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Dynamic determination of modulus of elasticity of full-size wood composite panels using a vibration method

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HIGHLIGHTS

- A dynamic testing method based on free vibration theory in a "free–free" support condition.
- Dynamic modulus of elasticity (MOE).
- Medium density fiberboard (MDF), particleboard (PB) and plywood (PW).
- A strong linear relationship was found between E_d and E_b for three types of full-size wood composite panels (MDF, PB and PW) tested.

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ABSTRACT

A vibration testing method based on free vibration theory in a "free–free" support condition was investigated for evaluating the modulus of elasticity (MOE) of full-size wood composite panels (WCPs). Vibration experiments were conducted on three types of WCPs (medium density fibreboard, particleboard, and plywood) to determine the dynamic MOE of the panels. Static bending test was performed on small specimens cut from the panels to determine the static MOE. A strong linear relationship was found between dynamic MOE of full size panels and static MOE of small specimens. Dynamic MOE of full-size WCPs was found 6.2% higher than the corresponding static MOE. This study demonstrated that free vibration method has a good potential to be used in WCP manufacturing facilities as a quality control procedure.

1. Introduction

As an engineered wood product, wood composite panels (WCPs) are widely used in furniture manufacturing, building construction, packaging, transportation and other industrial sectors [1]. Full-size WCPs refer to the panels with a standard size (length × width) of 2440 mm × 1220 mm that are most common in production sales. Modulus of elasticity (MOE) is a key index for evaluating the mechanical performance of WCPs. Studies have shown that MOE of a panel has a statistical linear relationship with other mechanical performance indices [2,3].

In WCPs manufacturing facilities, quality control procedures typically involved in mechanical testing of panels sampled from the production lines. According to the procedures, several small WCPs specimens need to be cut from different parts of a large-size panel, with a dimension of $(20\,h + 50) \times 50 \times h$ (unit: mm) of the length × width × thickness (h) [4]. The small specimens are then destructively tested in a testing machine to obtain the stiffness and strength properties. With the measurement results of several standard specimens, the overall stiffness and strength of full-size panels can be derived. This evaluation procedure is time-consuming, destructive in nature, and sometimes unreliable due to inherent variation within and between panels. Furthermore, the test results are usually not readily available to production personnel until some hours after the actual time of production, making the adjustment of production parameters difficult. From this standpoint, it is often desired to rapidly and nondestructively assess the mechanical performance of the full-size panels to complement their existing quality-control program in WCP facilities.

In recent years, many studies have been done on nondestructive evaluation of small wood composite specimens [5–13]. However, very limited information is available for nondestructive evaluation of full-size WCPs and other large-size WCPs. A technique that has

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been investigated is a torsional-bending vibration method [12,13]. During the testing, a large-size WCP member is clamped at one end like a cantilever beam, then an initial displacement is applied at one corner of the free end so that the panel is set into bending and torsional free vibrations. Through analysis of the vibration signals, MOE and shear modulus of the WCP member can be determined. In addition, based on the principle of static bending tests, several machine stress rating (MSR) equipment have been developed to nondestructively test full-size panels in manufacturing facilities [14,15]. For instance, through performing concentrated static, impact load and deflection test, a line of panel testing equipment called Metriguard Model 820 has been developed by Metriguard and TECO to acquire MOE of full-size wood panels [16].

In this study, we proposed a dynamic testing method, which is based on the vibration theory of a "free–free" support condition, as a potential quality control technique for WCP. The objective of this paper was to examine the feasibility and validity of the free vibration method for assessing the mechanical performance of full size WCP in production settings. More specifically, the first order natural vibration frequency of the full-size WCP supported on two nodal lines was measured and used to predict MOE of the panel. A total of 303 pieces of full-size WCP samples were tested using a laboratory testing apparatus. The panels tested include medium density fiberboard (MDF), particleboard (PB) and plywood (PW) panels with range of thickness specifications. The results of vibration testing on full-size panels were then compared with those of static bending tests performed on small specimens cut from the sample panels. The relationships between the results of these two testing methods were examined.

2. Theoretical basis

"Free–free" support refers to the panel being supported on its two nodal lines which are located at 22.4% and 77.6% of its length. A panel's free vibration under this support condition is called "free–free" support free vibration. Fig. 1 shows the first vibration mode of the full-size WCP under a "free–free" support condition. The first vibration mode of a full-size panel in this support condition is same as the vibration mode of a beam supported at the same position [17]. Therefore, the calculation method for MOE of the beam in this support condition can be used to calculate MOE of the full-size panels. And, this MOE corresponds to the modulus of elasticity in the length direction of the panel. In this paper, this MOE is called the dynamic MOE of the full-size WCP. Then, the dynamic MOE of the full-size WCP is calculated using Eq. (1) [18]:

$$E_d = \frac{f^2 M L^3}{12.65 I} \tag{1}$$

where E_d is the dynamic MOE of the panel (Pa), f is the first natural vibration frequency of the panel (Hz), M is the weight of the panel (kg), L is the length of the panel (m), I is the inertia moment of the cross section (m^4). And $I = \frac{bh^3}{12}$, b is the width of the panel (m), h is the thickness of the panel (m). When panel geometry size (L, b, h) is given, MOE of the panel can be calculated in the condition of detecting the first natural vibration frequency f and the weight M.

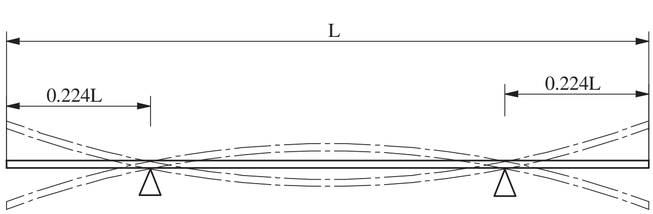


Fig. 1. First vibration mode of a full-size wood composite panel under "free–free" support condition.

This is theoretical basis for dynamic determination of MOE of the full-size WCP.

3. Materials and methods

3.1. Materials

A total of 303 pieces of full-size wood composite panels were used in this study, including 101 pieces of MDF panels with 6 different thicknesses (5, 8, 12, 16, 18, 20 mm), 100 pieces of PB panels with 6 different thicknesses (5, 9, 12, 16, 18, 25 mm), and 102 pieces of PW panels with 8 different thicknesses (5, 7, 9, 12, 15, 18, 20, 25 mm). The MDF panels were provided by a local MDF manufacturer, and the PB and PW panels were purchased from the local market. Table 1 shows the specifications of the full-size WCP samples. The length (L), width (b), and thickness (h) of the panel samples were measured prior to testing. Average density of the panels was calculated based on the weight and volume. The moisture contents of the panels were determined based on the National Standards of the People's Republic of China GB/T 17657-2013 [4].

Free vibration test was first conducted on each full size panel under the free–free support condition. Six small specimens were then cut from each full size panel according to the national standard [19,20]. Table 2 shows the dimensions of the small specimens for the three types of WCPs examined in this study. All small WCP specimens were then subject to a flatwise static bending test under a center loading.

3.2. Testing apparatus and dynamic detection test

We developed a vibration testing apparatus in the laboratory for evaluating the stiffness of full-size WCPs (Fig. 2). The apparatus consisted of two load sensors, one laser sensor and a supporting system. The load sensors located at the supporting rods were used to measure the weight of the panel being tested. Two supporting rods were used to provide line supports at the nodal lines of the panel. The laser sensor was located at the middle of the panel to sense the vibration displacement signal. A LabVIEW based software was written and used to collect and process both load and vibration signals and calculate MOE based on Eq. (1).

During the vibration test, a full size panel was placed on the supporting rods with the rods located at the nodal lines of the panel (22.4% and 77.6% of the length). The testing software was then initiated so that the computer was ready to collect the signals from the load censors and laser sensors. A mechanical displacement was applied on the edge of the panel pressing down with both hands, then by releasing the hands from the end of the panel, it's a free vibration of the panel generated. The vibration signal detected by the laser sensor was transmitted to the computer through a data acquisition card and processed through the LabVIEW software to obtain the first natural frequency of the panel vibration. Based on Eq. (1), the calculation module in the testing software calculated the dynamic MOE (E_d) of the panel tested.

3.3. Static bending test

To examine the validity of the vibration testing method that we proposed, we conducted static bending test on all the small specimens cut from the full size panel samples according to the testing standard of the People's Republic of China GB/T

Table 1
Specifications of full-size wood composite panels tested.

Panel code	Quantity (panels)	Panel average sizes (thickness × length × width, mm)	Average density (kg/m^3)	Average moisture content (%)
MDF5	10	5.92 × 1221.2 × 2442.7	763.69	9.0
MDF8	9	8.11 × 1220.8 × 2442.2	818.91	4.0
MDF12	25	11.94 × 1220.4 × 2439.7	788.20	6.8
MDF16	41	15.98 × 1220.0 × 2442.4	745.01	4.9
MDF18	7	18.04 × 1220.6 × 2439.4	793.41	4.7
MDF20	9	19.88 × 1220.3 × 2441.4	697.63	9.0
PB5	8	4.64 × 1221.8 × 2444.9	730.54	9.0
PB9	15	9.00 × 1222.9 × 2442.2	658.03	4.5
PB12	17	12.20 × 1223.1 × 2442.2	707.68	4.1
PB16	25	16.04 × 1223.1 × 2441.0	698.96	4.3
PB18	25	18.03 × 1220.2 × 2437.0	656.06	5.7
PB25	10	25.05 × 1220.9 × 2440.7	680.68	6.8
PW5	7	4.98 × 1218.6 × 2439.4	513.51	9.0
PW7	8	6.52 × 1218.9 × 2437.9	527.16	9.5
PW9	19	9.42 × 1219.1 × 2438.1	505.33	9.4
PW12	7	11.34 × 1224.9 × 2438.9	529.04	9.0
PW15	19	14.45 × 1220.8 × 2439.3	507.66	10.5
PW18	18	17.04 × 1221.1 × 2438.4	521.67	8.6
PW20	8	19.46 × 1218.0 × 2439.4	509.85	9.0
PW25	16	24.36 × 1219.2 × 2439.5	529.77	9.8

Table 2
Dimensions of small specimens cut from the full size panels.

Thickness *h* (mm)	Length *l* (mm)	Width *b* (mm)	No. of specimens
5	150	50	150
7	190	50	48
8	210	50	54
9	230	50	204
12	290	50	294
15	350	50	114
16	370	50	396
18	410	50	300
20	450	50	102
25	550	50	156

Note: The small specimen quantity for each type of panel was six times of the quantity of that panel.

17657-2013 [4] (Fig. 3). Each small specimen was tested flatwise under a center point loading using the universal mechanical testing machine (RGW-3010, Shenzhen Reger Instrument Co., Ltd., China). All the small specimens were tested to obtain MOE. The average value of MOE of the six small specimens represents static MOE E_b of a full-size WCP.

4. Results and discussion

4.1. Comparison between the average measured results

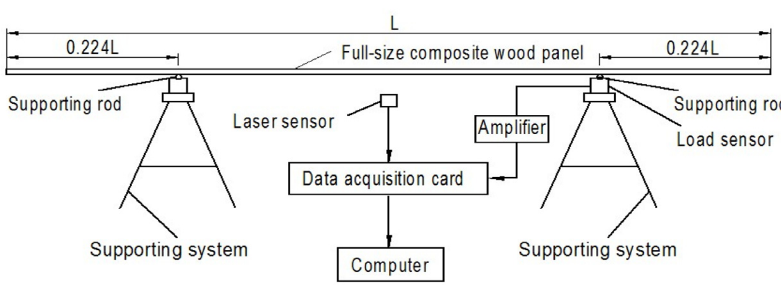
The overall measurement results of three hundred and three pieces of full-size WCPs in the dynamic detection method and center-loading bending method are given in Tables 3–5. It can be seen from these tables, that the average MOE measured by the two methods are very close and the ratio of E_d and E_b are in the range of 0.94–1.18; in most cases, the dynamic MOE E_d is slightly higher than the static MOE E_b; all the full-size WCPs as the research object, the average dynamic MOE E_d is slightly higher (6.2%) than the average static MOE E_b. The slightly higher E_d values may be mainly on account of faster displacement rate during panel vibration compared with that used for the center-loading bending test.

Fig. 3. Flatwise static bending test on a small specimen cut from the wood composite panels.

Table 3 shows the MOE measurement results of MDF panels for the two methods and their comparison. It can be seen that the average dynamic MOE E_d of six kinds of thicknesses of MDF panels is slightly higher than their average static MOE E_b and their ratio are in the range of 1.02–1.12. Table 4 shows the MOE measurement results of PB panels for the two methods and their comparison. It can be seen that the average dynamic MOE E_d of six kinds of thicknesses of PB panels is slightly higher than their average static MOE E_b and their ratio are in the range of 1.01–1.13. Table 5 shows the MOE measurement results of PW panels for the two methods and their comparison. It can be seen that, in addition to the PW panels with the thickness of 12 mm and 20 mm, the average dynamic MOE E_d of other six thicknesses of PW panels is slightly higher than their average static MOE E_b and their ratio are in the range of 1.04–1.18.

4.2. Correlation relationship between dynamic MOE E_d and static MOE E_b of full-size wood composite panels

Through the laboratory testing apparatus for measuring mechanical performance of full-size WCPs and the universal



(a)

(b)

Fig. 2. Vibration testing apparatus for assessing the mechanical performance of full-size wood composite panels. (a) Schematic of vibration testing under free-free support condition. (b) Laboratory vibration testing of a full size panel.

Table 3
Modulus of elasticity (MOE) of medium density fiberboard (MDF) panels determined using dynamic and static test methods [a].

Panel code	Method	MOE(MPa)			SD	Ratio of MOE (E_d/E_b)
		Average	Min	Max		
MDF5	Dynamic	4183.87	3686.59	4498.42	285.45	1.04
	Static	4010.97	3540.59	4235.60	247.14	
MDF8	Dynamic	3693.49	2803.25	4342.82	423.78	1.06
	Static	3486.67	2582.42	4259.98	482.06	
MDF12	Dynamic	3933.18	3295.65	4378.28	336.06	1.02
	Static	3841.25	3029.43	4344.10	359.60	
MDF16	Dynamic	3431.64	2561.00	4144.59	246.57	1.12
	Static	3066.03	2010.00	4051.98	299.95	
MDF18	Dynamic	3660.69	2978.18	4042.61	355.05	1.09
	Static	3354.88	2593.98	3541.57	341.51	
MDF20	Dynamic	3126.93	2709.59	3976.00	357.27	1.11
	Static	2818.77	2446.91	3674.89	397.65	

[a] SD—standard deviation; E_d—dynamic MOE; E_b—static MOE.

Table 4
Modulus of elasticity (MOE) of particleboard (PB) panels determined using dynamic and static test methods [a].

Panel	Method	MOE (MPa)			SD	Ratio of MOE (E_d/E_b)
		Average	Min	Max		
PB5	Dynamic	3855.73	3616.00	4204.55	179.58	1.01
	Static	3831.28	3601.08	4118.91	148.60	
PB9	Dynamic	2946.55	2640.91	3531.00	241.87	1.08
	Static	2732.01	2461.28	2975.18	139.46	
PB12	Dynamic	3704.77	2862.00	4379.50	424.11	1.02
	Static	3632.47	2824.15	4193.67	485.57	
PB16	Dynamic	3677.43	3399.87	3949.61	143.24	1.07
	Static	3421.19	3230.89	3750.44	122.20	
PB18	Dynamic	2368.07	1966.20	2725.30	166.29	1.14
	Static	2083.80	1842.31	2520.79	187.93	
PB25	Dynamic	3060.73	2464.27	3595.15	427.96	1.13
	Static	2697.27	2168.93	3236.42	433.03	

[a] SD—standard deviation; E_d—dynamic MOE; E_b—static MOE.

Table 5
Modulus of elasticity (MOE) of plywood (PW) panels determined using dynamic and static test methods [a].

Panel	Method	MOE (MPa)			SD	Ratio of MOE (E_d/E_b)
		Average	Min.	Max.		
PW5	Dynamic	3760.75	3166.00	4121.00	339.72	1.12
	Static	3355.19	3021.26	3821.71	273.47	
PW7	Dynamic	3419.63	2804.06	4308.03	473.24	1.18
	Static	2907.57	2529.00	3406.03	316.38	
PW9	Dynamic	3728.86	2865.76	4250.21	322.92	1.07
	Static	3480.46	2449.88	4320.78	459.50	
PW12	Dynamic	4739.48	4131.00	5142.68	329.43	0.94
	Static	5034.74	4558.33	5384.30	283.65	
PW15	Dynamic	3288.14	2902.69	3747.11	226.07	1.04
	Static	3159.08	2355.29	3664.01	338.82	
PW18	Dynamic	4683.79	4084.69	5331.54	336.72	1.09
	Static	4301.59	3552.95	5346.43	522.49	
PW20	Dynamic	4611.26	4150.61	4888.84	242.00	0.96
	Static	4810.87	4343.18	5176.44	317.65	
PW25	Dynamic	4781.30	4173.00	5372.02	297.64	1.12
	Static	4260.87	3347.44	5011.19	452.91	

[a] SD—standard deviation; E_d—dynamic MOE; E_b—static MOE.

mechanical testing machine for measuring MOE of the small specimens, the dynamic MOE E_d of three types of full-size WCPs and their static MOE E_b are obtained, and the overall relationship between them are shown in Figs. 4–7 show that the relationships between MDF, PB, PW panel's E_d and E_b respectively. It can be seen from the figures, whether three kinds of panels' measured results are put together, or are analyzed separately, a statistical linear relationship is found between dynamic MOE E_d and static MOE E_b of full-size WCPs.

Based on the R language modeling, these test data are analyzed using regression analysis in one variant linear regression analysis method, analysis of variance and t test [21]. The linear regression equations and the related parameters are given in Table 6. It can be seen from Table 6, regardless of three types of panels' overall data or each type of panel's data, that a positive linear relationship is found between E_d and E_b, and their relationships are all highly significant at the 0.001 level. In addition, the correlation coefficient of full-size WCPs' overall data between E_d and E_b is 0.923; the correlation coefficients of MDF and PB panels between E_d and E_b are 0.956 and 0.953 respectively, exceeding 0.95; the correlation

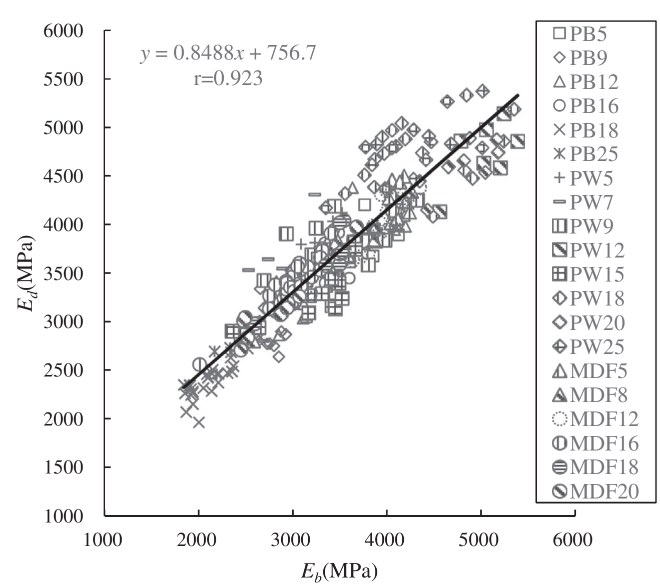


Fig. 4. Relationship between dynamic MOE of full size panels and static MOE of small specimens cut from full size panels (all three types of panels included).

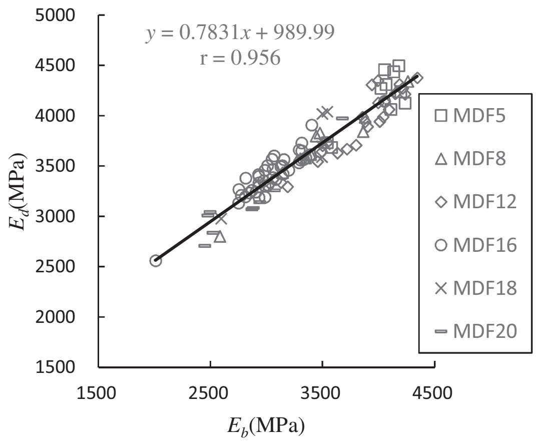


Fig. 5. Relationship between dynamic MOE of MDF panels and static MOE of the small specimens cut from the panels.

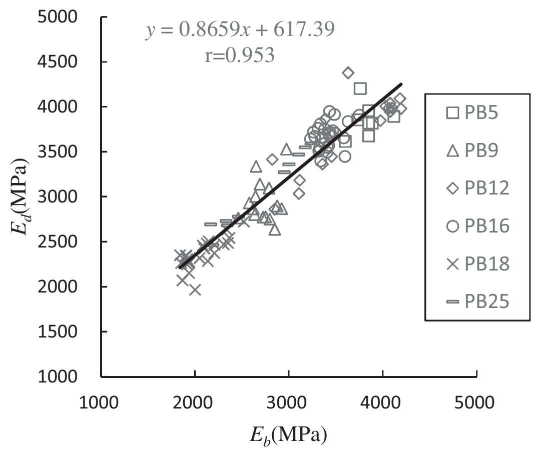


Fig. 6. Relationship between dynamic MOE of particleboard panels and static MOE of the small specimens cut from the panels.

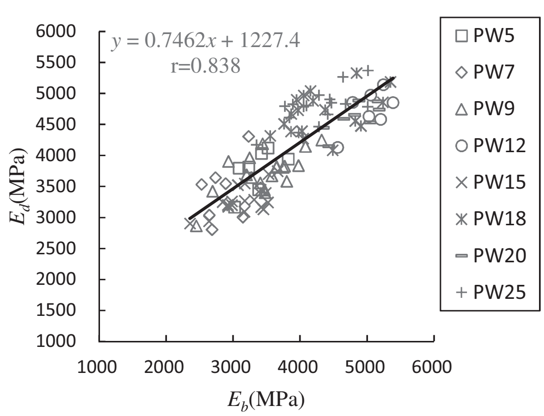


Fig. 7. Relationship between dynamic MOE of plywood panels and static MOE of the small specimens cut from the panels.

coefficient of PW panels between E_d and E_b is 0.838, but more than 0.8. According to the experience of statistics theory, based on significant linear relationship between two groups of data, as long as the correlation coefficient is greater than or equal to 0.8, two groups of data' correlation are considered to be highly relevant. It can be concluded that the correlation of full-size WCPs' overall

Table 6
Linear regression equations for relationships between dynamic MOE and static MOE of full-size wood composite panels.[a]

Panel	No. of panels	$y = ax + b$		Correlation coefficient r	F	Level of significance
		a	b			
MDF	101	0.7831	989.99	0.956	1039	0.001
PB	100	0.8659	617.39	0.953	963.8	0.001
PW	102	0.7462	1227.4	0.838	236.3	0.001
MDF, PB, PW	303	0.8488	756.7	0.923	1740	0.001

[a] MDF—medium density fiberboard; PB—particleboard; PW—plywood.

data and each full-size WCP' data between E_d and E_b are highly relevant. Compared with other two kinds of panels, the correlation coefficient of PW panels between E_d and E_b is smaller. The reason may be that PW panel's material is most uneven and small specimen's material uniformity and densities are rather variable compared with other two kinds of panels. As a result the average MOE of small specimens fails to fully characterize MOE of full-size WCPs.

We understand that moisture content has a strong influence on material properties. If there is time between testing for E_d and E_b, moisture control is not possible for this test sequence. And there may been slight property differences due to moisture content fluctuation that would then have influenced the mechanical properties obtained from either dynamic detection test or center-loading bending test. Therefore, during E_d and E_b testing, in order to eliminate any moisture content influences for determining correlation relationship between them, there would be nearly no time difference because after measuring every panel in dynamic detection test, the panel was cut into small specimens to conduct center-loading bending test immediately. As for different average moisture content for the panels in this study, there is little effect for determining correlation relationship between E_d and E_b. Si et al. [22] also proved that different moisture content had little effect on correlation relationship between MOE values obtained in different ways through Larchwood samplings test.

In summary, a significant and highly correlated linear relationship is found between MOE of full-size WCPs obtained according to two kinds of detection methods, which proves that dynamic determination of MOE of full-size WCPs based on "free–free" support free vibration theory is feasible.

5. Conclusions

In this study, a dynamic testing method based on free vibration theory in a "free–free" support condition was proposed to predict MOE of full-size WCPs. Following the vibration testing of full-size panels, static bending tests were conducted to obtain static MOE of the panels. The feasibility and validity of dynamic testing method was examined by comparing the dynamic MOE with the static counterpart. Based on the results and analysis, we concluded the following:

(1) Strong linear relationships were found between dynamic MOE and static MOE for three types of full-size WCPs (MDF, PB and PW) tested.
(2) Dynamic MOE values of MDF, PB and PW panels were very close to the static MOE values obtained from small specimens, with the dynamic MOE to static MOE ratio in the range of 0.94–1.18.
(3) Overall, the average dynamic MOE of the full-size panels tested was 6.2% higher than the average static MOE of the corresponding small specimens.

(4) Comparing with the static bending test procedures, the vibration testing method proposed in this study has the advantages of achieving a rapid and nondestructive evaluation of full size panels, making the on-line quality control possible in WCP manufacturing facilities.

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