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Simultaneous Determination of Orthotropic Elastic Constants of Standard Full-Size Plywoods by Vibration Method*1

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振動現象を利用した実大合板の異方性弾性定数の同時決定*1

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実大サイズの合板の三つの弾性定数(長辺方向ヤング率, 短辺方向ヤング率, せん断弾性係数)を板振動法によって同時決定する方法について検討した。合板は, 通称3×6のJAS 1級相当の構造用合板, 厚さ7.5 mm, 9.5 mmおよび12 mm, 単板樹種カプールで製造したものそれぞれ10枚ずつ用いた。合板を水平に支持すると大きな初期たわみが発生するので, その長辺を下にしてV型の溝に鉛直に立てかけ, 一辺単純支持-三辺自由の境界条件として支持し, 小さな硬質ゴム製のボールで合板上辺の自由端を打撃した。もう一方の合板上辺の自由端で振動を検出し, 高速フーリエ変換スペクトルアナライザで周波数分析をした後, パーソナルコンピュータを利用してスペクトルピークの帰属を行った。

板振動法によって得られた弾性定数は, 静的な曲げおよびねじり試験法によって得られた値とよく一致した。ただし, 実大サイズの合板のせん断弾性係数を板振動法によって求めるとき低次振動モードを用いると支持辺における振動の拘束が起こるので, 高次振動の固有振動数を用いるべきであることが明らかとなった。

A simultaneous determination of elastic constants, two Young's moduli and a shear modulus, of standard full-size plywoods using a vibration method was studied from the viewpoint of development of non-destructive tests of structural members. A full-size plywood was supported vertically on a long edge of SFFF, one-edge simply supported and three edges free, boundary condition and tapped with a small rubber ball, and a frequency analysis using a Fast Fourier Transformation, FFT, analyzer was used. A computer supported identification of spectrum peaks of the frequency spectra was examined.

The elastic constants measured by vibration method well agreed with those obtained by static bending and twisting tests. The use of the resonance frequencies of higher vibration modes is recommended for determination of shear moduli of full-size plywoods, because restriction of vibration at supported edge affects resonance frequencies of low vibration modes.

Keywords : elastic constants, full-size plywoods, vibration technique, simultaneous determination, non-destructive test.

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1. INTRODUCTION

Growing social demand for the conservation of forest resources requires more effective use of wood. Production of engineered components, such as stress-skin panels, I-beams, and box beams will contribute not only to save wood resource but also to enable a large scale wood construction. Polywood is one of the fundamental materials for these engineered components. An automated-, quick-, and simple-measurement of elastic constants in full-size is the key process which enables reasoned arrangements of structural plywoods in such engineered materials.

At present, there are some standard testing methods for the measurement of Young's moduli of full-size plywood as follows: for example, the Japan Agricultural Standard for the concrete-form plywood and the Pure Moment Test for large specimens of ASTM D3043-76. However, no standard method for the measurement of shear modulus of the full-size plywoods, but for small specimen, JAS for structural plywoods and ASTM D3044-76 are recommended.

Present paper deals with a simultaneous determination of orthotropic elastic constants of standard full-size plywoods for structural use by a vibration technique. For this purpose, there are some problems to be solved: (1) Boundary condition of the vibration; how to support the specimens considering a practical application to the full-size specimens in industrial processing. (2) Vibration analysis; how to identify the individual resonance peak of power spectra. (3) Validity of the constants determined by the vibration tests; the results should be compared with the corresponding constants determined by the static tests.

2. FUNDAMENTALS OF VIBRATION OF ORTHOTROPIC PLATES

The choice of the boundary condition of the specimen is very important considering the application to full-size plywood. We chose the SFFF (one-edge simply supported and three edges free) boundary condition. Specimens were supported vertically on the simple supported edge, because this procedure can avoid an effect of the initial deflection by weight of specimens on the resonance frequency, which occurs when the specimen is laid horizontally.

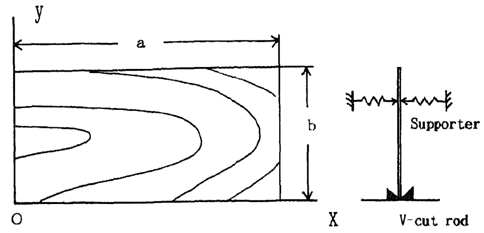

Fig. 1. Specimen support and coordinate system.

Figure 1 shows the specimen support and the coordinate system of an orthotropic plywood.

The resonance frequency of the orthotropic plate $f(i, j)$ is given by Equation 1.[1)]

$$f(i, j)=k\left\{D_{11}\frac{\gamma_1(i, j)}{a^4}+D_{22}\frac{\gamma_2(i, j)}{b^4}+2D_{12}\frac{\gamma_3(i, j)}{a^2b^2}+4D_{66}\frac{\gamma_4(i, j)}{a^2b^2}\right\}$$

$$k=\frac{1}{2\pi}\sqrt{\frac{1}{\rho h}} \tag{1}$$

$$D_{11}=\frac{E_x h^3}{12(1-\nu_{xy}\nu_{yx})},\quad D_{22}=\frac{E_y h^3}{12(1-\nu_{xy}\nu_{yx})}$$

$$D_{12}=D_{11}\nu_{yx}=D_{22}\nu_{xy},\quad D_{66}=\frac{G_{xy}h^3}{12} \tag{2}$$

where i and j are numbers of vibration modes, D_{kl}s are flexural rigidities and torsional rigidity of the plywood, and $\gamma_n(i, j)$s are the constants which are given for SFFF boundary condition[1)] (c.f.: Table 1). The number of vibration mode is equal to that of the nodal lines.

The object variables, two Young's moduli E_x, E_y, and a shear modulus G_{xy}, are given by solving Equation 1 for some vibration modes, at least for three modes (2, 1), (0, 2), and (1, 1) modes, as follows:

$$D_{11}=\frac{a^4}{500.6}\left\{4\pi^2\rho h f^2(2, 1)-\frac{4\times 148.44}{a^2b^2}D_{66}\right\} \tag{3}$$

Table 1. Constant γ_n (i, j) in SFFF condition.

i	j	γ_1	γ_2	γ_3	γ_4
1	1	0	0	0	36
2	1	500.6	0	0	148.44
3, 4, 5, ···	1	X^4	0	0	$3X(X+6)$
0	2, 3, 4, ···	0	Y^4	0	0
1	2, 3, 4, ···	0	Y^4	0	$12Y(Y+3)$
2	2, 3, 4, ···	500.6	Y^4	$12.3Y(Y-1)$	$49.48Y(Y+3)$
3, 4, ···	2, 3, 4, ···	X^4	Y^4	$XY(X-2)(Y-1)$	$XY(X+6)(Y+3)$

Note: $X=(M-0.5)\pi$, $Y=(N-0.75)\pi$.

$$D_{22}=4\pi^2\rho hf^2(0,\ 2)/237.82 \tag{4}$$

$$D_{66}=\pi^2\rho ha^2b^2f^2(1,\ 1)/36 \tag{5}$$

where ν_{xy} and ν_{yx} are given to be 0.1 and 0.05, respectively, because their effects on calculation of E_x and E_y are negligibly small.[2] Then D_{11}, D_{22}, and D_{66} are converted to the engineering constants E_x, E_y, and G_{xy} by using Eq. 2.

3. EXPERIMENT

3.1 Materials

Factory made standard plywoods for structural use (equivalent to the JAS No. 1 grade) whose dimensions are 182 cm×91 cm×thickness (7.5 mm, 9.5 mm, and 12 mm) were used. Number of specimens was ten for each thickness. Kapur (*Dryobalanops* sp.) veneer was used. Mean density of plywoods was 0.675 g/cm³.

3.2 Vibration tests of full-size plywoods

3.2.1 Methods

A plywood was supported vertically on a V-cut aluminium rod fixed on a floor base and lightly supported from both sides with two pieces of sponge rubber to keep the specimen from falling as shown in Figure 1.

A plywood was lightly tapped twice with a hard rubber ball for each specimens at 15 cm from one corner on the upper edge line.

The vibration was detected by two vibration sensors located at the other corner and the center of the upper edge line, because the corner is the loop position of all vibration modes and the center is the nodal position of odd-numbered vibration modes. The detected signals were introduced to a Fast Fourier Transformation, FFT, spectrum analyzer which was controlled by a personal computer to obtain frequency spectra.

Ten spectrum peaks were searched automatically by using the auto-search function of the FFT analyzer which identifies ten strong peaks in object frequency range. Spectrum frequency ranges were 0 to 50 Hz for plywoods of 7.5 and 9.5 mm in thickness and 0 to 100 Hz for those of 12 mm in thickness.

3.2.2 Calculation of elastic constants

The elastic constants are determined as the mean of rigidities calculated from combination of the resonance frequencies of two or three different vibration modes, except for (0, 2) and (1, 1) modes. Table 2 shows combinations of the equations used for calculation of the rigidities of plywood.

Table 2. Combinations of the equations used.

Rigidities	Vibration modes	Equations used
D_{11}	1. (1,1), (2,1)	(6), (11)
	2. (2,1), (3,1)	(7)
	3. (1,1), (3,1)	(8), (11)
D_{22}	1. (0,2)	(9)
	2. (1,1), (1,2)	(10), (11)
	3. (1,2), (2,1), (3,1)	(10), (13)
D_{66}	1. (1,1)	(11)
	2. (2,1), (3,1)	(13)
	3. (0,2), (1,2)	(9), (12)

Notes: Rigidities were calculated as the mean of the three combinations. Equations used were as follows;

$$D_{11}=\frac{a^4}{500.6}\left\{4\pi^2\rho hf^2(2,\ 1)-\frac{4\times 148.44}{a^2b^2}D_{66}\right\} \tag{6}$$

$$D_{11}=\frac{4\pi^2\rho ha^4\{f^2(2,\ 1)\times 326.43-f^2(3,\ 1)\times 148.44\}}{500.6\times 326.43-148.44\times 3805.04} \tag{7}$$

$$D_{11}=\frac{a^4}{3805.04}\left\{4\pi^2\rho hf^2(3,\ 1)-\frac{4\times 326.43}{a^2b^2}D_{66}\right\} \tag{8}$$

$$D_{22}=4\pi^2\rho hb^4f^2(0,\ 2)/237.82 \tag{9}$$

$$D_{22}=\frac{b^4}{237.82}\left\{4\pi^2\rho hf^2(1,\ 2)-\frac{4\times 326.43}{a^2b^2}D_{66}\right\} \tag{10}$$

$$D_{66}=\pi^2\rho ha^2b^2f^2(1,\ 1)/36 \tag{11}$$

$$D_{66}=\frac{a^2b^2}{4\times 326.43}\left\{4\pi^2\rho hf^2(1,\ 2)-\frac{237.82}{b^4}D_{22}\right\} \tag{12}$$

$$D_{66}=\frac{\pi^2\rho ha^2b^2\{f^2(2,\ 1)\times 3805.04-f^2(3,\ 1)\times 500.6\}}{148.44\times 3805.04-500.6\times 326.43} \tag{13}$$

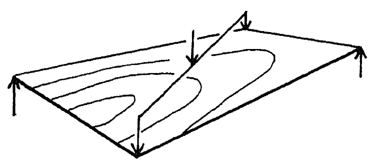

Fig. 2. Plate shear test for full-size plywood.

3.3 Static flexural and torsional tests of full-size specimens

The flexural Young's moduli of full-size plywoods in two principal directions were measured according to JAS standard for concrete-form plywoods.

A full-size plate shear test shown in Figure 2 als was applied.

3.4 Torsional tests of small specimens

The static shear modulus of small specimens measured according to ASTM D3044-76. dynamic shear modulus of small specimens by usir plate twisting vibration of a completely-free pl also was measured.[3]

3.5 Automated identification of spectrum peaks

The power spectrum pattern of orthotropic materials depends on combination of elastic constants; E_x, E_y, G_{xy} and ν_{xy} (or ν_{yx}). The identification of the spectrum peaks of orthotropic materials such as wood and plywoods usually is confirmed by observing the Chladni-figure whose procedure is time-consuming. Accordingly an automated identification procedure which doesn't require the Chladni-figure observation is desired to be developed from the viewpoint of non-destructive tests for industrial use. However, this is a very complicated problem.

The general feature of model spectrum pattern of the object plywoods was then examined by using a Monte-Carlo simulation based on knowledge base which involves fundamental data of veneer composition prescribed by JAS standard for structural plywoods, and density and elastic constants for the cases of the kapur plywood of 7.5 mm, 9.5 mm and 12 mm in thickness. The resonance frequencies of object plywood were estimated from Equation 1 by using random numbers generated from a computer program. Here, the variation of the elastic constants was assumed to be 30%.

Figure 3 shows the model spectrum pattern obtained for plywood of 9.5 mm in thickness. The result shows that (1, 1) mode peak isolates at the lowest frequency, that (2, 1) mode peak locates at the second lower frequency with high probability, and that the location of higher vibration modes depends on combination of elastic constants of plywoods.

The flow-chart of the computer identification of individual peaks is shown in Figure 4. First, ten pairs of peak frequency data and intensity, which were collected by the corner vibration sensor, were introduced to the computer. Then, the peak of (1, 1) mode was determined because it locates at the lowest frequency of the spectrum. Next, the peak of (2, 1) mode was determined because its resonance frequency is secondarily small. Using these two resonance frequencies, preliminary values of D_{66} and D_{11} were calculated, then a probable resonance frequency of the (3, 1) mode was estimated by using Equation 1, searching a peak whose resonance frequency was most close to the estimated resonance frequency within ten peaks. Then, a preliminary value of D_{22} is given from knowledge base, and the probable resonance frequency of (1, 2) mode was determined as in the case of the peak of (3, 1) mode. The determined peak frequency of (1, 2) mode was substituted in Equation 1 to calculate the value of D_{22}. The probable resonance frequency of (0, 2) mode was estimated by using this calculated value of D_{22}, then the peak of (0, 2) mode was searched as in the case of the peak of (3, 1) mode.

The remaining large peaks are those of (2, 2) and

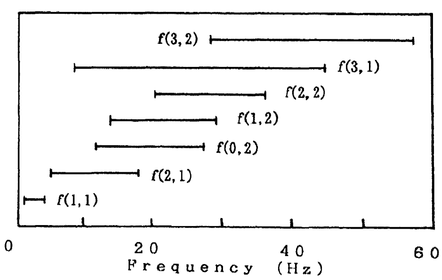

Fig. 3. Model spectrum pattern given by Monte-Carlo simulation.
Notes: The frequency range was given by simulation of a hundred times, and the deviation of elastic constant used was 30%. The plywood thickness was 9.5 mm.

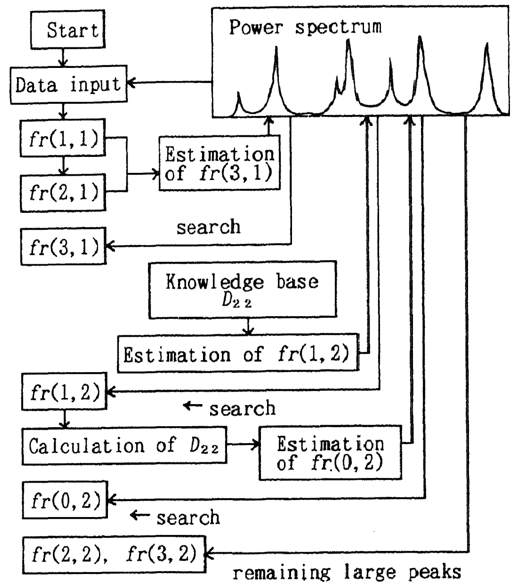

Fig. 4. Flow-chart of computer identification of spectrum peaks.
Notes: In the case of the plywood of 12 mm in thickness (4, 1) and (4, 2) modes are included in the remaining peaks.

(3, 2) modes, respectively. In the case of the plywoods of 12 mm in thickness higher-numbered vibration modes such as (4, 1) and (4, 2) modes also were searched.

4. RESULTS AND DISCUSSION

4.1 Effect of tap positions on spectra

An effective tap position was determined experimentally so that the spectrum peaks required in the vibration analysis had sufficient intensities. A full-size plywood was tapped at each 10 cm interval near the upper corner. Figure 5 shows the effect of the tap position on the relative spectrum intensities of some vibration modes. The effective tap position was chosen so that the intensities of (1, 1) and (0, 2) modes become relatively large because their spectrum intensities were weak.

In SFFF boundary condition, the corner of the upper edge line is a loop of all vibration modes. However, the most effective tap position for (1, 1) and (0, 2) modes was 30 cm from the corner on the upper edge line. But near this position, there are nodal lines of (3, 1) and (3, 2) modes (24 cm from the corner). Accordingly, the tapping position was finally chosen to be 15 cm from the corner on the upper edge line.

4.2 Computer supported automated identification of spectrum peaks

Table 3 shows the result of the computer identification of spectrum peaks. Very good identification was obtained. In the plywood of 7.5 mm in thickness, one misidentification occurred because the peak intensity of the (1, 1) mode was too weak to be searched by the automated peak search function of the FFT analyzer used. In the plywood of 12 mm in thickness, misidentification of (0, 2) and (1, 2) modes occurred because the spectrum peak of (0, 2) mode was absorbed in the shoulder of closing large peak of (1, 2) mode.

Figure 6 shows typical power spectra detected by the corner sensor (upper) and by the center sensor (lower). In the lower spectrum, even-numbered peaks are clearly detected by the center sensor. Accordingly, if information of the spectrum detected by the center sensor is used in computer identification, misidentification of (0, 2) mode occurred in the plywood of 12 mm in thickness will be avoidable.

4.3 Evaluation of elastic constants

4.3.1 Young's moduli in longitudinal direction E_x and perpendicular-to-longitudinal direction E_y

Figure 7 shows a relationship between Young's

Table 3. Degree of hit by the computer identification (in %).

Specimen	Vibration mode (1, 1)	(2, 1)	(0, 2)	(1, 2)	(3, 1)
7.5 K (9)	88.9	100	100	100	100
9.5 K (10)	100	100	100	100	100
12 K (10)	100	100	90	90	100
(29)	96.6	100	96.6	96.6	100

Note: The values in the parenthesis are the number of specimens.

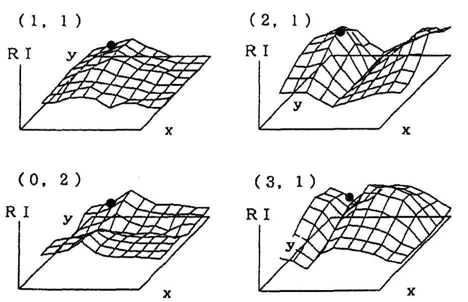

Fig. 5. Effect of tap position on relative spectrum intensity RI of some vibration modes.
Notes: Interval of tap position is 10 cm. Black circle means a tap position used in this work.

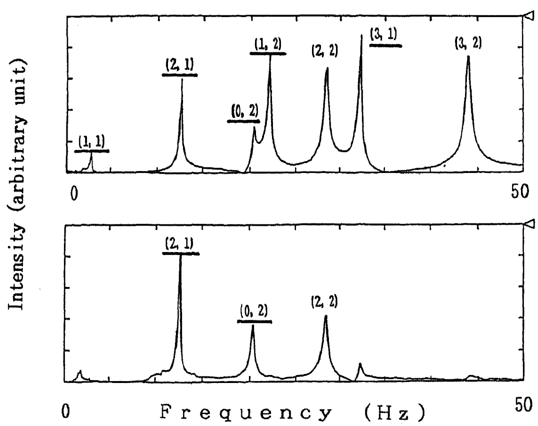

Fig. 6. Typical power spectra of full-size plywood.
Notes: upper ; detected by the corner censor, lower ; detected by the center censor. The plywood thickness is 9.5 mm.

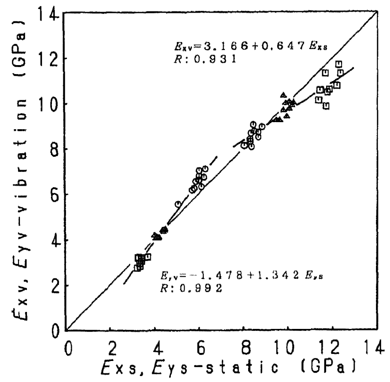

Fig. 7. Relationship between static Young's moduli, E_{xs} or E_{ys}, and dynamic Young's moduli, E_{xv} or E_{yv}.
Legend: □; 7.5 mm, △; 9.5 mm, ○; 12 mm.

Table 4. Shear moduli of specimens.

Specimen	Full-size Dynamic G_{xy} (GPa)	Small specimen Static[1] G_{xy} (GPa)	Dynamic[2] G_{xy} (GPa)	Dynamic / Static
7.5 K	0.997	0.473	0.474	1.002
	0.885	0.463	0.462	0.998
9.5 K	0.537	0.407	0.420	1.032
	0.698	0.426	0.434	1.019
12 K	0.618	0.435	0.467	1.074
	0.573	0.437	0.479	1.098
9 K	0.779	0.405	0.403	0.995
	0.679	0.401	0.401	1.000
	0.771	0.418	0.426	1.019
	0.772	0.454	0.390	0.859
	0.643	0.437	0.388	0.888
	0.645	0.466	0.402	0.863
12 K′	0.564	0.398	0.372	0.935
	0.502	0.402	0.393	0.978
			mean···	0.983

Notes: The plywoods of 9 mm (9 K) and 12 mm (12 K′) in thickness were added. 1) ASTM D3044-76 (plate shear). 2) FFFF (Free vibration).

modulus determined by the static tests (E_{xs} and E_{ys}) and that by the vibration tests (E_{xv} and E_{yv}).

The relationship of Young's moduli between the static test and the vibration test showed very good correlation:

$$E_{xv}=3.166+0.647\,E_{xs},\ R=0.931, \tag{14}$$

$$E_{yv}=-1.478+1.342\,E_{ys},\ R=0.992. \tag{15}$$

The mean value of E_{xv}-to-E_{xs} ratio was 0.970 (ranged from 1.075 to 0.841). The mean value of E_{yv}-to-E_{ys} ratio was 1.001 (ranged from 1.166 to 0.842).

However, in the case of the plywoods of 7.5 mm in thickness, E_{xv} is a little smaller than E_{xs} by about 9% on average. Probably, a damping effect by air affected decrease of the resonance frequency of thin plywoods, because stiffness of thin plywoods is small. On the other hand, E_{yv} of the plywoods of 12 mm in thickness is a little larger than E_{ys} by about 10% on average. Probably, a restriction for rotation of specimens at the supported edge as stated in the following section increased E_{yv} values.

4.3.2 Shear modulus G_{xy}

The shear modulus values of full-size plywoods were obviously divergent from what would be expected. The shear modulus by the static test G_{xys} was too large in the thin plywoods. The ratio of G_{xyv}-to-G_{xys} ranged from 0.29 to 2.0, where G_{xyv} is the shear modulus by vibration test. This may be due to an effect of weight of the plywood on the large initial deflection in static test. The same trend has been shown by McLain and Bodig.[4]

Then, the shear moduli of small specimens prepared from the corresponding full-size plywoods were measured by both static and vibration methods. In small specimens, the shear modulus by vibration test agreed very much with that by the static test as shown in Table 4. This result shows that the shear modulus determined with small specimens was a material constant which was not affected by the experimental conditions.

The shear moduli of the full-size plywoods used should be equal in all thickness, because the plywoods used were manufactured by using veneers of same quality and because the shear modulus of a plywood is theoretically not affected by veneer composition and plywood thickness.[5] However, there was still a large deviation of the shear modulus of full-size plywoods measured by vibration tests, ranging between 0.52 GPa to 1.29 GPa. Therefore, the discrepancy in shear modulus of full-size plywoods was considered to be induced by the boundary condition of vibration. The boundary condition chosen was one-edge simply supported and three-edges free. Therefore, if there exists a discrepancy of the experimental boundary condition from the theoretical one, it would be the condition of simply-supported edge, because there may be a friction between the specimen and V-cut rod at the simply-supported edge and because the

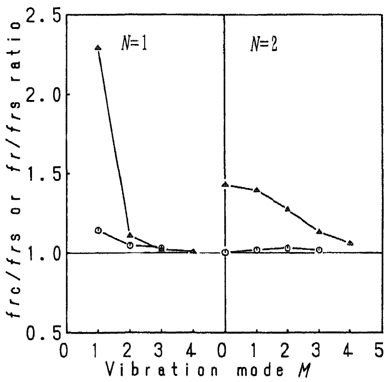

Fig. 8. Relationship between fr_c-to-fr_s or fr-to-fr_s ratio and vibration mode (M, N).
Notes: plywood thickness is 9.5 mm. fr_c; resonance frequency in CFFF boundary condition, fr_s; resonance frequency in SFFF boundary condition, fr; resonance frequency in experiment.
Legend: △; fr_c-to-fr_s ratio, ○; fr-to-fr_s raio.

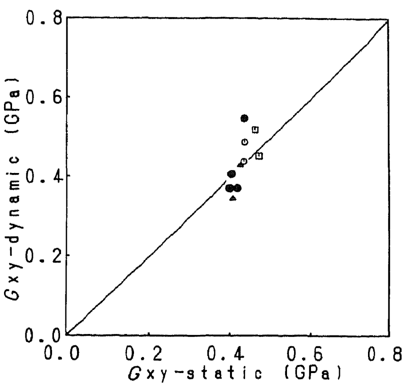

Fig. 9. Relationship between static shear moduli of small specimens, G_{xy}-static, and dynamic shear moduli calculated from resonance frequencies of higher-ordered vibration modes of full-size plywoods, G_{xy}-dynamic.
Legend: □; 7.5 mm, △; 9.5 mm, ○; 12 mm, ●; 9 mm.

other edges are completely free.

This presumption expects that the experimental resonance frequency fr ranges between the resonance frequency calculated for SFFF condition fr_s and that calculated for the one-edge clamped and three-edges free (CFFF) boundary conditions fr_c, because the one-edge clamped condition is considered as that rotation of the specimen at the simply-supported edge is completely restricted and because the experimental condition can be considered to be an imperfectly restricted condition.

Figure 8 shows the relationship between fr_c-to-fr_s ratio or fr-to-fr_s ratio and number of vibration mode. Here, the elastic constants measured from small specimans were used. The effect of restriction at the support edge decreases with increase of number of vibration mode M and/or N. The experimental condition was nearer to the simply-supported condition than the clamped condition.

This result means that the error of the estimated shear modulus of the full-size specimen was due to the use of resonance frequency of low vibration mode such as (1, 1) mode. Accordingly, the shear modulus G_{xyh} was calculated from combination of the resonance frequencies of higher ordered vibration, (2, 2), (3, 1) and (3, 2) modes.

The relationship between G_{xyh} by the full-size plywood vibration and the shear modulus of small specimens by the static test is shown in Figure 9. Both data agreed very much.

Shear moduli of full-size plywoods are useful not only as a design parameter for wood joist floor systems and plywood-skin panels but also as web members of composite I-beams and Box-beams.

Finally, Young's moduli E_x and E_y also were calculated from the resonance frequencies of (2, 2), (3, 1) and (3, 2) modes. However, fitness of values with those by the static bending test was not improved.

5. CONCLUSION

The proposed vibration method using the tapping technique enabled a simultaneous determination of orthotropic elastic constants (E_x, E_y and G_{xy}) of full-size plywoods.

The following experimental conditions are recommended:

(1) Boundary condition is SFFF (one-edge simply-support and three edges free). Experimentally, a plywood is vertically supported on a V-cut rigid rod.

(2) A plywood is tapped with a hard rubber ball at 15 cm from the corner on the upper edge line and vibration is detected by piezo-electric acceleration sensor located at the other corner on the upper edge line.

A computer supported identification of individual spectrum peaks enabled an automatic procedure.

The use of the resonance frequencies of higher ordered vibration modes is recommended for calculation of shear modulus of full-size plywoods.

The results prove that the proposed method has a potential for practical application to a computer-supported automatic elastic-constant determination of full-size plywoods as non-destructive tests.

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