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Estimation of mass and moisture content of flat square lumber in a stack during air-drying process by the vibration method with additional mass

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Abstract

A vibration test to measure the mass of a specimen without weighing it using the difference between the resonance frequency with an additional mass and that without it (vibration method with additional mass, VAM) was applied to Japanese cedar flat square lumber with dimensions of 210 mm × 135 mm × 3000 mm both with and without a pith in the process of air-drying. The longitudinal and bending vibration tests were performed on the specimens with and without an additional mass. The accuracy of VAM that was expressed by the estimated mass by VAM to the measured mass (M_{VAM}/M_0) was sufficiently high throughout the air-drying process. The accuracy of VAM for the longitudinal vibration was higher than that for the bending vibration. The moisture content based on the estimated mass by VAM was in the expected range.

Keywords Additional mass, Flat square lumber, Mass, Stack, Vibration test

Introduction

The ratio of old-age class forests to artificial forests has increased year by year in Japan. The ratio of forests over 50 years old has reached 50%. For the sustainable use of forest resources, the effective use of timber from mature artificial forests and reforestation are important.

The age classes of the logs produced from the conifer artificial forests have changed with time, and wood demand has influenced the required qualities of lumber. Since the appropriate uses and effective processing methods for large-diameter logs whose supply will increase are not established, they are not sufficiently used based on the quantitative and qualitative characteristics [1].

Flat square lumber is expected to be one of the uses of large-diameter logs. If the qualities of the flat square lumber are clarified before shipping, the yield of products will improve. If the quality variation can be reduced, the added value of the flat square lumber will increase.

Young's modulus, which positively correlates with strength [2], is helpful for an index before shipping. Since a vibration test is a non-destructive and simple testing method for measuring Young's modulus, it is expected to be promising for classifying the flat square lumber using Young's modulus. However, Young's modulus calculation based on the vibration theory needs the density (or mass) of the flat square lumber.

Flat square lumber is usually stored as a stack. Since it is large and heavy, handling it is difficult, and determining the output of a scale is time-consuming. When the stack is dismantled, space is required to place the flat square lumber.

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Since flat square lumber is stored as a stack, measuring the mass of each flat square lumber removed from the stack is inefficient. Therefore, the measuring method for the stacked flat square lumber is required.

The mass of a specimen can be measured without weighing the specimen using the difference between the resonance frequency with an additional mass and that without it [3–8]. If the mass (or density) can be obtained, Young's modulus can be calculated using the usual method shown in the following Eqs. (1a) and (1b). This method is called the "vibration method with additional mass (VAM)" in this study.

It is possible to measure the mass of the cross beam for the timber guardrail without removing the cross beam from the support using VAM [9]. This result will lead to a simple investigation method to assess the deterioration of the cross beam although the large amount of labor required for the investigation was one of the factors that hindered the widespread use of timber guardrails.

For a stacked squared lumber model and actual stacked round bars for the timber guardrail, the vibration restraint could be reduced by changing the position and materials of stickers. Consequently, the estimation accuracy of VAM was sufficiently high [10, 11].

In this study, the vibration method with additional mass was applied to measure the mass of each stacked flat square lumber during air-drying process.

Theory

Vibration method with additional mass

Here, longitudinal and bending vibrations under free–free conditions are considered. The effects of shear deflection and rotatory inertia on the bending vibrational deflection of a thin beam with a constant cross-section are negligible, and the Euler–Bernoulli elementary theory of bending can be applied to the bending vibration.

The resonance frequency, denoted by f_{n0} (n refers to the resonance mode number and 0 reflects the value without the additional mass), can be expressed as follows:

$$f_{n0} = \frac{m_{n0}}{2\pi l}\sqrt{\frac{E}{\rho}}(\text{Longitudinal vibration}) \tag{1a}$$

$$f_{n0} = \frac{1}{2\pi}\left(\frac{m_{n0}}{l}\right)^2\sqrt{\frac{EI}{\rho A}}(\text{Bending vibration}) \tag{1b}$$

where l, E, ρ, I, and A are the specimen length, Young's modulus, density, the second moment of area, and the cross-sectional area. m_{n0} is a constant depending on vibration modes and can be expressed as follows:

$$m_{n0} = n\pi(\text{Longitudinal}) \tag{2a}$$

$$m_{10} = 4.730, m_{20} = 7.853, m_{30} = 10.996,$$
$$m_{n0} = \frac{1}{2}(2n+1)\pi(n > 3))(\text{Bending}) \tag{2b}$$

The resonance frequency is experimentally reduced by attaching the additional mass while the dimensions, density, and Young's modulus are not altered. Hence, it can be said that m_{n0} changes to m_n. Thus, the resonance frequency after attaching the additional mass is expressed as follows:

$$f_n = \frac{m_n}{2\pi l}\sqrt{\frac{E}{\rho}}(\text{Longitudinal}) \tag{3a}$$

$$f_n = \frac{1}{2\pi}\left(\frac{m_n}{l}\right)^2\sqrt{\frac{EI}{\rho A}}(\text{Bending}) \tag{3b}$$

From Eqs. (1a), (1b), (2a) and (2b),

$$m_n = \frac{f_n}{f_{n0}}m_{n0}(\text{Longitudinal}) \tag{4a}$$

$$m_n = \sqrt{\frac{f_n}{f_{n0}}}m_{n0}(\text{Bending}) \tag{4b}$$

The frequency equation for the free–free vibration with concentrated mass M placed at position $x=al$ (x: distance along the bar, $0 \le a \le 1$, $a+b=1$) on a bar (Fig. 1) can be expressed as follows:

$$\sin m_n + \mu m_n \cos a m_n \cos b m_n = 0(\text{Longitudinal}) \tag{5a}$$

$$\begin{aligned}&(\cos m_n \cosh m_n - 1) - \frac{1}{2}\mu m_n\{(\cos a m_n \cosh a m_n + 1)\\&(\sin b m_n \cosh b m_n - \cos b m_n \sinh b m_n) + (\cos b m_n \cosh b m_n + 1)\\&(\sin a m_n \cosh a m_n - \cos a m_n \sinh a m_n)\} = 0(\text{Bending})\end{aligned} \tag{5b}$$

where μ is the ratio of the concentrated mass to the mass of the bar and can be defined as follows:

$$\mu = \frac{M}{\rho A l} \tag{6}$$

To calculate m_n, the measured resonance frequencies (f_{n0} and f_n) are substituted in Eqs. (4a) and (4b). The calculated m_n is substituted in Eqs. (5a) and (5b) to calculate μ. The specimen mass and density can be obtained by substituting the calculated μ, concentrated mass, and dimensions of a bar in Eq. (6). The Young's modulus can be calculated by substituting the estimated density, resonance frequency without the concentrated mass and dimensions of a bar in Eqs. (1a) and (1b) [3–8]. The specimen mass is not required for these calculations.

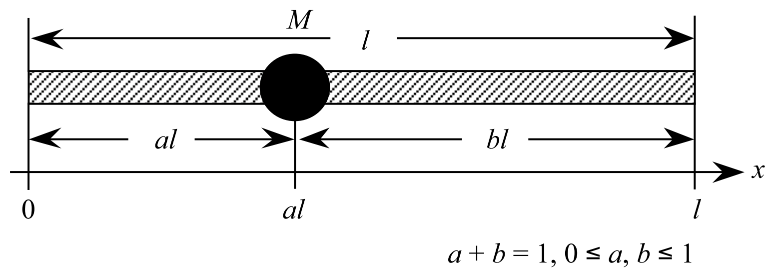

Fig. 1 Beam with an additional mass

These calculations are the VAM procedure. In this study, the estimation accuracy of VAM was expressed by the ratio of the specimen mass estimated by VAM (M_{VAM}) to the measured specimen mass (M_0). The estimation accuracy of VAM is considered sufficiently high at $0.9 \leq M_{VAM}/M_0 \leq 1.1$ in this study.

The moisture content based on the mass estimated by the VAM

The moisture content based on the measured mass (MC_0) is expressed as follows:

$$MC_0 = \frac{100(M_0 - M_{OD})}{M_{OD}}[\%] \tag{7}$$

where M_{OD} is the oven-dried mass.

The moisture content based on the mass estimated by VAM (MC_{VAM}) is expressed as follows:

$$MC_{VAM} = \frac{100(M_{VAM} - M_{OD})}{M_{OD}}[\%] \tag{8}$$

When M_{VAM} can be written as kM_0, using Eqs. (7) and (8), the accuracy of the moisture content based on the mass obtained by VAM (dMC) can be expressed as follows:

$$dMC = MC_{VAM} - MC_0 = \frac{100(M_{VAM} - M_0)}{M_{OD}} = \frac{100M_0(k-1)}{M_{OD}} = (k-1)(MC_0 + 100)[\%] \tag{9}$$

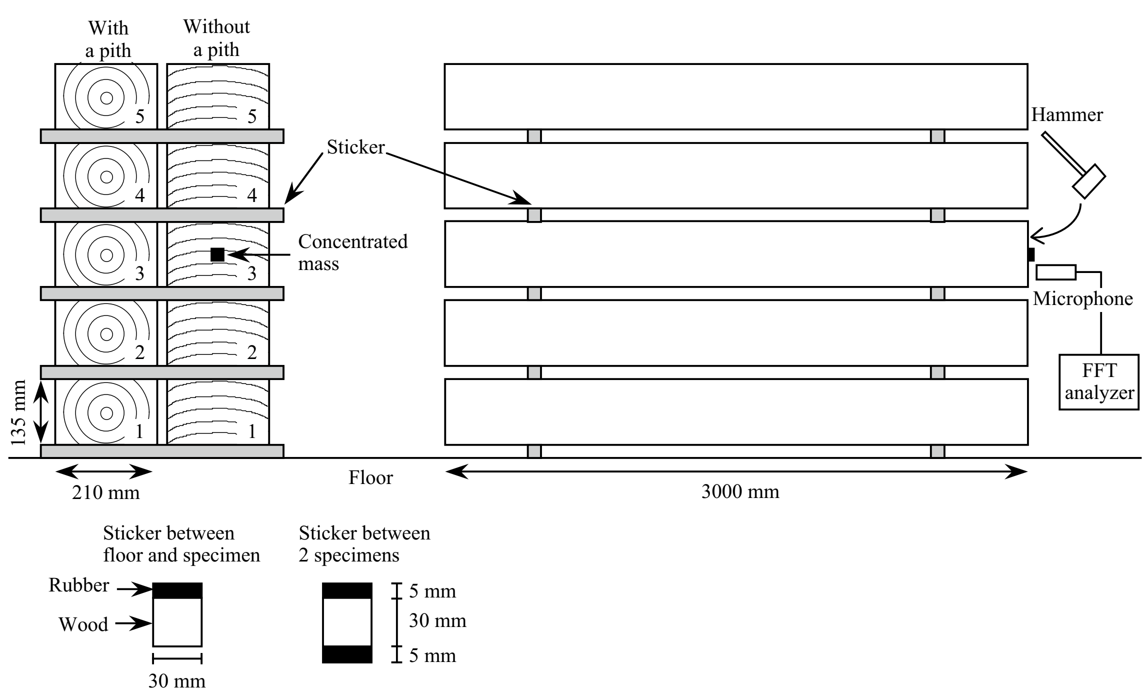

Fig. 2 Schematic diagram of the experimental setup for the free–free longitudinal and bending vibration tests

From Eq. (9), when $0.9 \leq k \leq 1.1$,

$$-0.1MC_0 - 10 \leq \mathrm{d}MC \leq 0.1MC_0 + 10[\%] \quad (10)$$

Materials and methods

Specimens

Japanese cedar (*Cryptomeria japonica*, D. Don) green logs with a diameter of about 400 mm were used. Five flat square lumbers with a pith with cross-sectional dimensions of 210 mm (T) × 135 mm (T) and with a length of 3000 mm (L) and five flat square lumbers without a pith with cross-sectional dimensions of 210 mm (T) × 135 mm (R) and with a length of 3000 mm (L) were made from the logs.

Table 1 The initial oven-dried moisture content, density and Young's modulus in the last longitudinal vibration test

Flat square lumber	Initial moisture content [%]	Density [kg/m^3]	Young's modulus [GPa]
	With a pith		
5	84	415	8.09
4	129	363	6.53
3	115	417	8.55
2	103	531	9.85
1	182	381	7.13
	Without a pith		
5	130	430	11.52
4	175	382	6.55
3	146	461	12.65
2	142	459	11.95
1	195	385	6.90

The flat square lumbers were placed in a room without controlling the temperature and relative humidity for a year until the masses became constant. The flat square lumbers were stacked in five layers on the floor in the room. The position of the stickers were the nodal positions of the free–free bending vibration corresponding to its first resonance mode as shown in Fig. 2. The stickers were composed of a Japanese cedar bar with cross-sectional dimensions of 30 mm × 30 mm and a length of 500 mm, and rubber sheet in order to reduce the vibration restraint caused by the mass of the upper flat square lumbers [10–12].

All the following vibration tests were conducted in the room on the day the flat square lumbers were delivered and 2 weeks, 1 month, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12 months after delivering. After the vibration tests, each flat square lumber was removed from the stack and its mass was measured, and then the lumber was stacked again. Flat square lumber was cut into 150 small pieces with dimensions of 40 mm × 25 mm × 500 mm and they were oven-dried at 105 °C.

Free–free longitudinal vibration test

The longitudinal vibration tests were conducted on the flat square lumbers with and without a steel plate, which was used as the concentrated mass (dimensions:

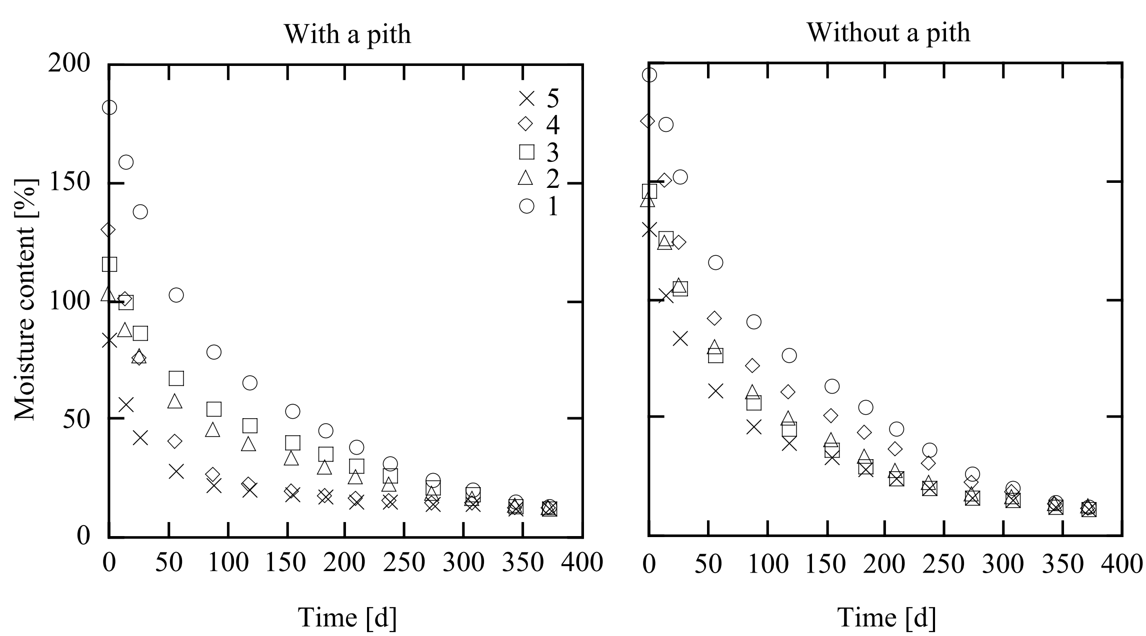

Fig. 3 Temporal change in moisture content based on the measured mass of the flat square lumbers during the air-drying process

70.10 mm × 70.10 mm × 19.05 mm, mass: 728 g) and the resonance frequency of the first mode was measured. The range of the mass ratio (measured concentrated mass/measured specimen mass) was 0.00843–0.0237. The steel plate was bonded on the RT-plane using a set of four wood screws through the holes of the plate.

The free–free longitudinal vibration tests were conducted according to the following procedure as shown in Fig. 2 [11]. The test bar was placed at the nodal positions of the free–free bending vibration corresponding to its first resonance mode. The longitudinal vibration was initiated by hitting the RT-plane of the flat square lumber at one end using a hammer with an iron head, whereas the bar motion was monitored using a microphone (MI-1235, Ono-Sokki, Co., Ltd., Yokohama, Japan) at the same end. The direction of the microphone was parallel to the L-direction. The signal was processed using a fast Fourier transform (FFT) digital signal analyzer (Multi-Purpose FFT Analyzer CF-9200, Ono-Sokki, Co., Ltd., Yokohama, Japan) to obtain high-resolution resonance frequencies of the first resonance mode. When the specimens were on the stickers at such positions, the accurate longitudinal resonance frequency of the first mode can be obtained [11, 13].

Free–free bending vibration test

The bending vibration tests were conducted on the flat square lumbers with and without a steel plate, which was used as the aforementioned concentrated mass and the resonance frequency of the first mode was measured. The steel plate was bonded on the RT-plane using a set of four wood screws through the holes of the plate as shown in Fig. 2.

The free–free bending vibration tests were conducted according to the following procedure [11]. The test bar was placed at the nodal positions of the free–free vibration corresponding to its first resonance mode. The bending vibration was initiated by hitting the RT-plane, the short side with a length of 135 mm and the long side with a length of 210 mm of the flat square lumbers at one end using the hammer, whereas the bar motion was monitored using a microphone at the same end. The bending vibration generated by tapping the 135 mm × 3000 mm plane and that by tapping the 210 mm × 3000 mm plane are referred to as "edgewise" and "flatwise", respectively in this study. The microphone's direction was adjusted so that the edgewise and flatwise bending vibrations could be detected. The signal was processed using the aforementioned FFT digital signal analyzer to obtain high-resolution resonance frequencies. According to the previous paper [13], the bending vibration can be generated by hitting the RT-plane.

Measurement of the oven-dried mass

After the last vibration tests, the flat square lumbers were divided into 5 × 5 = 25 small bars with dimensions of about 40 mm × 25 mm × 3000 mm and the short small bars with dimensions of about 40 mm × 25 mm × 600 mm were made from the 3000 mm small bars. The short small bars were heated at 105 °C and the oven-dried masses were measured. Using the sum of the oven-dried mass of each short small bar, the oven-dried mass of the flat square bar was calculated, supposing that the moisture content of the short small bar, that of the small bar, and that of the flat square lumber after the last vibration test were the same [14].

Results and discussion

The initial oven-dried moisture content, density and Young's modulus in the last longitudinal vibration test are shown in Table 1.

Figure 3 shows the temporal change in moisture content based on the measured mass of the flat square lumbers. The moisture content became stable during this experimental process.

Figure 4 shows the temporal change in the accuracy of VAM. There was not a significant difference between at the initial higher moisture content stage and at the later lower moisture content stage. This tendency was observed regardless the vibration mode and did not depend on the presence or absence of a pith. This result is proper because VAM can be applied in the moisture content range of air-dried moisture content (12%) to high moisture content (134% and 238%) [15, 16].

The factors that affect the accuracy of VAM are discussed. The accuracy of VAM depends on the constant m_n in Eqs. (4a) and (4b), that is to say, the measured resonance frequency. The constant m_n decreases monotonically with μ as shown in Fig. 5. [5, 7]. The value of μ is susceptible to m_n when the absolute value of the slope of the curve shown in Fig. 5 is small. The change in m_1 was $3.11534 \geq m_1 \geq 3.0692$ in the range of $0.00843 \leq \mu \leq 0.0237$ for the longitudinal vibration, which was calculated by solving Eq. (5a) using Mathematica 12.3 J software (Wolfram Research Co., Ltd.). Consequently,

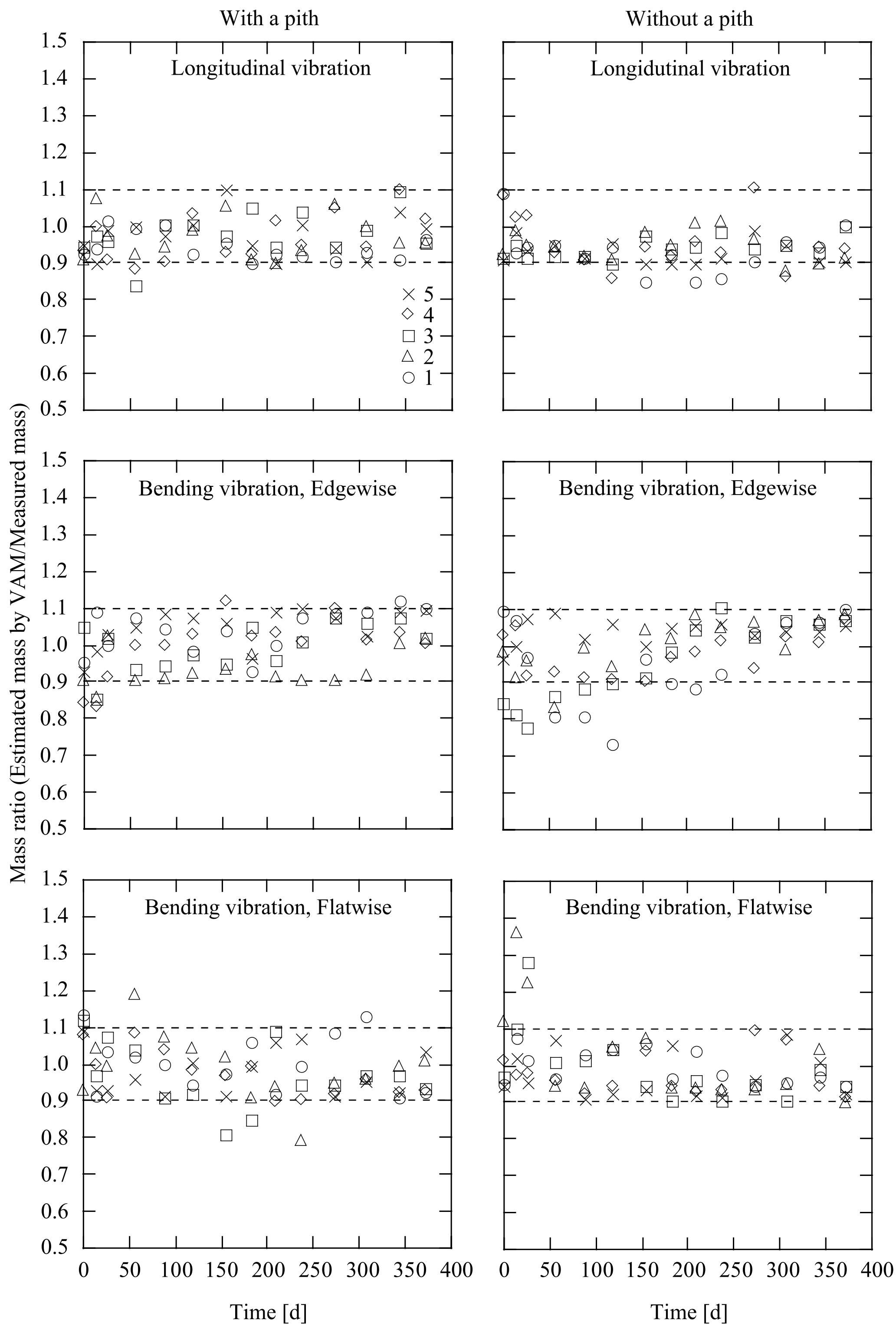

Fig. 4 Temporal change in the accuracy of VAM during the air-drying process

Table 2 Number of cases $0.9 \leq M_{VAM}/M_0 \leq 1.1$

Longitudinal vibration	Specimen with a pith	68
	Specimen without a pith	64
Bending vibration	Specimen with a pith	Edgewise 64 Flatwise 63
	Specimen without a pith	Edgewise 60 Flatwise 66

M_{VAM}: estimated mass by the vibration method with additional mass, M_0: measured mass

the absolute ratio of the change in m_1 to that of μ ($dm_1/d\mu$) was 3.305. In the same way, the change in m_1 was $4.69199 \geq m_1 \geq 4.63132$ in the range of $0.00843 \leq \mu \leq 0.0237$ for the bending vibration, which was calculated by solving Eq. (5b). Consequently, the absolute $dm_1/d\mu$ was 3.976. Since $dm_1/d\mu$ for the longitudinal vibration was smaller than $dm_1/d\mu$ for the bending vibration, it was expected that the accuracy of VAM was lower for the longitudinal vibration than for the bending vibration. However, there were more cases of $0.9 \leq M_{VAM}/M_0 \leq 1.1$ for the longitudinal vibration than the bending vibration as shown in Table 2. This result was caused by the larger difference between the resonance frequency without the concentrated mass and that with it ($f_{10} - f_1$) for the longitudinal vibration than $f_{10} - f_1$ for the bending vibration as shown in Table 3: $f_{10} - f_1$ decreased with the decrease in f_{10}. Therefore, the longitudinal vibration is more suitable for estimating the mass of each stacked flat square lumber with the dimensions in this study. The reduction in the accuracy of VAM due to the deviation of the resonance frequency from the true value can be improved: averaging several frequencies near the true resonance frequency is effective [17].

Figure 6 shows the moisture content based on the estimated mass by VAM. Since the result of $0.9 \leq M_{VAM}/M_0 \leq 1.1$ was obtained for almost all of the cases, the moisture content was in the range of Eq. (10) for almost all the cases.

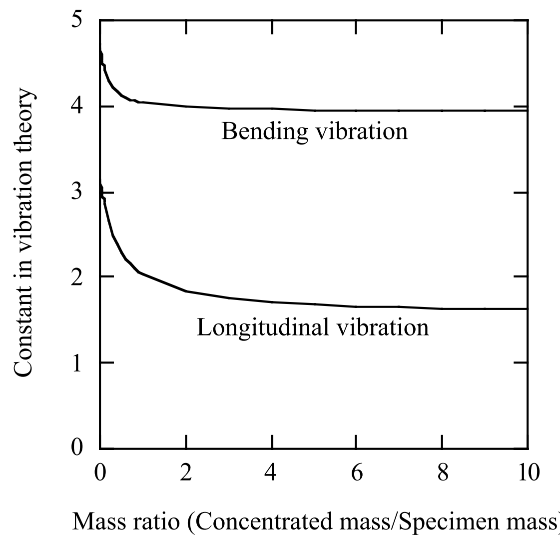

Fig. 5 Relationship between the constant m_1 and the mass ratio μ

Conclusions

VAM estimated the mass and moisture content of the stacked flat square lumber in the air-drying process, and the following results were obtained:

1) The accuracy of VAM was sufficiently high for all the processes of natural drying.
2) The accuracy of VAM for the longitudinal vibration was higher than the bending vibration for the flat square lumber with dimensions in this study.
3) The moisture content based on the estimated mass by VAM was in the expected range.

Table 3 Resonance frequency without additional mass and difference between resonance frequency without additional mass and that with it

		f_{10} [Hz]	$f_{10} - f_1$ [Hz]
Longitudinal vibration	Specimen with a pith	638.8 (74.3)	11.3 (3.6)
	Specimen without a pith	675.1 (122.6)	11.5 (4.2)
Bending vibration	Specimen with a pith	Edgewise 91.2 (10.2) Flatwise 59.4 (6.6)	Edgewise 2.8 (0.8) Flatwise 1.9 (0.6)
	Specimen without a pith	Edgewise 91.7 (14.4) Flatwise 60.0 (10.8)	Edgewise 2.7 (0.8) Flatwise 1.8 (0.7)

Mean (standard deviation), f_{10}: Resonance frequency of the first mode without an additional mass, f_1: Resonance frequency of the first mode with an additional mass

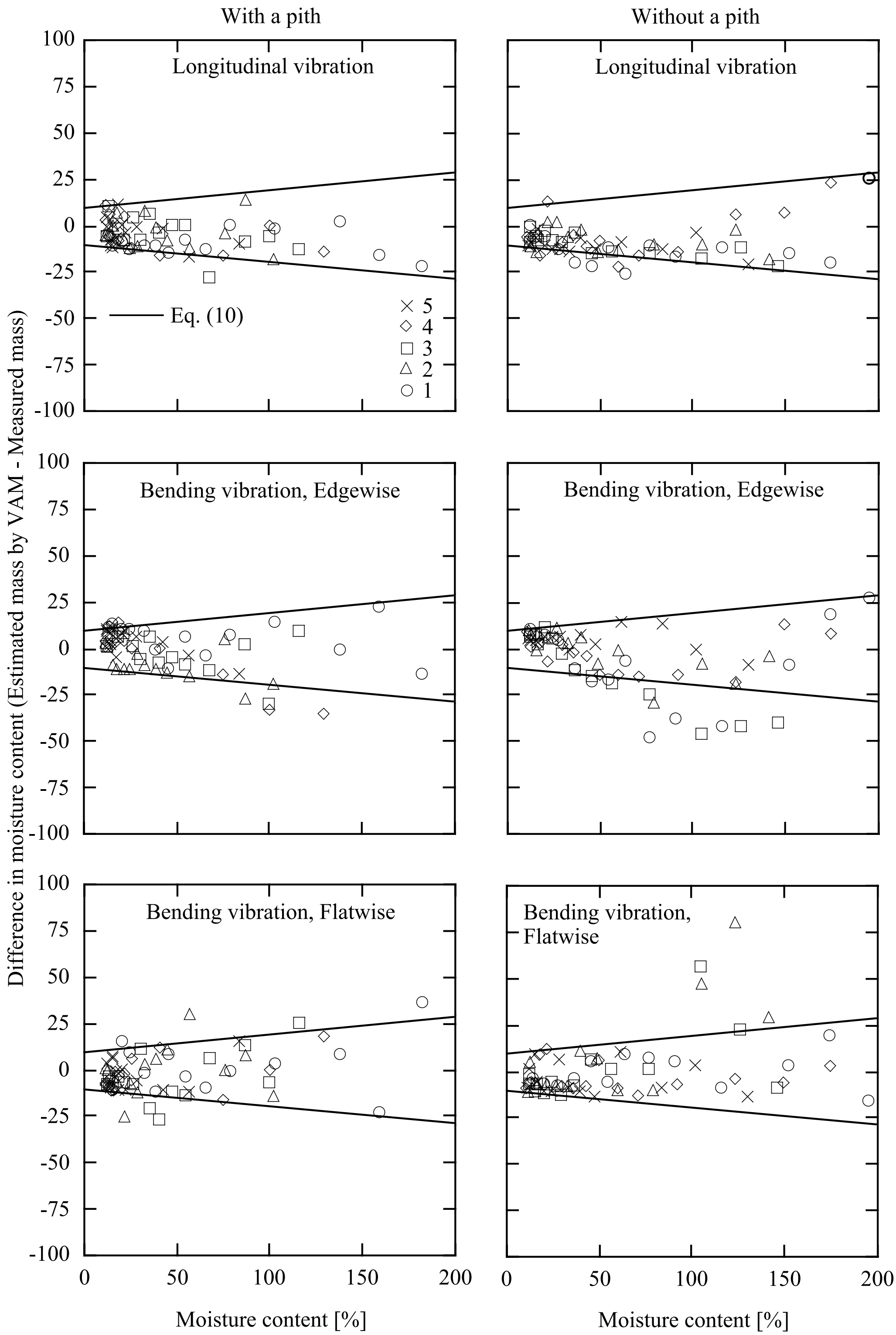

Fig. 6 Moisture content based on the estimated mass by VAM

Abbreviations

VAM Vibration method with additional mass
L Longitudinal direction
R Radial direction
T Tangential direction
FFT Fast Fourier transform

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Author contributions

All the authors designed the experiments. YK performed the experiments, analyzed the data, and was a major contributor in writing the manuscript. All the authors contributed to interpretation and discussed results, and read and approved the final manuscript.

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Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Declarations

Competing interests

The authors declare that they have no competing interests.

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