Measurement of the in-plane shear modulus of medium-density fibreboard by torsional and flexural vibration tests

(Abbreviated title: In-plane shear modulus of MDF)

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Abstract

The in-plane shear modulus (IPSM) of medium-density fibreboard (MDF) was obtained via a torsional vibration (TV) test using the specimen with various configurations and a subsequent numerical analysis. Because the out-of-plane shear modulus (OPSM) of MDF was much lower than the IPSM, the difference between the IPSM and OPSM had to be considered in the TV test. Therefore, the OPSM value was measured from the flexural vibration (FV) tests, and it was applied for the calculation of the IPSM value. The experimental and numerical results indicated that the TV test is effective to obtain the IPSM of MDF accurately under various configurations of the specimen.

Keywords: finite element analysis (FEA); flexural vibration (FV) test; in-plane shear modulus (IPSM); medium-density fibreboard (MDF); out-of-plane shear modulus (OPSM); torsional vibration (TV) test

1. Introduction

There are several experimental methods to determine the shear modulus of solid wood and wood-based materials [1]. For medium-density fibreboard (MDF), it is important to know the in-plane shear modulus (IPSM) accurately because the MDF is subjected to the in-plane shearing force when it is used as a structural wall. In a previous study, the IPSM of MDF was measured with the flexural vibration (FV) method based on Timoshenko's vibration theory [2]. The results obtained suggested that the IPSM is dependent on the specimen configuration such that the length of the specimen must be less than 7.5 times the height to measure the IPSM accurately. Nevertheless, the restriction of the specimen configuration should also be a drawback, and it is desirable to measure the IPSM value accurately using the specimens with various configurations. A torsional vibration (TV) test can induce a pure shear stress condition in the specimen so it may be promising for measuring the IPSM value accurately.

There are many examples of measuring the shear modulus of solid wood by the TV test because the shear moduli in the longitudinal-radial (LR) and longitudinal-tangential (LT) planes are relatively close to each other [3-9]. Even when supposing that the shear moduli in the LR and LT planes are equal to each other, the error induced by the approximation can be restricted. For MDF, however, this approximation is null because the IPSM is much larger than the out-of-plane shear modulus (OPSM). Another attempt of the TV test was conducted using a thin square plate specimen to reduce the effect of OPSM [10-12]. In this method, however, the accuracy of the IPSM value cannot be expected when the aspect ratio of the specimen is not large enough. Therefore, it is often difficult to measure the IPSM of MDF accurately by the TV test.

In spite of these difficulties, the TV test is still attractive for measuring the IPSM of MDF because it can induce a pure shear stress condition in the specimen, as described above. In this study, TV and FV tests were performed on MDF specimens with various configurations, and the IPSM values were obtained by three different analyses. The validity of the analysis methods was examined by comparing their results with finite element (FE) calculations. The objective of this study was to use the TV test for determining the IPSM of MDF.

2. Torsional vibration (TV) equation

Figure 1(a) shows the diagram of the torsional vibration (TV) test. As shown in this figure, the *x*, *y*, and, *z* directions are defined as the length, width, and thickness of the specimen, respectively. When the first TV mode, the resonance frequency of which is defined as f_T, is excited in the specimen with the length, width, and thickness of *L*, *a*, and *b*, respectively, the shear modulus in the length-width (*xy*) plane, G_{xy}, is derived as:

$$G_{xy} = \frac{4\pi^2 \rho J L f_{\mathrm{T}}^2}{K} \tag{1}$$

where

$$J = \frac{ab\left(a^2 + b^2\right)}{12} \tag{2}$$

and

$$K = \frac{ab^3}{3}\left[1 - \frac{192b}{p^5 a}\sqrt{\frac{G_{xy}}{G_{xz}}}\sum_{n=1}^{\infty}\frac{\tanh\frac{(2n-1)pa}{2b}\sqrt{\frac{G_{xz}}{G_{xy}}}}{(2n-1)^5}\right] \tag{3}$$

In this study, the G_{xy} and G_{xz} values correspond to the in-plane shear modulus (IPSM) and out-of-plane shear modulus (OPSM) of the MDF panel, respectively.

As described above, in several previous studies for measuring the shear modulus of solid wood by a single TV test, the G_{xy} and G_{xz} values are regarded as equal to each other [3-9]. For the MDF panel, however, this method is not effective because the G_{xy} value of the MDF panel is much larger than the G_{xz} value. Therefore, multiple vibration tests are required to separate the G_{xy} and G_{xz} values from each other. Suzuki [13] conducted static torsional tests of the specimens with multiple aspect ratios. Although this method can be applied for the torsional vibration method, there is an inconvenience in that multiple specimens with different configurations should be prepared. In the ordinary MDF, however, the Young's modulus in the length and width directions of the panel (MOE) is usually larger than the OPSM, as demonstrated below. Therefore, the G_{xz} value can be obtained accurately by the FV method. When using the G_{xz} value obtained by the FV method, the G_{xy} value can be determined from Eq. (1) without using multiple specimens with different aspect ratios. Nakao et al. conducted the FV tests for solid wood to determine the G_{xy}/G_{xz} ratio, and the shear modulus in the LR plane was determined by the TV test using the G_{xy}/G_{xz} value [14].

3. Finite element analysis (FEA)

Three-dimensional (3D) FEA was performed independently of the TV and FV tests, the details of which are described below, using the FEA program ANSYS 12. Figure 2 shows the homogeneously divided FE mesh of the specimen. Similar to the definitions in previous studies [2, 15, 16], the directions along the length, width, and thickness of the board, which correspond to the *x*, *y*, and *z* directions, respectively, as shown in Fig. 1, were defined as the L, T, and Z directions, respectively. The lengths in the L (*x*), T (*y*), and Z (*z*) directions were defined as *L*, *a*, and *b*, respectively. In the model, L = 300 mm, b = 12 mm, and the value of *a* was varied from 10 to 60 mm with an interval of 10 mm. The model consisted of eight-node brick elements. It was confirmed that the mesh size was fine enough and that the effect of mesh size could be ignored. The Young's moduli in the L, T, and Z, directions were defined as E_L, E_T, and E_Z, respectively. The shear moduli in the LT, LZ, and TZ planes were defined as G_{LT}, G_{LZ}, and G_{TZ}, respectively, whereas the Poisson's ratio in these planes were defined as ν_{LT}, ν_{LZ}, and ν_{TZ}. Table 1 lists the derived elastic constants of MDF. The values of E_L, E_T, G_{LT}, and ν_{LT} were taken from [2], the G_{LZ} and G_{TZ} values were from [17], and the E_Z value was from [18]. The ν_{LZ} and ν_{TZ} values were assumed to be equal to ν_{LT} in this study. In the thickness direction of actual MDF, a density profile exists so that it is better to consider the profile of the elastic properties in the thickness direction [18, 19]. Nevertheless, it was difficult to determine the profile of the elastic properties. Therefore, the material variation in the thickness direction was ignored in this study. Further study should be conducted on the profile in the thickness direction.

Modal analyses were conducted and the resonance frequencies corresponding to the FV and TV modes were extracted. Initially, the MOE (E_L) and OPSM (G_{LZ}) were obtained using the resonance frequencies from the 1st to the 4th FV modes about the LZ plane by the flatwise FV simulation. Similar to several previous studies [2, 20-22], the E_L and G_{LZ} values were determined from the following rigorous solution derived by Goens [23].

$$\begin{cases} \dfrac{\tan\dfrac{k_n}{2}\sqrt{\sqrt{\beta^2 k_n^4+1}+\alpha k_n^2}}{\tanh\dfrac{k_n}{2}\sqrt{\sqrt{\beta^2 k_n^4+1}-\alpha k_n^2}} + \dfrac{\sqrt{\sqrt{\beta^2 k_n^4+1}+\alpha k_n^2}}{\sqrt{\sqrt{\beta^2 k_n^4+1}-\alpha k_n^2}} \cdot \dfrac{\sqrt{\beta^2 k_n^4+1}-\beta k_n^2}{\sqrt{\beta^2 k_n^4+1}+\beta k_n^2} = 0 \quad \text{(symmetric mode)} \\ \dfrac{\cot\dfrac{k_n}{2}\sqrt{\sqrt{\beta^2 k_n^4+1}+\alpha k_n^2}}{\coth\dfrac{k_n}{2}\sqrt{\sqrt{\beta^2 k_n^4+1}-\alpha k_n^2}} - \dfrac{\sqrt{\sqrt{\beta^2 k_n^4+1}+\alpha k_n^2}}{\sqrt{\sqrt{\beta^2 k_n^4+1}-\alpha k_n^2}} \cdot \dfrac{\sqrt{\beta^2 k_n^4+1}-\beta k_n^2}{\sqrt{\beta^2 k_n^4+1}+\beta k_n^2} = 0 \quad \text{(anti-symmetric mode)} \end{cases} \tag{4}$$

where n is the mode number, and α and β are derived as follows:

$$\begin{cases} \alpha = \dfrac{1}{24}\left(\dfrac{H}{L}\right)^2\left(\dfrac{sE}{G}+1\right) \\ \beta = \dfrac{1}{24}\left(\dfrac{H}{L}\right)^2\left(\dfrac{sE}{G}-1\right) \end{cases} \tag{5}$$

where H is the height of the specimen, which corresponds to b, ρ is the density, and s is Timoshenko's shear factor. In this study, the s value is set as 1.2 for the specimen. In this simulation, E and G correspond to E_L and G_{LZ}, respectively. When the resonance frequency for the n^{th} FV mode is defined as f_n, k_n is derived as follows:

$$k_n = \sqrt[4]{\frac{48\pi^2\rho}{EH^2}} L f_n \tag{6}$$

Both E_L and G_{LZ}/s terms are contained in the solution, the G_{LZ}/s values corresponding to each vibration mode were calculated by altering the value of E_L, and the coefficient of variation (COV) among the G_{LZ}/s values was determined. The E_L value that generates the minimum COV among the G_{LZ}/s values and the mean value of G_{LZ}/s can be regarded as the most feasible. This procedure was undertaken using the goal seek function incorporated in Excel ver. 14.4.1 [20]. The s value was derived as 1.2 in this study, and thus the G_{LZ} value was obtained by multiplying 1.2 with the G_{LZ}/s.

After determining the G_{LZ} value, the in-plane shear modulus G_{LT} was determined by the following three procedures: (1) Similar to the determination of the G_{LZ} value, the G_{LT} value was determined using the resonance frequencies from the 1^{st} to 4^{th} FV modes about the LT plane obtained by the edgewise FV simulation. The s value was also derived as 1.2 in this procedure. In this simulation, E, G, and H in Eqs. (5) and (6) correspond to E_L, G_{LT}, and a, respectively. (2) The resonance frequency of the 1^{st} TV mode f_T, the G_{LZ} value obtained from the flatwise FV simulation, and a virtual value of

G_{LT} were substituted into Eqs. (1)-(3), and the refined value of G_{LT} was obtained. The refined value of G_{LT} was repeatedly substituted into Eqs. (1)-(3) until its regression. In this procedure, the G_{LT} and G_{LZ} values correspond to the G_{xy} and G_{xz} values in Eq. (1), respectively. (3) When the effect of OPSM is ignored and G_{xz} is assumed to be equal to G_{xy}, Eq. (3) can be derived as follows:

$$K = \frac{ab^3}{3}\left[1 - \frac{192b}{\pi^5 a}\sum_{n=1}^{\infty}\frac{\tanh\frac{(2n-1)\pi a}{2b}}{(2n-1)^5}\right] \qquad (3)'$$

The G_{LT} value was obtained using Eqs. (1), (2), and (3)'.

The G_{LT} values obtained from these three procedures were compared with each other, and the effects of specimen configuration and measurement methods were examined.

4. Materials and methods

4.1. Materials

A commercially sold MDF sheet sized to 300, 900, and 12 mm in length, width and thickness, respectively, was used to obtain the test specimens for this study. The board was fabricated in a board mill using softwood with a typical fibre length of 2-4 mm and urea-formaldehyde (UF) resin. The resin content of the MDF sheet was 7%. It had a density of 740 ± 2 kg/m^3 and was stored in a room kept at a constant 20ºC and 65%

relative humidity before the test, and the moisture content in the air dry condition was 10%. All of the specimens were cut from this board. Similar to the definitions in FEA, the directions along the length, the width, and the thickness of the board were defined as the L, T, and Z directions, respectively.

Initially, ten specimens with L × T × Z directions of 300 × 60 × 12 mm^3, respectively, were cut from the board. After conducting the FV and TV tests described below, the length of the T direction was decreased, and the succeeding series of vibration tests were conducted using the specimens with decreased height. The T direction of the specimens was decreased from 60 to 10 mm in intervals of 10 mm. The average densities were 740, 738, 740, 741, 742, and 740 kg/m^3 corresponding to the length of the T direction from 60 to 10 mm, respectively.

4.2. Flexural vibration (FV) and torsional vibration (TV) tests

Previous to the TV tests, FV tests were conducted to measure the OPSM and IPSM. The specimen was suspended by threads at the nodal positions of the free-free resonance vibration mode f_n and excited along the depth direction with a hammer (Fig. 1b). The suspended points were the outermost positions of each vibration mode. In the FV test, the 1^{st}- to 4^{th}-mode resonance frequencies were measured. The resonance frequencies were measured and analysed by a Fast Fourier transform (FFT) analyser (SA-78, Rion

Co., Tokyo). The IPSM and OPSM, the G_{LT} and G_{LZ} values were obtained by a similar method used in the FEAs as described above.

In the TV test, the specimen was supported by a polystyrene foam at the mid-point of the LT plane (Fig. 1a), which corresponds to the nodal point in the first mode of torsional vibration. TV was generated by striking a corner, and the resonance frequency of the first torsional vibration mode, f_t, was measured and analysed by the FFT analyser used in the FV tests. The G_{LT} value was obtained by substituting the f_t value and G_{LZ} value obtained from the FV tests into Eqs. (1)-(3). The G_{LT} value was also calculated using Eqs. (1), (2), and (3)' without considering the effect of the OPSM.

5. Results and discussion

5.1. FEA

Figure 3(a) shows the dependence of MOE (E_L) on the value of a, which corresponds to the height and width values in the vibrations along the T and Z directions, respectively, obtained from the FV simulation by FEA. The FEA results show that the E_L value obtained from the edgewise FV simulation is larger than that obtained from the flatwise FV simulation. The E_L value obtained from the flatwise FV simulation is almost independent of the value of a, whereas that obtained from the edgewise FV simulation decreases with decreasing *a*. Several previous studies suggested that the deviation of the high-order resonance frequencies in the actual vibration from those predicted by Timoshenko's vibration theory is more pronounced when the slenderness ratio of the beam decreases. The dependence of the E_L value on the *a* value in the edgewise FV simulation may be because of the deviation [24-26]. Even if so, however, the effect of the *a* value is not so significant on the E_L value.

Figure 3(b) shows the dependence of the IPSM (G_{LT}) and OPSM (G_{LZ}) on the value of *a* obtained by FEA. The G_{LZ} value obtained from the flatwise FV simulation is independent of the *a* value, which corresponds to the width of the model. In contrast, the G_{LT} value obtained from the edgewise FV simulation increases with decreasing *a*, which corresponds to the height of the model. This dependence was commonly found in the numerical and experimental results obtained in a previous study on the FV test of MDF [2]. In the TV simulations, the G_{LT} value is independent of the *a* value when using Eqs. (1)-(3) containing the G_{LZ} value. Therefore, it is promising that the IPSM can be measured accurately using Eqs. (1)-(3). When using Eqs. (1), (2), and (3)', the effect of the OPSM is ignored; however, the G_{LT} value decreases with decreasing *a* because the small value of G_{LZ} is more pronounced with decreasing *a*.

5.2. FV and TV tests

Figure 4(a) shows the dependence of the MOE (E_L) value on the value of a obtained from the FV tests. As described above, the material profile in the thickness direction of MDF was not considered in the FEAs, so the E_L values obtained from the flatwise and edgewise FV simulations are close to each other. In the actual MDF panel, however, the density at both surfaces is larger than that at the core, so the Young's modulus at the surface of the panel is usually larger than that at the core [18, 19]. The distribution of the Young's modulus in the panel induces the difference between the E_L values obtained from the flatwise and edgewise FV tests. Similar to the FEA results, the E_L value obtained from the flatwise FV test is almost independent of the value of a, whereas that obtained from the edgewise FV test decreases with decreasing a.

Figure 4(b) shows the dependence of the IPSM (G_{LT}) and OPSM (G_{LZ}) on the value of a obtained by the actual vibration tests. In the TV test using the specimen with an a of 10 mm, it was difficult to measure the resonance frequency for the TV mode because the amplitude of the 1st TV mode was much smaller than those of the FV modes. Therefore, the G_{LT} values in this condition are not demonstrated in this figure. Similar to the FEA results, the G_{LZ} value obtained from the flatwise FV test is independent of the value of a. In contrast, the G_{LT} value obtained from the edgewise FV test markedly increases with decreasing a. In the TV tests, the G_{LT} value is independent of a when using Eqs. (1)-(3), whereas that obtained from Eqs. (1), (2), and (3)' markedly decreases with decreasing a. A previous study suggested that the G_{LT} value can be measured by the FV test while reducing the effect of specimen configuration when the length L is less than 7.5 times the height a, which corresponds to the range from 40 to 60 mm in this study (Yoshihara 2011). In this range, the G_{LT} value obtained from the TV test using Eqs. (1)-(3) is significantly larger than that obtained from the FV test because the shear modulus at the surface is larger than that at the core of the MDF panel. This difference indicates that the test method has a significant influence on the measurement of the IPSM value of MDF, so the test method conducted should be addressed in the actual test. From the experimental and numerical analyses, however, the TV test using Eqs. (1)-(3) is more advantageous than the FV test because the IPSM can be measured while reducing the effect of specimen configuration.

6. Conclusions

A test of medium-density fibreboard (MDF) was conducted to determine the in-plane shear modulus (IPSM). The torsional vibration (TV) and flexural vibration (FV) test methods were analysed experimentally and numerically.

The experimental and numerical results indicated that the IPSM of MDF could be measured accurately by the TV test while reducing the effect of specimen configuration when using the OPSM value obtained from the FV test, although the IPSM value obtained from this method was often larger than that obtained from the FV test because of the variation of the material in the thickness direction.

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Figure captions

Figure 1 (a) and (b) Diagram of the torsional vibration (TV) and flexural vibration (FV) tests, respectively.

Figure 2 Finite element (FE) model for vibration test analysis. Unit = mm. L, T, and Z directions represent the length, width, and thickness directions of the MDF panel, respectively.

Figure 3 Dependence of (a) the MOE (E_L) and (b) the IPSM (G_{LT}) and OPSM (G_{LZ}) on the value of a obtained from the FEAs.

Figure 4 Dependence of (a) the MOE (E_L) and (b) the IPSM (G_{LT}) and OPSM (G_{LZ}) on the value of a obtained from the FV and TV tests. Experimental results are averages ± SD.

Table 1 Elastic properties used for the finite element calculations

Young's modulus (GPa)			Shear modulus (GPa)			Poisson's ratio		
E_L	E_T	E_Z	G_{LT}	G_{LZ}	G_{TZ}	ν_{LT}	ν_{LZ}	ν_{TZ}
3.00	3.00	0.12	1.50	0.20	0.20	0.27	0.27	0.27

L, T, and Z represent the length, width, and thickness directions of the MDF panel, respectively. The E_L, E_T, G_{LT}, and ν_{LT} values are referred from [2], G_{LZ} and G_{TZ} are referred from [17], the E_Z value is referred from [18], and the ν_{LZ} and ν_{TZ} values are assumed to be equal to ν_{LT}.

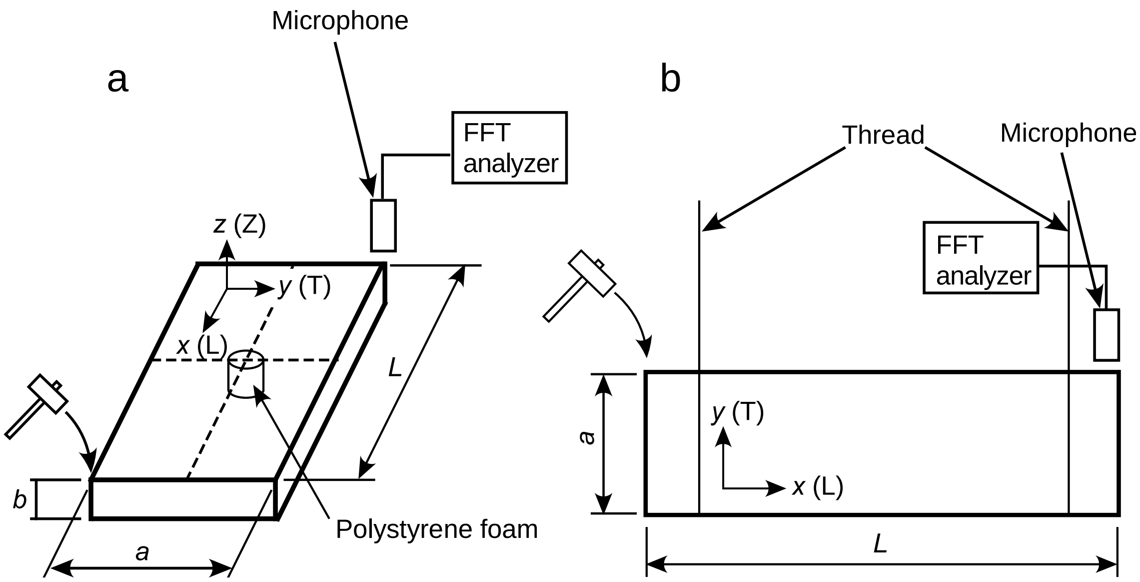
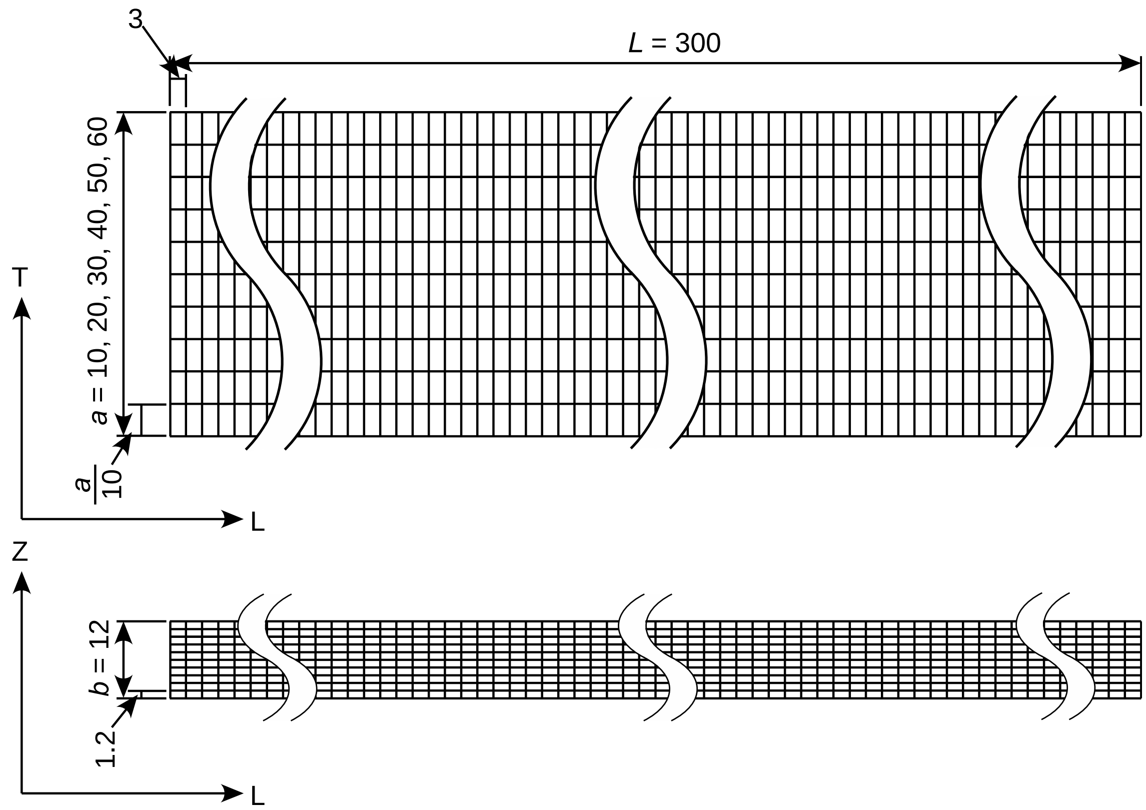


Figure 1 (a) and (b) Diagram of the torsional vibration (TV) and flexural vibration (FV) tests, respectively.



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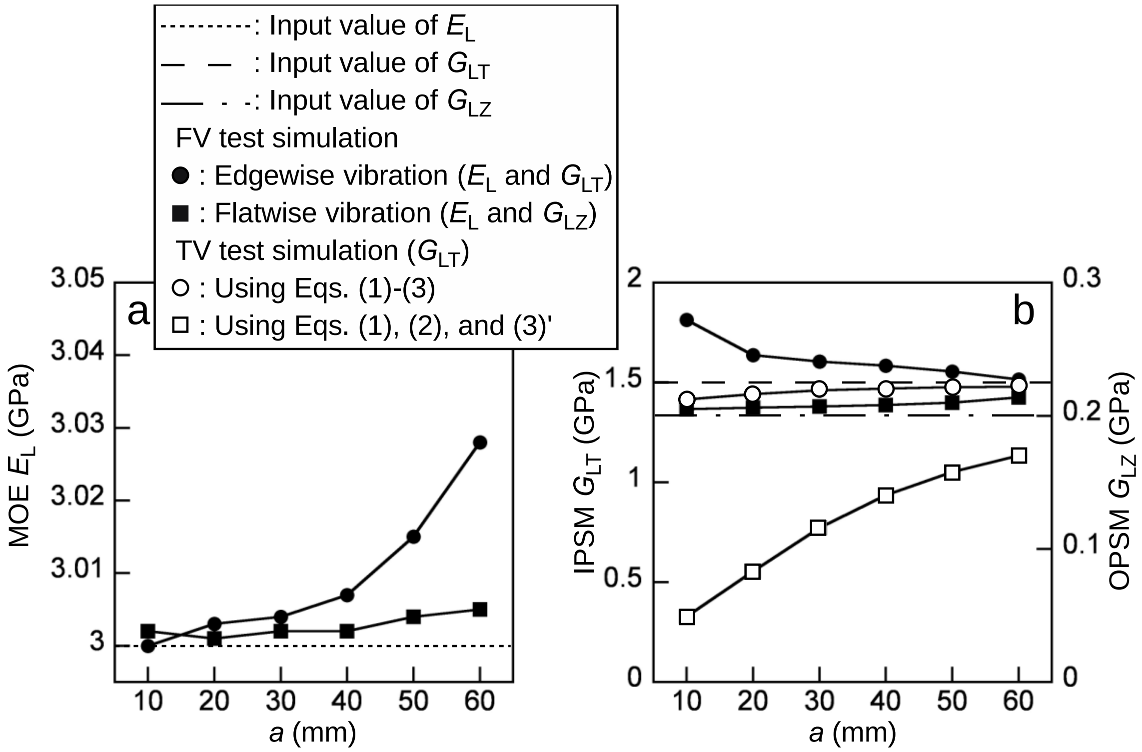

Figure 3 Dependence of (a) the MOE (E_L) and (b) the IPSM (G_{LT}) and OPSM (G_{LZ}) on the value of *a* obtained from the FEAs.

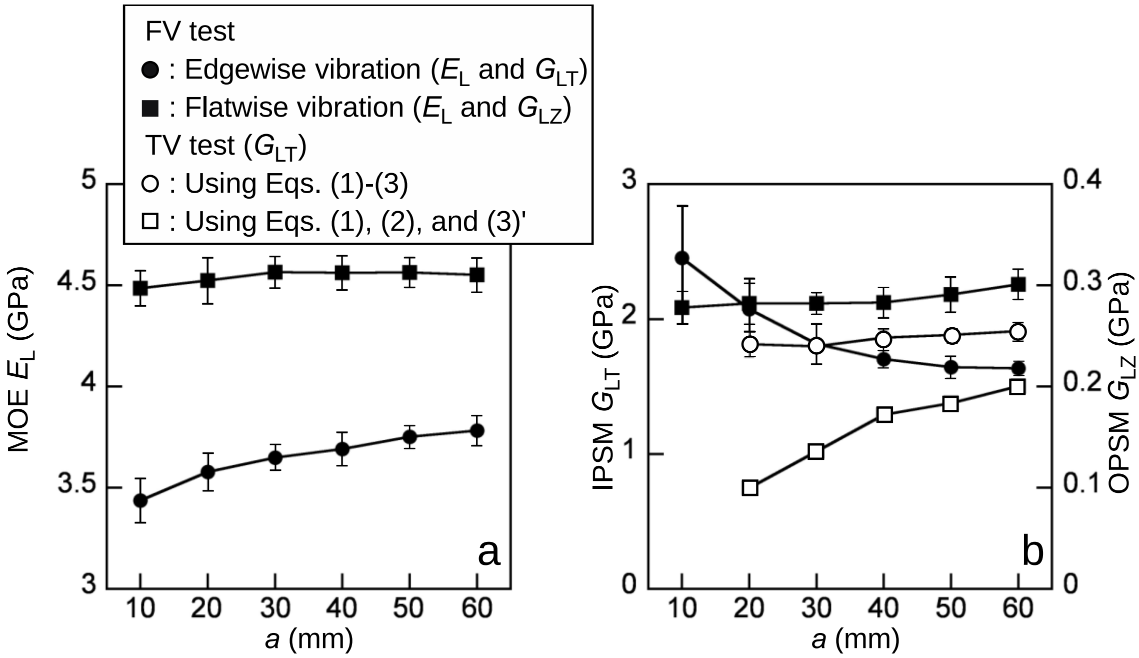

Figure 4 Dependence of (a) the MOE (E_L) and (b) IPSM (G_{LT}) and OPSM (G_{LZ}) on the value of a obtained from the FV and TV tests. Experimental results are averages ± SD.