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EMPIRICAL FORMULA PREDICTING EMBEDMENT STRENGTH OF COCONUT WOOD

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ABSTRACT: Embedment strength is an important parameter in the design of dowel-type connections for timber construction. Coconut wood, abundant in South Asia, demonstrates good mechanical performance and could be used for construction. However, no standards are currently available for predicting coconut wood embedment properties. Consequently, this research aims to identify the best analytical model to predict the embedment strength of coconut wood (monocot). To achieve this, the investigation employed dowels with diameters of 10 mm and 14 mm and incorporated data from 12 mm and 16 mm from previous studies. Furthermore, a range of methods, including single variate, multivariate, linear regression, nonlinear regression, and cross-validation methods, were implemented. The findings suggested that single linear and multivariate non-linear equations provided the best fit and reliability for parallel- and perpendicular-to-gain loading, respectively.

KEYWORDS: Coconut wood; dowel embedment properties; half-hole test; timber engineering and structural performance.

1 – INTRODUCTION

Palm trees belong to the family Arecaceae and include hundreds of species [1]. Among them, coconut palm (*Cocos nucifera*) is one of the economically significant species and widely cultivated across Southeast Asia. Coconut wood has the potential to be used as a construction material for building components such as beams, trusses, posts, and floors, however, its application limited to small-scale buildings [2, 3].

Glued laminated timber (GLT) [4] and cross-laminated timber (CLT) [5, 6], are frequently used for mass timber construction due to their lightweight, prefabrication, and sustainability. Coconut wood has the potential to be used as an alternative raw material for producing GLT and CLT, which can enhance its value and utilization while reducing waste from plantation crops. Coconut wood's physical and mechanical properties were well-studied [4, 7, 8]. Unlike conventional wood, which has been widely used in timber construction, monocot stems, mainly made up of fibre and parenchyma cells [9], it does not have secondary growth due to a lack of cambium [7, 8]. Thus, due to the lack of theoretical and constructional standards, it has not been widely used for mass timber construction.

When using coconut wood as construction timber, embedment properties as an important mechanical parameter that are critical for designing dowel-type connections of timber construction should be considered. Embedment strength predictive equations, developed from empirical models based on experimental data, are used to estimate the load-carrying capacity of the connection system [10].

Eurocode 5 [11] and National Design Standard (NDS) for Wood Construction [12] standards provide empirical equations for predicting embedment properties. These equations were developed based on extensive experimental studies [10, 13, 14] considering the influencing factors such as timber density, fastener diameter and load-to-grain angle. However, these embedment strength prediction equations

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were developed for common softwood and hardwood species, and there are no standardized equations for predicting coconut wood embedment properties.

Wang et al. [3] reported that the NDS embedment strength prediction equations [12] overestimate for coconut wood and proposed empirical equations for predicting the embedment strength properties in parallel- and perpendicular-to-grain directions based on the half-hole tests with 6 mm, 12 mm, and 16 mm diameter dowels. The equations were established based on a single parameter, density, while the effect of dowel diameters was deemed insignificant based on the limited data. However, according to NDS [12] and Wilkinson's [14] research, dowel size is one of the critical embedment strength determinants.

This research aims to determine the most suitable empirical model that can accurately predict the embedment strength of coconut wood, while confirming whether a dowel diameter is a critical factor. Various analytical techniques were implemented: single variate analysis, multivariate analysis, linear regression, and nonlinear regression methods. Cross-validation procedures were also integrated into the study to ensure the derived equations' robustness and precision.

2 – MATERIAL AND METHODS

2.1 MATERIALS

Approximately 55 years old coconut trees were harvested from Thasala district, Nakhon Si Thammarat province, Thailand. Rough sawn coconut wood was kiln-dried to moisture content around 12% -15% and further processed to the half-hole embedment test specimens according to ASTM D5764-97a [15]. The holes with the diameters of 10 mm and 14 mm were drilled on the coconut wood blocks with the dimensions of 50 mm × 50 mm× 40 and mm 80 mm × 70 mm × 50 mm (Length × Width × Thickness), respectively. The oven-dry density of wood was measured following ASTM D2395-17 [16], ranging from 173 kg/m^3 to 1062 kg/m^3. Thirty specimens were prepared for each dowel size and loading orientation.

2.2 EXPERIMENTAL METHODS

Half-hole embedment test was conducted following ASTM D5764-97a [15]. Load was applied at the rates of 1.5 mm/min for 10 mm dowels and 2 mm/min for 14 mm dowels using an MTS machine (Figure 1). A displacement gauge was used to measure the movement of the loading head. Each test was terminated when the loading head displacement reached half of the dowel diameter, or the post-peak load dropped to 60 % of the peak load. To determine the yield load (f_y), linear regression analysis was performed on the data between 20% and 40% of the maximum load to estimate the initial slope of the load-deformation curve [17]. The slope was then offset by 5 percent of the dowel diameter while the yield load was identified where the offset line intersects the load-displacement curve (Figure 2a). If displacements at the intersection points exceeded those corresponding to the maximum loads, the maximum loads were taken as the yield loads (Figure 2b). The embedment strength (f_e) was calculated by dividing the yield load (f_y) by the product of the dowel diameter (d) and the specimen thickness (t).

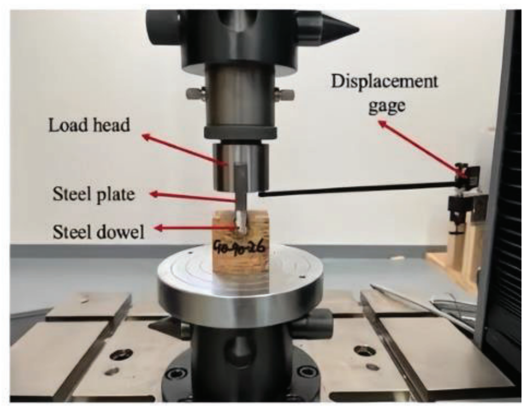
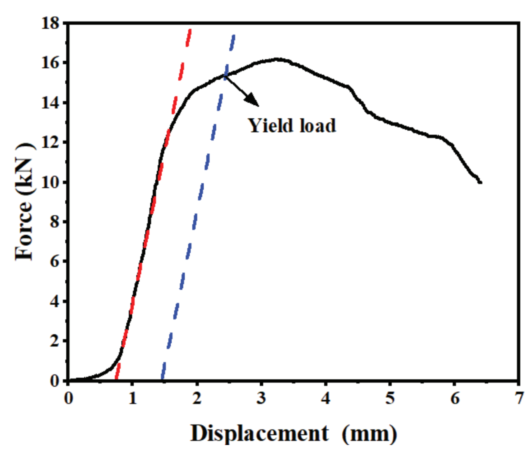
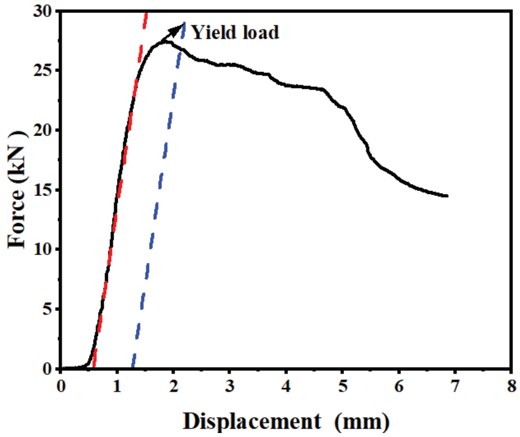


Figure 1. Embedment test settings.



(a)



(b)

Figure 2. Typical embedment force-displacement curves of 14 mm dowel diameter specimens load parallel to grain. (a) intersection as the yield load, (b) peak load as the yield load.

2.3 MODELLING METHODS

The empirical equation (1), (2) proposed by Wang et al. [3] were examined to determine their correspondence with the extended experimental data. It was evaluated based on root mean squared error (RMSE) and coefficient of determination (R^2), as presented in Table 1. RMSE quantifies the average difference between experimental data and a statistical model's predicted values, with lower RMSE values indicating less prediction errors and more precise predictions [18]. The R^2 measures the proportion of variance in the dependent variable explained by the independent variables, with values closer to 1 signifying a higher explanatory power of the model [19]. In this study, single-variate, multivariate, linear, and nonlinear regression models [20] were constructed. Density and dowel diameters were selected as independent variables based on the studies by Wang et al. [3] and NDS [12]. These regression models include parameters that define the intercept and slope of the regression line. The least squares method was implemented to estimate these parameters by minimizing the sum of the squared differences between the experimental values and the predicted values [20]. The statistical significance of each independent variable was evaluated on the p-value, with a p-value less than 0.05 indicates the variable has a significant influence on the model predictions. Model performance was assessed using a 5-fold cross-validation method [21], wherein the original sample is randomly partitioned into five equal-sized subsamples. One subset was designed for validation, while the remaining subsets were utilized for training. The cross-validation process is repeated five times, with each subsample serving as validation data once.

Parallel $$f_{e,0} = 0.09171\rho - 15.01918 \tag{1}$$

Perpendicular $$f_{e,90} = 10^{-4} \times 1.02\rho^{1.91} \tag{2}$$

Table 1. Expressions of analytical models and statistical indicators

	Regression model	RMSE	R^2
linear	$y = \beta_0 + \beta_1\rho$ $y = \beta_0 + \beta_1\rho + \beta_2 d$ $y = \beta_0 + \beta_1\rho + \beta_2\rho d + \beta_3 d$	$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$	$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2}$
Non-linear	$y = \alpha\rho^{\beta_1}$ $y = \alpha\rho^{\beta_1}d^{\beta_2}$		

Note: y is the embedment strength in MPa, ρ is the oven-dry density of wood in kg/m^3; d is the dowel diameter in mm, β_i is the intercept, RMSE is root mean squared error, R^2 is coefficient of determination, y_i is the observation value, and $\hat{y}_i$ is the corresponding predicted value.

3 – RESULTS AND DISCUSSIONS

The embedment strength of coconut wood under two loading directions was analysed using data from 10 mm and 14 mm dowels, along with 12 mm and 16 mm dowels [3]. Table 2 presents the accuracy assessment results of the empirical equations proposed by Wang et al.[3]. The equation partially explained the trend of embedment strength increasing with wood density. The R^2 values of the empirical equations were over 0.9 for predicting the embedment strength of wood under loading with 12 mm and 16 mm dowels in both parallel- and perpendicular-to-grain loading directions (Table 2). However, when the two additional data sets (i.e. 10 mm and 14 mm) were considered, the empirical equations yielded RMSE and R^2 values of 7.76 and 0.83; as well as 6.88 and 0.85, for the parallel- and perpendicular-to-grain embedment strength, respectively, indicating a potential prediction bias (Table 2).

Table 2. The RMSE and R^2 values of Wang et al. [3] equations for different data sets

Equation	Data sets (*d* in mm)	RMSE	R^2
(1) [3]	12,16	5.18	0.91
(2) [3]	12,16	5.59	0.91
(1) [3]	10,12,14,16	7.76	0.83
(2) [3]	10,12,14,16	6.88	0.85

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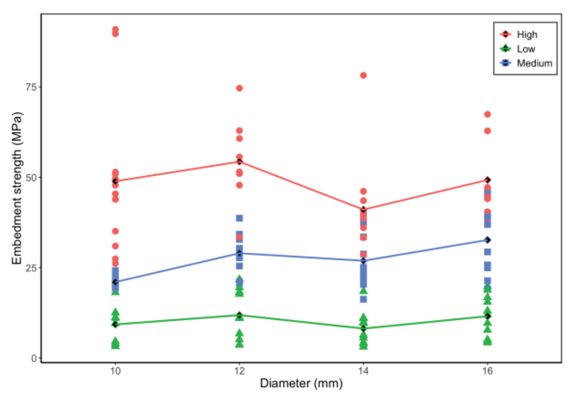
Thus, to improve the predictive accuracy, the influence of density (ρ), dowel diameter (d) and the interaction between ρ and d were proposed to be considered for the embedment strength prediction in this study. The best-fitted regression models are presented in Table 3 with their statistical indicators (i.e., RMSE, R^2, and p-value). The results indicated that d has an insignificant effect on the embedment strength under parallel-to-grain loading (p-value > 0.05). In contrast, d has a significant impact on embedment strength under perpendicular-to-grain loading (p-value ≤ 0.05).

Table 3. Comparison of Linear and Nonlinear Models' performance for predicting embedment strength under parallel and perpendicular-to-grain loading directions

Model	loading direction	Regression analysis results				Cross-validation results	
		Equation	RMSE	R^2	p-value	RMSE	R^2
Linear	Parallel-to-grain	$f_{e,0} = 0.08408\rho - 13.42869$ (3)	7.27	0.85	ρ: 2×10^{-16} *	7.25	0.85
		$f_{e,0} = 0.08471\rho + 0.84527d - 15.85856$ (4)	7.30	0.85	ρ: 2×10^{-16} * d: 0.16	7.25	0.85
		$f_{e,0} = 0.09616\rho + 3.25679d - 0.00473\rho d - 21.84792$ (5)	7.24	0.85	ρ: 2×10^{-16} * ρd: 0.10 d: 0.04*	7.44	0.85
Nonlinear		$f_{e,0} = 10^{-3} \times 1.6346\rho^{1.56}$ (6)	7.06	0.86	ρ: 2×10^{-16} *	7.11	0.84
		$f_{e,0} = 10^{-3} \times 1.54\rho^{1.57} d^{0.03}$ (7)	7.07	0.86	ρ: 2×10^{-16} * d: 0.48	7.13	0.85
Linear	Perpendicular-to-grain	$f_{e,90} = 0.07017\rho - 17.52614$ (8)	8.14	0.79	ρ: 2×10^{-16} *	8.10	0.82
		$f_{e,90} = 0.07016\rho - 0.18857d - 15.07469$ (9)	8.16	0.79	ρ: 2×10^{-16} * d: 0.58	8.41	0.82
		$f_{e,0} = 0.08997\rho + 0.56482d - 0.00148\rho d - 25.14169$ (10)	8.16	0.79	ρ: 5.78×10^{-15} * ρd :0.33 d: 0.50	8.83	0.79
Nonlinear		$f_{e,90} = 9.61 \times 10^{-6} \rho^{2.28}$ (11)	6.32	0.88	ρ: 2×10^{-16} *	7.11	0.85
		$f_{e,90} = 1.71 \times 10^{-5} \rho^{2.41} d^{-0.57}$ (12)	5.83	0.89	ρ: 2×10^{-16} * d: 1.94×10^{-6} *	6.36	0.86

To further verify the influence of d, the mean values of embedment strength at each d for both parallel- and perpendicular-to-grain loading directions were plotted for three density groups (i.e., high (600-900 kg/m^3), medium (400-600 kg/m^3) and low (100-400 kg/m^3)), as shown in Figure 3. No clear trend was observed between embedment strength and d under parallel-to-grain loading, while embedment strength decreased as d increased under perpendicular-to-grain loading.



(a)

Classification: In-Confidence

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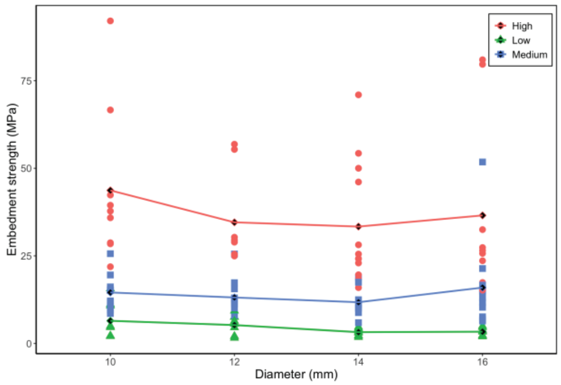
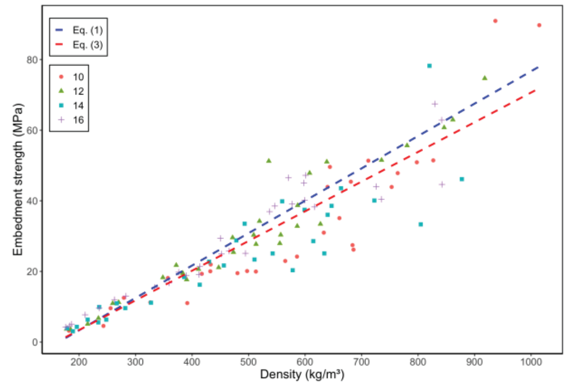


(b)

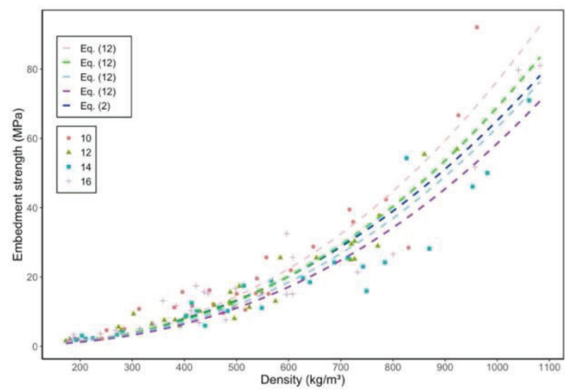
Figure 3. Experimental and mean value of embedment strength of three density groups: High (600-1000 kg/m^3); Medium (400-600 kg/m^3); Low (100-400 kg/m^3) at each dowel diameter for a) parallel-to-grain and b) perpendicular-to-grain loading directions.

Since d has an insignificant effect on the embedment strength under parallel-to-grain loading, a more generalized and stable predictive equation is preferred to enhance the model's applicability and reliability. The cross-validation results indicated that the linear regression model (Eq 3) demonstrated good stability, with an R^2 value of 0.85 and an RMSE value of 7.25, which is lower than the RMSE value of 7.27 obtained from initial regression analysis (Table 3). In contrast, d has a significant impact on embedment strength under perpendicular-to-grain loading, multivariate non-liner equation (Eq 12) provides the best fit for the data, with an RMSE and R^2 value of 5.83 and 0.89 (Table 3), and the cross-validation results further confirmed its reliability and accuracy, showing RMSE and R^2 values of 6.36 and 0.86. Thus, the best fitted equations for predicting coconut wood embedment strength are Eq (3) and (12).

Figure 4 presents the parallel- and perpendicular-to-grain embedment strength test data and predicted values according to Eq. (1), (2), (3) and (12). The prediction equations established by Wang et al. [3] overestimate the embedment strength in a parallel-to-grain direction (Figure 4a) while underestimating such property in a perpendicular-to-grain direction (Figure 4b). The newly proposed equations, Eq. (3) and (12), show the improved prediction accuracy in the same figures. The inclusion of dowel diameter in the perpendicular-to-grain embedment strength prediction leads to an inverse relationship between the strength and dowel diameter given the same density.



(a)



(b)

Figure 4. Relationship between the embedment strength, dowel diameter and density for a) parallel-to-grain and b) perpendicular-to-grain loading directions.

4 – CONCLUSION

A comprehensive assessment of the embedment strength prediction models for coconut wood was conducted for both parallel- and perpendicular-to-grain load directions, considering wood density and dowel diameter as modeling parameters. Through regression and cross-validation analysis, single and multivariate equations were proposed for predicting the embedment strength under parallel- and perpendicular-to-grain loading, as they best fitted the experimental data based on R^2 and RMSE, respectively. This study confirms that wood density is the only parameter that significantly influences the embedment strength of coconut wood under parallel-to-grain loading, while both wood density and dowel diameter significantly influence its perpendicular-to-grain embedment strength. To further expand the use of palm wood, beyond just coconut palm

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wood, in building construction, future research should focus on evaluating the applicability of the proposed embedment prediction equations to other common palm species, such as oil palm. Additionally, exploring other fundamental connection properties, such as nail and screw withdrawal strength, is recommended.

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