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ORIGINAL ARTICLE

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Vibrational properties of wood plastic plywood

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Abstract Wood plastic plywood (WPPW), composed of veneer and styrofoam, was manufactured without special adhesives such as urea–formaldehyde or phenol–formaldehyde resins, and its vibrational properties were investigated. WPPW can be produced at 1 MPa and 160°C for 9 min (three-ply) and 12 min (five-ply). The dynamic Young's modulus reached its highest value when the styrofoam thickness was 30 mm. The sound velocity and dynamic Young's modulus had minimum values at a grain angle of 45°. The results for dynamic Young's moduli measured by a longitudinal vibration method and an in-plane flexural vibration method were almost the same. Dynamic shear moduli were measured by an in-plane surface wave propagation test and an in-plane flexural vibration method. From the experimental results, the dynamic shear moduli at 0° and 90° by the two methods were relatively close, although the surface wave propagation test results were higher than those from the flexural vibration method. Dynamic shear moduli at a grain angle of 45° measured by the in-plane surface wave propagation test and calculated from theory were relatively close. The surface wave propagation test results were smaller than the results calculated from theory. The shear stress distribution factors were about 1.000–1.189 for WPPW.

Key words Wood plastic plywood · Sound velocity · Dynamic Young's modulus · Dynamic shear modulus · Vibration method

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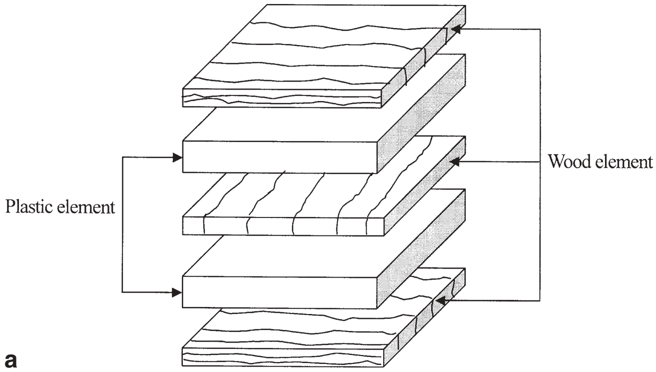
Introduction

Plywood is an important wood-based panel with many advantages. However, formaldehyde released from plywood, especially from urea–formaldehyde bonded plywood, is a pollution problem. Formaldehyde can pollute outdoor and indoor air and is harmful to human health. Formaldehyde in the air irritates the eyes, nose, and throat, and may even contribute to cancer. On the other hand, styrofoam is very useful as a packaging material. However, unless it is properly recycled after use it can become a pollution problem. Wood plastic plywood (WPPW) is made by combining wooden elements and plastic elements (styrofoam). Not only can WPPW decrease pollution caused by styrofoam waste and formaldehyde released from plywood, it is also economical because no special adhesives such as urea–formaldehyde resins or phenol–formaldehyde resins are required. In our study, wood plastic plywood (WPPW) composed of veneer and styrofoam was manufactured, and its vibrational properties were investigated.

The sound velocity, Young's modulus, and shear modulus are important properties for wood and wood-based panel products. The Young's modulus and shear modulus can be used to predict bending strengh.[1] In this article, the effects of the grain angles of face veneer on sound velocities and dynamic Young's moduli of WPPW are discussed. The effect of styrofoam thickness on dynamic Young's modulus of WPPW was also investigated. Various testing methods are available to determine the shear modulus, however, there exists a considerable difference between the shear modulus values determined by each method. Furthermore, these tests have their drawbacks.[2–4] For example, the Timoshenko-Goens-Hearmon (TGH) flexural vibration method is a very useful dynamic method. Dynamic shear and Young's moduli can be measured at the same time using the TGH flexural vibration method. However, it is not suitable for measuring plywood in the 45° grain angle of face veneer. In this article, the possibility of measuring the dynamic shear moduli of WPPW by surface wave propagation test is also discussed.



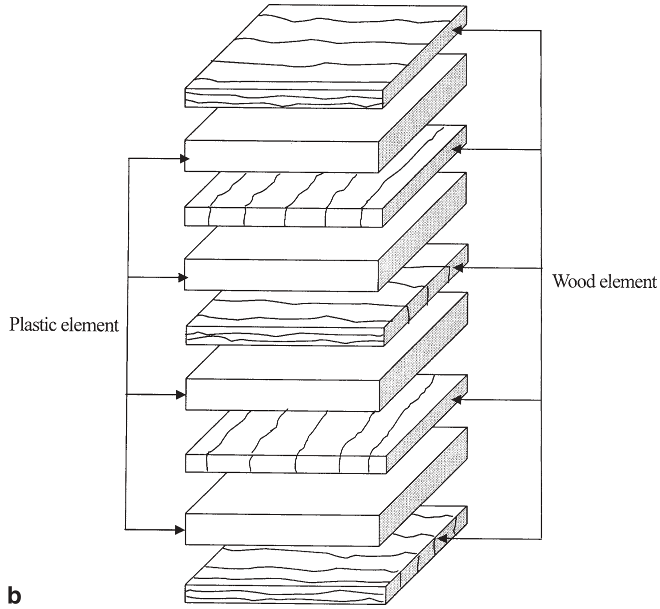


Fig. 1. Construction of WPPW before hot pressing for **a** three-ply and **b** five-ply

Materials and methods

Materials

The experimental panels were made from wood and plastic elements. As shown in Fig. 1, lauan (*Shorea* spp.) veneer (density: $0.455\,g/cm^3$, thickness: 3.5 mm) was chosen as the wood (W) element. Styrofoam (density: $0.013\,g/cm^3$, thickness: 10, 20, 30, 40, and 50 mm) was chosen as the plastic (P) element.

Panel manufacturing

All experimental panels (600 × 600 mm) were fabricated in the laboratory. There was no adhesive between the wood and plastic elements. The wood–plastic plywoods were hot-pressed at 1 MPa and 160°C for 9 min (three-ply) and 12 min (five-ply). Specimen size was 300 × 50 mm.

Vibration method

Longitudinal transmission method

The longitudinal transmission method is shown in Fig. 2. The sound transmission time propagating through the specimen was measured with a fast Fourier transform (FFT) analyzer.

The sound velocity and dynamic Young's modulus were calculated based on Eqs. 1 and 2:[5]

$$V = L/T \tag{1}$$

$$E = \rho V^2 \tag{2}$$

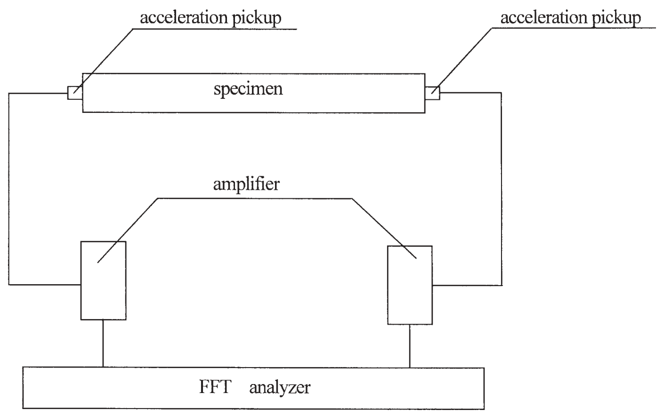


Fig. 2. Longitudinal transmission method. *FFT*, fast Fourier transform

where V is sound velocity, L is length of the specimen, T is transmission time, E is dynamic Young's modulus, and ρ is density of the specimen.

Longitudinal vibration method

The specimen was lightly supported in a horizontal orientation by the fingers at the center of the specimen while they were tapped by a small hammer at the end of the specimen. The tap tone was detected by a microphone at the other end of the beam. The resonance frequencies of the tap tone were identified by the FFT analyzer. The Young's modulus of free–free longitudinal vibration (E_p) was calculated using the following equation:

$$E_p = \rho\left(\frac{2Lf_n}{n}\right)^2 \qquad n = 1, 2, 3, \ldots \tag{3}$$

where ρ is density of the specimen, L is length of the specimen, f_n is the resonance frequency, and n is the number of the vibration modes.

Flexural vibration test

The specimens in the freely vibrating free–free beam test were supported by two strings. The supporting positions of the strings were $0.224L$ from both ends. This position corresponds to the nodal points for the fundamental node of this vibration system. The vibrating frequency was detected by a high-sensitivity microphone connected to an amplifier and a FFT analyzer. The resonant frequencies of the first, second, and third nodes were obtained by giving a blow to an edge of the beam and recording the results with the FFT analyzer. In this study, in-plane vibration tests were carried out. The dynamic in-plane Young's modulus (E_f) and the ratio of dynamic shear modulus and shear stress distribution factor (G/κ_f) were obtained from the TGH flexural vibration method, including the influence of shear and rotatory inertia.[6]

Surface wave propagation test

As shown in Fig. 3, the acceleration pickups were glued to the specimen with adhesive. The specimen was supported at the nodal points by the foamed styrene. One side of the specimen was struck with a small wood bar. The time difference of the wave arriving at the two acceleration pickups on the specimen was measured by the FFT analyzer. The dynamic shear modulus (G/κ_v) was calculated using the following equation:

$$G/\kappa_v = \rho V^2, \qquad V = L/T \tag{4}$$

where ρ is density of the specimen, V is surface wave propagation velocity, L is length between the two acceleration pickups, T is surface wave propagation time, and κ_v is shear stress distribution factor.

The measurements were carried out in a room maintained at 20°C and 65% relative humidity.

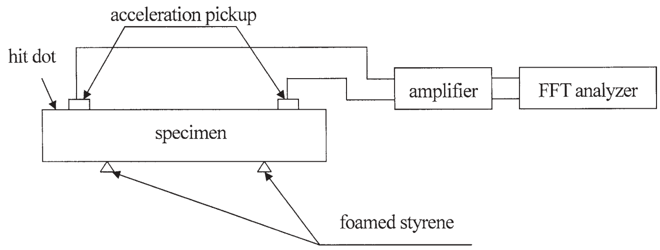


Fig. 3. Surface wave propagation method

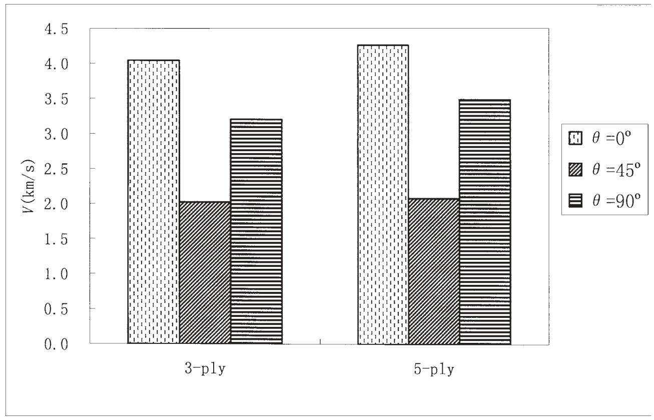


Fig. 4. Effect of grain angle (θ) of face veneer on sound velocity (V) of WPPW

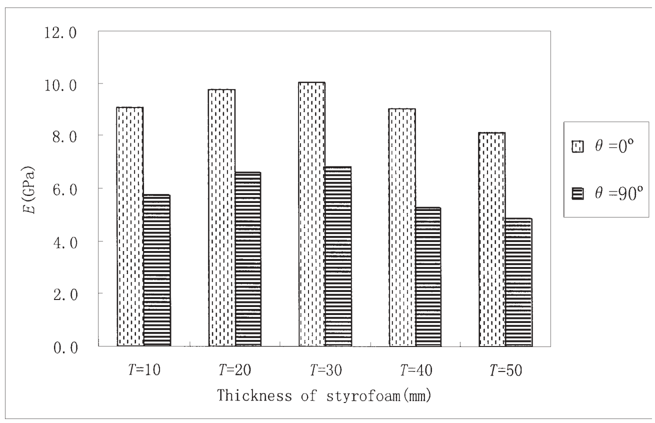


Fig. 5. Effect of styrofoam thickness (T) on dynamic Young's modulus (E) of WPPW

Results and discussion

Sound velocity

The effect of grain angle of face veneer on sound velocity of WPPW is shown in Fig. 4. It is obvious from Fig. 4, in WPPW (styrofoam thickness before hot press was 10mm), the sound velocity decreased with increases of grain angle from 0° to 45°. The sound velocity of WPPW with a face veneer grain angle of 0° was approximately twice that of WPPW with a face veneer grain angle of 45°. On the other hand, the sound velocity increased with increasing grain angle from 45° to 90°. Sound velocity in WPPW with a face veneer grain angle of 45° was approximately 60% of that of WPPW with a face veneer grain angle of 90°.

Dynamic Young's modulus

The effect of styrofoam thickness on the dynamic Young's modulus of WPPW by longitudinal transmission method is shown in Fig. 5. The result shows that the dynamic Young's modulus increased with increases of styrofoam thickness of 10mm to 30mm. However, in the range of 30–50mm, the dynamic Young's modulus gradually decreased with increasing styrofoam thickness. The dynamic Young's modulus reached its largest value when styrofoam thickness was 30mm.

Table 1. Dynamic Young's modulus of wood plastic plywood (WPPW) by longitudinal vibration method

Types of WPPW	Density (g/cm^3)	E_0 (GPa)	E_{45} (GPa)	E_{90} (GPa)	E_0/E_{45}	E_0/E_{90}
Three-ply WPPW	0.536	7.760	1.127	3.899	6.886	1.990
Five-ply WPPW	0.553	7.935	1.324	4.966	5.993	1.598

E_0, Dynamic Young's modulus in the face veneer grain angle of 0°; E_{45}, dynamic Young's modulus in the face veneer grain angle of 45°; E_{90}, dynamic Young's modulus in the face veneer grain angle of 90°

Table 2. Dynamic Young's modulus of WPPW by in-plane flexural vibration method

Types of WPPW	Density (g/cm^3)	E_0 (GPa)	E_{90} (GPa)	E_0/E_{90}
Three-ply WPPW	0.536	7.614	3.944	1.931
Five-ply WPPW	0.553	7.772	4.856	1.600

Table 3. Comparison of in-plane dynamic shear modulus of WPPW by two methods

Types of WPPW	θ (°)	G_f (GPa)	G_{cp} (GPa)	G_v (GPa)	G_v/G_f	κ_v (45°)	κ_v (0°, 90°)
Three-ply WPPW	0	0.291	–	0.315	1.082	–	1.109
	45	–	1.520	1.392	–	1.092	–
	90	0.289	–	0.339	1.173	–	1.023
Five-ply WPPW	0	0.359	–	0.402	1.120	–	1.072
	45	–	2.386	2.007	–	1.189	–
	90	0.353	–	0.381	1.079	–	1.112

θ, Grain angle of face veneer of WPPW; $G_f = G/\kappa_f$, dynamic shear modulus of WPPW by in-plane flexural vibration method; G_{cp}, shear modulus of WPPW calculated by Eq. 9; $G_v = G/\kappa_v$, dynamic shear modulus of WPPW by in-plane surface wave propagation test; κ_v (45°), shear stress distribution factor calculated by G_{cp}/G_v; κ_v (0°, 90°), shear stress distribution factor calculated by $G/G_v = (\kappa_f \times G_f)/G_v$ where, $\kappa_f = 1.2$

The results of measuring dynamic Young's moduli of WPPW (styrofoam thickness before hot press was 10 mm) by the longitudinal vibration method and in-plane flexural vibration method are shown in Tables 1 and 2. The dynamic Young's moduli for three-ply WPPW with a face veneer grain angle of 0° were approximately seven times higher than those of WPPW with a face veneer grain angle of 45°, and approximately twice those of WPPW with a face veneer grain angle of 90°. The dynamic Young's moduli for five-ply WPPW with a face veneer grain angle of 0° were approximately six times higher than those of WPPW with a face veneer grain angle of 45°, and approximately 1.6 times higher than those of WPPW with a face veneer grain angle of 90°. This result was similar to that for conventional plywood.[7] In addition, it is obvious from Tables 1 and 2 that the dynamic Young's moduli of WPPW measured by longitudinal vibration and in-plane flexural vibration methods were almost the same. This result is similar to that of others.[8]

Dynamic shear modulus

The results of dynamic shear moduli of WPPW (styrofoam thickness before hot press was 10 mm) by surface wave propagation and flexural vibration methods are shown in Table 3. For WPPW, in-plane dynamic shear moduli at grain angles of 0° and 90° measured by the two methods were relatively close. However, the surface wave propagation test results were greater than those from the flexural vibration tests.

To verify the validity of in-plane dynamic shear moduli for the face veneer grain angle of 45° by a surface wave propagation test, the following equations were examined:[9,10]

$$\frac{1}{G_\theta} = \frac{1}{G_{\mathrm{LT}}}\cos^2 2\theta + \left(\frac{1}{E_{\mathrm{L}}} + \frac{1}{E_{\mathrm{T}}} + \frac{2\gamma_{\mathrm{LT}}}{E_{\mathrm{T}}}\right)\sin^2 2\theta \tag{5}$$

$$\frac{1}{E_\theta} = \frac{1}{E_{\mathrm{L}}}\cos^4\theta + \frac{1}{E_{\mathrm{T}}}\sin^4\theta + \left(\frac{1}{G_{\mathrm{LT}}} - \frac{2\gamma_{\mathrm{LT}}}{E_{\mathrm{L}}}\right)\sin^2\theta\cos^2\theta \tag{6}$$

where θ is the grain angle of face veneer of the specimen, G_θ is the shear modulus, E_θ is the Young's modulus, E_{L} and E_{T} are the Young's moduli in the L and T directions, G_{LT} is the shear modulus in the LT plane, and γ_{LT} is Poisson's ratio in the LT plane.

When $\theta = 45°$, Eq. 5 can be represented as follows:

$$\frac{1}{G_{45}} = \frac{1}{E_{\mathrm{L}}} + \frac{1}{E_{\mathrm{T}}} + \frac{2\gamma_{\mathrm{LT}}}{E_{\mathrm{T}}} \tag{7}$$

When $\theta = 45°$, Eq. 6 can be represented as follows:

$$\frac{2\gamma_{\mathrm{LT}}}{E_{\mathrm{L}}} = \frac{1}{E_{\mathrm{L}}} + \frac{1}{E_{\mathrm{T}}} + \frac{1}{G_{\mathrm{LT}}} - \frac{4}{E_{45}} \tag{8}$$

Substituting Eq. 8 into Eq. 7, G_{45} can be calculated as follows:

$$\frac{1}{G_{45}} = \frac{2}{E_{\mathrm{L}}} + \frac{2}{E_{\mathrm{T}}} + \frac{1}{G_{\mathrm{LT}}} - \frac{4}{E_{45}} \tag{9}$$

The results of calculated shear moduli are shown in Table 3. It is obvious that dynamic shear moduli for a grain angle of 45° measured by the in-plane surface wave propagation test and calculated by Eq. 9 were relatively close. However, the surface wave propagation test results were lower than the results calculated by Eq. 9.

Shear stress distribution factor

According to the report by Hearmon,[11] the following equation is given:

$$(1-d)q^3 - (1-e+2f)q^2 + f(f+2)q - f^2 = 0 \tag{10}$$

where

$$q = \frac{1}{c_{66}},\quad d = \frac{c_{66}}{c_{22}},\quad e = \frac{c_{11}}{c_{22}},\quad f = \frac{c_{11}}{c_{66}} - \frac{c_{12}^2}{c_{22}c_{66}}$$

and

$$\begin{bmatrix} c_{11} & c_{12} & \\ c_{21} & c_{22} & \\ & & c_{66} \end{bmatrix} = \begin{bmatrix} \dfrac{1}{E_{\mathrm{L}}} & \dfrac{-\gamma_{\mathrm{LT}}}{E_{\mathrm{L}}} & \\ \dfrac{-\gamma_{\mathrm{LT}}}{E_{\mathrm{L}}} & \dfrac{1}{E_{\mathrm{T}}} & \\ & & \dfrac{1}{G_{\mathrm{LT}}} \end{bmatrix}$$

To surface wave propagation, q can be represented as follows (0° and 90° grain angle WPPW):

$$q = \frac{1}{\kappa_v} \tag{11}$$

In general, Eq. 10 has one real root. Therefore, the shear stress distribution factor κ_v can be calculated. For three-ply WPPW, $\kappa_v = 1.001$. For five-ply WPPW, $\kappa_v = 1.000$.

Table 3 and the above analysis show that $\kappa_v = 1.000$–1.189 for WPPW.

Conclusions

The vibrational properties of WPPW were discussed. The following conclusions have been drawn. The sound velocity and dynamic Young's modulus had minimum values at a grain angle of 45°. Dynamic Young's moduli at the face veneer grain angle of 0° were approximately six to seven times greater than that of WPPW with a face veneer grain angle of 45°; and were approximately 1.6–2 times greater than that of WPPW with a face veneer grain angle of 90°. The results for the dynamic Young's moduli measured by the longitudinal vibration method and the in-plane flexural vibration method were almost the same. The dynamic Young's modulus reached its largest value when styrofoam thickness was 30 mm.

Dynamic shear moduli were measured by an in-plane surface wave propagation test and an in-plane flexural vibration method. From experimental results, the dynamic shear moduli at 0° and 90° by the two methods were relatively close. The surface wave propagation test results were greater than those from the flexural vibration method. Dynamic shear moduli a grain angle of 45° measured by the in-plane surface wave propagation test and calculated from theory were relatively close. The surface wave propagation test results were smaller than those calculated by theory. The shear stress distribution factors were about 1.000–1.189 for WPPW.

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