Effects of strand length and layer structure on some properties of strandboard made from bamboo

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Key words: Bamboo · Strand length · Layer structure · Alignment angle · Bending properties

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Abstract

Strandboard panels were experimentally produced from moso bamboo (*Phyllostachys pubescens*) using various strand lengths and layer structures to evaluate the effects of manufacturing parameters on panel properties. The strandboard was fabricated in a laboratory using diphenylmethane diisocyanate (MDI) resin and laboratory-made strands of four lengths and four different structures. Strand alignment distributions and concentration parameter (k) values were greatly affected by strand length. A linear correlation was found between the value of k and the modulus of rupture (MOR), with coefficients of 0.81 and 0.93 for unidirectional boards and three-layer boards, respectively. This correlation may be used to predict the strength properties of boards. Bending properties were significantly affected by both the strand length and the layer structure of the bamboo strandboard tested. Elasticity data from unidirectional boards and random boards can be used to predict the elastic properties of three-layer boards. The linear expansion (LE) of the random boards increased with decreasing strand length. The difficulty in mat forming and resin distribution for longer strands could cause deviation in modulus of elasticity (MOE) and LE, especially in strand lengths around 80 mm.

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Introduction

In recent years, an increase in housing construction has resulted in a high demand for lumber products. On the other hand, the quantity and quality of wood resources from forests have declined. Consequently, there is great interest in using non-wood resources as alternative raw materials. Bamboo is a non-wood lignocellulosic material that has potential for composite panels such as particleboard and fiberboard. Several papers have reported the utilization of bamboo in various composite panels such as plywood[1], zephyr-board[2], particleboard,[3,4] fiberboard,[5-7] waferboard,[8] and oriented strandboard.[9]

Understanding the basic properties of bamboo is important when considering it as a raw material, especially for oriented strandboard (OSB). The properties of strandboard are strongly influenced by layer-structure, density, strand-length, adhesive, and the aligned angle of strands. Previous studies on wood have reported the effects of layer-structure, strand length, and linear expansion of raw material.[10-13] Similar information on bamboo as a raw material is limited.

Some work has been done relating board density, resin content, and bending strength on bamboo strandboard manufactured using phenol formaldehyde (PF) as a binder.[14] Positive correlations were found between the density, resin content (RC) and bending strength of the panels. However, internal bond (IB) strength was not satisfactory with PF resin. Diphenylmethane diisocyanate (MDI) was used as an alternative binder to improve board properties. Rool[15] reported that MDI was more suitable for cellulose material, spread out spontaneously on a wood surface, and has self-activated distribution characteristics superior to those of PF resin.

Because information on bamboo to be used for structural panels is very limited, further studies on OSB with bamboo as raw material are necessary, especially for strand length and layer structure as basic properties of OSB from bamboo. The objective of this study was to determine the effect of strand length and layer structure on some panel properties of strandboard made from bamboo.

Materials and methods

Board fabrication

Moso bamboo (*Phyllostachys pubescens*) poles were collected from the Shizuoka University bamboo plantation. Each bamboo pole was cut from its base to a height of approximately 8 m. Strands were produced using a laboratory ring-type flaker. Target strand dimensions were 20, 40, 60, and 80 mm long, 0.5 mm thick, and 5–20 mm wide. Their actual dimensions, determined from 100 strands, were 20.4, 41.1, 58.4, and 73.8 mm long, 0.45-0.61 mm thick and 7.8 -10.6 mm wide. Strands were screened on a 10-mesh sieve before being oven-dried at 60 °C to a moisture content of less than 3 %.

Strandboards with dimensions 370 x 370 x 12 mm and 0.65 g/cm^3 in density were manufactured. Six percent of a commercial liquid MDI (M-200, Mitsui Chemicals Polyurethanes, Inc.) resin content was applied to 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. Four types of board were fabricated with different layer-structures: randomly oriented homogenous board (RAND), uni-directionally oriented homogenous board (UNID), three-layered OSB with a cross-oriented core layer (3LYC), and three-layered OSB with a random core (3LYR). The UNID-boards were produced at ten combinations of three parameters, which were strand length, plate spacing, and free fall distance. The RAND- and 3LYC-boards were produced at four different strand lengths, whereas 3LYR boards were made only at strand length of 40 mm for comparison. A set of thin plates with 20-mm spacing was used to orient strands during UNID-, 3LYC-, and 3LYR-board mat forming. The layer structure of 3LYR-board was based on the oven-dried weight, and the face-to-core-to-face ratio was 25:50:25. A random board of 40 mm strand length was used as an experimental control. Four panels were produced for each strand length and each type of layer structure.

Four strand lengths (20, 40, 60, and 80 mm) were used to determine the strand alignment angle distribution of bamboo. Photographs of strands were recorded as digital image data for measuring orientation angle, and the deviations between orientation and strand length direction angles were determined using 1,000 strands oriented at a 20-mm free-fall distance (FFD) and with a 20-mm plate spacing (PS) as shown in Fig.1.

Board evaluation

Prior to the bending test, all boards were conditioned at a relative humidity of 65% and a temperature of 25 ^{o}C for at least 2 weeks. The bending strength test was conducted in accordance with the Japanese Industrial Standard (JIS) for particleboard.[16] Eight trials were performed for each type of sample to measure modulus of elasticity (MOE) and modulus of rupture (MOR). The plate shear modulus (Gp) was determined by the edgewise vibration method using a Fast Fourier Transform analyzer and a specimen with dimensions of 300 x 300 mm. From the peak frequency of the tapping tone, Gp was calculated as follows.[17]

$$Gp = \pi^2 L^4 \rho f^2 / (12 h^2) \quad (1)$$

where L, ρ, *h, f, and* π denote the length (300 mm), density, and thickness (12 mm) of the specimen, the peak frequency, and the circular constant (3.14), respectively.

Dimensional stability in plane direction was evaluated by measuring linear expansion (LE). Two specimens with dimensions of 300 x 50 mm were used based on initial measurements taken after boards were dried at 60 °C for 22 h. Changes in length were regularly measured during treatment under humid conditions of 40 °C and 90 % RH for 150 h, followed by dry conditions of 60 °C for 150 h, using a dial gauge comparator at an accuracy of 0.01 mm.[18]

Results and discussion

Angle distribution

Characteristic of angle distribution is basic information that influences the properties of strandboard. Strand length, FFD and plate spacing are factors that affect strand angle distribution.

Figure 2 shows some typical angle distributions for bamboo strands under identical conditions (FFD and PS 20 mm) for UNID-board. The distribution shows that the sharpness of curves increases gradually with increasing strand length. Based on the data on strand alignment angle, curve fitting can be performed using a modified von Mises distribution function (Eq. 2),[14,19] which is defined as follows:

$$f(\mathrm{x},\mathrm{k}) = \frac{1}{\pi \mathrm{I}_0(\mathrm{k})}\exp(\mathrm{k}\cos 2\mathrm{x}) \tag{2}$$

where x, k, and I_0 are the angle defined between $-\pi/2$ and $\pi/2$, the concentration parameter, and a modified Bessel function of the first kind and order zero, respectively. The concentration parameter (k) value was obtained by the least squares method. Those values corresponded to the shape of the curve.

Figure 3 illustrates the relationships between strand length and the k value. The value of k increased with increasing strand length, and it increased rapidly when strand length increased from 20 to 60 mm. Theoretically, the value of k should increase exponentially with increasing strand length. Regarding the difficulty in uniform mat forming with longer strands, deviation was observed between the theoretical and actual values especially for a strand length of 80 mm under the forming condition of this experiment.

The value of concentration parameter (k) is a measure of variance of the angle in the von Mises distribution function.[20] This is a good indicator for estimation of the curve of the standard distribution angle for the shape of the curve. In addition, this may be used to predict the strength properties of the panels. As illustrated in Fig. 4, we found a linear relationship between k value and MOR, which was a mean of eight measurements, with coefficient values of 0.81 and 0.93 for UNID- and 3LYC-boards, respectively. The value of MOR increased linearly with increasing value of k, and MOR of UNID-board was higher than that of 3LYC-board. Similar to the trend in MOR, a linear relationship was also found between k and MOE with coefficient values of 0.85 and 0.94 for UNID- and 3LYC-boards, respectively.

Effect of strand length

The effect of strand length on bending strength is illustrated in Fig. 5, where the strands were oriented under FFD of 20 mm and PS of 20 mm. The value of MOR increased with increasing strand length. In the parallel direction (Pr in Fig.5), MOR increased greatly among strand lengths of 20 to 40 mm, and increased slightly beyond this range. Averaged MORs of UNID-board for strand lengths of 20, 40, 60, and 80 mm in the parallel direction reached 46, 70, 83, and 93 MPa, respectively, and were relatively constant in the perpendicular direction. These results showed that longer strands can give a high MOR because of effective contributions of the longitudinal properties of the bamboo itself to the board properties especially in UNID-board. On the other hand, the increasing MOR values for RAND- and 3LYC-boards were not as high as those for UNID-board.

The higher MOR values of the panels manufactured using longer strands were also supported by the curve shape of longer strand alignment in terms of angle distribution as illustrated in Fig. 2. This showed that the frequency distribution of strands 60 and 80 mm long was narrower than that of 20 and 40 mm long; therefore, it affected mechanical properties especially in the parallel direction.

Figure 6 shows effects of the manufacture parameters on MOE. Strength ratio could be an indicator of board strand alignment and layer structure. The MOE ratios at strand lengths of 40 mm in the parallel direction were 3.8 and 1.7 times for the perpendicular direction of UNID- and RAND-boards, respectively. The ratios for 3LYC- board were 2.5 and 1.5 for the cross-oriented direction of 3LYC- and RAND-boards, respectively. These values approximated those measurements of Douglas fir strands.[11]

Furthermore, the MOE of 3LYC-board can be calculated using two MOEs from the parallel and perpendicular directions of UNID-board as elastic constants for each layer of 3LYC-board in Fig. 6. The calculation used the weight ratio of each layer (25:50:25) as the thickness ratio of each fabricated board. The results indicated good estimation of MOE-predicted in the perpendicular direction and in the parallel direction only for strand lengths of 20 and 40 mm. Some deviations between the theoretical and actual values at strand lengths of 60 and 80 mm were observed in the parallel direction. It appeared that inhomogeneous resin distribution on longer strands resulted in some problems during mat forming; this influenced the accuracy of prediction of MOE values of the panels.

MOE-predicted of 3LYR-board at a strand length of 40 mm can be calculated using two MOEs from UNID- and RAND-boards as elastic constants for each layer of 3LYR-board. The results show that the ratios of predicted to actual values were 99 and 101 % for parallel and perpendicular directions, respectively. They indicated that elastic data from UNID- and RAND-boards can be used to predict elastic properties of three-layered boards with a strand length of 40 mm.

Effect of layer-structure

The plate shear modulus (Gp) is a modulus of rigidity related to the performance of a board when used as wall sheathing. The Gp was affected by layer structure and strand length. The values of RAND-board for strand length of 20, 40, 60, and 80 mm were 1.37, 1.50, 1.53, and 1.65 GPa, respectively, and for UNID-, 3LYR-, and 3LYC-boards for a strand length of 40 mm were 1.21, 1.33, and 1.24 GPa, respectively. The values indicated that random board with strand lengths of 40 mm or more yielded fairly good shear modulus of OSB (ca.1.5 GPa). Although these values were slightly lower than those of sugi strands,[12] bamboo could exhibit fairly good performance.

Figure 7 shows the effect of layer structure on the MOR of strandboard in parallel and perpendicular directions for a strand length of 40 mm. In the parallel direction, MOR decreased in order from UNID-, 3LYR-, 3LYC-, and RAND-boards. In contrast, for the perpendicular direction, MORs increased from UNID-, 3LYR-, 3LYC-, to RAND-boards. Furthermore, Fig. 7 shows that the decrease in MOR in the parallel direction could be comparable to the increase of MOR in the perpendicular direction. Apparently, contributions of the longitudinal properties of the bamboo shifted gradually from the aligned direction to the cross direction from UNID- to RAND-boards.

Linear Expansion

Stability in the longitudinal direction is an important property in the use of strandboard. This property was investigated by a linear expansion (LE) test under various conditions of strand length. Figure 8 shows that LE of the random board (RAND) was affected by strand length. These results were for samples after they had been subjected to a humidity test at 40 ^{o}C and 90 % RH for 150 h, followed by a drying test at 60 ^{o}C for 150 h. During the first 50 h, LE increased rapidly; it almost leveled off after 150 h, producing values of 0.28, 0.24, and 0.20 % for strand lengths of 20, 40, and 60 mm, respectively. In the drying stage, LE values became negative.

In this paper, total LE (dLE) and total moisture content change (dMC) were measured from humid and dry conditions for 150 h and 300 h. The value of dLE decreased from 0.32 to 0.23 % when strand length increased from 20 to 60 mm (Table 1). Linear expansion per unit moisture content change (LE/MC) decreased from 0.028 to 0.020 %/% within the same range. These values were lower than the values reported for strandboard made from Japanese cedar[21] and particle board.[22] The dMC of samples examined here was lower than that of bamboo strandboard with PF as a binder.[14] The MC of MDI resin-board was lower than that of PF resin board at the 90% RH exposure level.[22] In contrast, the LE of strand lengths near 80 mm was higher than that of shorter strands (40 and 60 mm). This may be caused by inhomogeneous blending of adhesive and difficulty in mat forming with longer strands.

Conclusions

We investigated the influence of strand length and layer structure on mechanical properties of bamboo strandboard. Strand alignment distribution and k values depend strongly on the length of the strand formed. The von Mises distribution function can be used to predict bamboo strand distribution. A linear correlation between k values and MORs was revealed, which may be used to predict the strength properties of boards. Bending properties were strongly affected by both strand length and layer structure of the bamboo strandboard tested in this experiment. Elasticity data from UNID- and RAND-boards can be used to predict the elastic properties of 3LYC- and 3LYR-boards. The LE increased with decreasing strand length, and the LE/MC ranged from 0.020 to 0.028 %/%. These values were comparable to or lower than those for commercial boards. The difficulty in mat forming and resin distribution for longer strands was evident in the deviation results for MOE-predicted and LE, especially at a strand length of 80 mm.

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FIGURE CAPTIONS

Fig. 1. Plate spacing (A) and free-fall distance (B) of the orienter.

Fig. 2. Effect of strand length on strand angle distribution for unidirectional boards.

Fig. 3. Effect of strand length on concentration parameter (k) values for unidirectional boards.

Fig. 4. Effect of k values on modulus of rapture (MOR) of UNID- and 3LYC-boards. UNID: unidirectionally oriented homogenous board, 3LYC: three-layer board with a cross-oriented core layer, R^2: coefficient determination.

Fig. 5. Effect of strand length on MOR. RAND: randomly oriented homogenous board, Pr: parallel direction, Pp: perpendicular direction. Other symbols were referred to the caption of Fig. 4.

Fig. 6. Effect of strand length on modulus of elasticity (MOE). Dotted lines represent estimated MOE of 3LYC-board using MOE of UNID-board. Other symbols were referred to the caption of Fig. 4 and Fig. 5.

Fig. 7. Effect of layer-structure on MOR at a strand length of 40 mm, FFD of 20 mm, and PS of 20 mm. Other symbols were referred to the caption of Fig. 4 and Fig. 5.

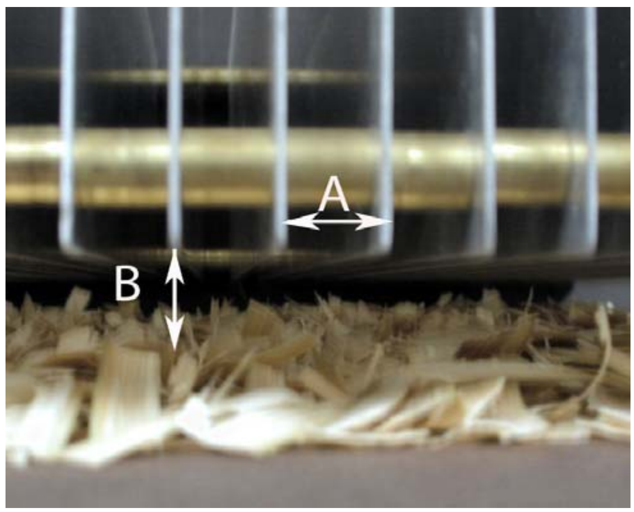
Fig. 8. Effect of strand length on linear expansion (LE) of random board under humid conditions followed by dry conditions

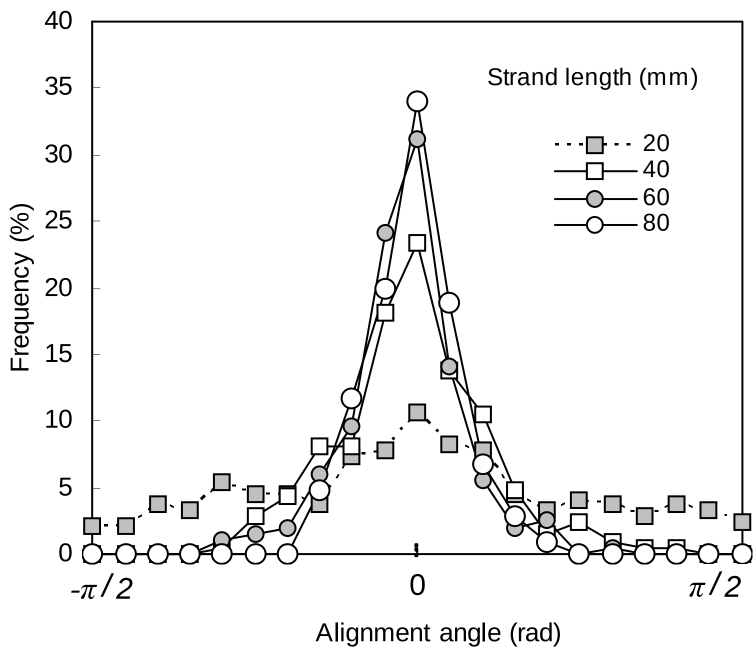
TABLE

Table 1 Linear expansion (LE) and LE per unit moisture content change (LE/MC) for humid and dry conditions.

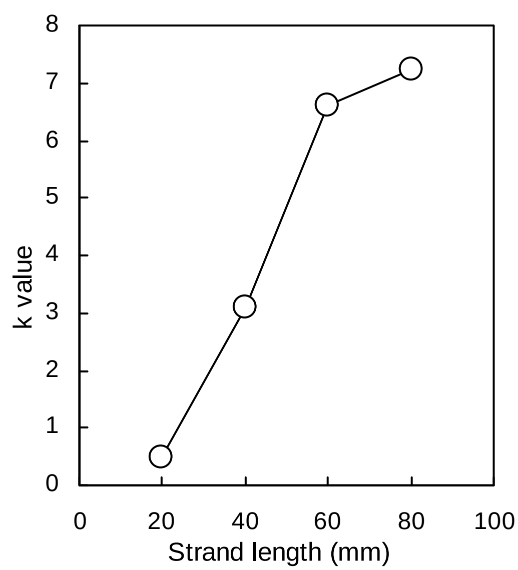
Board type	Strand (mm)	dMC %	dLE %	LE/MC %/%
RAND	20	11.4	0.32	0.028
RAND	40	11.2	0.28	0.025
RAND	60	11.5	0.23	0.020
RAND	80	10.5	0.28	0.026

dMC: total MC change, dLE: total LE change.

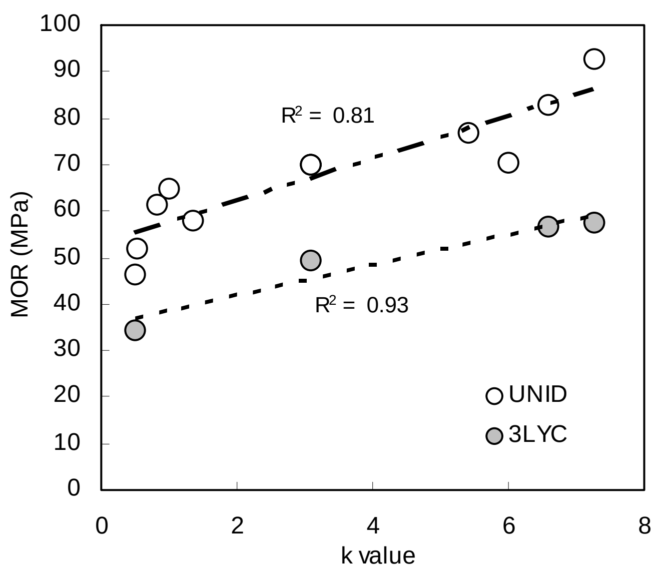

A
B

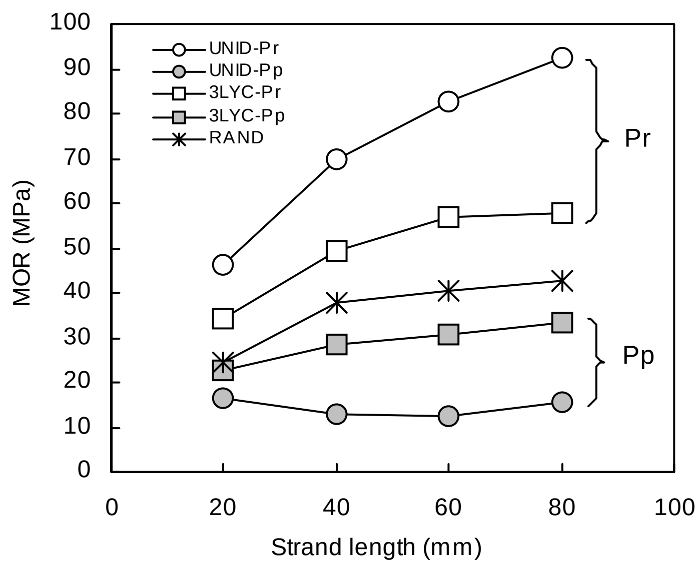


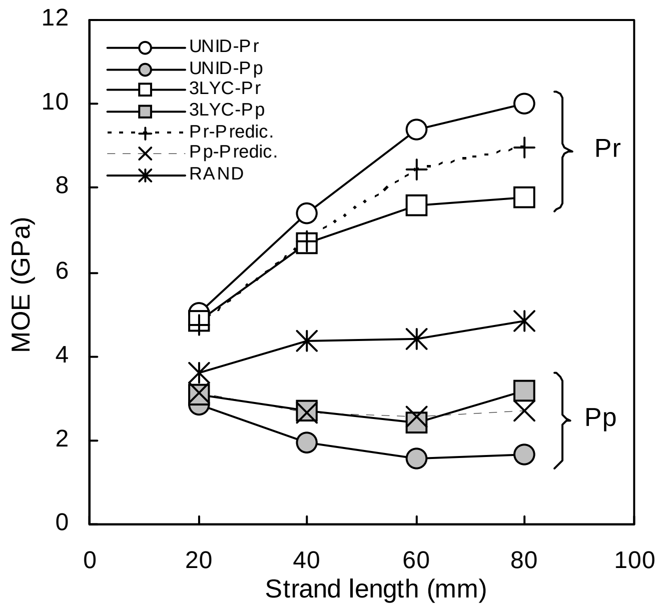
Strand length (mm)
20
40
60
80
Frequency (%)
40
35
30
25
20
15
10
5
0
-π/2
0
π/2
Alignment angle (rad)



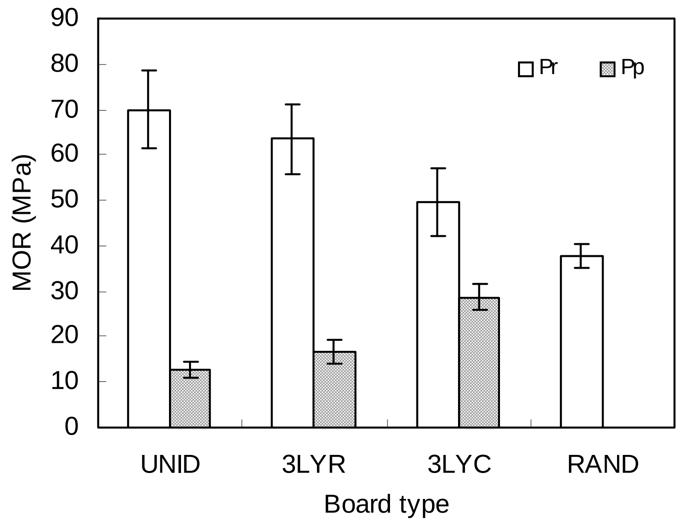
k value
Strand length (mm)
0
1
2
3
4
5
6
7
8
0
20
40
60
80
100


100
90
80
70
60
50
40
30
20
10
0
MOR (MPa)
0
2
4
6
8
k value
R2 = 0.81
R2 = 0.93
UNID
3LYC

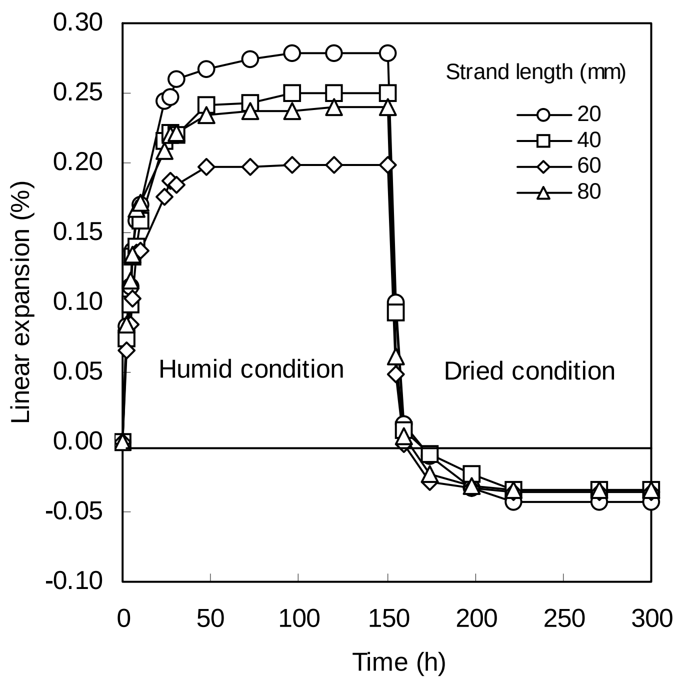

UNID-Pr
UNID-Pp
3LYC-Pr
3LYC-Pp
RAND
Pr
Pp
MOR (MPa)
Strand length (mm)
0
10
20
30
40
50
60
70
80
90
100



UNID-Pr
UNID-Pp
3LYC-Pr
3LYC-Pp
Pr-Predic.
Pp-Predic.
RAND
Pr
Pp
MOE (GPa)
Strand length (mm)
0
2
4
6
8
10
12
0
20
40
60
80
100



90
80
70
60
50
40
30
20
10
0
MOR (MPa)
Pr
Pp
UNID
3LYR
3LYC
RAND
Board type


0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
Linear expansion (%)
0
50
100
150
200
250
300
Time (h)
Strand length (mm)
20
40
60
80
Humid condition
Dried condition