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**Yingcheng Hu · Tetsuya Nakao · Takahisa Nakai
Jiyou Gu · Fenghu Wang**

# Effects of grain angles of face veneer on surface wave velocities and dynamic shear moduli of wood-based composites

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**Abstract** The effects of grain angle of face veneer on surface wave velocity and dynamic shear modulus of three types of wood-based composites were examined using a surface wave propagation method. It was found that grain-angle dependence of surface wave velocity and dynamic shear modulus indeed exists for wood-based composites. Grain angles of face veneer were found to have substantial effects on the surface wave velocities and dynamic shear moduli of wood–plastic composite (WP), wood–fiberboard composite (WF), and wood–metal composite (WM). The orthotropic properties of the three composites were defined as the ratio of surface wave velocities at 0° and 90° grain angles ($V_0/V_{90}$), which were 3.7, 2.2, and 2.0 for WP, WF, and WM, respectively. For WP, WF, and WM, the dynamic shear moduli in the 90° grain angle of face veneer were approximately 7%, 19%, and 25% of that in the 0° grain angle, respectively. The relationships between grain angles of face veneer and the shear moduli of the three types of wood-based composites could be represented by Hankinson's equation, and their optimal *n* values were 2.1, 1.2, and 1.3 for WP, WF, and WM, respectively.

**Key words** Wood-based composite · Grain angle · Surface wave velocity · Dynamic shear modulus

Y. Hu · J. Gu · F. Wang
Key Laboratory of Bio-based Material Science and Technology of Ministry of Education, College of Material Science and Engineering, Northeast Forestry University, Harbin 150040, China

T. Nakao (✉) · T. Nakai
Faculty of Science and Engineering, Shimane University, Matsue 690-8504, Japan
Tel. +81-852-32-6564; Fax +81-852-32-6123
e-mail: nakaote@riko.shimane-u.ac.jp

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## Introduction

Wood is an anisotropic, orthotropic material. There are many reports on the effects of grain angle on ultrasonic velocity,[1–3] but most of them were conducted in wood only and without consideration of wood-based composites and surface wave velocity. In other words, few investigations have been concerned with the effects of the grain angle on the surface wave velocity and the dynamic shear modulus of wood-based composites. The dynamic shear modulus is important for wood and wood-based composites and various testing methods are available for its determination. However, there exists a considerable difference between the shear modulus values determined by different methods. Furthermore, these tests have their drawbacks.[4–6] Soma et al.[7] studied the calculation of grain angle and verified their results with spherical wood specimens using ultrasonic waves. Zigzag and diagonal propagation pathways of ultrasonic waves were expressed by a simple cell model, and equations to calculate the ultrasonic propagation time at arbitrary grain angles from times in the L, R, and T directions were proposed.[7]

In our study, the surface wave velocities and dynamic shear moduli (out-plane shear moduli) of three types of wood-based composites were measured by surface wave propagation tests. The effects of grain angles of face veneer on the surface wave velocities and dynamic shear moduli and the possibility that the shear moduli can be predicted by means of an empirical formula were also examined.

## Materials and methods

### Materials

Experimental materials used for this study consisted of wood–plastic composite (WP), wood–fiberboard composite (WF), and wood–metal composite (WM), all with a three-layer structure. The construction of the materials is shown in Fig. 1. The face layers of the composite were wood (grain

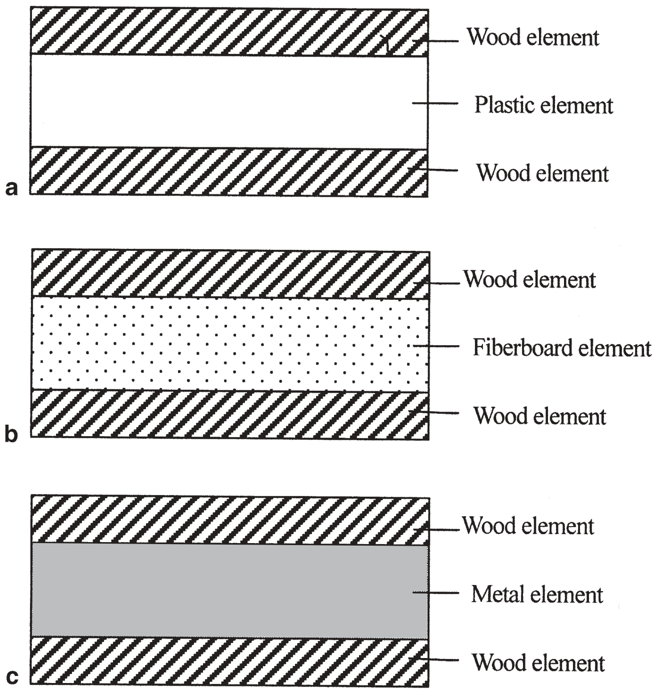


**Fig. 1a–c.** Construction of wood-based composites. **a** Wood–plastic composite (WP), **b** wood–fiberboard composite (WF), and **c** wood–metal composite (WM)

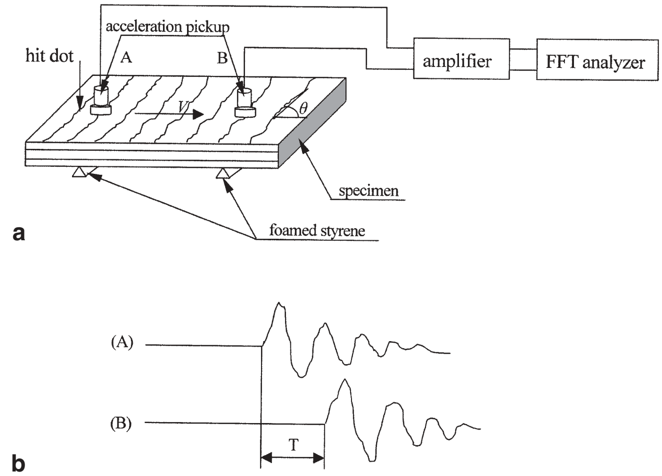


**Fig. 2a,b.** Surface wave propagation method. **a** Measuring system, **b** surface wave signals captured by fast Fourier transform (*FFT*) analyzer

angle: 0°, 15°, 30°, 45°, 60°, 75°, 90°) and the core layers of the composite were plastic, fiberboard, and metal. Japanese larch (*Larix leptolepis* Gordon) veneer (density: 0.64 g/cm$^3$, thickness: 3.5 mm), was used as the wood element (W). Polystyrene foam (density: 0.01 g/cm$^3$, thickness: 20 mm), insulation fiberboard (density: 0.25 g/cm$^3$, thickness: 10 mm), and aluminum plate (density: 2.75 g/cm$^3$, thickness: 2 mm) were used as the plastic (P), fiberboard (F), and metal (M) elements, respectively. Specimen size was 300 × 100 mm.

### Surface wave propagation test

As shown in Fig. 2a, the acceleration pickups were glued to the specimen with adhesive. The specimen was supported at the nodal points by foamed styrene. One side of the specimen was struck with a small wooden bar. The difference in time ($T$) in which the surface wave reached the two acceleration pickups on the specimen was measured by a fast Fourier transform (FFT) analyzer as shown in Fig. 2b.

The surface wave velocity and dynamic shear modulus were calculated from Eqns. 1 and 2.

$$V = L/T \quad (1)$$

$$G_V = \rho V^2 \quad (2)$$

where $V$ is surface wave velocity, $L$ is the distance between the two acceleration pickups, $T$ is surface wave propagation time, $G_v$ is shear modulus, and $\rho$ is the density of the specimen. The surface wave velocity and dynamic shear modulus were the average of five specimens for each condition. The measurements were carried out in a room maintained at 20°C and 65% relative humidity.

## Results and discussion

### Surface wave velocity

The relationships between surface wave velocity and grain angle of face veneer of three types of wood-based composites are shown in Fig. 3. As is obvious from the figures, the surface wave velocities decreased with increasing grain angle. This implies that the grain-angle dependence of surface wave velocity also exists for surface wave propagation through a wood-based composite. For wood (W), the loss of surface wave velocity was over 9.3% per degree in grain angle from 0° to 90°. For WP, WF, and WM, the losses of surface wave velocity were approximately 8.1%, 6.0%, and 5.6% per degree in grain angle of face veneer from 0° to 90°, respectively. Because the density and mechanical properties of plastic and fiberboard elements were smaller than the wood element, the anisotropy of WP and WF were mostly affected by the wood element and the effects of the plastic and fiberboard elements were secondary. However, for WM, because the density and mechanical properties of the metal element were much greater than the wood element, the anisotropy of WM was mostly affected by the metal element. Therefore, the surface wave velocity of WM decreased more slowly than those of WP and WF with increases of grain angle.

The orthotropic properties of the three wood-based composites were evaluated as the values of $V_0/V_{90}$. These values were 3.7, 2.2, and 2.0 for WP, WF, and WM, respectively.

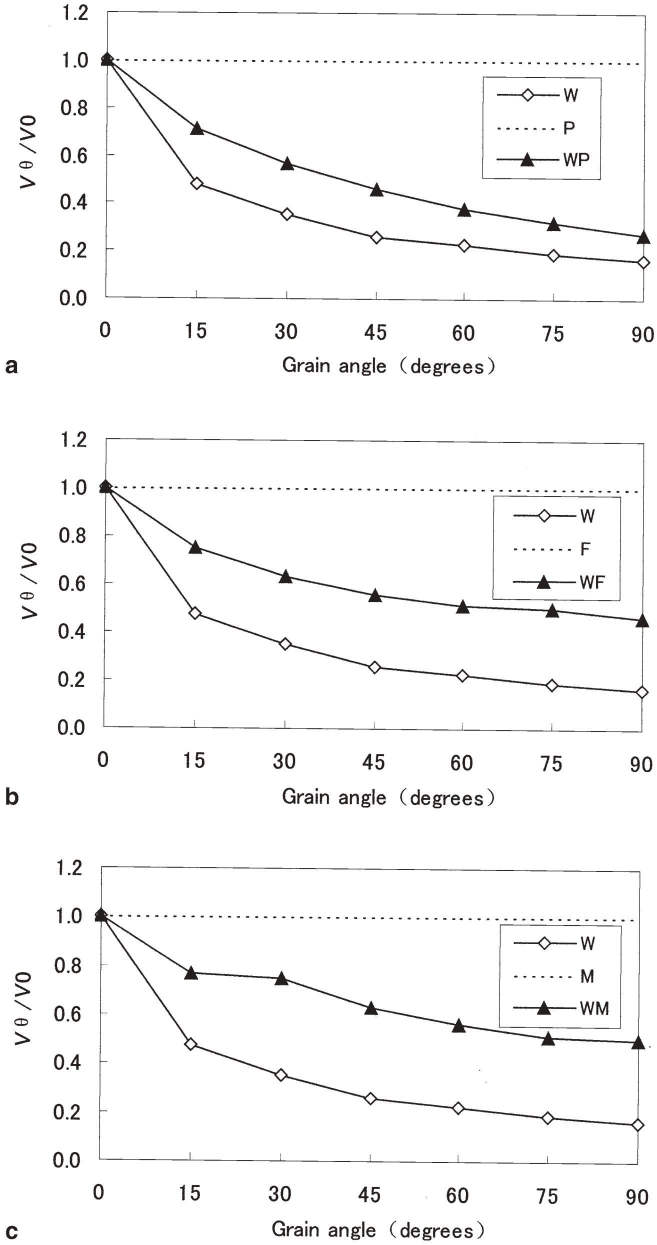


**Fig. 3a–c.** Relationships between surface wave velocities and grain angles of face veneer. **a** Wood–plastic composite, **b** wood–fiberboard composite, and **c** wood–metal composite. *W*, *P*, *F*, *M*, *WP*, *WF*, and *WM* represent the surface wave velocities from surface wave propagation tests of wood, plastic, fiberboard, and metal elements, and wood–plastic, wood–fiberboard, and wood–metal composites, respectively

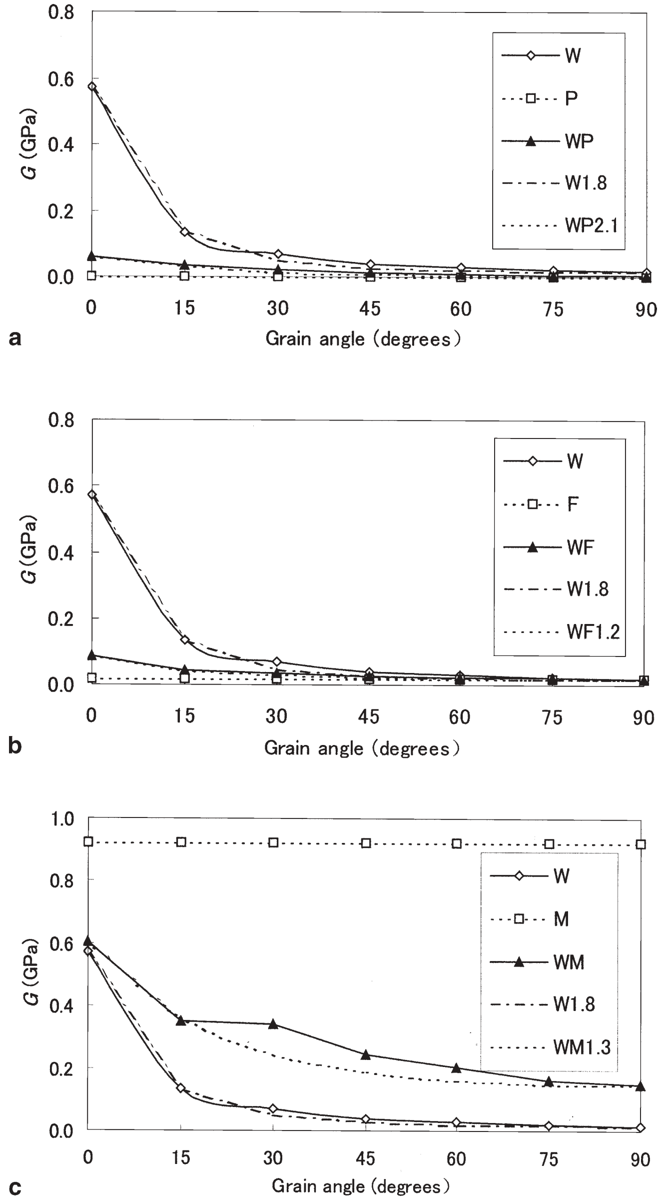


**Fig. 4a–c.** Relationships between dynamic shear moduli and grain angles of face veneer. **a** Wood–plastic composite, **b** wood–fiberboard composite, and **c** wood–metal composite. *W*, *P*, *F*, *M*, *WP*, *WF*, and *WM* represent the dynamic shear moduli from surface wave propagation tests of the elements and composites as listed in Fig. 3. *W1.8*, *WP2.1*, *WF1.2*, and *WM1.3* represent the dynamic shear moduli of wood, wood–plastic, wood–fiberboard, and wood–metal composites, respectively, calculated from the Hankinson equation

## Dynamic shear modulus

The relationships between grain angle of face veneer and dynamic shear modulus of the three wood-based composites are shown in Fig. 4. As is obvious from the figures, the dynamic shear moduli decreased with increasing grain angles. This implies that the grain-angle dependence of the dynamic shear modulus also exists for wood-based composites. For wood (W), the shear modulus in the 90° grain angle was approximately 3% of that in the 0° grain angle. For WP, WF, and WM, the dynamic shear moduli in the 90° grain angle of face veneer were approximately 7%, 19%, and 25% of that in the 0° grain angle of face veneer, respectively. The dynamic shear modulus of WM decreased slower than those of WP and WF with increases of grain angle because of the effect of the metal plate.

Figure 4 shows the dynamic shear moduli from surface wave propagation test and those calculated from the Hankinson equation:[8]

$$G_\theta = \frac{G_0 G_{90}}{G_0 \sin^n \theta + G_{90} \cos^n \theta} \tag{3}$$

where $G_\theta$ is the shear modulus at angle $\theta$ from the grain direction, $G_0$ is the shear modulus parallel to the grain, $G_{90}$ is the shear modulus perpendicular to the grain, and $n$ is an empirically determined constant. For wood, the value of $n$ is 1.8, while those of WP, WF, and WM are 2.1, 1.2, and 1.3, respectively.

## Conclusions

The effects of grain angle of face veneer on surface wave velocity and dynamic shear modulus of three types of wood-based composites were examined. The results are summarized as follows:

1. Grain angles of face veneer showed substantial effects on surface wave velocities and dynamic shear moduli of three types of wood-based composites. The surface wave velocities and dynamic shear moduli decreased with increasing grain angle. This implies that the grain-angle dependence of surface wave velocities and dynamic shear moduli also exists for wood-based composites.
2. The orthotropic properties of three types of wood-based composites were defined as the ratio of $V_0/V_{90}$. These values were 3.7, 2.2, and 2.0 for wood–plastic composite (WP), wood–fiberboard composite (WF), and wood–metal composite (WM), respectively.
3. The dynamic shear moduli of the three types of wood-based composites were largest at the 0° grain angle of the face veneer, but decreased rapidly with increasing grain angle, while the lowest values of the dynamic shear moduli occurred at the 90° grain angle. For WP, WF, and WM, the dynamic shear moduli in the 90° grain angle were approximately 7%, 19%, and 25% of that in the 0° grain angle, respectively. For wood, the shear modulus in the 90° grain angle was approximately 3% of that in the 0° grain angle.
4. The relationships between grain angles of face veneer and shear moduli of three types of wood-based composites could be represented by the form of Hankinson's equation, and their optimal $n$ values were 2.1, 1.2, and 1.3 for WP, WF, and WM, respectively.

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