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Application of Weibull's Theory to Assess the Depth Effect of Malaysian Tropical Hardwoods According to Eurocode 5

Nasroien Bambang Purwanto [1], Norshariza Mohamad Bhkari [1,2,*], Zakiah Ahmad[1,2], Rohana Hassan[1,2], Lum Wei Chen[3], Adnie Baharin[1], Muhammad Amirul Akmal Rosli[1], Aamir Khokhar[4]

1 School of Civil Engineering, College of Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
2 Institute for Infrastructure Engineering and Sustainable Management, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
3 Faculty of Bioengineering and Technology, Universiti Malaysia Kelantan, Jeli Campus, 17600 Jeli, Kelantan, Malaysia
4 School of Computing Engineering and the Built Environment, Edinburgh Napier University (ENU), United Kingdom

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ABSTRACT

The adoption of limit state design according to Eurocode 5 (EC5) has brought about design strength optimisation in design practices worldwide. However, the implementation of EC5 may not be suitable for Malaysian tropical timber species as the design strength data in European Standard (EN) 338:2016 is based on softwood and temperate hardwood species. EC5 has a well-established 1/k value of 0.2 for softwood and temperate hardwood with characteristic densities below 700 kg/m^3. The value of 0.2 is still uncertain for tropical hardwood timber and it is predicted that the 1⁄k value for characteristic density above 700kg/m^3 will be different. Therefore, in this study, the application of Weibull's theory is being used to determine the 1/k value for selected species namely, Balau (*Shorea spp.*), Kempas (*Koompassia malaccensis*), Kapur (*Dryobalanops spp.*), Keruing (*Dipterocarpus spp.*), Geronggang (*Cratoxylon arborescens*), and Light Red Meranti (*Shorea spp.*) with density ranges from 300 kg/m^3 to 1000 kg/m^3. Experimental bending data from previous researchers were analysed and verified using this theory. From the theoretical prediction, the calculated 1/k value for the selected species ranges from 0.158 to 0.204 which is close to the established value of 0.2. This study provides the actual k value as well as the true depth modification factors for tropical hardwood which important for safe and economical structural timber design.

1. Introduction

Malaysian tropical hardwood has gained significant attention in engineering applications due to its high strength, stiffness, and durability. Its superior properties make it an excellent choice for use in structural applications, including bridges, high-rise buildings, and industrial facilities. Despite its impressive mechanical properties, the use of Malaysian hardwood in engineering applications requires careful consideration of its characteristics, including density, moisture content, and drying

* *Corresponding author.*
E-mail address: nshariza@uitm.edu.my

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properties, to ensure its proper performance and longevity [1]. To this end, extensive research has been conducted to better understand the behaviour of Malaysian hardwood under different loading conditions, and guidelines have been developed to help engineers design structures that incorporate this valuable resource. In Malaysia, the design of timber structure is still based on the permissible theory in accordance with Malaysian Standard (MS) 544: Part 2: 2017 [2] adopts British Standard (BS) 5268-2:1991 [3] in terms of design procedures. The design stress values for tension, compression, shear, and bending, as specified in MS 544: Part 2: 2017, are based on data from small, defect-free timber specimens, typically obtained through standard laboratory testing methods. These small clear specimens are commonly used in laboratory testing and usually not suitable to represent the true mechanical strength of timber used in structural applications. Different with the structural sized specimens that may have unseen defects which can affect the mechanical properties of wood. Consequently, the practice of using permissible stress design has been abandoned for the past decade in certain country such as European, America, Australia, New Zealand etc. [4].

There is a recommendation for designers within the local context to embrace the limit state design approach outlined in Eurocode 5 (EC5) [5,6]. This approach not only prioritizes safety but also cost-effectiveness in structural design. However, due to the unique properties of Malaysian tropical hardwoods compared to other types of timber, a straightforward application of EC5 may not be suitable. Therefore, the utilization of Weibull's theory is employed to verify the *k* value. Generally, Weibull's theory of timber is ~~a~~ widely used statistical method for predicting the strength and reliability of timber in engineering applications. The theory was developed by Waloddi Weibull [7] in the early 20th century, and it has since been applied to a variety of timber products, including timber beams and timber-based composites by Bohannan [8]. Weibull's theory provides a framework for understanding the statistical distribution of strength and failure probability of timber samples subjected to different loads. The strength of timber tends to decline as the size of the specimen increases [9,10]. This information is essential for engineers to design and construct safe and efficient timber-based structures [11]. By analysing the distribution of strength and failure probability, engineers can estimate the maximum load capacity of timber products and design structures that will withstand various environmental conditions and loads.

The amount of stressed material and the manner in which stress is distributed play crucial roles in determining the strength of timber and timber-based materials in tension or shear, which are typically considered brittle failure modes [12]. Weakest link concept used to predict the probability of failure of a 'perfectly brittle', homogeneous, isotropic material at a given volume according to the empirically based Eq. (1)

$$F_v = 1 - e^{-\frac{1}{V^*}\int_Y \left(\frac{\sigma-\sigma_0}{m}\right)^k dV} \tag{1}$$

where F_v is the probability of failure, where V^* is a reference volume, m, k, and σ_0 are material constants. Commonly σ_0 accepted as being equal to zero, simplifying the problem and the resulting formulation is called a two-parameter (2-P) Weibull distribution. Size effects have commonly been expressed as a function of *k* [13]. According to [14], the importance feature should be $1/k$, not *k*, as one wants to use these size effects for design purposes. Eq. (1) changes to the following when the structural element is subject to uniform stresses and the (2-P) model is assumed, with reference volume V^* set to $1m^3$.

$$\ln (1-F_v) = -V\left(\frac{\sigma}{m}\right)^k \tag{2}$$

Considering two volumes, V_1 and V_2, with corresponding strengths of σ_1 and σ_2, and assuming that V_1 and V_2 have an equal likelihood of failing under bending, thus Eq. (2) becomes

$$\ln(1\text{-}F_v) = -\left(\frac{\sigma_1}{m}\right)^k V_1 \tag{3}$$

$$\ln(1\text{-}F_v) = -\left(\frac{\sigma_2}{m}\right)^k V_2 \tag{4}$$

From Eq. (3) and (4), it can be shown that at any given failure probability level, the strengths of two pieces are related as in Eq. (5) based on the assumption of independent identically distributed random variables [15]

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{V_2}{V_1}\right)^{\frac{1}{k}} \tag{5}$$

Nonetheless, the classical Weibull size effect law's tendency to overestimate the impact of size on strength can be attributed to the independent spatial allocation of strength to smaller segments within a larger volume [16]. This method fails to consider the spatial correlation in the strength field, which can be addressed by implementing the random field approach. Additionally, the classical Weibull size effect law's scalability is implied by Eq. (5), which means that its structure remains unchanged for even the smallest material volumes. This can lead to unrealistic outcomes as, in reality, there is a maximum limit to the strength of materials as their volume decreases.

This paper presents the application of Weibull's theory to develop a mathematical model that can be used to assess the depth effect on the k value of Malaysian tropical hardwood species. The mathematical model developed in this study is compared with the European Standard (EN) 384:2016 [17] modification factor, which is commonly used in engineering applications to account for the depth effect on wood strength. The study aims to provide insights into the accuracy and effectiveness of the model in predicting the strength of Malaysian tropical hardwood under different loading conditions by comparing the results of the mathematical model with the EN 384:2016 modification factor. A series of bending tests has been done for each structural size species in this study with different sizes. Testing on the structural size of specimens gives all the material heterogeneity found in the wood [18].

From previous studies, most of the outcome were focusing on evaluation of size effects of structural size specimens from hardwood timber in Malaysia and around the world. Limited of the studies has been taken in the verification of Weibull's theory on the depth effect specifically on Malaysian tropical hardwood to be compared with the EN 384:2016 modification factor [19-22]. The verification of Weibull's theory on local timber was conducted by [19], was the closest study related although the study was restricted to the Dark Red Meranti species under tension. On the other hand, [20,21] investigated the effect of depth on bending strength but utilized structural timber from Chinese larch and Japanese larch while [22] studied the impact of size on Chinese larch under tension.

2. Methodology

2.1 Sample Preparation

A certified grader from the Malaysian Timber Industry Board (MTIB) was graded each timber piece in accordance with the Malaysian Standard (MS) 1714:2003 [23], as illustrated in Figure 1. In this study, only the timber pieces graded as hardwood structural (HS) were utilized.

Fig. 1. Timber specimens graded by MTIB certified graders

2.2 Test Method

The four-point bending test for the structural size specimens was set up in accordance with EN408: 2012 as shown in Figure 2. Kempas, Kapur, Keruing, Geronggang and Light Red Meranti were prepared in three different sizes which were 30x50x1000mm, 30x100x2000mm, and 30x125x2500mm. As the continuation of depth effect study and to further another depth variation, two-dimensional size was proposed for Balau which were 30x60x1200mm and 30x75x1500.

Fig. 2. Set up machine for bending test

In order to avoid lateral buckling of the test samples, the depth-to-width ratio (d/b) of specimens should be three or more [24]. Lateral support should be placed at several points between the reaction and load point if the test setup was not fulfilling the specified d/b ratio. The vertical movement of each support must be allowed without any frictional resistance. The samples were tested using a Universal Testing Machine (UTM) (Mfg. In Scottsdale, Arizona, USA) with load capacity of 500 kN until total failure.

2.3 Modulus of Rupture (MOR)

The bending strength or Modulus of Rupture (MOR) was calculated using Eq. (6) based on BS EN 408 [25]. This equation is a basic formula to estimate the bending stress in a beam under simple bending where F = load at a given point on the load deflection curve (in N); a = distance between a loading point and the nearest support (in mm); b = beam width (in mm); h = beam height (in mm).

$$fm = \frac{M}{s} = \frac{F_{px}a}{\frac{bxh^2}{6}} = \frac{3xFxa}{bxh^2} \quad (6)$$

2.4 Modulus of Elasticity (MOE)

In accordance with standard BS EN 408 [25], Eq. (7) was used to calculate the local modulus of elasticity in bending where α = distance between a loading point and the nearest support (a=6xh); $F_2 - F_1$= (total) load increase in the linear range with a correlation coefficient of 0.99; $w_2 - w_1$ = corresponding increase in the relative vertical displacement between the midpoint of the beam and the attached rod;ℓ = span (ℓ = 18*h).

$$E_{m,l} = \frac{al_1^2 (F_2 - F_1)}{16l(w_2 - w_1)} \quad (7)$$

The global modulus of elasticity was calculated using the following formula in Eq. (8) from the standard. Shear deformation was not considered (G→∞), which is conservative.

$$E_{m,g} = \frac{3al^2 - 4a^3}{2bh^3(2\frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh})} \quad (8)$$

2.5 Moisture Content and Density Test

The moisture content of the test samples was measured through the oven dry method according to EN 13183-1:2002 [26] after bending test. The density for test samples was then determined from 50mm thick sections (thickness measured parallel to grain) using the below equation (Eq.9).

$$\rho = \frac{m}{v} \quad (9)$$

2.6 Determination of Characteristics Density

Characteristic density was calculated through the 5th percentile density value and computed in accordance with EN14358 [27] and EN 384:2016 [17]. The density obtained from the oven-dry method was corrected to the reference moisture content of 12% [17]. Later, the corrected density was calculated under the 5th percentile value using the formula obtained in EN14358 [27]. In order to determine the characteristic density, the formula in Section 5.5.2.2.3, EN 384:2016 [17] was referred and calculated based on 5th percentile density value.

2.7 Determination of Depth Factor

The depth factor given in the EN384 [17] is only applicable to characteristic density less than 700 kg/m^3. In this study, two types of local timber have density more than 700 kg/m^3, which is Balau and Kempas with density of 855 kg/m^3 and 731 kg/m^3, respectively. Another four local timber of Kapur, Keruing, Geronggang and Light Red Meranti have density below 700 kg/m^3. Each of the species has undergone a series of bending tests to evaluate value needed in the derivation of Weibull's theory.

3. Results and Discussions

3.1 Experimental Data for Bending Test

The experimental data for bending test for Balau, Kempas, Kapur, Keruing, Geronggang, and Light Red Meranti is based on Rosli [28] and Baharin *et al*., [29]. Table 1 summarised the average bending strength and characteristic density of the test samples for selected species.

Table 1
Dimensions and number of specimens used for all hardwood species

Timber Species	Beam Dimensions	Total Number of Species	Average Bending Strength (MPa)	Characteristic Density (kg/m^3)
Balau	30x60x1200 30x75x1500 30x100x2000 30x125x2500	29	119.90 94.37 85.19 92.55	855
Kempas	30x50x1000 30x100x2000 30x125x2500	153	112.85 96.65 91.20	731
Kapur	30x50x1000 30x100x2000 30x125x2500	151	87.38 80.91 77.31	652
Keruing	30x50x1000 30x100x2000 30x125x2500	157	91.01 72.36 82.74	578
Geronggang	30x50x1000 30x100x2000 30x125x2500	154	45.47 35.71 38.30	390
Light Red Meranti	30x50x1000 30x100x2000 30x125x2500	158	50.25 46.98 43.00	327

3.2 Determination of Weibull's Parameters for Malaysian Tropical Hardwood

In order to determine Weilbull's parameters, the 5kN interval of bending strength data from experimental work were arranged for each test specimen. As tabulated in Table 2, the cumulative number of specimens and cumulative probability were calculated. These values were needed to plot the Weibull's theoretical graph. A graph of cumulative probability versus bending strength was plotted and shown in Figure 3. In this paper, only data from Kempas was presented as example to determine the Weilbull's parameters. However, Weilbull's parameters for other species was summarised as in Table 3.

Table 2
Cumulative probability of failure for Kempas's specimen loaded in Bending

Bending Strength (MPa)	Average Bending Strength (MPa)	Number of Samples KPS	Cumulative Number	Cumulative Probability
0	0	0	0	0.00
25 - 29	27	1	1	0.01
40 - 44	42	1	2	0.01
45 - 49	47	1	3	0.02
50 - 54	52	2	5	0.03
55 - 59	57	4	9	0.06
60 - 64	62	1	10	0.07
65 - 69	67	3	13	0.08
70 - 74	72	5	18	0.12
75 - 79	77	5	23	0.15
80 - 84	82	4	27	0.18
85 - 89	87	10	37	0.24
90 - 94	92	8	45	0.29
95 - 99	97	17	62	0.41
100 - 104	102	16	78	0.51
105 - 109	107	11	89	0.58
110 - 114	112	24	113	0.74
115 - 119	117	18	131	0.86
120 - 124	122	8	139	0.91
125 - 129	127	4	143	0.93
130 - 134	132	6	149	0.97
135 - 139	137	3	152	0.99
140 - 144	142	1	153	1.00

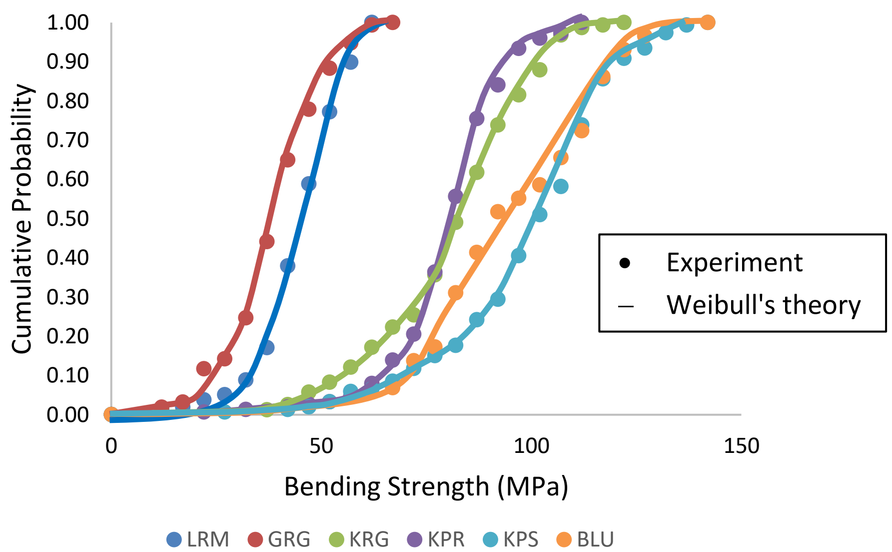

Fig. 3. Cumulative probability idealization for Malaysian tropical hardwoods using brittle fracture theory

Table 3
Summary of value *m*, *k*, and 1/*k* for each species in this study

Malaysian Tropical Hardwood Species	Characteristic Density (kg/m^3)	*m*, (MN/m^2)	*k*	1/*k*
Balau (*Shorea spp.*)	855	25.18	5.250	0.190
Kempas (*Koompassia malaccensis*)	731	42.53	6.328	0.158
Kapur (*Dryobalanops spp.*)	652	25.2	4.802	0.208
Keruing (*Dipterocarpus spp.*)	578	33.78	6.168	0.162
Geronggang (*Cratoxylum spp.*)	390	10.32	4.970	0.201
Light Red Meranti (*Shorea spp.*)	327	14.56	4.910	0.204

The-value of *k* and *m* attained in this study were acquired from varying sizes of test specimens (Table 1). For the example of Kempas species, the values of *k* and *m* were obtained by using two cumulative probabilities, 0.51 and 0.97 as per bold in Table 2 and shown in Figure 4. Value of 0.51 represent the point of gradient in the elastic region under bending and 0.97 is the value of yield point in the elastic to plastic transition zone, respectively. The morphological turning point is the target yield point to identify the transition zone which evaluated visually and manually.

Using Eq. (3), by substituting the value of $F\nu_1 = 0.51$ and $\sigma_1 = 102$ MPa, given

$$253.493 = \left(\frac{102}{m}\right)^k V \tag{9}$$

Likewise substituting the value of $F\nu_2 = 0.97$ and $\sigma_2 = 132$ MPa, given

$$1295.695 = \left(\frac{132}{m}\right)^k V \tag{10}$$

The study assumed that the bending stress is uniform within the shaded area of the bending specimen as shown in Figure 4, and the volume is calculated to substitute into the equations equal to 2.813 x 10^{-3} m^3. Using Eq. (10) and (11), these values were substituted and solved simultaneously which give m = 42.53 MN/m^2 and k = 6.328.

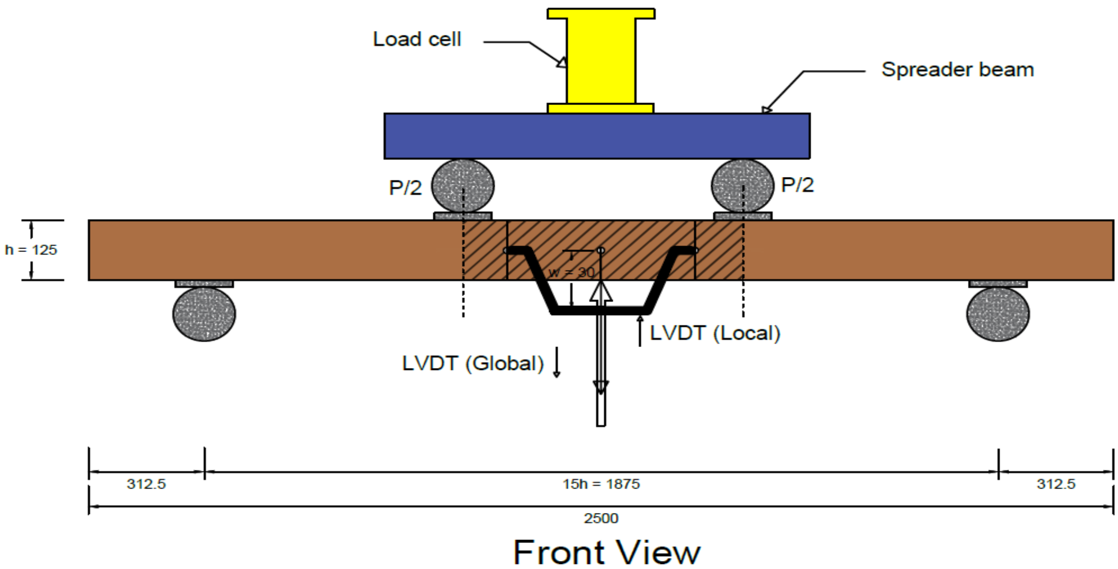

Fig. 4. Test piece for bending parallel to grain test

Using these values, the Weibull's cumulative curve was plotted in Figure 3. As the study used three different specimen sizes, the value of *m* changed according to their volume, but *k* remained constant. The value of Weibull's parameter m = 42.53 MN/m^2 and k = 6.328 for Kempas timber with characteristic density of 731 kg/m^3 are found reasonable. In accordance with EC5, any specimens that have depths and widths less than 150mm must be adjusted using the modification factor specified in EN384. EN384 provides a modification factor formula that is designed for softwood and temperate hardwood with characteristic densities below 700 kg/m^3 and has a fixed value of 0.2 for $1/k$. Using the Weakest Link Theory, as the k value is 6.328, the calculated value of $1/k$ is 0.16, which is close to 0.2. According to the verification, this proves that Weibull's theory can be used to access the depth effect for Malaysian tropical hardwood with higher density than established in EN384.

To address the depth effect, the modification factor can be used to adjust the design values of the strength properties of the timber to account for the reduction in strength with increasing depth. In general, as the depth of the timber specimens increases, the modification factor decreases, which accounts for the decreasing strength properties of the wood with depth. In addition to the depth effect, the modification factor is also influenced by other factors, such as the density of the local timber species. Different species have different densities, which can impact their strength properties and modification factors. From Table 3 tabulated, the study revealed that all the species tested produced a value of $1/k$ that is relatively close to 0.2. It is worth noting that the modification factor value differs for each species based on its density. This indicates that the density of a species can impact its modification factor value, which is used to adjust the strength properties of the timber in the design process. Therefore, it is important to consider the density of the timber species when determining its modification factor, as it can ultimately affect the safety and reliability of the final product.

4. Conclusions

In conclusion, the Weibull theory of brittle fracture has been substantiated as a relevant model for assessing the fracture characteristics of both local and hardwood timber, including tropical hardwoods. Notably, in the case of tropical hardwoods with a characteristic density below 700 kg/m^3, the values of $1/k$ were found to be approximately 0.208, 0.162, 0.201, and 0.204. These values closely align with the established value of 0.2 as stipulated in EN384, the industry standard. Similarly, for tropical hardwoods with a characteristic density exceeding 700 kg/m^3, the corresponding values of $1/k$ were 0.190 and 0.158, both of which approach the benchmark value of 0.2.

As a result, at present, it appears reasonable to apply the modification factor value specified in EN384 for tropical hardwoods in Malaysia. Nonetheless, it is important to acknowledge that this study involved a limited representation of timber species. Therefore, to draw more robust and comprehensive conclusions, further investigations encompassing a broader array of tropical hardwood species should be undertaken. This will ensure that the modification factor value remains a reliable and accurate tool for assessing the fracture behaviour of tropical hardwoods in Malaysia.

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