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Effects of fiber length and orientation on elasticity of fiber-reinforced plywood

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Abstract Short carbon fibers, a reinforced material in wood veneer composites, were used to investigate the effects of fiber length and orientation of fibers on the elasticity of plywood. The technical feasibility, elasticity, and strength of the reinforced plywood with short carbon fiber were evaluated. In a short fiber reinforcement system, the fiber length does not directly influence the reinforcement in Cox's theory when the fiber length exceeded a certain length. When the length of short carbon fiber is beyond 3 mm, the high reinforced result was obtained in the experiment. However, if fiber length was too long, the reinforced result was less owing to the bridge between fibers and the increase of holes. The optimum fiber length must be considered. The orientation of fibers has a strong influence on the reinforcement. Unidirectional, perpendicular, and random orientation displayed different influence on the elasticity. Experimental results were discussed with Cox's method. Reinforced plywood with short carbon fibers in random orientation has a higher shear modulus and bending strength than the controls, in addition to other mechanical properties.

Key words Short fiber · Reinforcement · Fiber length · Fiber orientation · Plywood

Introduction

The design of wood composite with high strength and durability is always an important issue in construction. Advances in fiber-reinforced plastics motivated us to evaluate the feasibility of manufacturing reinforced wood composites with high-performance synthetic fibers. Numerous investigations have focused on fiber-reinforced wood composites.[1–5] Most of these pursuits have involved nonmetallic synthetic fiber-woven-cloth reinforcement, such as glass fiber, carbon cloth, and fiber-reinforced plastic (FRP). The fiber reinforcement is beneficial for increasing the mechanical properties of plywood, decreasing its variations, and improving its durability. Up to now, fewer investigations have been done on nonmetallic synthetic short fibers (discontinuous filament) in wood composite reinforcement.[4]

The elasticity and strength of a material depend on the detail of its minute structure. The factors influencing elasticity and strength, such as fiber volume fraction, fiber orientation, and compound structure, have been investigated in fiber-reinforced wood composites.[2,3,5] Because of the substituted fiber cloth with short fibers in the reinforcement system, the other factors, such as fiber length and orientation of short fibers, must be considered.[6] In this study, the contributions of fiber length and orientation of fibers to elasticity in a short carbon fiber reinforcement system were investigated using Cox's theory and were demonstrated experimentally. From a practical point of view, technical feasibility, elasticity, and strength of reinforced plywood with short carbon fibers were evaluated.

Experimental

Short carbon fiber reinforcement system

To investigate the contribution of fiber length and orientation to elasticity, specimens of wood fiber reinforcement systems with short carbon fibers were prepared in a laboratory. The wood fiber reinforcement systems were compounded with three plies of parallel veneers and two fiber-resin lamina-inserted veneers, shown in Fig. 1. Birch (*Becula* spp.) sliced veneer, 0.5 mm thick, was chosen as a wood element. The short fiber was chopped carbon fiber (TORAYCA, T008; Toray, Tokyo, Japan), which has been widely applied for reinforcing the matrix of resin, rubber, paper, and cement. It was made from high-performance

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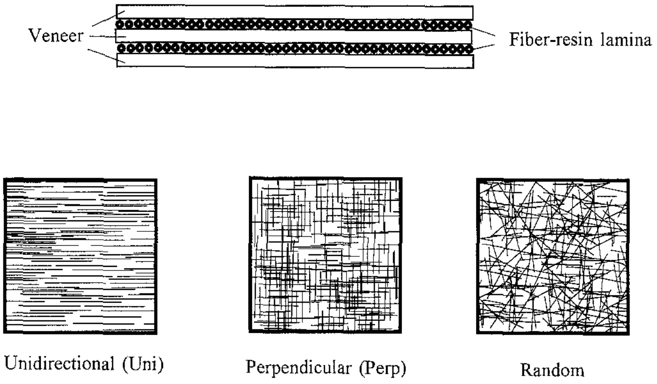
carbon fiber filament and set with epoxy resin beforehand. To explore the effect of fiber length, 3, 6, and 14 mm long chopped carbon fibers under unidirectional orientation of fibers were used as a fiber element. Phenol-resorcinol-formaldehyde resin (PRF resin: D-33; Oshika Resin, Tokyo, Japan) was used as an adhesive between elements. The resin spread rate per a single glueline was 350 g/m^2 for the wood-to-fiber glueline in fiber–wood composites. Fiber volume was about 50% in the fiber–resin lamina. To obtain Young's modulus of wood veneer, a control specimen was produced in which the resin spread rate per a single glueline was 250 g/m^2 for the wood-to-wood glueline without fiber reinforcement. After the composites were assembled, they were pressed together for at least 48 h at room temperature and a pressure of 98 kPa. In the case of 6 mm long chopped carbon fibers, specimens were fabricated with three orientations of the fibers: unidirectional (all fibers in the wood grain direction), perpendicular (half of the fibers in each direction), and random orientations. The orientations of fibers are shown in Fig. 1. Other fabrication conditions were the same as stated above. The specimens are listed in Table 1.



Unidirectional (Uni) Perpendicular (Perp) Random

Fig. 1. Composition of wood fiber reinforcement system (**top**) and orientation of short fibers in the fiber-resin lamina (**bottom**)

The elasticity of the reinforcement system was determined by the vibration method. A sample (15 × 150 mm) was fixed at one end and excited by impacting the other, free end. The resonance signal was detected by a microphone and the resonance frequencies obtained though an FFT analyzer. Young's modulus (E) of the wood fiber reinforcement system was obtained by the following equation.

$$E = \frac{4\pi^2 l^4 \rho A}{a_n^2 I} f^2 \qquad (1)$$

where l is the sample length, ρ is the density, A is the cross area; I is the moment of inertia, f is the resonance frequency, and $a_n = 1.875$ when f is the first mode.

According to the experimental value of the wood fiber reinforcement system, Young's modulus of fiber–resin lamina (E_{FR}) can be conversely calculated by the following mixture law in bending.

$$EI = \sum E_W I_W + \sum E_{FR} I_{FR} \qquad (2)$$

where E and I = Young's modulus and the moment of inertia, respectively, of the wood fiber reinforcement system, obtained from Eq. (1); E_W is Young's modulus of the veneer element computed from the control specimen; and I_W and I_{FR} are the moments of inertia of each veneer and fiber–resin lamina element, respectively.

Short carbon fiber-reinforcd plywood

To explore the feasibility of using short carbon fiber reinforcement in wood composites, short carbon fiber-reinforced plywoods were fabricated and their elasticity and strength determined. The experimental plywoods are listed in Table 2.

The fiber-reinforced plywoods (300 × 300 mm) were three-ply and five-ply panels, fabricated in a laboratory. Yellow merati (*Shorea* spp.) rotary veneers, 3 mm thick, were used. The PRF resin was applied to each glueline at the same spread rate as in the above experiments. Chopped

Table 1. Description of specimens of wood fiber reinforcement system

Type of specimen	Fiber-resin lamina			Composite	
	Length[a] (mm)	Orientation[b]	Thickness[c] (mm)	Thickness (mm)	Average SG
W	–	–	–	1.550	0.767
FW_3	3	Uni	0.224	1.998	1.010
FW_6	6	Uni	0.267	2.084	0.972
FW_{14}	14	Uni	0.284	2.118	0.946
FW_P	6	Perp	0.220	1.990	1.009
FW_R	6	Random	0.306	2.162	0.953

The measurement of the composite thickness was averaged for three points on the specimen. Values for the thickness and specific gravity (SG) of the composite were obtained from 10 specimens.

[a] Length of short carbon fiber.

[b] Orientation of fibers shown in Fig. 1.

[c] Thickness of the fiber–resin lamina estimated from the thickness of the composite

Table 2. Description of specimens of tested plywood

Types of specimen[a]	Thickness (mm)	Average SG	Construction		
			Thk. V[b]	No. of V[c]	No. of F-R[d]
P_1	9.23	0.50	3.2	3	–
RP_1	9.82	0.55	3.2	3	2
P_2	15.54	0.47	3.2	5	–
RP_2	15.79	0.56	3.2	5	4

Measurement of the thickness of plywood is the same as in Table 1. Values an average of 10 specimens (300 × 50 mm).

[a] P_1, three-ply control plywood; RP_1, three-ply fiber-reinforced plywood; P_2, five-ply control plywood; RP_2, three-ply fiber-reinforced plywood.

[b] Thk. V, thickness of veneer (mm).

[c] Number of veneer lamina.

[d] Number of fiber-resin lamina (F-R)

carbon fibers, 6 mm long, were randomly spread between veneers at a rate 220 g/m^2. As a reference, control plywoods without fiber reinforcement were produced. The fiber-reinforced plywoods were fabricated at 98 kPa and 145°C for 6 min (three-ply plywood) and 9 min (five-ply plywood); the controls were at the same hot pressure and temperature for 5 and 8 min, respectively.

Using the flexural vibration method (TGH method),[7–10] the dynamic Young's modulus for bending and panel shear modulus were measured with the beam. The plate shear modulus was obtained using torsional vibration of a free square plate (300 × 300 mm).[10] Using the three-point static bending test, we determined the bending strength in the direction parallel to the face grain. Beams used for the dynamic and static flexural tests were 50 × 300 mm. The static bending span was 250 mm. The average of 10 replicates comprised the values for elasticity and strength.

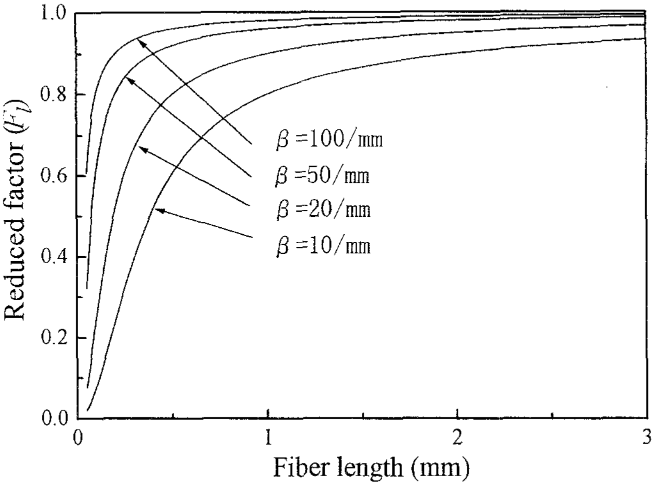


Fig. 2. Relations between fiber length and reduced factor under different conditions

Table 3. Summary of Young's modulus of wood-fiber reinforcement system with various fiber lengths

Type of specimen[a]	E^b (GPa)	$E_{FR}{}^c$ (GPa)
W	13.2 (0.75)	–
FW_3	20.3 (1.70)	88.1
FW_6	21.5 (2.15)	87.2
FW_{14}	19.8 (1.83)	68.6

[a] Expressed in Table 1.

[b] Experimental values of wood-fiber reinforcement system averaged for 10 specimens. Standard deviations of experimental values are in parentheses.

[c] Values of fiber-resin lamina computed from Eq. (2)

Results and discussion

Effect of fiber length on elasticity

According to Cox's theory, if a straight fiber of length l is embedded in a solid matrix (resin) in the fiber–resin reinforcement system, the transfer of load from fiber to fiber could reduce the modulus of the reinforcement. Considering the means of transfer of load from fiber to fiber, the reduced factor F_l is the ratio[6]

$$F_l = 1 - \frac{\tanh \beta l/2}{\beta l/2} \tag{3}$$

where l is fiber length, and

$$\beta = \sqrt{\frac{2\pi G_m}{E_F A_F \ln\sqrt{1/V_F}}} \tag{4}$$

where G_m is the shear modulus of the matrix; E_F and A_F are Young's modulus and the area of section of the fiber, respectively; and V_F denotes the fiber volume fraction in a fiber–resin lamina. If $\beta l/2$ is large, the reduced factor F_l approaches 1. If $\beta l/2$ is small, it becomes close to 0. In the short carbon fiber and PRF resin-reinforcement system, β is believed to be in the range of 10/mm to 100/mm, if it is supposed in Eq. (4) that E_F = 235 GPa, G_m = 1–4 GPa, A_F = $3.5^2\pi$ µm^2, and V_F = 50%. The changes of F_l corresponding with l in various β values are shown in Fig. 2. If the fiber length exceeded a certain length, that the factor F_l is 1 could be believed. In other words, the reduction could be probably negligible in the theory when the fiber is long enough.

Demonstrating the effect of fiber length on Young's modulus, the experimental values are given in Table 3. A higher Young's modulus is found in the unidirectional orientation (FW_3, FW_6, and FW_{14}), regardless of fiber length. There were not significant differences among specimens reinforced using 3- and 6-mm long chopped carbon fibers. However, Young's modulus of the specimens reinforced by 14-mm long chopped carbon fibers was a little lower than that of the others. It is somewhat different from the above theoretic analysis. The reasons could lie in the fact that the longer fibers are easily bridged and the holes increase in the lamina because the fiber–resin lamina of FW_{14} is thicker than the others under the same conditions.

As mentioned above, theoretically the direct effect of fiber length on reinforcement can be neglected when the carbon fibers are longer than 3 mm. However, when the fiber is too long, other negative effects could appear during a real application.

Effect of orientation of short fibers on elasticity

In a planar mat of fibers, the effect of orientation of fibers on the elasticity can be analyzed using Cox's method.[11] When fibers arrange at angle θ to the axis direction, the load–strain relation is defined as

$$
\begin{aligned}
P_1 &= K\int_0^{\pi}\left(e_1\cos^2\theta + e_2\sin^2\theta + \phi\cos\theta\sin\theta\right)\cos^2\theta f_{(\theta)}d\theta \\
P_2 &= K\int_0^{\pi}\left(e_1\cos^2\theta + e_2\sin^2\theta + \phi\cos\theta\sin\theta\right)\sin^2\theta f_{(\theta)}d\theta \\
Q &= K\int_0^{\pi}\left(e_1\cos^2\theta + e_2\sin^2\theta + \phi\cos\theta\sin\theta\right) \\
&\qquad \cos\theta\sin\theta f_{(\theta)}d\theta \qquad (5)
\end{aligned}
$$

where P_1, P_2, e_1, e_2 are tensile loads (P) and strains (e) in two axis directions at right angles, respectively; Q and ϕ are shear loads and strains, respectively; K = a constant (i.e., the product of fiber Young's modulus and the total number of fibers of unit length per unit of area); $f_{(\theta)}$ is the "distribution function" expressing the manner in which fibers are grouped according to the angle θ. If fibers are unidirectionally oriented at one axis direction in which $\theta = 0$ and $f_{(\theta)} = 1$, the Young's modulus of the planar mat of fibers is K at this axis direction from Eq. (5). When fibers are half arranged at two axis directions, respectively, $\theta = 0$ and $\pi/2$, and $f_{(\theta)}$ is 1/2. The Young's modulus is $K/2$ at each axis direction. When the fibers are completely randomly oriented, Young's modulus is $K/3$, substituting $f_{(\theta)} = 1/\pi$ into Eq. (5).

The experimental values of Young's modulus under various orientations of fibers are listed in Table 4. Among the fiber–resin lamina values, differences exist among three cases, i.e., unidirectional, perpendicular, and random orientation (FW_6, FW_P, and FW_R). Based on the additional effects of fiber length and orientation of fibers, in theory Young's modulus of the fiber–resin lamina (E_{FR}) with short carbon fibers in various orientations can be calculated using the following rule of mixture equation.[6]

$$E_{FR} = E_F V_F F_l C_d + \left(1 - V_F\right)E_R \qquad (6)$$

where E_F and E_R are Young's moduli for carbon fiber and matrix (resin), respectively; V_F denotes the fiber volume fraction; F_l and C_d are the reduced factors drawn by length and orientation of short fibers.

Because the used fiber was long enough (6 mm), the additional effect of fiber length can be neglected based on the above analysis. It could be believed that the reduced factor $F_l = 1$ in Eq. (6) based on the above discussion. In regard to the additional effect of orientation, if the reduced factor $C_d = 1$ is assumed for unidirectional orientation,[6] it can be seen that $C_d = 1/2$ for perpendicular orientation and 1/3 for random orientation from the above the results on the effect of fiber orientation on elasticity. The calculated results are contained in Table 4. If E_F = 235 GPa and E_R = 18.9 GPa are assumed on the basis of the standard carbon fiber and resin,[12] theoretical values are larger than experimental ones because there were some defects in the fiber–resin lamina in practice (e.g., "bridges" between fibers, holes in the resin, or other reasons). If E_F = 160 Gpa and E_R = 14 GPa, estimated from the experimental value of FW_6, are substituted, the calculated values are close to the experimental ones.

Table 4. Summary of Young's modulus of wood-fiber reinforcement system under various distribution of fibers

Type of specimen[a]	E^b (GPa)	$E_{FR}{}^c$ (GPa)		
		Exp.[d]	Est.[e]	Est.[f]
FW_6	21.5 (2.15)	87.2	122.5	87.2
FW_P	16.3 (3.28)	47.6	63.7	46.1
FW_R	15.0 (3.75)	30.0	43.8	32.1

[a] Expressed in Table 1.
[b] Experimental values of wood-fiber reinforcement system averaged for 10 specimens. Standard deviations of experimental values are in parentheses.
[c] Values of fiber-resin lamina.
[d] Experimental values computed from Eq. (2).
[e] Estimated values computed from Eq. (6) based on E_F = 235 GPa and E_R = 18.9 GPa.
[f] Estimated values computed from Eq. (6) based on E_F = 160 GPa and E_R = 14 GPa

The different orientations of fibers influenced the elasticity in the fiber reinforcement system. The reinforced results for the elasticity are different when fibers are distributed at unidirectional, perpendicular, and random orientations in a composite reinforcement.

Flexural and shear properties of fiber-reinforced plywood

Based on the above analysis, 6 mm long fiber was suitable for reinforcement, and random orientation of fibers caused some improvement in Young's modulus for the short fiber reinforcement system. The shear rigidity of fiber-reinforced plywood inserted in the fiber cloth in $\pi/4$ orientation was clearly superior to that inserted in perpendicular orientation, as demonstrated in a previous study.[3] Similarly, $\pi/4$ orientation and random orientation of short fibers can display higher reinforcement than other orientations for shear rigidity on the basis of Cox's theory,[11] even though the details should be investigated further. Moreover, random orientation of fibers is simple and applicable in practice. To reinforce not only flexural property but also shear rigidity, 6 mm long carbon fiber in random orientation was chosen as reinforcement in fiber-reinforced plywood.

Figure 3 shows the shear rigidity of the fiber-reinforced plywood. Compared with the controls, the increments of the panel and plate shear moduli of plywood were remarkable

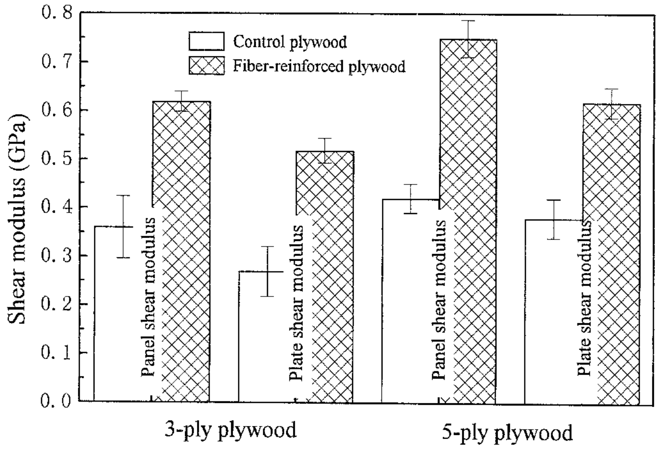


Fig. 3. Panel and plate shear moduli of fiber-reinforced plywoods. There were 15 pieces from three experimental panels for the panel shear test. There were three pieces of plates for the plate shear test. *Open bars*, control plywood; *hatched bars*, fiber-reinforced plywood

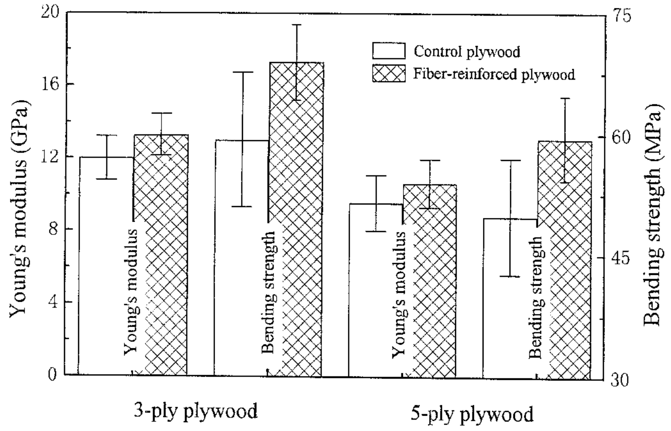


Fig. 4. Bending properties of fiber-reinforced plywoods. Each test comprised 15 pieces from three experimental panels. *Open bars*, control plywood; *hatched bars*, fiber-reinforced

for both kinds of the reinforced plywood (three-ply and five-ply). The values were much higher than those of the controls. It is concluded that short carbon fiber reinforcement in random orientation beneficially enhances panel and plate shear properties. Because of the application of plywood in construction (e.g., wall sheathing and pallets) the panel and plate shear moduli are important factors to help resist angular or shape deformations in sides and surfaces. These results are similar to those in the reinforcement with carbon fiber cloth in π/4 orientation.[3]

Figure 4 shows the bending properties of the fiber-reinforced plywood. Compared with the controls, Young's modulus and the strength increased to different extents. Because fibers were laid between veneers in the reinforced plywood, the moment of inertia about the neutral axis in the thickness of the fiber–resin lamina was lower. Young's modulus of the reinforced plywood for bending increased only a little compared with the values of corresponding controls. It is known that there is a proportional inclination between Young's modulus and bending strength. By inserting short fiber reinforcement between veneers in plywood the reinforced effect on bending strength is more marked than the effect on Young's modulus. This might be attributed to a "hybrid effect,"[6] which will be investigated in further studies.

Conclusion

On the basis of the above theoretical presentation and experimental demonstration, the effects of length and orientation of short fibers on the elastic properties of short fiber reinforcement were studied. From a practical point of view, the technical feasibility and reinforced functions of the reinforced plywood with short fibers were evaluated. The following conclusions can be drawn.

Theoretically, in the short fiber reinforcement system the fiber length does not directly influence the reinforcement when the carbon fiber length is long enough. However, if the fiber length is too long, the reinforced result is not as good owing to the bridge between fibers and the increase of holes in the glue layer.

Orientations of fibers in the wood–fiber composite has a marked impact on the reinforcement. That is, the unidirectional, perpendicular, and random orientation of fibers in fiber reinforcement exhibited different effects on elasticity. Fiber-reinforced plywood, which is internally reinforced with short carbon fibers in random orientation, showed a better reinforcing influence on panel shear, plate shear moduli, and bending strength than other mechanical properties.

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