve a deflection limit to failure of the wood (Table 3). The value of the load duration to reach estimated failure deflection is plotted on a Cartesian diagram and fitted with a logarithm or power approach (Fig. 7). This method was applied several time ago and it is succeed estimating the remaining service-lifetime of wooden cooling tower in PT Indonesia Power in Kamojang West Java Indonesia [8].

The curve in Fig. 7 applies to estimate the remaining service-lifetime of the wood without considering the changes in moment of inertia due to the wood deterioration. For achieving reliable and better estimation, the decreasing rate of cross sectional area and its moment of inertia should be considered. Based on this research, wood taken most severe deterioration rate of 0.25 cm deep for 17 years (0.0147 cm/year) so that the ratio of moment of inertia in the next period compared to today

Table 3
Creep deflection, initial deflection, and the duration of load to reach targeted deflection.

Sample Code	Load (kgf)	Average failure deflection (y_f) (cm)	Deflection under load ≈ initial deflection (y_{inst}) (cm)	Targeted deflection estimation ($y_i = y_f - y_{inst}$) (cm)	Load Duration to reach targeted deflection in creep test (T_i) (years)
J	15	0.854	0.143	0.712	2.5×10^{102}
	30	0.854	0.189	0.665	4.02×10^{46}
	40	0.854	0.215	0.640	1.41×10^{27}
	50	0.854	0.260	0.594	0.002567
	60	0.854	0.298	0.556	7.12×10^{12}
L	15	0.589	0.114	0.475	6.07×10^{17}
	20	0.589	0.129	0.459	3.03×10^{19}
	30	0.589	0.165	0.424	22773.21
	40	0.589	0.203	0.386	5.1×10^{08}
	50	0.589	0.245	0.344	0.466125
	60	0.589	0.289	0.299	0.895641
M	15	0.790	0.122	0.668	5.41×10^{37}
	20	0.790	0.138	0.652	2.57×10^{34}
	30	0.790	0.172	0.618	3.74×10^{20}
	40	0.790	0.207	0.583	1.09×10^{37}
	50	0.790	0.245	0.545	1.1×10^{20}
	60	0.790	0.284	0.506	2.4×10^{11}
P	15	1.077	0.163	0.914	2.1×10^{124}
	20	1.077	0.177	0.900	5.09×10^{75}
	30	1.077	0.212	0.865	2.54×10^{69}
	40	1.077	0.246	0.830	1.71×10^{35}
	50	1.077	0.264	0.812	1.65×10^{30}
	60	1.077	0.314	0.762	6.82×10^{23}

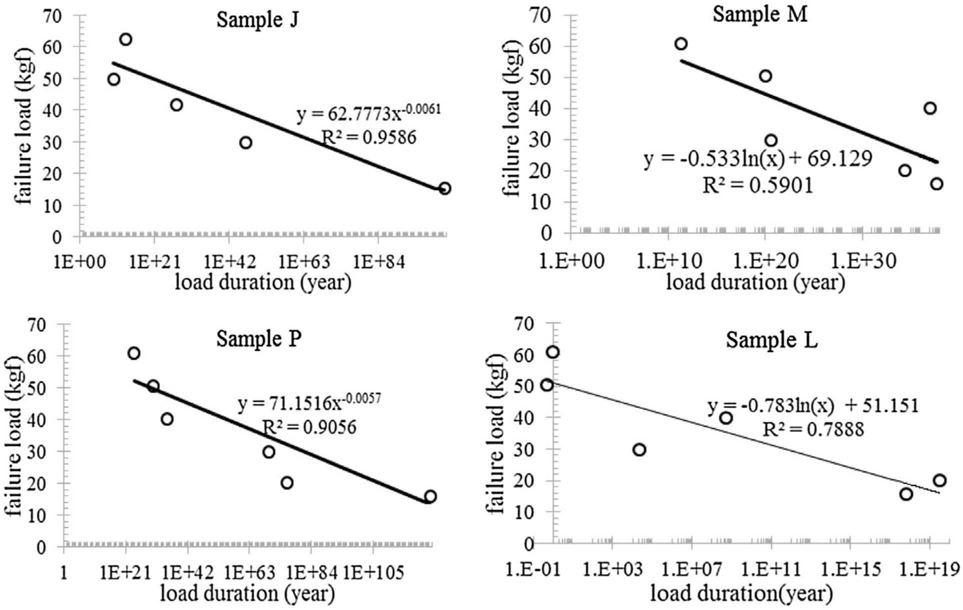

Fig. 7. Relationship of load duration and failure load in long term loading without considering the dimensional deterioration.

can be calculated by the formulae:

$$\frac{I_{later}}{I_{today}} = \frac{(b - 0.0147T)(h - 0.0147T)^3}{bh^3}$$

The maximum distance from centroid is shortened due to cross-sectional area reduction, so that stress become higher and the ratio could be calculated by following formulae:

$$\frac{\sigma_{later}}{\sigma_{today}} = \frac{bh^2}{(b - 0.0147T)(h - 0.0147T)^2}$$

Following that equation, the remaining service-lifetime of structural member of wooden cooling tower in Star Energy Geothermal (Wayang Windu) Ltd can be estimated by:

- Wood J: $\sigma = 456 \times \left(0.42725T^{-0.006}\right) \times \frac{(b-0.00147T)(h-0.00147T)^2}{bh^2}$

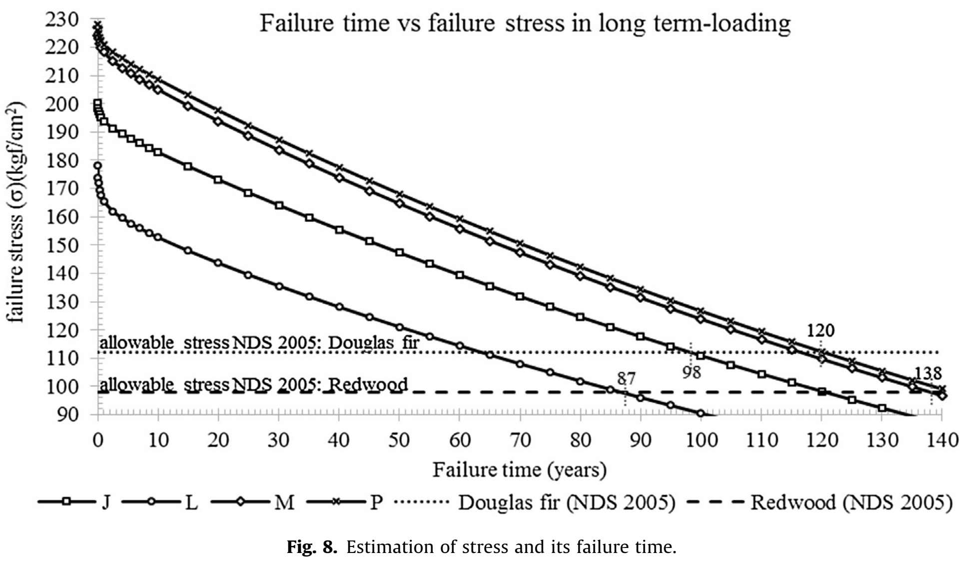

Fig. 8. Estimation of stress and its failure time.

- Wood L: $\sigma = 332 \times (-0.00767\ln T + 0.501) \times \frac{(b-0.0147T)(h-0.0147T)^2}{bh^2}$
- Wood M: $\sigma = 393 \times (-0.0043\ln T + 0.558) \times \frac{(b-0.0147T)(h-0.0147T)^2}{bh^2}$
- Wood P: $\sigma = 690 \times \left(0.3219T^{-0.006}\right) \times \frac{(b-0.00147T)(h-0.00147T)^2}{bh^2}$

By substituting the allowable stress from NDS 2005 as a stress that is planned, the remaining service-lifetime for each timber are 98, 86, 136, and 120 years for timber J, L, M and P, respectively. The graph of this relation is shown in Fig. 8.

4. Conclusion and recommendation

4.1. Conclusion

The wood used for structural component of Star Energy Geothermal (Wayang Windu) Ltd.'s cooling tower are Redwood (*Sequoia sempervirens*) and Douglas fir (*Pseudotsuga menzieesi*). The mechanical properties of the wood greatly reduced compared to FPL release, but they were still higher than the allowable stress in building code (NDS 2005), unless the compression perpendicular to grain, compression parallel to grain and modulus of elasticity that were lower than the code value. The wood remaining service-lifetime estimation of structural component at cooling towers in Star Energy Geothermal (Wayang Windu) Ltd can be done by mathematical models based on its creep deflection until reach the failure deflection. The coefficient determination of regression (R^2) are 57–90%, so that the estimation of remaining service-lifetime of the wood is reliable enough with the estimation results were 98, 87, 138, and 106 years for timber J, L, M, and P, respectively. For safety reason it is better to choose the shortest remaining service-lifetime, that is 87 years.

4.2. Recommendation

The structural component of cooling tower at Star Energy Geothermal is reliable enough to service for next 87 years. But the other component such as bracing and connection must be well evaluated to support this result since the weakness may occur on those components which affected in reducing cooling tower remaining service-lifetime.

References

[1] E.C. Ozelton, J.A. Baird, Timber Designers' Manual, Blackwell Science, Oxford, 2006.
[2] J.P. Dahlen, D.R. Jones, R.D. Seale, Shmulsky, Bending strength and stiffness of in-grade Douglas-fir and southern pine no. 2 2 × 4 lumber, Can. J. For. Res. 42 (2012) 858–867, doi:http://dx.doi.org/10.1139/X2012-041.
[3] H.W. Stanford, HVAC Water Chillers and Cooling Towers Fundamentals, Application and Operation, Marcel Dekker, New York, 2003.
[4] [AF&PA] American Forest and Paper Association, National Design Specification for Wood Construction ASD/LRFD, American Forest and Paper Association, 2005.
[5] [ASTM] American Society for Testing and Materials, Test Methods for Small Clear Specimen of Wood. ASTM D 143, American Society for Testing and Materials, 2003.
[6] E.D. Schulze, A. Borner, F.H. Schweingruber, Atlas of Woody Plant Stems-Evolution, Structure and Environmental Modification, Springer, Berlin, 2006.
[7] B.R. Hoadley, Identifying Wood Accurate Results with Simple Tools, Taunton Press, Connecticut, 1990.
[8] E.T. Bahtiar, N. Nugroho, Arinana, A. Darwis, Pendugaan sisa umur pakai kayu komponen cooling tower di pembangkit listrik tenaga panas bumi (PLTP) unit II kamojang, Jurnal Teknik Sipil 19 (2012) 103–114.
[9] E.T. Bahtiar, N. Nugroho, D. Hermawan, W. Wirawan, Arinana, R.K. Sari, M.M. Rahman, M. Sidik, Wood deterioration of cooling tower structure at geothermal power plant, Asian J. Appl. Sci. (2017), doi:http://dx.doi.org/10.3923/ajaps.2017.
[10] [ASTM] American Society for Testing and Materials, Standard Practice for Evaluating Allowable Properties for Grades of Structural Lumber ASTM D2915-03, American Society for Testing and Materials, 2003.
[11] E.T. Bahtiar, N. Arinana, D. Nugroho, Daily cycle of air temperature and relative humidity effect to creep deflection of wood component of low-cost house in cibeureum –Bogor, west java, Indonesia, Asian J. Sci. Res. 7 (2014) 501–512.
[12] E.T. Bahtiar, N. Nugroho, L. Karlinasari, S. Surjokusumo, Human comfort period outside and inside bamboo stands, J. Environ. Sci. Technol. 7 (2014) 245–265.
[13] D.V. Rosowsky, W.M. Bulleit, Load duration effects in wood members and connections: order statistics and critical loads, Struct. Saf. 24 (2002) (2002) 347–362.
[14] R.S. William, M.T. Knaebe, J.W. Evans, W.C. Feist, Erosion rate of wood during natural weathering part III. effect of exposure angle on erosion rate, Wood Fiber Sci. 33 (2001) 50–57.
[15] T. Shupe, S. Lebow, D. Ring, Causes and control of wood decay, Degradation and Stain, LSU Ag Center Research Center and Extension, USA, 2010.
[16] [FPL] Forest Products Laboratory, Wood Handbook- Wood as an Engineering Material. Gen. Tech. Rep. FPL-GTR-190, US Department of Agriculture, Forest Service, Forest Products, Laboratory, Madison, 2010.