Parameters of Strand Alignment Distribution Analysis and Bamboo Strandboard Properties

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Strand length, free-fall distance (FFD), and plate spacing was varied to control the strand alignment distribution of strandboard. To determine the strand angle distribution, photographs of strands were recorded as digital image data, and strand angle analysis was conducted using a modified von Mises distribution function. A part of this measurement was used as a reference for the alignment in the board produced. The results of strand alignment distributions showed that the *k* value was a function of strand length, FFD, and plate spacing. The *k* value can be improved by adjusting the plate spacing closer to the strand width, shortening the FFD, and using long strands. The power equation model can describe those relations. The bending properties and linear expansion (LE) were greatly affected by the FFD and the plate spacing. The use of low FFD and narrow plate spacing improved the bending properties. The decreasing bending properties in the parallel direction could be comparable to the increasing ones in the perpendicular direction. The contribution of bamboo strand in the longitudinal direction affected these results.

Keywords: Strand alignment analysis; Free fall distance; Plate spacing; Strand length; Strandboard

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INTRODUCTION

Structural oriented strandboard (OSB) is a special board product in which the strands are oriented such that the grain directions of the individual wafers/flakes are assembly-parallel. It is well-known that the board properties of OSB are influenced by the orientation of the strands. Many variables influence the oriented strand, including the strand length (SL), free fall distance (FFD), plate spacing (PS), and width of strands.

Several studies have investigated the effect of orientation angle, angle measurement using a percent of alignment (Geimer 1976), and predicting the modulus of elasticity of oriented waferboard using a numerical approach (Wing and Lau 1981). The von Mises function is the best method to describe strand distribution (Shaler 1991) and describe the characteristics of oriented flake board (Harris and Johnson 1982). Free fall distance and strand length were found to affect the strand alignment distribution (Suzuki and Takeda 2000). The board properties were affected by alignment angle, layer structure (Kajita 1987), and strands dimension (Nishimura *et al.* 2004).

Previous studies on the topic of orientation have focused primarily on manufactured particleboards and OSB at various degrees of orientation, from random orientation to highly oriented. However, the basic parameters that control the strand alignment angle have not yet been investigated. Without measuring the strand length, FFD, plate spacing, and width of the strand, the alignment angle distribution cannot be predicted using mathematical relationships.

The objective of this study was to evaluate the basic relationship among strand length, FFD, and plate spacing on strand alignment angle distributions using bamboo strands. The board properties of bamboo OSB at various FFDs and plate spacings are also discussed.

EXPERIMENTAL

Strand Preparation

Strands were produced from moso bamboo using a ring-type flaker in the laboratory. The target dimensions of strands were 20, 40, 60, and 80 mm length, 0.5 mm thickness, and 10 mm width. The actual dimensions measured for 100 pieces of strand were 20.4, 41.1, 58.4, and 73.8 mm length, 0.45 to 0.61 mm thickness, and 7.8 to 10.6 mm width.

Angle Measurement

In a previous research study, Sumardi *et al*. (2008) determined the strand angle distribution via forming tests of 96 combinations of strand length, FFD, and plate spacing (Fig. 1). Four levels of strand length (*i.e.*, 20, 40, 60, and 80 mm), six levels of FFD (*i.e.*, 10, 20, 30, 50, 70, and 100 mm), and four levels of plate spacing (*i.e.*, 10, 20, 30, and 40 mm) were used. For each combination, about 1000 strands were tested.

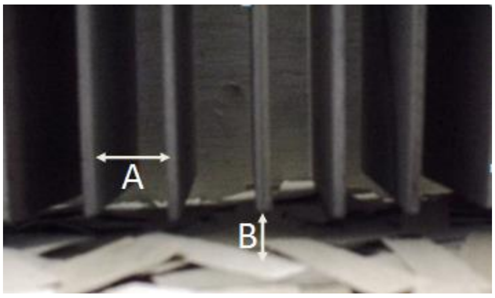

Fig. 1. Plate spacing (A) and free fall distance (B) of a manual-aligning device (redrawn from Sumardi e*t al.* 2008)

To measure the strand angle, photographs of strands were recorded as digital image data. The orientation angle was measured with a personal computer using the free software Scion Image version 3.0.4 (2005). The orientation angle of each strand was measured from $-\pi/2$ to $+\pi/2$, with 0 radian as the principal axis direction. The strand angle analysis was conducted using a modified von Mises distribution function, and the *k* value, which is the concentration parameter of this function, was obtained by the least squares method (Sumardi *et al.* 2008). The distribution frequency and the *k* value were used for the analysis of strand angle distributions. A part of this measurement was used as a reference for the board alignment produced.

To clarify the effects of strand length, FFD, and plate spacing on the *k* value, a power form shown in Equation (1) was employed to model the relationships. The analysis was conducted using SPSS-13 software,

$$k = \mathrm{a}\, F^{\mathrm{b}}\, SL^{\mathrm{c}}\, PS^{\mathrm{d}}\, W^{\mathrm{e}} \qquad (1)$$

where F = FFD (mm); SL = strand length (mm); PS = plate spacing (mm); W = strand width (mm); and a, b, c, d, and e are regression constants. In fitting Equation (1), natural logarithm transformations of both the dependent variable (*k*) and independent variables (*F, SL, PS,* and *W*) were first performed. A multi-linear regression analysis was then made with the transformed variables. For this experiment, the same strand width was used, so that the equation is:

$$k = a\,F^{b}\,SL^{c}\,PS^{d} \qquad (2)$$

Board Fabrication

Uni-directional homogenous boards (UNID-board) with dimensions of 370 mm × 370 mm × 12 mm and 0.65 g/cm^3 density were manufactured using strands that were 40 mm long. A commercial liquid diphenylmethane diisocyanate (MDI) with 6% resin content was applied to the strands using a pressurized spray gun in a box-type blender. No waxes or other additives were used. Hand-formed mats were pressed for 10 min at a temperature of 180 ^{o}C using a maximum pressure of 2.5 MPa. No surface sanding was performed. A random board of 40 mm strand length was used as a control.

Two panels were produced for each FFD and plate spacing level. The orientation of the bamboo strand was made by passing the strands through plate spacings of 20 mm parallel to each other for various FFDs of 10, 20, 30, and 70 mm. The FFD distance (between the end of the plates and the top of the mat) was kept at 20 ± 5 mm. The plate spacing treatments were conducted at 10, 20, 30, and 40 mm.

Board Evaluation

The board property tests for bending strength, internal bond strength (IB), and eight replication samples for thickness swelling (TS) were conducted in accordance with the Japanese Industrial Standard (JIS) for particleboard (JIS 1994). Five replication samples for modulus of elasticity (MOE) and modulus of rupture (MOR) in bending, and eight replication samples for IB, were determined under air-dried conditions.

Linear expansion (LE) was evaluated using two specimens with dimensions of 300 mm × 50 mm, based on the initial dimensions obtained after drying at 60 °C for 22 h. The change in length was measured using a dial gauge comparator (ASTM 1988) at intervals during treatment in humid conditions of 40 °C and 90% relative humidity (RH) for 150 h.

RESULTS AND DISCUSSION

Alignment Angle Distribution

The distribution frequencies of the angle of alignment for various FFDs and PSs are shown in Fig. 2. The distribution shows that the sharpness of the curves increased gradually with decreasing FFD (Fig. 2 left) and PS (Fig. 2 right), and the distribution curve gradually became flat and approached the random (RND) distribution curve. These results demonstrate the same phenomena as previously reported (Kajita 1987; Suzuki and Takeda 2000), which is that FFD, PS, and SL affected the alignment angle distribution.

Based on the angle distribution data, the curve fitting can be made using a modified von Mises distribution function. The *k* values were obtained by the least squares method and correspond to the shape curve shown in Fig. 3.

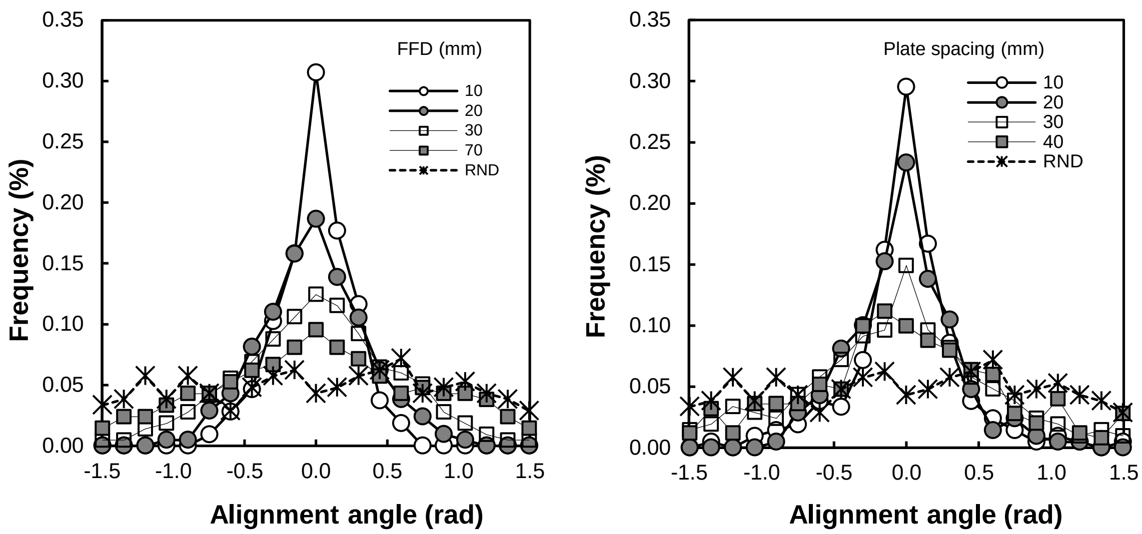

Fig. 2. The plotted data points of strand alignment angle at various free-fall distances (left) and plate spacings (right) using strands of 40 mm length

Figure 3 (left) shows that the *k* value of the von Mises distribution function increased exponentially with decreasing FFD and PS. It also shows that the distribution was improved by adjusting the plate spacing closer to the strand width and/or lowering the FFD, and that the FFD strongly affected the *k* value when the FFD was shorter than the SL. For FFDs of 50 to 100 mm, the *k* value was similar for all PSs when the SL was 40 mm.

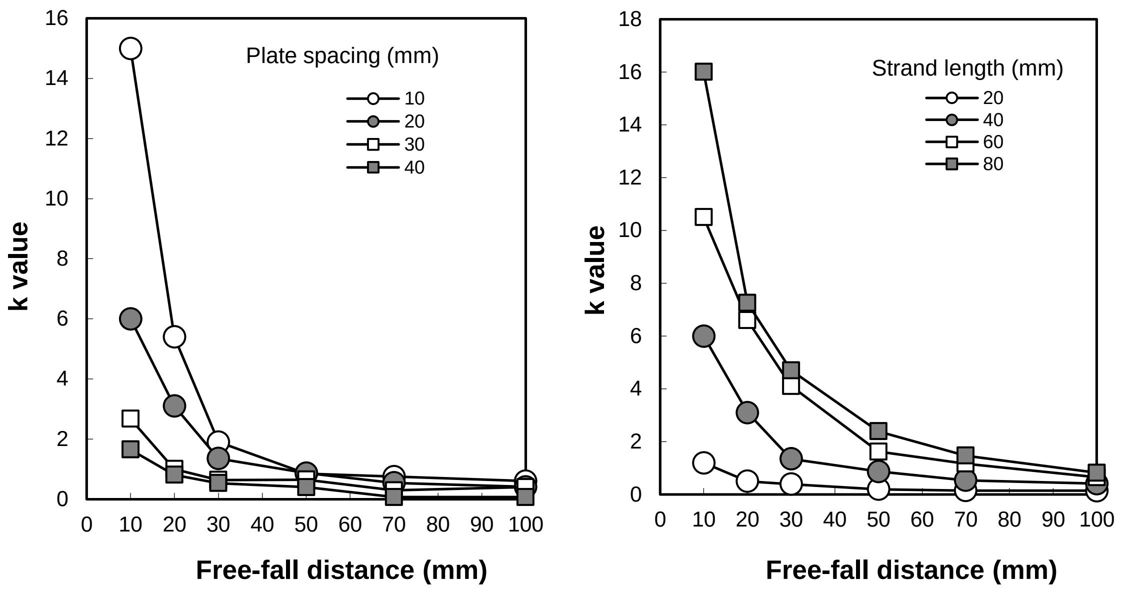

Fig. 3. The effect of free-fall distances on *k* values at various plate spacings (left) and strand lengths (right), using 40 mm strands. (The *k* value in the figure was obtained by least square method.)

The same trend found with plate spacing was found in relationships between strand length and FFD at the plate spacing of 20 mm, as displayed in Fig. 3 (right). The *k* value increased exponentially with decreasing FFD. The *k* value was more affected for long strands than for short strands. It was obvious that the gradient of the *k* value in Fig. 3 was different for each strand length. For strand lengths of 20, 40, 60, and 80 mm, the high *k* values were obtained at FFDs of 10, 20, 30, and 50 mm. Higher *k* values resulted when the FFD was shorter than the SL.

Relationships among FFD, Plate Spacing, and Strand Length

To understand the effect of strand length, FFD, and plate spacing on *k* value, a sample figure (Model 2 in Table 1) in three dimensions was drawn (Fig. 4). Figure 4 is based on the measurement of about 1000 strands at various strand lengths and FFDs for the plate spacing of 20 mm. Generally, the *k* value increased with increasing strand length and decreasing FFD. The *k* value is more influenced by strand length than by FFD, and there were two noticeable observations in these relationships. Firstly, the *k* values are more sensitive to increasing strand length. Secondly, the influence of FFD was clearly seen at FFDs of 50 mm or lower for the strand length of 40 mm, as shown in Fig. 3.

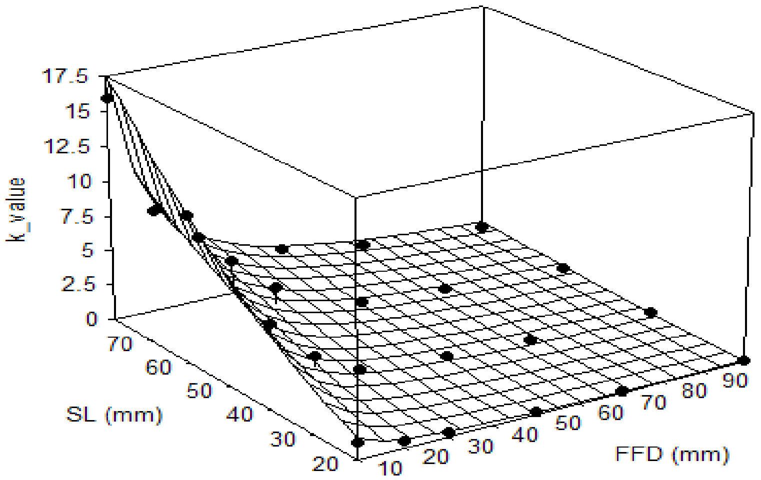

Fig. 4. The sample concentration parameter (*k* value) of the von Mises distribution as a function of strand length and free-fall distances at a plate spacing of 20 mm (Equation 2)

The regression results for the relationships among strand length, FFD, and plate spacing and for the *k* value are summarized in Table 1 based on the regression equations (Eq. 2). Regression analysis at the 5% significant level revealed that FFD, strand length, and plate spacing in the model were significant variables for the alignment angle distribution. Based on the R-squared values of the regression and regression constants, the effect of strand length on *k* value was more important than either plate spacing or FFD. The power form relationships fitted for those parameters were applicable for use in practical fabrication.

There was fairly good agreement between the equation estimate (model 2 in Table 1) and the experimental data (Fig. 4). Some deviations between the estimates and the test results were due to difficulties in handling the strand in this study. However, the simulation of the *k* value as a function of strand length, FFD, and plate spacing as described in Equation 2 and in the model (No. 4 in Table 1) can be used to predict the *k* value of the von Mises distribution function. Equation 2 could be useful for further research on the simulation of *k* for predicting the strength properties of bamboo strandboard.

Generally, based on the R-squared values of the regression in Table 1 the best model number are namely 2, 3, 1, and 4. Model number 2, 3, and 1 were used for two independent variables and model number 4 for three independent variables.

Table 1. Regression Results on the Relationships between the *k* Value and FFD (F), Strand Length (SL), and Plate Spacing (PS)

No	Model	Regression constants				r^2
		a	b	c	d	
1	$k = a F^b PS^c$	3296.0	-1.246	-1.217		0.90
2	$k = a F^b SL^c$	0.1172	-1.174	1.761		0.98
3	$k = a PS^b SL^c$	0.0175	-1.230	2.241		0.95
4	$k = a F^b SL^c PS^d$	0.6576	-1.225	2.073	-1.011	0.91

Board Properties

To determine physical and mechanical properties, two panels were produced for each FFD and plate spacing level with the strand length of 40 mm. The average values of the bamboo strandboard properties at different FFDs and plate spacings are summarized in Table 2. The IB strength and TS after 24-h water immersion ranged from 1.31 to 1.49 MPa and 4.07% to 5.31%, respectively, and no significant differences were found among the tests of the board types. This result was similar to that observed for bamboo OSB (Lee *et al.* 1996) and wood OSB (Kajita 1987; Canadido *et al*. 1988), where the IB strength of boards was affected by the density and resin content levels, but there were no clear differences between UNID and random boards. On the other hand, the board using a 6% resin content satisfied JIS requirements for both IB and TS.

The bending properties showed distinct differences between the MOR and MOE (Table 2) along the parallel and perpendicular directions associated with the FFD and plate spacing. In the parallel direction, the property difference decreased with increasing FFD and plate spacing. This indicated that adding FFD and plate spacing resulted in a better balance of bending properties in the two directions. Furthermore, decreases in the MOR in the parallel direction could be comparable to the increases of the MOR in the perpendicular direction. The same trend with MOR, the MOE values increased with decreasing FFD and plate spacing for parallel direction and the opposite occurred for perpendicular direction. The contribution of bamboo strand in the longitudinal direction affected these results. It was shown that the MOR and MOE values could be a function of the alignment angle distribution.

Figure 5 shows, in the in-plane direction, the LE behavior toward a perpendicular direction at various FFDs after the humidity test at 40 °C and 90% RH for 150 h. There were apparent effects on the LE, and the substantial factor that affected the LE was the degree of orientation. The LE increased rapidly at the beginning of the humidity test and leveled off toward the saturation point. The LE of 30 mm FFD seemed to reach its saturation value at about 50 h, whereas the LE of 10 mm FFD still increased after 50 h (Fig. 5). In the case of short FFD, there was a larger saturation LE value, and more time was required to reach it. This result was the same as that of the LE of the plate spacing effect. Narrow plate spacing meant more time was required to reach the saturation LE value. This result was supported by the value of the MOR in the perpendicular direction, as listed in Table 2; those values showed a slight difference.

The linear expansion for parallel direction increased slightly with the increase of FFD and plate spacing. On the other hand, in the perpendicular direction, the LE was strongly affected by the FFD and plate spacing. This result indicated that swelling differed between the perpendicular and parallel directions of the bamboo strand, which affected the board properties.

Table 2. Summary of Bamboo OSB Properties at Various Free Fall Distances and Plate Spacings for Unidirectional Homogeneous Board Using the Strand Length of 40 mm

SL	PS	FFD	Direction	MOR (MPa)	MOE (GPa)	IB (MPa)	TS (%)	LE (%)	*k* value	
									test	simulation
40	20	10	Pr	70.2	8.7	1.49	5.07	0.11	6.00	5.20
			Pp	8.2	1.8			1.32		
40	20	20	Pr	70.0	7.4	1.41	5.10	0.11	3.10	2.31
			Pp	12.9	2.0			1.06		
40	20	30	Pr	57.8	7.3	1.35	4.81	0.13	1.35	1.43
			Pp	13.4	2.0			0.82		
40	20	70	Pr	52.0	6.1	1.31	5.31	0.14	0.54	0.53
			Pp	21.4	2.7			0.52		
40	10	20	Pr	76.8	8.0	1.43	4.36	0.09	5.40	4.01
			Pp	11.9	1.8			1.05		
40	20	20	Pr	70.0	7.4	1.41	5.10	0.10	3.10	1.71
			Pp	12.9	2.0			1.04		
40	30	20	Pr	65.0	7.3	1.34	4.07	0.10	1.00	1.04
			Pp	18.5	2.4			0.74		
40	40	20	Pr	61.3	6.0	1.37	4.33	0.13	0.81	0.73
			Pp	20.2	2.6			0.48		
RAND				37.9	4.4	1.35	4.81	0.25		

SL: strand length, PS: plate spacing, FFD: free fall distance, Pr: parallel direction, Pp: perpendicular direction, RAND: random board

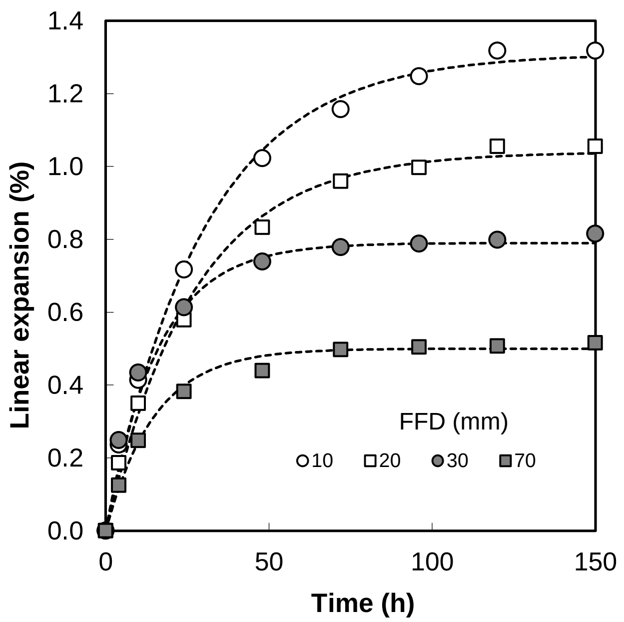

Fig. 5. Linear expansion (LE) behaviors in the perpendicular direction for bamboo OSB at various FFDs

CONCLUSIONS

1. The effects of free fall distance, plate spacing, and strand length on the strand alignment and board properties of bamboo strandboard were investigated. The results of investigating the strand alignment distributions showed that the *k* value depended on the strand length, free fall distance, and plate spacing.

2. The distribution of the strand alignments and corresponding *k* values can be improved by adjusting the plate spacing closer to the strand width, shortening the free fall distance, and using long strands.

3. The relationships among strand length, free fall distance, and plate spacing on the *k* value can be described by a power form equation. The variables that strongly influenced the *k* value were strand length, free fall distance, and plate spacing, in that order.

4. Regarding panel properties, IB strength, and TS were not significantly different among the board types tested.

5. On the other hand, the bending properties and LE were greatly affected by free fall distance and plate spacing. The use of low free fall distance and narrow plate spacings improved the bending properties. Decreasing bending properties in the parallel direction could be comparable to the increase of those in the perpendicular direction. The contribution of bamboo strand in the longitudinal direction affected these results.

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