2D Model of Strength Parameters for Bamboo Scrimber

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Experiments were performed to test the compressive strength of bamboo scrimber board at different grain angle directions. Investigation of test samples allows for the identification of the correlation between compression failure stress and various failure mechanisms at different grain angles. The results of the experiments showed that the density of bamboo scrimber influenced compression failure stress linearly. A new approach to describe the failure stresses of bamboo scrimber was proposed. The density was introduced as a model parameter to describe compressive properties at varying angles of grain. In comparison to a one-dimensional model, there was much less relative error between predicted values and measured values by this 2D model. This report aims to improve the precision of existing strength models for various grain angles and to provide a competing method for the practical use of bamboo scrimber.

Keywords: Bamboo scrimber; Compressive properties; Density; Grain angle; 2D model

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INTRODUCTION

A bamboo scrimber includes a plurality of pressure-pressed bamboo strips impregnated with an adhesive and modified through heat-treatment. Each of the bamboo strips is formed with a plurality of slots penetrating through the bamboo strip substantially in a direction of thickness defined by the bamboo strip (Zhang *et al*. 2011). Reconsolidated wood, which is proposed by Coleman (Coleman and Hills 1980), provides references for bamboo scrimber. Research related to bamboo scrimber started about 20 years ago in Asian countries (Zhang and Yu 2008). Due to its excellent processing performance, bamboo scrimber has been widely used in indoor decoration and in the civil engineering field (Zhang *et al*. 2008; Zhang *et al*. 2012; Yu *et al*. 2014). In the development of manufacturing technique for bamboo scrimber, press technology and glue immersion have been studied, and ideal process parameters for bamboo scrimber have been determined (Cheng *et al*. 2009; Wang *et al*. 2013; Yu and Yu 2013). However, mechanical models of bamboo scrimber have not been widely reported. In the aspect of being as a building material for wooden structures, the development of strength models for bamboo scrimber is important for future applications of the material and in the dissemination of the material in the wood structure field.

Grain angle, which affects the mechanical properties, is a significant factor in the application of bamboo scrimber. Researchers have proposed many strength models regarding to the relationship between grain angle and mechanical properties. Among those models, the Hankinson formula (Hankinson 1921), Norris formula (Norris 1962), Maximum stress theory, and Tsai-Hill theory (Tsai 1965) are the most widely used criteria for predicting mechanical properties of structural materials (Liu 1984; Mascia and Simoni

2013). The compressive behavior of spruce wood under uniaxial loading has been studied by Reiterer and Stanzl-Tschegg (2001) at different orientations with regard to the longitudinal and radial direction. Tsai-Hill strength criterion was used to describe the tendency of crushing strength at various grain angles. The predicted values from the model were in accordance with the observed values because the density of the wood sample was fairly uniform. The Hankinson formula, Maximum stress theory, and Tsai-Hill theory are applied to estimate the strength of laminated veneer lumber by uniaxial tension test at various angles to the grain (Oh 2011). These criteria predict the approximate tension strength at different grain angles. However, there are errors between prediction data and measured values. This may be due to density variation caused by uneven sizing. However, the presumption of these models is the uniform density of samples used in them. Materials with uneven density in real processes are normal. This reality should not be neglected.

Density is another strength parameter affecting the mechanical properties of biomass materials. In most studies, material density and grain angle are studied separately (Galicki and Czech 2005; Machado *et al*. 2014). A linear regression analysis indicated that 84% of the variability of compression strength could be explained by density (Gindl and Teischinger 2002). Failure mechanisms of pine wood under off-axis compression had been studied by Oh (2011), but the correlation between density and off-axis strength was not considered as in the study of Galicki and Czech (2013), causing errors in the practical application for biomass materials with various densities. Density and grain angle have been considered in a 2D model by Galicki (2009) and resulted in a high degree of agreement between experimental and model data. Therefore, establishing a 2D strength model relating to density and grain angle as two parameters of strength could be a potential method for predicting bamboo scrimber mechanical properties.

Due to uneven sizing during the production process and the density discrepancy between bamboo fiber and adhesive, density differences exist on the same bamboo scrimber board. The predicted values from existing strength models are not accurate when including both the parameters of density and grain angle. In this paper, a 2D model for strength parameters of bamboo scrimber was established. The new model improves prediction accuracy, refines the compressive model for various grain angles, and provides technical support to the field of wood structure for the application of bamboo scrimber.

EXPERIMENTAL

Materials

Neosino calamus affinis, age 3-4 years, was used as a raw material to produce bamboo scrimber. The nominal dimension of each board was 250 cm (length) × 64 cm (width) × 3.4 cm (thickness). Untreated bamboo fiber bundles were laid in parallel, and a PF162510 phenol-formaldehyde resin (Dynea Co., Beijing City, China) (45.59% of solids content, 36CP · s of viscosity, 10-11 pH) was used. The amount of glue was controlled to about 15% of the dry weight of the bamboo scrimber during dipping glue process. After that, bamboo scrimber fiber bundles were kept at a temperature of 140 °C and a pressing pressure of 5.0 MPa for a holding time of 34 min (1 min/mm ×34 mm). The average air-dry density and moisture content of the bamboo scrimber boards were 1.12 ± 0.9 g/cm^3 and 7.42 ± 0.96%, respectively.

The nominal dimension of the sample used for compression studies was 20 mm (length) × 20 mm (width) × 30 mm (height). Specimens with grain angles of 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, and 90° were prepared for the compression test, as shown in Fig. 1.

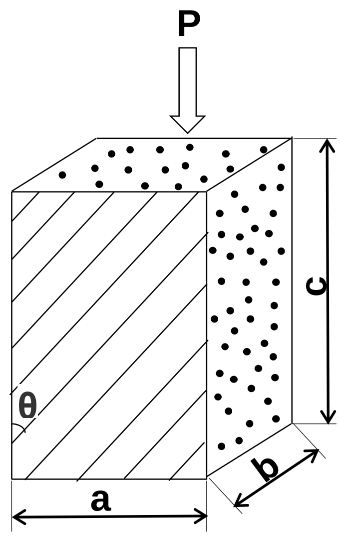

Fig. 1. Specimens for compressive test at θ (ranged from 0 ° to 90 °). P is compressive load; a, b and c are 20 mm, 20 mm and 30 mm, respectively

Methods

Compression testing

Bamboo scrimber is an orthotropic material, so there are three principal axes for which the mechanical properties differ. The angles (θ) between loading direction and fiber direction ranged from 0° to 90°. A total of 400 samples were tested, 40 samples at each grain angle.

The densities of the samples (total of 400 samples) ranged from 0.85 g/cm^3 to 1.35 g/cm^3. To ensure the random distribution of the samples, specimens of one grain angle were cut from different parts of the five boards, as shown in Fig. 2.

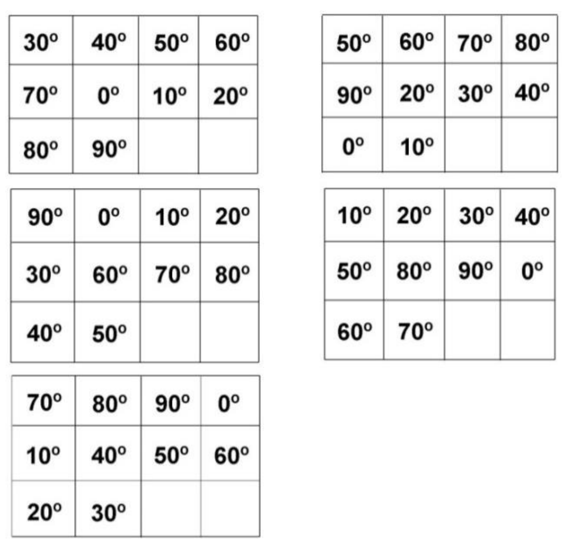

Fig. 2. Sawing pattern of grain angles

Eight samples for each grain angle were prepared from one board. The sampling distribution for ten grain angles on each board is shown in Fig. 2. Sawing patterns in Fig. 2 could guarantee the samples of each grain angle to be obtained from both the middle and the edge of the board.

Forty samples, with known densities, were prepared and tested at each grain angle on an Instron 5582 Universal Testing Machine with an accuracy of 0.001MPa (Instron Co., Grove City, PA, USA) (Fig. 3). The samples were loaded to failure at 1 mm/min, and the maximum load was taken as the failure load.

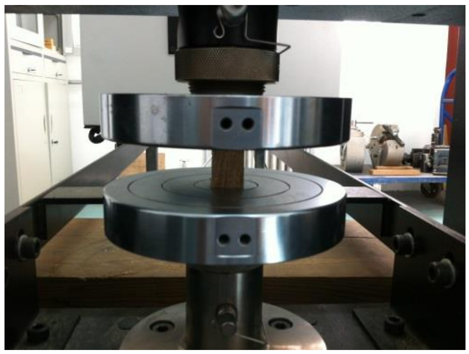

Fig. 3. Compression test set-up

Model formulas

The mechanical models used to predict compressive properties at various grain angles in this experiment were the Hankinson formula (Hankinson 1921) and the Chinese National Standard GB 50005 (2003) formula,

Hankinson formula:

$$f = \frac{f_1 f_2}{f_1 \sin^2\theta + f_2 \cos^2\theta} \tag{1}$$

GB 50005 formula:

$$f = \frac{f_1}{1 + \left(\frac{f_1}{f_2} - 1\right)\frac{\theta - 10°}{80°}\sin\theta} \tag{2}$$

where f denotes the compressive properties when the angle is θ between loading direction and grain direction (Fig. 1), and f_1 and f_2 are the compressive properties parallel and perpendicular to the grain, respectively.

Kolmogorov-Smirnov test

The Kolmogorov-Smirnov test (K-S test) can serve as a goodness of fit test (Kolmogorov 1933). In the case of testing for normality of distribution, samples are standardized and compared with a standard normal distribution. The formula is,

$$D = \max\left(|S(x) - F(x)|\right) \tag{3}$$

where *S(x)* and *F(x)* are the cumulative probability value from the sample and theoretical distribution, respectively. Normal distribution is chosen to be *F(x)*, and maximum absolute difference between *S(x)* and *F(x)* was taken as *D*.

If $D<\alpha$, then the difference between *F(x)* and *S(x)* is significant. If $D>\alpha$, the difference between *F(x)* and *S(x)* is not significant. The α is chosen to be 0.05.

Shapiro-Wilk test

The Shapiro-Wilk test can check whether a sample came from a normal distributed population (Shapiro and Wilk 1965). The test formula is,

$$W = \frac{(\sum_{i=1}^{n} a_i x_i)^2}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{4}$$

where x_i is the *i*th order statistic, $\bar{x}$ is the sample mean, and the a_i series represents the constants, which are calculated by,

$$(a_1, \cdots, a_n) = \frac{m^{\mathrm{T}} V^{-1}}{(m^{\mathrm{T}} V^{-1} V^{-1} m)^{1/2}} \tag{5}$$

where $m=(m_1, \ldots, m_n)^T$, $m_1, \ldots, m_n$ are the expected values of the order statistics of independent and identically distributed random variables sampled from the standard normal distribution, and *V* is the covariance matrix of the order statistic.

If $W<\alpha$, then the difference between the normal distribution and the tested distribution is significant. If $W>\alpha$, then the difference between the normal distribution and the tested distribution is not significant. The α value is chosen to be 0.05.

RESULTS AND DISCUSSION

Failure Types

The failure types of the tested bamboo scrimber samples according to grain direction are shown in Fig. 4. The shear failure parallel to grain was predominant at all grain angles except for 0° and 90°. The failure type of 10° samples was similar to the 0° sample due to the slight grain angle of 10° samples.

Dislocation occurred from 20° to 50° grain angles samples. This was because shear force parallel to grain was large among these grain angles. Samples from 60° to 90° displayed cracking along the sample grain and approached compression perpendicular to the grain gradually.

Test of Normality for Density

A histogram and the normal distribution curve of density for the 400 samples are shown in Fig. 5. Kolmogorov-Smirnov test was used in the normality test of density.

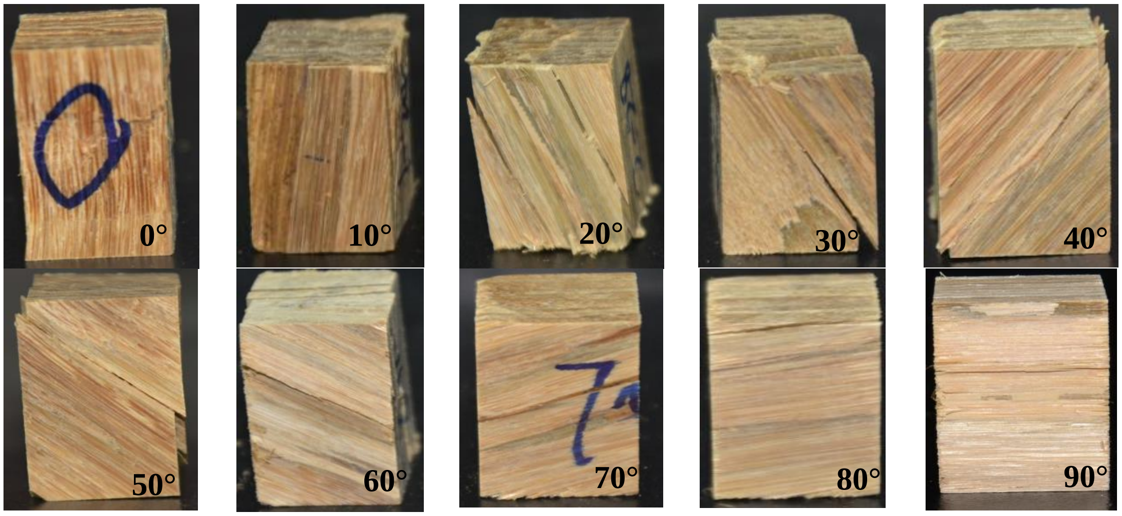

Fig. 4. Failure types of tested bamboo scrimber specimens according to grain direction (from left to right: 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, 90°)

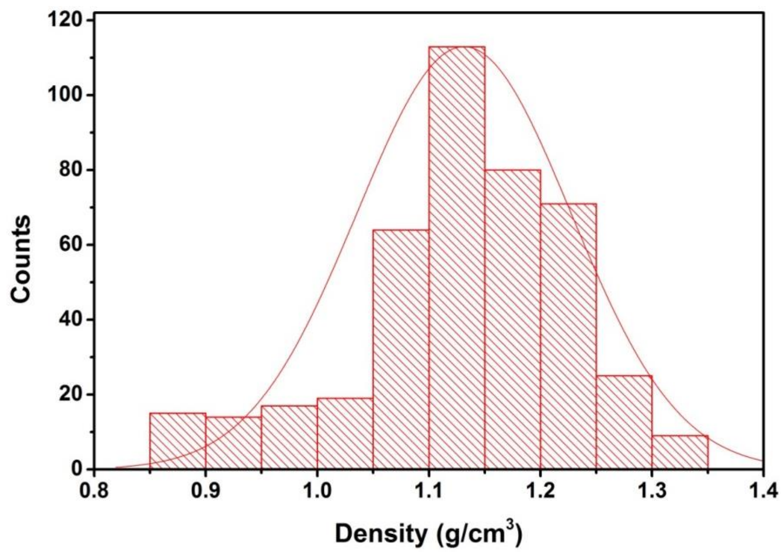

Fig. 5. Histogram and the normal distribution curve for sample density data

Table 1. Normality Test of Density using Kolmogorov-Smirnov (K-S) Method

Statistic	K-S test
0.040	0.187

The maximum frequency of the sample density was around 1.1 g/cm^3, which was close to the average density of the sample. This result shows that density deviation, which can affect mechanical properties, exists in bamboo scrimber board despite much efforts directed to alleviating it during manufacturing. In Table 1, the K-S test, which requires a relatively large number of data points (Zhang 2004), shows that the level of significance is over 5%. It indicates that density data are consistent with a normal distribution. Since normal distribution of the sample density illustrates the independence and randomness of sampling, the data are considered reliable and can be used for modeling.

Test of Normality for Ultimate Strength

Samples of various grain angles were selected from five boards. The ultimate strengths were tested, and the data followed normal distributions. Histograms and normal distribution curves for the angles θ=0° and θ=90°, which are the required angles in Hankinson formula and the GB 50005 formula, are shown in Fig. 6. Shapiro-Wilk test was used in the normality test of ultimate strength.

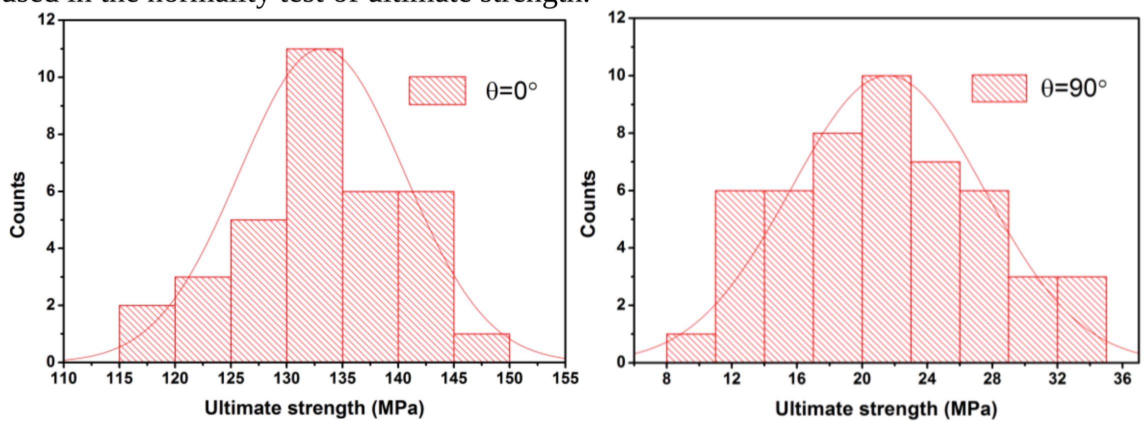

Fig. 6. Histograms and normal distribution curves for ultimate strength with θ = 0° and θ = 90°

Table 2. Normality Tests of Ultimate Strengths using Shapiro-Wilk Method

Grain angle	Shapiro-Wilk test
0°	0.812
90°	0.603

The ultimate strengths for specimens of θ = 0° and θ = 90° show normal distributions. The maximum frequency of ultimate strength parallel to grain was around 133 MPa, which equals the average strength for θ = 0° angle samples. The maximum frequency of ultimate strength perpendicular to grain was around the average strength (21 MPa). The Shapiro-Wilk test (Table 2), which is limited to samples between 3 and 50 elements (Zhang 2004), shows that significance levels for both 0° and 90° samples are over 5%. This result verifies that samples of θ = 0° and θ = 90° obey normal distribution and that the ultimate strength data are reliable for use in modeling.

Compressive strengths of grain angles

Compressive strength of bamboo scrimber declined while the grain angles increased from 0° to 90°. In Fig. 7, compressive strength decreased dramatically from 0° to 50° grain angles, and changed slightly from 60° to 90°. Thus, more attention should be paid to grain angles from 0° to 50° than from 60° to 90° in the application of bamboo scrimber. The trend of the curves predicted by GB 50005 formula and Hankinson formula agreed with the test values. Calculated values by GB 50005 formula were higher than that predicted by Hankinson formula, and values predicted by GB 50005 deviated from test values greater than that of Hankinson formula from 0° to 50° grain angles. However, predicted values of GB 50005 formula were closer to test values from 60° to 90° grain angles. From Fig. 7, it can be seen that the accuracy of Hankinson formula was higher than GB 50005 formula.

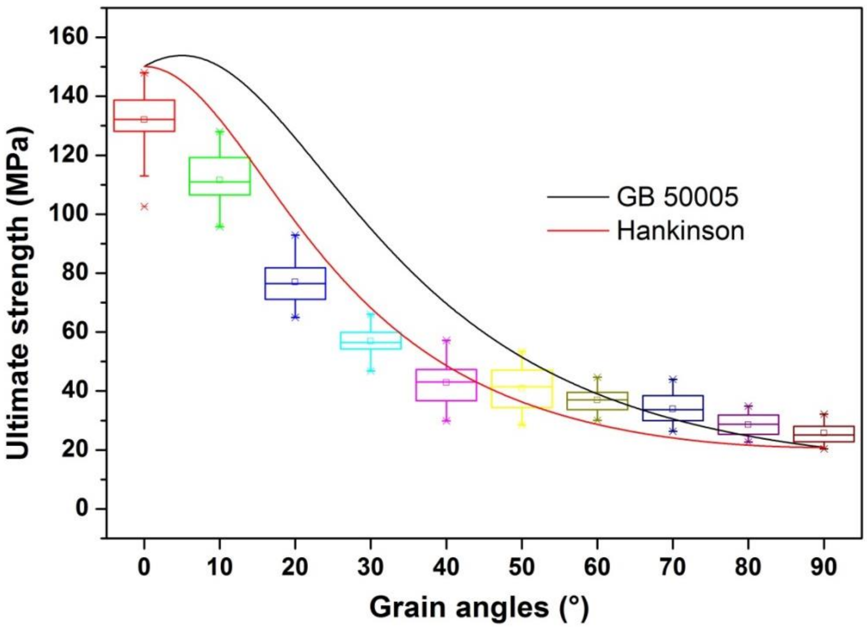

Fig. 7. Compressive strengths at various grain angles

2D models of Compressive Strength for Density and Grain Angle

A linear relationship was found between bamboo scrimber density and ultimate strength (Fig. 8). Linear expressions were chosen to fit the relationship between density and ultimate strength at various grain angles. Simulated expressions were obtained and are shown in Table 3.

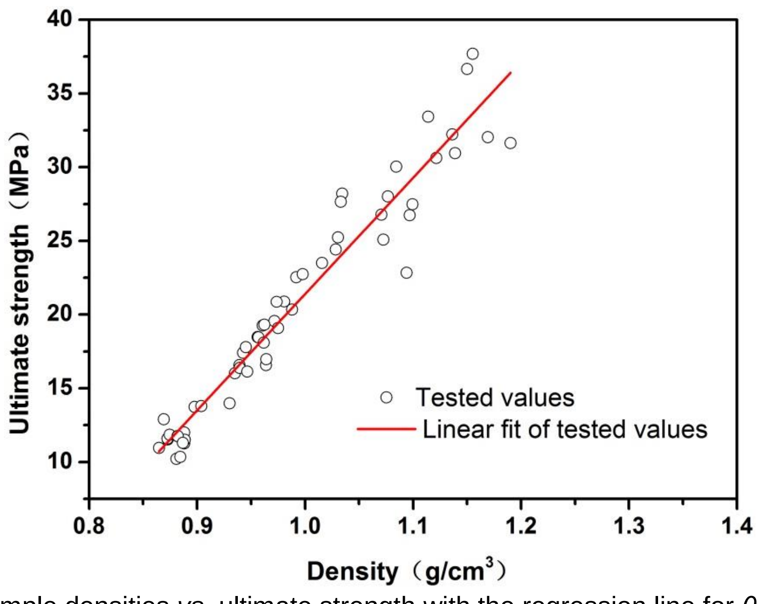

Fig. 8. Plot of sample densities *vs*. ultimate strength with the regression line for θ = 90°

Table 3. Simulated Expressions of Ultimate Strength at Various Grain Angles

Grain angles	Simulated expressions	R^2
0°	f = 105.18ρ+16.31	0.624
90°	f = 78.87ρ-57.48	0.940
f is the ultimate strength, MPa; ρ is density, ranges from 0.85 g/cm^3 to 1.35 g/cm^3; R^2 is coefficient of determination		

Results in Table 3 show that the simulated expressions could properly represent the correlation of the two variables with a high determination coefficient. The coefficients in the simulated expressions in Table 3 expressions varied. However, the angles of inclination for the straight lines of θ = 0° and θ = 90° were 89.455° (arctan105.18) and 89.274° (arctan78.87), respectively. This illustrates that the simulated lines were almost parallel to each other, and the strength increased with increasing density at the same rate for both θ = 0° and θ = 90° samples. Therefore, the expressions fitting the relationship between grain angle and density were reliable. The difference of intercept of the two expressions was caused by different strengths between θ = 0° and θ = 90° at the same density. The difference of coefficient in the expressions was also found in fitting the relationship of wood. Simulated expressions for fir (*Cunninghamia lanceolata* (Lamb.) Hook.) are f=1455ρ-151 in Hunan province and f=1119.34-43 in Fujian province (Pan and Zhu 2009). The ultimate strengths of bamboo scrimber at various grain angles can be obtained by substituting density value into the simulated expressions.

Simulated expressions of ultimate strengths for θ = 0° and θ = 90° were substituted into Eqs. (1) and (2), respectively.

Modified Hankinson formula:

$$f = \frac{(105.18\rho + 16.31)(78.87\rho - 57.48)}{(105.18\rho + 16.31)\sin^2\theta + (78.87\rho - 57.48)\cos^2\theta} \tag{6}$$

Modified GB 50005 formula:

$$f = \frac{105.18\rho + 16.31}{1 + \left(\frac{105.18\rho + 16.31}{78.87\rho - 57.48} - 1\right)\frac{\theta - 10°}{80°}\sin\theta} \tag{7}$$

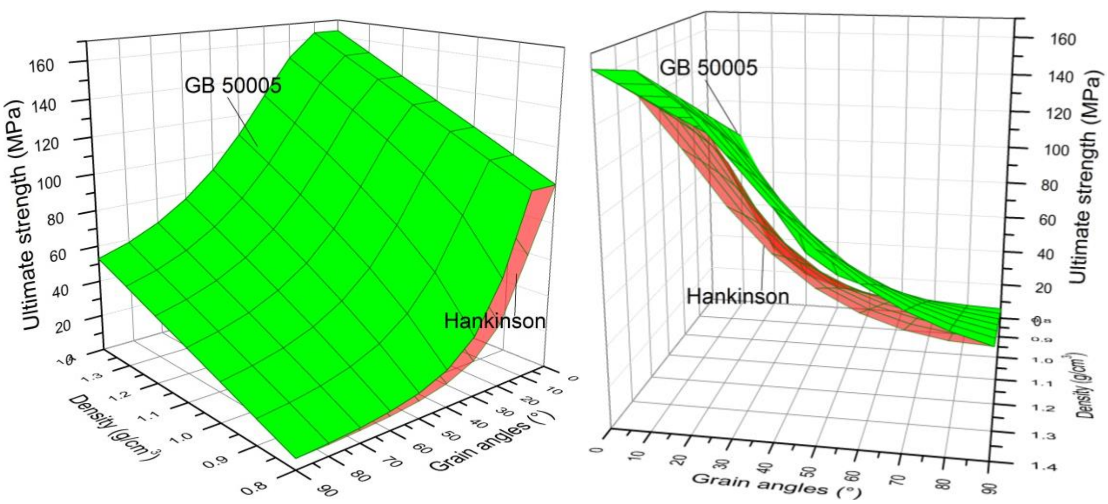

Fig. 9. 2D models of ultimate strength for various grain angles and different densities

Figure 9 shows that the predicted values from the two models formed inclined surfaces and that GB 50005 (2003) derived values were higher than Hankinson (1921) derived values. The ultimate strengths decreased with increasing grain angle, while decreasing with decreasing density. The grain angle showed a curved surface, while density showed a linear tendency. In the 2D model of the GB 50005 formula, the ultimate strength for θ = 10° was slightly higher than that for θ = 0° at the same density, which deviates from the actual test data. In the compression process, inclination of grain angle (θ = 10°) produces shear, which reduces the ultimate strength. The actual ultimate strength data for θ = 10° were lower than that for θ = 0°, so the predicted values of Hankinson were closer to the actual test data. In Fig. 9, the largest decline of ultimate strength occurred between θ = 20° and θ = 50° in the density range. The slopes of the curves showed a greater rate of change along with the change in grain angles rather than along with the density. This suggests that the grain angle of bamboo scrimber had more impact on compressive strength than density.

Table 4. Measured Values and Predicted Values of Ultimate Strengths

Density (g/cm^3)	Measured Value (MPa)	GB 50005[1] (MPa)	Hankinson[1] (MPa)	GB 50005[2] (MPa)	Hankinson[2] (MPa)
1.21 (0°)	143.91	133.42 (7.20%)	133.42 (7.20%)	143.53 (0.26%)	143.53 (0.26%)
1.05 (10°)	101.29	133.42 (31.71%)	118.46 (16.95%)	126.76 (25.14%)	113.11 (11.66%)
1.01 (20°)	66.83	113.17 (66.15%)	89.56 (31.50%)	106.93 (56.98%)	84.88 (24.61%)
1.02 (30°)	51.16	87.60 (71.23%)	66.20 (29.40%)	81.09 (58.51%)	60.15 (17.57%)
0.93 (40°)	26.81	66.42 (147.76%)	48.88 (82.33%)	46.56 (73.68%)	32.70 (21.97%)
1.11 (50°)	45.59	51.26 (12.43%)	38.60 (15.33%)	58.34 (27.97%)	44.88 (1.56%)
1.29 (60°)	61.18	40.86 (33.20%)	32.23 (47.31%)	66.00 (7.88%)	54.16 (11.47%)
1.21 (70°)	41.43	33.78 (18.45%)	28.41 (31.42%)	48.68 (17.50%)	41.70 (0.66%)
1.11 (80°)	30.77	28.97 (5.85%)	26.37 (14.30%)	34.17 (11.05%)	31.25 (1.56%)
1.16 (80°)	32.58	28.97 (11.08%)	26.37 (19.06%)	38.22 (17.31%)	35.03 (7.52%)
1.21 (80°)	43.00	28.97 (32.63%)	26.37 (38.67%)	43.02 (0.05%)	39.53 (8.07%)
1.26 (80°)	51.79	28.97 (44.06%)	26.37 (49.08%)	47.03 (9.19%)	43.30 (16.39%)
0.88 (90°)	11.25	25.73 (128.71%)	25.73 (128.71%)	12.56 (11.64%)	12.56 (11.64%)

[1]1D model; [2]2D model
Values in parentheses denote relative errors

To test the accuracy of the model, experimental values of θ = 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, 90°, and values of θ = 80° with various densities were selected randomly from the test values. These test values were compared with the predicted values obtained by 1D and 2D models (Table 4). Disparities existed between measured values and predicted values calculated by 1D models. The relative error reached up to 147.76% deviation from test values. The 1D models cannot accurately predict the mechanical properties of bamboo scrimber in comparison to the 2D models, which include the density parameter in the equation. Modified formulas can predict compressive strength of bamboo scrimber more accurately, overcoming the errors caused by specimen density. Galicki (2009) uses coordinate system to study 2D model parameters. A coordinate system is used to simulate grain angles at three principal coordinates relative to structure of wood theoretically. The result showed that stresses models with grain angle and density parameters can agree with experimental data well. Test values of θ = 80° in this experiment reflect that the compressive strength is influenced by density. In 1D models, the predicted values of θ = 80° with densities of 1.11 and 1.26 g/cm^3 had errors of 5.85% and 44.06% in the GB 50005 formula and 14.30% and 49.08% in the Hankinson formula, respectively. This means that relative errors were smaller when sample densities were close to the average density. When deviating from average density, the discrepancy of relative errors between the 2D models and 1D models increased. This is because the density parameter is not included in the 1D models.

CONCLUSIONS

1. The GB 50005 formula and Hankinson formula are applicable in predicting the trend of compressive strength at various grain angles. GB 50005 formula generates higher data than Hankinson formula. The accuracy of Hankinson formula is higher than GB 50005 formula for predicting compressive strength of scrimber bamboo.
2. Compressive strength between 0° to 50° grain angles should be more influential in application due to its greatly decreasing performance. According to 2D model, impact of density on ultimate strength is less than that of grain angle.
3. The accuracy of the 2D model to predict the ultimate strength of bamboo scrimber board is higher than that of the 1D model. It is believed that the combination of the two parameter, grain angle and density, in the model could avoid the problem arose from density variation.

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