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ORIGINAL ARTICLE

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# Determining Young's modulus of timber on the basis of a strength database and stress wave propagation velocity I: an estimation method for Young's modulus employing Monte Carlo simulation

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**Abstract** In this article, we report on an estimation method for Young's modulus that entails measuring only the stress wave propagation velocity of timber built into structures such as wooden buildings. Methods of estimating Young's modulus that use the stress wave propagation velocity and characteristic frequency of timber in conjunction with timber density have long been used. In this article, we propose a method of easily and accurately estimating Young's modulus from the stress wave propagation velocity without knowing the timber density. This method is based on a database of wood strength performance and density accumulated from a variety of research data and the method estimates Young's modulus by a simulation method. We compared the Young's moduli estimated by this method with those obtained by the bending test and by the measurement of the stress wave propagation velocity and density, and found similar results. This coincidence suggests that the method of estimating Young's modulus presented in this article is valid. For example, the method is effective for convenient evaluation on site when determining whether a wooden building's structural components should be reused or replaced when repairing or remodeling a building.

**Key words** Monte Carlo simulation · Strength database · Stress wave propagation velocity · Young's modulus · Estimation

## Introduction

Young's modulus is the most commonly used index of the strength of timber. There are several methods of obtaining this parameter: (i) load method, (ii) frequency analysis (impact method), (iii) ultrasonic method, and (iv) stress wave method. Among these, the load method requires us to specify the cross-sectional shape of the materials, and cannot be used for measuring timbers that are part of a complete structure. With the frequency analysis (impact method), the manner in which tested materials are supported in a structure plays a significant role; therefore, it is also difficult to test materials in situ using frequency analysis. This method also requires knowledge of the density of the tested materials. The ultrasonic method has difficulties in that it requires contact between the material (timber) and sensors, as well as knowledge of the density of the material. Although it has some technical advantages, its use is still confined to the laboratory and it is difficult to employ on site. When compared with these three methods, the stress wave method, i.e., stress wave propagation velocity measurement, is simple. In this method, the manner in which materials are supported is irrelevant, making this a simple method that can be used on site.

Considering the above factors, we have developed a new method of estimating the Young's modulus of structural timbers using only stress waves for use in the cases where timber density cannot be measured (Japanese patent pending: No. 2006-058443). In this article, the estimation method and the results of real-size timber bending tests are reported, and the estimated Young's modulus is compared with experimental Young's moduli in order to examine the validity of our estimation method.

In the stress wave method, Young's modulus can be obtained from the velocity of stress waves that propagate in the material and the material's density in general. However, to determine the density of a material, it is necessary to sample the whole material or obtain a small piece of it in order to measure its volume and weight. This procedure is complicated and the density cannot be obtained easily and, even if obtained, can be quite variable. The density determined from a small piece only represents the local density of the timber and does not necessarily represent that of the timber as a whole. The method presented in this article uses a database of wood strengths that

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Part of this article was presented at the 56th Annual Meeting of the Japan Wood Research Society, Akita, Japan, August 2006, and published as a patent application represents research data accumulated from various reports, and estimates Young's modulus using only the stress wave propagation velocity without measuring density.

## Estimation method without measuring density

Monte Carlo simulation

The relationship between the Young's modulus ($E$), density ($\rho$), and stress wave propagation velocity ($v$) of a material is given by $E = \rho v^2$. The basic concept of our estimation method is to statistically obtain the likely set of Young's modulus and density for the measured stress wave propagation velocity using a simulation method and a database.

Our procedure for determining the relationship between the estimated Young's modulus and density, which is the heart of the Monte Carlo approach, is now described. Figure 1 shows a flowchart for the estimation of Young's modulus through Monte Carlo simulation, and Fig. 2 gives a schematic diagram of the estimation method.

Step 1: First, prepare a set of actual data that show the relationship between the Young's modulus and density of wood (hereafter referred to as the reference distribution database). For this relationship between the Young's modulus and density data in the reference distribution database, a regression line is obtained. Figure 3 shows an example of the reference distribution database and its regression line.

Step 2: Obtain a cumulative frequency curve for the density data in the reference distribution database, as shown in Fig. 4.

Step 3: Extract an arbitrary density ($\rho_i$) from this curve using a nonparametric method. Here, a random number generated for the interval [0, 1] is applied to the vertical axis of the cumulative frequency curve obtained in Step 2, and then the corresponding density ($\rho_i$) expressed in the horizontal axis is obtained.

Step 4: Substitute the density data ($\rho_i$) extracted in Step 3 into the regression line in order to obtain the average Young's modulus ($E_{iave}$) that corresponds to the density ($\rho_i$), as given by Eq. 1 and shown in Fig. 2:

$$E_{i\text{ave}} = a \cdot \rho_i + b \tag{1}$$

where $a$ and $b$ are regression coefficients.

Step 5: Extract the arbitrary regression residual ($Y\text{rr}_i$) of the Young's modulus that corresponds to the arbitrary density ($\rho_i$). Here, it is assumed that the regression residual ($Y\text{rr}_i$) forms a normal distribution (average = $E_{iave}$, variance = $\text{SD}_i^2$). Specifically, the regression residual ($Y\text{rr}_i$) is equal to the standard normal probability variable ($V$) multiplied by the residual standard deviation ($\text{SD}_i$) of Young's modulus obtained from the reference distribution database, as given by Eq. 2 and shown in Fig. 2:

$$Y\text{rr}_i = V \cdot \text{SD}_i \tag{2}$$

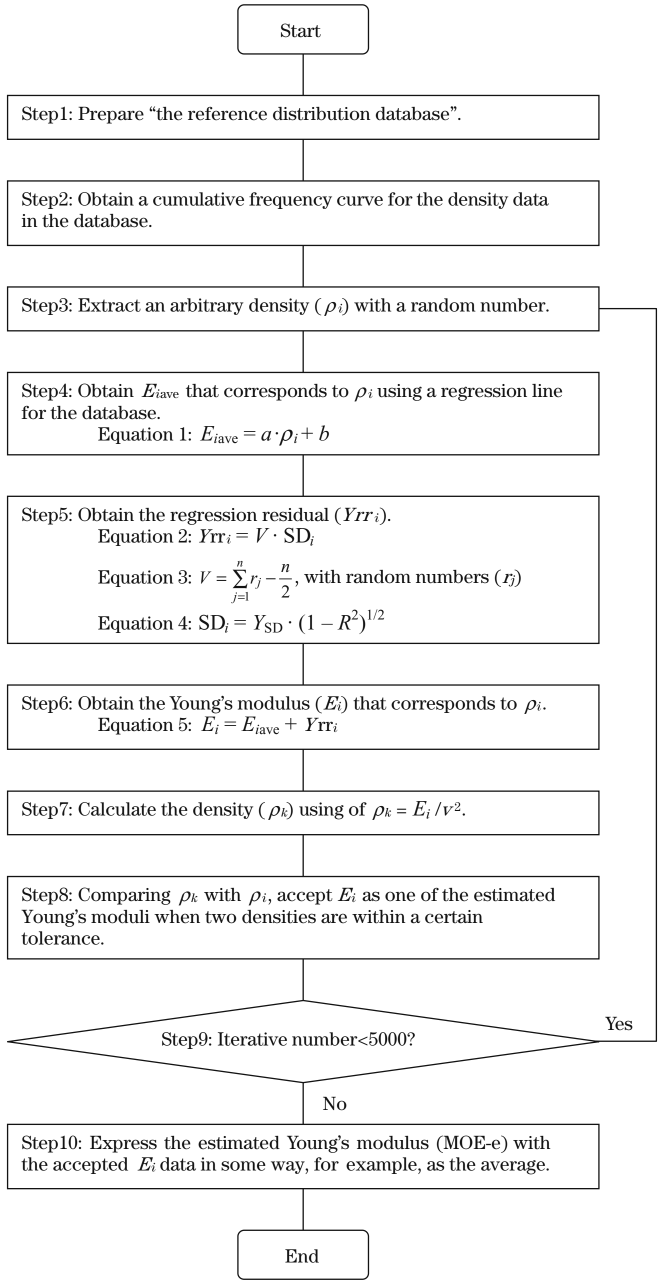


**Fig. 1.** Flowchart for estimation of Young's modulus by Monte Carlo simulation. $E_{iave}$, the average Young's modulus corresponding to the density ($\rho_i$); $V$, standard normal probability variable; $\text{SD}_i$, residual standard deviation; $Y_{\text{SD}}$, the SD of Young's modulus of the reference distribution database; $R^2$, the coefficient of determination of the relationship between Young's modulus and density in the reference distribution database

where the standard normal probability variable ($V$) is calculated using the central limit theorem with multiple random numbers, as given by Eq. 3:

$$V = \sum_{j=1}^{n} r_j - \frac{n}{2} \tag{3}$$

In Eq. 3, $r_j$ represents the $j$-th random number, and the first term represents the sum of $n$ uniform random numbers ($r_1, r_2, \ldots, r_n$) of interval [0,1]. Generally, $n = 12$ is considered sufficient.[1,2] If the Young's moduli are

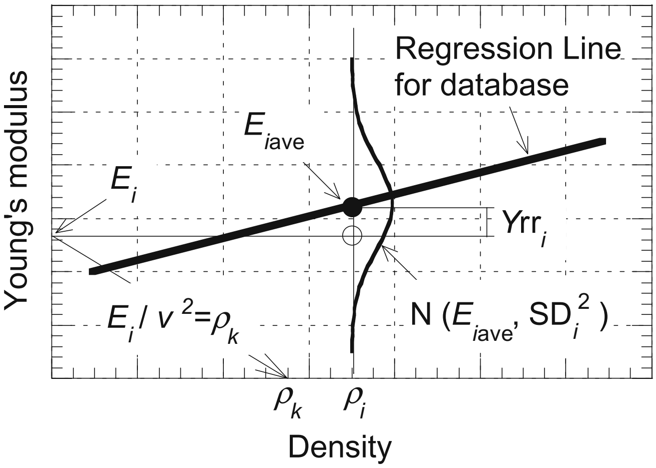


**Fig. 2.** Schematic of estimation method

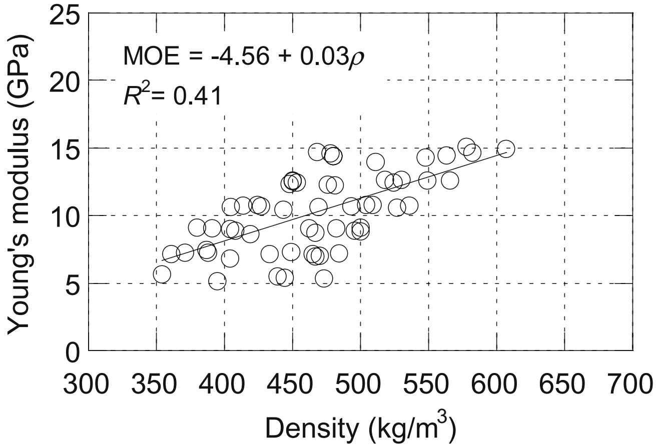


**Fig. 3.** Example of reference distribution database (data of MSR lumber). *MOE*, Young's modulus; $\rho$, density

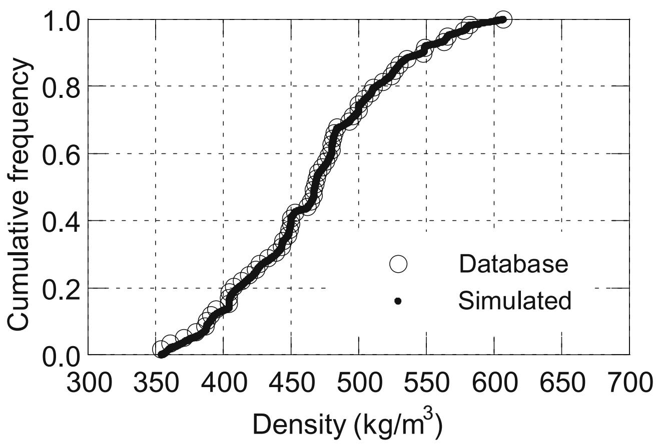


**Fig. 4.** Conformity of simulated density distribution and reference distribution database

evenly distributed against densities in the reference distribution database, the residual standard deviation ($SD_i$) is constant, independent of $\rho_i$, and is given by Eq. 4:[3]

$$SD_i = Y_{SD} \cdot \left(1 - R^2\right)^{1/2} \tag{4}$$

where $Y_{SD}$ is the standard deviation of Young's modulus of the reference distribution database and $R^2$ is the coefficient of determination of the relationship between Young's modulus and density in the reference distribution database. However, if the data is not evenly distributed, then the value of $SD_i$ that corresponds to a given $\rho_i$ must be obtained by another method.[1,4]

Step 6: Then, the Young's modulus ($E_i$) that corresponds to the density ($\rho_i$) arbitrarily extracted in Step 3 can be obtained using Eq. 5 (refer to Fig. 2):

$$E_i = E_{iave} + Yrr_i \tag{5}$$

where $E_{iave}$ is the average Young's modulus obtained in Step 4 and $Yrr_i$ is the arbitrary regression residual obtained in Step 5.

Step 7: The relationship among Young's modulus ($E$), density ($\rho$), and stress wave propagation velocity ($v$) is given by $\rho = E/v^2$. Therefore, the density ($\rho_k$) can be calculated backwards with the Young's modulus ($E_i$) obtained in Step 6 and the measured stress wave propagation velocity (refer to Fig. 2).

Step 8: If the two densities, i.e., $\rho_i$ extracted in Step 3 and $\rho_k$ obtained by the reverse calculation in Step 7, are within a certain tolerance (for example, less than 5% or 1%), this density ($\rho_i$) and the corresponding Young's modulus ($E_i$) are accepted as one group of estimated values that satisfy the relationship among stress wave propagation velocity ($v$), density ($\rho$), and Young's modulus ($E$).

Step 9: Repeat Steps 3 through 8 for a sufficient number of times (e.g., 5000 times) to obtain an accepted data group of $\rho_i$ and $E_i$. By a sufficient number of iterative calculations, the simulated density distribution, which is a set of repeatedly extracted $\rho_i$ values, agrees well with the reference distribution database, as shown in Fig. 4. Note that the density data ($\rho_i$) are created only in the range of the database's density. The simulated Young's moduli when the two densities, i.e., $\rho_i$ and $\rho_k$, are within a certain tolerance are called "accepted $E_i$ data," i.e., they are accepted as the estimated Young's modulus when only one stress wave propagation velocity is measured.

Step 10: The estimated Young's modulus (MOE-e) is expressed with the accepted $E_i$ data in some way, for example, as the average.

We have developed a Young's modulus estimation program for the processes described above and installed it on a personal computer. For the generation of random numbers in the simulation, the RAND() function of Microsoft's Excel spreadsheet software was used.

## Estimating Young's modulus

Prior to estimating the Young's moduli of actual timber specimens, Young's modulus was estimated by assuming that the stress wave propagation velocity is 4000 m/s as a round value, which generally holds for most wood specimens. To estimate the Young's modulus of framework timbers by our estimation method, we used the reference distribution database of the strength performance of commercial lumber (mechanical classification data) No. 7 from the research group of the Forestry and Forest Products Research Institute.[5] The relationship between Young's modulus and density in this database is shown in Fig. 3. The database represents mechanical classification data of Japanese red pine (*Pinus densiflora*), larch (*Larix kaempferi*), todomatsu (*Abies sachalinensis*), Japanese cypress (*Chamaecyparis obtusa* Endl.), hiba (*Thujopsis dolabrata*), Japanese cedar (*Cryptomeria japonica* D. Don), Douglas fir (*Pseudotsuga menziesii*), hemlock (*Tsuga heterophylla*), and Jezo spruce (*Picea jezoensis*) from Japan and Siberia. These data are corrected to values corresponding to a moisture content of 15%.

Figure 5 shows the histogram of accepted $E_i$ data corresponding to a stress wave propagation velocity of 4000 m/s. It took 3–5 s to simulate one data point. The percentage of accepted data, i.e., the percentage of [the number of accepted $E_i$ data] / [the number of repetitions from Steps 3 to 8 (5000 times)], differs depending on the tolerance. This percentage became lower for a more stringent tolerance value. When the tolerance was tightened, the effective data rate decreased. In other words, the effective data rate was 7.00% (350/5000) at a 5% tolerance, while the effective data rate was 1.74% (87/5000) at a 1% tolerance. However, the variation in accepted $E_i$ data (i.e., the difference between the minimum and maximum values) scarcely changed. The distribution shown in Fig. 5 is almost in the form of a normal distribution, with the average ± SD being 7.19 ± 0.87 GPa at a 5% tolerance, and 7.16 ± 0.74 GPa at a 1% tolerance.

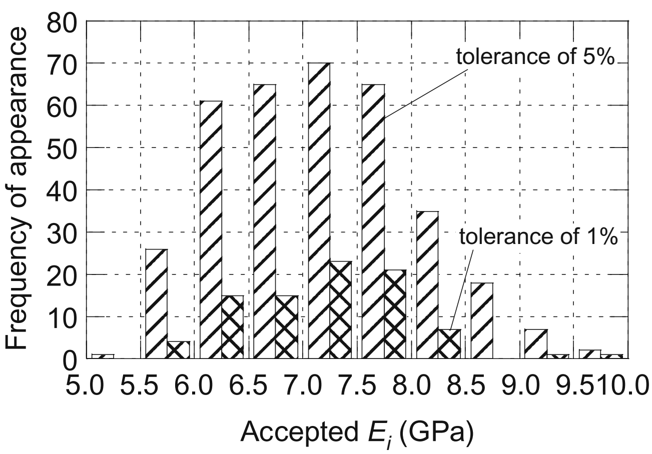


**Fig. 5.** Distribution of accepted Young's modulus ($E_i$) data obtained by Monte Carlo simulation

It is important to define which value is representative when showing an estimated Young's modulus (Step 10). Because the distribution of accepted $E_i$ data approaches a normal distribution as shown in Fig. 5, it is most likely that our estimates are close to the mean of the distribution. On the other hand, to present the estimated Young's modulus on the safe side, it may be good to represent it using the minimum or 5% lower limit of accepted $E_i$ data. As to which value should be treated as the representative value (MOE-e), we will examine this question in the section "Verification of Young's moduli of timber."

## Verification of estimation method

### Materials

To verify the validity of the estimated Young's modulus (MOE-e) generated using our method, MOE-e was compared with the Young's modulus obtained from the bending test of an actual-size timber (MOE-b) and that obtained from the measured stress wave velocity and density (MOE-d).

A total of 71 pieces of sawn timber from three wood species were used: Japanese cedar (*Cryptomeria japonica* D. Don), Japanese cypress (*Chamaecyparis obtusa* Endl.), and Douglas fir (*Pseudotsuga menziesii*). The physical properties of these timbers are shown in Table 1. All the samples were air-dried and had dimensions of 120 mm (width) × 200 mm (depth) × 4000 mm (length).

### Measurement of stress wave propagation velocity

Before the bending test, the stress wave propagation velocity was measured in order to obtain the Young's moduli MOE-d and MOE-e. To measure the stress wave propagation velocity, we used a portable stress wave propagation timer (FAKOPP, Hungary), as shown in Fig. 6. The equipment measures the time (in μs) it takes for the energy

**Table 1.** Physical properties and Young's moduli of sawn timber

| Species | Number of specimens | Moisture content (%) | | Density (kg/m³) | | Stress wave velocity (m/s) | | MOE-b[a] (GPa) | | MOE-b15[b] (GPa) | | MOE-d[c] (GPa) | | MOE-d15[d] (GPa) | | MOE-d0[e] (GPa) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | S.D. | Mean | S.D. | Mean | S.D. | Mean | S.D. | Mean | S.D. | Mean | S.D. | Mean | S.D. | Mean | S.D. |
| Japanese cedar | 31 | 25.2 | 4.7 | 568.4 | 70.5 | 3814.4 | 353.3 | 7.7 | 1.1 | 8.4 | 1.2 | 8.2 | 1.1 | 7.6 | 1.2 | 6.6 | 1.0 |
| Japanese cypress | 30 | 19.9 | 3.4 | 558.2 | 28.6 | 4628.9 | 203.6 | 10.3 | 1.3 | 11.0 | 1.4 | 12.0 | 1.3 | 11.5 | 1.3 | 10.0 | 1.1 |
| Douglas fir | 10 | 14.3 | 0.9 | 507.9 | 48.1 | 5309.0 | 320.4 | 12.6 | 2.1 | 12.4 | 2.1 | 14.5 | 2.8 | 14.5 | 2.8 | 12.6 | 2.5 |

[a] MOE-b, Young's modulus obtained from the bending test
[b] MOE-b15, Young's modulus MOE-b corrected to a value corresponding to a moisture content of 15%
[c] MOE-d, Young's modulus obtained from the measured density and stress wave velocity
[d] MOE-d15, Young's modulus obtained from density corrected to moisture content of 15% and stress wave velocity
[e] MOE-d0, Young's modulus obtained from density corrected to moisture content of 0% and stress wave velocity

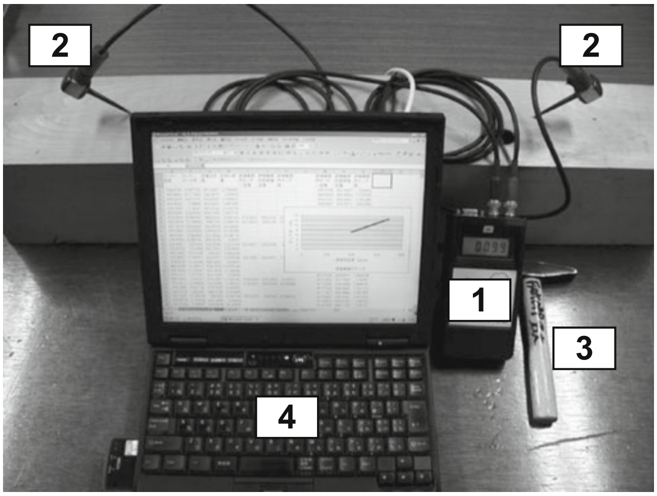


**Fig. 6.** Test apparatus: *1*, stress wave timer (FAKOPP); *2*, transducers; *3*, hammer; and *4*, PC calculation software

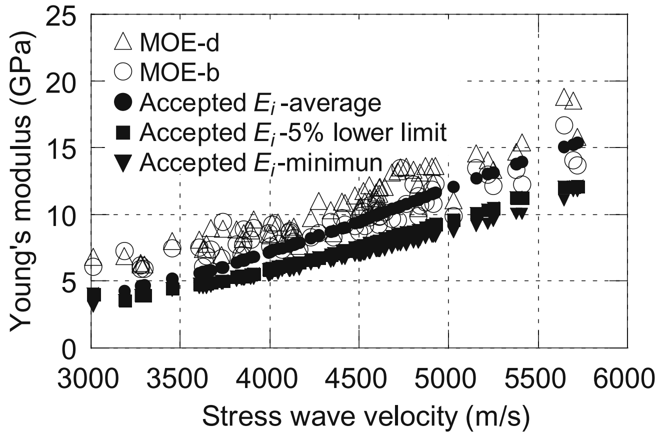


**Fig. 7.** Relationships of stress wave velocity with Young's moduli estimated using different methods and observed Young's moduli obtained from bending test (*MOE-b*) and from measured density and stress wave velocity (*MOE-d*)

(stress wave) generated by an impact to travel from a transmitter to a receiver. Two stress wave sensors were knocked into the center of the side of the timber (in the direction of its axis) with a propagation distance of 3800 mm and an angle of approximately 30° to the surface of the timber (the measurement method referred to in Fig. 6). The stress wave propagation velocity of each specimen was represented as the average of three measurements. The Young's modulus estimated using the relation shown in Fig. 3 was defined as MOE-e, whereas MOE-d was obtained from the measured density and stress wave velocity. Moreover, the Young's moduli MOE-d15 and MOE-d0 were obtained from the density corrected at moisture contents of 15% and 0%, respectively, and from the stress wave velocity. These Young's moduli were calculated using Eqs. 6 and 7:[5]

$$\text{MOE-d15} = \frac{115}{100 + \text{MC}} \cdot \rho \cdot v^2, \tag{6}$$

$$\text{MOE-d0} = \frac{100}{100 + \text{MC}} \cdot \rho \cdot v^2, \tag{7}$$

where MC, $\rho$, and $v$ are the measured moisture content, density, and stress wave velocity, respectively. These measured values and Young's moduli are shown in Table 1.

## Timber bending test

The timber bending test was performed on three equally spaced points (the four-point loading method) and complied with the ISO standard test method.[6] The specimens were simply supported and the span distance between the support points ($L$) was 3600 mm, 18 times the depth of the specimen. The distance between the load points was 1200 mm and the specimen overhang was 200 mm. Loading was performed with stroke control at a constant displacement speed of 20 mm/min using an actual-size strength tester (Shimadzu Corporation UH-G1000kNA, maximum capacity: 1000 kN). The time required to reach the ultimate load was 3 to 5 min. We measured the bending load with the load cell attached to the tester, and the bending deflection was measured using displacement gauges located on the neutral axis at the center and at the loading points of the specimen with data loggers. The data was then fed into and recorded by a personal computer. Young's modulus in bending (MOE-b) was obtained from the relationship between the measured load ($P$) and the bending deflection, using Eq. 8:

$$\text{MOE-b} = \frac{PL^3}{36BH^3(\delta_\text{M} - \delta_\text{L})}, \tag{8}$$

where $B$ and $H$ are the width and depth of the specimen, respectively and $\delta_\text{M}$ and $\delta_\text{L}$ are the deflection at the center and loading points of the specimen, respectively. Moreover, the corrected value corresponding to a moisture content of 15% (MOE-b15) was obtained from ASTM D-1900.[7] Both Young's moduli are shown in Table 1. According to Table 1, MOE-b is lower than MOE-d, as is as commonly known.[8] It is considered that shear deflection might have been induced even though the bending test was performed on three equally spaced points.

## Verification of Young's moduli of timber

In order to verify the validity of our estimates, the estimated Young's modulus (MOE-e) was compared with the observed Young's moduli obtained from the bending test (MOE-b) and the measured density (MOE-d) of the timber. Prior to these comparisons, it is necessary to determine the representative value MOE-e among the accepted $E_i$ data. As described in the section "Estimating Young's modulus," the accepted $E_i$ data obtained by the Monte Carlo simulation are plural and distributed as shown in Fig. 5. In order to determine the representative value of MOE-e, the average, the 5% lower limit, and the minimum accepted $E_i$ data were compared with MOE-b and MOE-d. Figure 7 shows the relationship between the Young's moduli obtained using

**Table 2.** Comparison between Young's modulus obtained from timber test and Young's modulus estimated from stress wave velocity

| Comparative Young's modulus | Method | Moisture content | Regression line | $R^{2a}$ | Estimation accuracy[b] | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Minimum | Maximum | Average | S.D. |
| MOE-b | Bending test | Measured | MOE-e = −1.92 + 1.15 MOE-b | 0.84 | 0.59 | 1.22 | 0.94 | 0.13 |
| MOE-b15 | Bending test | Corrected 15% | MOE-e = −2.53 + 1.15 MOE-b15 | 0.77 | 0.54 | 1.26 | 0.89 | 0.15 |
| MOE-d | $E = \rho v^2$ | Measured | MOE-e = −0.98 + 0.94 MOE-d | 0.89 | 0.55 | 1.10 | 0.84 | 0.10 |
| MOE-d15 | $E = \rho v^2$ | Corrected 15% | MOE-e = −0.008 + 0.88 MOE-d15 | 0.91 | 0.62 | 1.14 | 0.88 | 0.09 |
| MOE-d0 | $E = \rho v^2$ | Corrected 0% | MOE-e = −0.008 + 1.02 MOE-d0 | 0.91 | 0.71 | 1.31 | 1.01 | 0.10 |

[a] $R^2$, coefficient of determination
[b] Estimation accuracy, ratio of estimated Young's modulus (MOE-e) to Young's modulus obtained from timber test

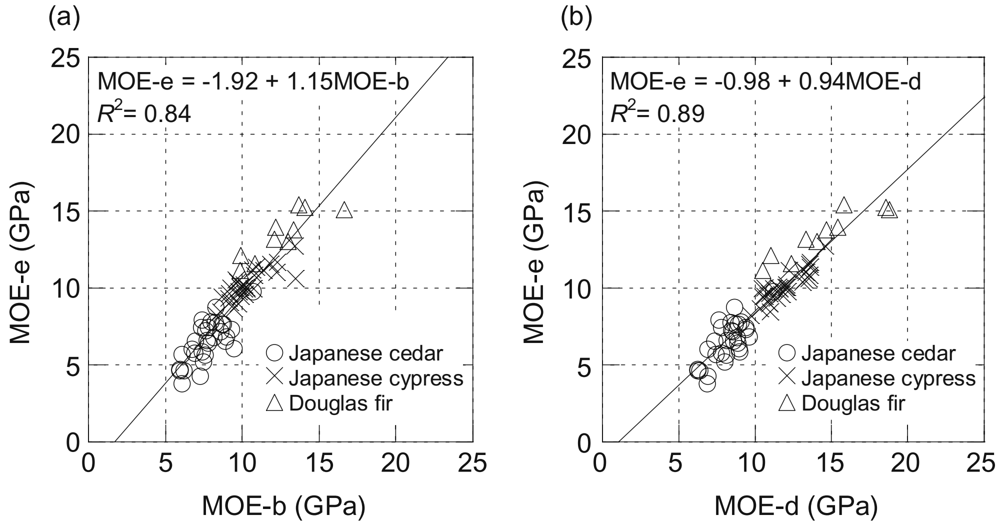


**Fig. 8.** Comparison of estimated Young's modulus (*MOE-e*) with observed Young's modulus obtained from bending test (**a**) or from measured density and stress wave velocity (**b**)

different methods and the stress wave propagation velocity. According to Fig. 7, the average accepted $E_i$ data are generally lower than MOE-b regardless of the stress wave propagation velocity, but they are reasonable. The 5% lower limit and minimum accepted $E_i$ data seem to be too low to be used here. Therefore, in this report, the average accepted $E_i$ data are used as MOE-e since, in this section, we aim to investigate the validity of our estimation method.

Comparisons of MOE-e with MOE-b and MOE-d are shown in Fig. 8. Table 2 also shows comparisons of MOE-e with the various observed Young's moduli (MOE-b, MOE-b15, MOE-d, MOE-d15, and MOE-d0). As seen in the figure, both values agree relatively well. Therefore, it is suggested in Fig. 8 that it is promising to obtain Young's modulus using our estimation method. It is also possible to use the average accepted $E_i$ data as the representative estimated Young's modulus. These tendencies are also found in the relationships between MOE-e and other Young's moduli (MOE-b15, MOE-d15, and MOE-d0).

From Table 2, since the coefficients of determination ($R^2$) are all high, MOE-e is proportional to all the observed Young's moduli (MOE-b, MOE-b15, MOE-d, MOE-d15, and MOE-d0) with a high correlation. The average estimation accuracies are in the order of MOE-d0 > MOE-b > MOE-b15 = MOE-d15 > MOE-d. Figure 9 shows the relationships between the moisture content of timber during mechanical testing and the estimation accuracy expressed through the ratio of MOE-e to each observed Young's modulus. Table 3 shows the results of regression analysis for each relation in Fig. 9. As seen in Fig. 9, MOE-e agrees well with MOE-b at a moisture content of approximately 15% (the average estimation accuracy ± standard deviation is 1.02 ± 0.10 within the moisture content range from 13% to 18%). On the other hand, the estimation accuracies com-

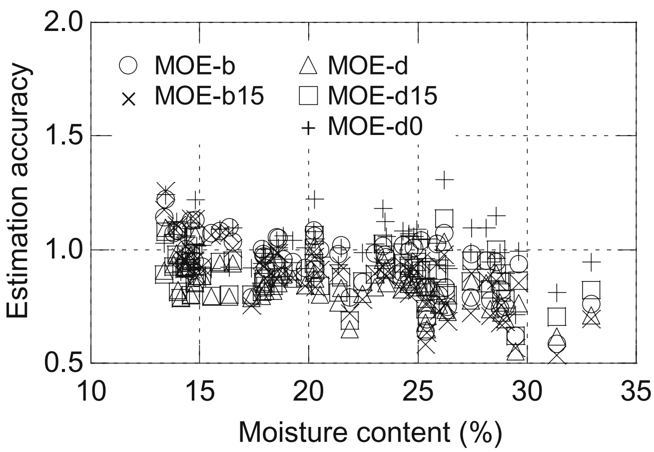


**Fig. 9.** Influence of moisture content of timber on estimation accuracy expressed through the ratio of MOE-e to each observed Young's modulus. For the definition of estimation accuracy, see Table 2

**Table 3.** Influence of moisture content of timber on estimation accuracy

| Estimation accuracy (EA)[a] | Regression line | $R^{2c}$ | $p$ value[d] |
|---|---|---|---|
| MOE-e/MOE-b | EA = 1.264 − 0.015 MC[b] | 0.39 | $2.7 \times 10^{-11}$ |
| MOE-e/MOE-b15 | EA = 1.329 − 0.021 MC | 0.58 | $1.1 \times 10^{-19}$ |
| MOE-e/MOE-d | EA = 1.059 − 0.010 MC | 0.31 | $1.2 \times 10^{-8}$ |
| MOE-e/MOE-d15 | EA = 0.962 − 0.004 MC | 0.05 | 0.039 |
| MOE-e/MOE-d0 | EA = 1.106 − 0.004 MC | 0.05 | 0.039 |

[a] EA, estimation accuracy (refer to Table 2)
[b] MC, moisture content of timber
[c] $R^2$, coefficient of determination
[d] $p$ value, probability obtained by the regression analysis

pared with MOE-d or MOE-d15 are low within the entire moisture content range shown in Fig. 9. The above-mentioned result suggests that, except in the high-moisture-content range, MOE-e is close to MOE-b, even though it is estimated using the stress wave propagation velocity. The primary cause of this result is considered to be the fact that our estimation method uses a database consisting of Young's moduli obtained from a bending test as the reference distribution database. The high estimation accuracy for MOE-d0 may be due to the fact that the calculated MOE-d0 was low owing to the use of dry density. As a result, the difference between MOE-d0 and MOE-e may decrease. From the coefficients of determination ($R^2$) shown in Table 3, there are two groups of estimation accuracies in terms of the dependence on moisture content: one group made up of estimation accuracies with MOE-b, MOE-b15, and MOE-d, and the other with MOE-d15 and MOE-d0. Although the latter group, whose $R^2$ values are very small, is independent of moisture content, the former group is influenced by moisture content, and its Young's modulus estimation accuracy decreases as moisture content increases, as shown in Fig. 9. This result seems to be caused by some interaction of the following factors: (i) the Young's modulus obtained from the bending test decreases as moisture content increases, (ii) the density of the timber specimen increases as moisture content increases, (iii) no moisture content correction was made in the stress wave propagation velocity because there is no method for such correction at present, and (iv) the Young's moduli and densities in the reference distribution database used in our estimation method were corrected to those corresponding to a moisture content of 15%. The mechanism of interaction between the above factors is not clear at present. Note that Young's moduli such as MOE-d15 and MOE-d0 are independent of moisture content, despite the lack of correction made for the stress wave propagation velocity. Therefore, it is suggested that the influence of moisture content may be larger on the density than on the stress wave propagation velocity. Further investigation is necessary to resolve this matter.

## Conclusions

In this article, a method of estimating Young's modulus was proposed using the stress wave propagation velocity only. As a result of comparing the estimated Young's modulus (MOE-e) with the observed Young's moduli obtained from the bending test (MOE-b) and the measured density (MOE-d) of the timber, MOE-e was found to be proportional to every observed Young's modulus with a high correlation. Moreover, MOE-e agreed well with MOE-b at a moisture content of approximately 15%. The validity of our estimates, therefore, was confirmed.

Our estimation method makes it promising to estimate the Young's modulus of structural timbers, in which the measurement of the density is difficult, using only the stress wave propagation velocity. This method is expected to be useful for the maintenance of wooden structures as it allows Young's modulus to be determined for structural timber that is part of the structure.

Actually, the estimated Young's modulus may depend on the reference distribution database employed in the simulation even though the stress wave propagation velocity is the same. We need to further investigate several factors including the influence of the type of database employed on the estimation accuracy. This issue will be reported in our upcoming articles. We expect the results of this research to be used to develop a portable Young's modulus instrument in which a stress wave propagation timer, a laser rangefinder, and our software are incorporated.

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