MATERIAL CHARACTERISTICS ESTIMATION OF EXISTING WOODEN STRUCTURES BY NON-DESTRUCTIVE TESTS

Noriko Takiyama¹, Yasuhiro Hayashi², Jiao Jian³, Kazutaka Namie⁴, Takuya Matsumoto⁵

ABSTRACT: We report the progress of our research projects on improvement of Young’s modulus measuring system for existing wooden structures by one of test device, Fakopp based on stress wave velocity. First, we study relation to results from some material test methods such as Tapping-tone technique, Fakopp and bending test. Using improved measuring method of Young’s modulus, it can be measured precisely for existing structures.

KEYWORDS: Non-destructive material test, Fakopp, Propagation velocity

1 INTRODUCTION

There are many traditional wooden structures in Japan. While, there have been occurred frequent earthquakes in recent years. And many structures were damaged by the past earthquakes [1]. So it is very important to understand about seismic behaviour of them. In seismic performance estimation of wooden structures, it is needed to find material characteristics such as Young’s modulus, density and so on. The material characteristics of standing trees are measured by some non-destructive tests. And there are some researches about these [2-5]. However, it is difficult to apply these tests to timbers or members of existing wooden houses because most of them involve a slight wound and some tests involve destruction.

In this paper, we propose to improve measuring method of material characteristics for timbers without even a slight wound at existing wooden structures.

2 MATERIAL TEST METHODS

There is some material testing devices to find Young’s modulus. In this chapter, we explained three devices and their handling methods: one is Tapping-Tone Technique, another is Fakopp and the other is bending test.

There is Tapping-Tone Technique as one of the system to investigate Young’s modulus. As shown in Fig.1, we tap on the end grain of timber, catch natural frequency of longitudinal vibration at other end and calculate fundamental frequency by fast fourier transform analyzer. Young’s modulus is calculated from fundamental frequency and density. Therefore, it is needed to bring down member and to tap cross section. In short, it is difficult to use for existing buildings which are in use.

There is also Fakopp as another test. The instrument estimates Young’s modulus of standing trees from stress wave velocity. Two sharp pins are driven into tree two meter apart as shown in Fig.2. Here, each pin is the input and output sensors, the pins are leaned at 45 degrees facing: the manual recommend this angle. We tap the input pin on the head, and the output pin receive stress wave.
Stress wave velocity is made corrective by

\[ V_f = \frac{L}{T_f - \alpha} \]  

(1)

where \( L \) = length among pins, \( T_f \) = measured propagation time of stress wave, \( \alpha = 7 \) (recommended corrective factor which depend on the instrument) and \( V_f \) = corrected stress wave velocity. Young’s modulus can be calculated by

\[ E_f = \rho \cdot V_f^2 \]  

(2)

where \( E_f \) = Young’s modulus and \( \rho \) = density.

But this test is with a slight wound by pins and difficult to use for existing buildings too. There is also three-point bending test for timbers as shown in Fig.3. The flexural strength and flexural stiffness of members are calculated. But this is destructive test, and can’t apply existing structures.

3 RELATION BETWEEN DENSITY AND YOUNG’S MODULUS

In this chapter, we perform the material tests referred in chapter 2 and report on the results of the tests.

We found Young’s modulus from each test with a regression line as shown in Fig. 4. Here, \( E_i \) = one from Tapping-Tone Technique, \( E_f \) = one from Fakopp, and \( R \) = correlation coefficient. Assuming that Young’s modulus \( E \) of bending test is standard, \( E \) is calculated by

\[ E = E_i / 1.18 + 0.805 \]  

(3)

It’s said that Young’s modulus from Tapping-tone technique and Fakopp are correspond roughly with one from bending test. Therefore, we’ll improve Fakopp to apply in existing structures in next chapter.

4 IMPROVED SYSTEM OF FAKOPP

We improve the method of using Fakopp on existing wooden structures as shown in Fig.5. Supports made of wood plate are put on the point drive in pins. The member and the supports are tightened with
the simple device made of plates, steel bars and wing nuts. The device is shown in Fig.6. Being careful not to touch member, two pins of Fakopp are drove in supports by hummer to the surface of member. Here, wood plate of device is cedar and the size is 105 x 45 x 300 (mm). And steel bars of device have a diameter 12mm and coarse thread all length.

4.1 INSPECTION TEST

We perform some experiment posed parameters such as the length among pins $L$ (mm), the way to hit the head of pins such as height dropped hammer head $h$ (mm), the driven angle of pins $\theta$ (rad), the length of support $l$ (mm), wooden species of support, the driven depth of pins $d$ (mm), the strength tightened nuts of device or difference between standing and lying as shown in Fig.7.

We conduct tests for 4 specimens. To study effects by driven angle of pins, we use cypress column which section is 140 x 140mm. To study difference by density, we choose 3 timbers are cedar, zelkova and oak. Based on Recommendations for Loads on Buildings in AIJ [6], the densities are $0.38 \times 10^3$ (kg/m$^3$) as cedar, $0.62 \times 10^3$ (kg/m$^3$) as zelkova and $0.90 \times 10^3$ (kg/m$^3$) as oak. The specimens are the column which section is 120 x 120mm. And we use 9 supports. The differences among the supports are the kind of timbers and/or length $l$ (mm) of supports. The kinds of timbers are cedar, zelkova and oak. The supports are rectangular parallelepiped: thick is 30mm, width is 120mm and length $l$ is 3 types such as 67.5, 150 and 180mm. The length direction of the support is parallel to wood fibre of supports, and the length direction of the supports is also set up to parallel with the fibre direction of specimen.

Tests are conducted with 4 patterns as shown in Fig.8. In test pattern 1, the pins are driven into specimen’s section to parallel with fibre direction. Test pattern 2 is traditional way. In test pattern 3, improved system, the pins are driven into supports with angle. In test pattern 4, improved system, the pins are driven into support’s section to parallel with fibre direction. In one test, we tap 10 times under same condition. And the figures which are over 3 percent away from the average are removed and tap again until 10 data are collected.

And test scene in laboratory to use Fakopp and scene of investigation at existing structures are shown in Fig. 9(a).

4.2 DRIVEN ANGLE OF PINS

Here, the value measured by using traditional way in case leaned pins forward 90 degree (test pattern 1) and 2000mm interval pins is as ideal value. Using cypress specimen, comparison the ideal value with the values in
4.3 LENGTH AND WOODEN SPECIES OF SUPPORT

In this paragraph, we study about difference caused the length of the support and the wooden species used as the support. Figure 11 shows the results of propagation time when support length is changed and when species combination of specimens and supports is changed. Here, we use cedar, zelkova and oak specimens and driven angle is 90 degree (test pattern 4). In case of cedar and zelkova specimen, propagation times are resulted even by all size and all species of supports as shown in Fig. 11(a), (b). On the others hands, in case of oak specimen, propagation time is uneven by length $l = 67.5$ and $180$ (mm) as shown in Fig. 11(c).

It is easy for the supports which length $67.5$(mm) to be broken by pins. And it is easy for oak to transform and to be broken by seasoning. So, in this system, zelkava is used as support.

4.4 WAY TO HIT HEAD OF PINS AND STRENGTH TIGHTENED NUTS

In this paragraph, we study about difference caused the way to hit the head of the pins such as specifications of using hummer and strength hit the head and about difference caused the strength tightened wing nuts of the device. Here, we conduct test pattern 4.

First, to measure the strength tightened nuts, two strain

- (a) cedar specimen, (b) zelkova specimen, (c) oak specimen

Each case is as shown in Fig.10.

In case that pins is driven in 45 degree, correcting usual method, the value by improved way (test pattern 3) is record further from ideal value than one by traditional way(test pattern 2). As to degree pins leaned, the value in 45 degree (test pattern 3) is further from ideal value than one is 90 degree (test pattern 4). So, in this paper, we focus and develop about test pattern 4.

Moreover, with the length among pins shortening, measured values are further from ideal value in all cases.

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Table 1: Margin settings

<table>
<thead>
<tr>
<th>axial force [N]</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
<th>1.2</th>
<th>1.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>rotation angle</td>
<td>~ 100 degree</td>
<td>100 ~ 150 degree</td>
<td>measurement</td>
<td>unstable</td>
<td>stable</td>
<td></td>
</tr>
</tbody>
</table>

Figure 14: Driven depth of the pins which is measured stable. (a) Driven depth of pins as tapping step. (b) Propagation time as driven depth of pins

Figure 15: Comparison of propagation time between standing and lying member

gages are put facing on the steel bar as shown in Fig. 12(a), and calculated axial force. Next, to visualize the relation between axial force and rotation angle of wing nuts after touching wood plate and nuts, initial position of wing nuts are marked on section of steel bolts by marker as shown in Fig. 12(b). Finally, to decide tapping strength for stable measurement, free fall height dropped hammer head is changed 50, 100 and 150mm. Here, we use test hammer which head’s weight is 100g. Figure 13 said the relation between strength tightened nuts and propagation time of stress wave by all support using. Here, the result about only zelkova specimen is shown, but similar results are about other specimen. And Table 1 is said the relation between axial force owed steel bar and rotation angle of wing nuts. Here, rotation angle of wing nuts indicated the rotation angle from when the wing nuts touch the wooden plate of device completely. The propagation time is stable in all species of support when the strength tightened nuts is over 0.8N of axial force. As shown in Table 1, it is good that the wing nuts are rotated from 100 to 150 degree from when they touch the wooden plate completely. Finally, to decide tapping strength for measurement, free fall height dropped hammer head is changed. Using test hummer which head has 100g weight, the free fall height dropped hammer head is 50mm enough to measure stable figures.

4.5 DRIVEN DEPTH OF PINS

In this paragraph, we study about difference caused the driven depth of the pins. The change of driven depth of pins increasing tapping step is as shown in Fig. 14(a). The change of propagation time as the driven depth of the pins is as shown in Fig. 14(b). In this figure, the result of cedar specimen (length among pins $L = 500\text{mm}$), zelkova specimen ($L = 2,500\text{mm}$) and oak specimen ($L = 2,500\text{mm}$) by test pattern 1 is shown.

About cedar specimen, as the tapping step increase, the driven depth of pins approach 30mm asymptotically. Following that, propagation time is stable. In the same way, in case of zelkova and oak specimen, when pins are driven each 7 mm and 5 mm in depth, propagation time is stable. So, in this method, pins are driven 30mm in depth based on result of cedar specimen.

4.6 LYING AND STANDING MEMBERS

In this paragraph, we study about difference caused position of the members in case of standing and lying. The comparison of propagation time between standing and lying member is as shown in Fig. 15. In case without support (test pattern 2), on each specimens, propagation time of standing member is even with one of lying member. On the other hand, for example, as to oak specimen with the device (test pattern 4), it is said that the propagation time don’t depend on position of standing or lying.

So, it is evident that we can apply improved device on the columns of existing structures.

4.7 INTERVALS OF PINS

In this paragraph, we study about difference caused the intervals of the pins. The relation between interval of pins and propagation time about cedar, zelkova and oak specimens is shown in Fig. 16. Here, supports are changed all kind of wood and
interval of pins are \( L = 500, 1000, 1500, 2000 \) mm. It is obvious that the relation between interval of pins and propagation time is linear on each specimen. And, whichever support is used, on every interval length, the difference among spices of specimen is roughly equal.

5 **UNIFORM DIRECTIONS AND REVISED FORMULA**

In this chapter, we will decide the directions of use the improved device and investigate two calculated methods based on chapter 4. Here, two calculated methods are proposed to separate about enough long members and about short members. At the same time, comparison the values from improved method of *Fakopp* and the ones from Tapping-Tone Technique is conducted.

### Table 2: Material quality

<table>
<thead>
<tr>
<th>member</th>
<th>density (t/m(^3))</th>
<th>water content (%)</th>
<th>( E ), from Tapping-Tone Technique (kN/mm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>cedar</td>
<td>0.406</td>
<td>10.0 %</td>
<td>9.10</td>
</tr>
<tr>
<td>zelkova</td>
<td>0.720</td>
<td>22.6 %</td>
<td>11.19</td>
</tr>
<tr>
<td>oak</td>
<td>1.033</td>
<td>23.2 %</td>
<td>14.64</td>
</tr>
</tbody>
</table>

Is the column long enough to measure more than two point?

*Yes*  

**PHASE II**

New corrective factor is proposed.

**PHASE I**

### Figure 16: Relation between interval of pins and propagation time about 3 specimens with support made of (a) cedar, (b) zelkova, (c) oak

### Figure 17: Flowing of investigation on one column

### Figure 18: Relation between interval of pins and propagation time with regression line on: (a) cedar specimen, (b) zelkova specimen
Table 3: Intercepts as corrective factor $\bar{\alpha}$

<table>
<thead>
<tr>
<th></th>
<th>test pattern 1</th>
<th>test pattern 2</th>
<th>test pattern 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>cedar</td>
<td>14 ($\mu$s)</td>
<td>16 ($\mu$s)</td>
<td>39 ($\mu$s)</td>
</tr>
<tr>
<td>zelkova</td>
<td>40 ($\mu$s)</td>
<td>42 ($\mu$s)</td>
<td>69 ($\mu$s)</td>
</tr>
<tr>
<td>oak</td>
<td>46 ($\mu$s)</td>
<td>-</td>
<td>76 ($\mu$s)</td>
</tr>
</tbody>
</table>

Table 4: Combination of test results and the value $L_r$

<table>
<thead>
<tr>
<th>$L$ (mm)</th>
<th>500</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>pair 6</td>
<td>$L_r=500$</td>
<td>$L_r=1000$</td>
<td>$L_r=1500$</td>
</tr>
<tr>
<td>1000</td>
<td>pair 5</td>
<td>pair 4</td>
<td>$L_r=500$</td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td>pair 3</td>
<td>pair 2</td>
<td>pair 1</td>
<td></td>
</tr>
</tbody>
</table>

Figure 19: Relation between density and intercept

Figure 20: Comparison between Young’s modulus from Tapping-tone Technique and Fakopp using combination in Table 3

5.1 DIRECTIONS OF USE

Based on the result in chapter 4, the directions of use are decided on.

First, method of setting up the device is following:
1) The fibre direction of the supports is parallel to one of object to measure.
2) Zelkova support which length is 105.0mm is used.
3) Turn angle of nut is from 100 to 150 degree from when nuts touch wood plate of device.
4) The pins are driven 30mm in depth.
5) Using test hummer which head has 100g weight, the head of hammer is been free fall from 50mm height.

Investigation is conducted along two routes in Fig 17. Phase I and II are explained in chapter 5.2 and 5.3.

5.2 NEW CORRECTIVE FACTOR ON SHORT MEMBERS (PHASE I)

In this paragraph, we propose the new corrective factor $\bar{\alpha}$. This factor is considered some effects such as device and so on. With this correction, measured value is nearly equal to ideal value in case of the length among pins below 2000 (mm).

The relation between interval of pins and propagation time on cedar and zelkova specimens is shown in Fig.18. Here, the data which conduct in traditional method (test pattern 2), method using improved device (test pattern 4) and method driven the center of section (test pattern 1) is indicated in with regression lines. It is found that each data is in straight line and all regression lines are nearly parallel. And the regression line from test pattern 1 and one from test pattern 2 are laid to overlap each other. These intercepts is corrective factor $\bar{\alpha}$ which control the results.

The intercepts are depend on species of specimen and whether with device or without it as shown in Table 3. And the relation between density and intercept is as indicated in Fig.19. Increasing the density, the intercept of test pattern 1, 4 and growth rate of these when improved device are used increase as curving. We must conduct tests for many kinds of timbers to decide this function. But, in case of cedar, zelkova and oak, $\bar{\alpha}$ is given as Table 3.

5.3 PROPAGATION TIME ON ENOUGH LONG MEMBERS (PHASE II)

We study another calculating way of Young’s modulus because of linear relation between interval of pins and propagation time as shown in Fig.17. Here, we propose the calculated methods on enough long members.

The method of finding Young’s modulus is following:
1) The measurements are conducted more than 2 times, which are changed the length among pins $L$.
2) Finding the reminder of propagation time among the data which differ in $L$, reminder among $L$ (called $L_r$) divided by the value makes stress wave velocity. In short, it can cancel error from instrument and support, and corrective factor $\bar{\alpha}=0$.

For example, we’ll verify the above based on Fig.16. Young’s modulus is found using material quality as shown in Table 2.

First, according to data comb inations as shown in Table 4, the reminders of propagation time among the data which differ in $L$ are found. Here, the value $L_r$ and the number of the combination ‘pair’ are indicated in the table. Next, each stress wave velocity is found by eq.1 on $\bar{\alpha}=0$. Finally, each Young’s modulus is found by eq.2. Comparison Young’s modulus between improved Fakopp and Tapping-Tone Technique is shown in Fig.20.
Here, value from Tapping-Tone Technique is modified by eq.3. It seems that they are roughly matching.

6 CONCLUSIONS

We report the progress of our research projects on improvement of Young’s modulus measuring system for existing wooden structures by one of test device, Fakopp, based on stress wave velocity. First, we study relation to results from some material test methods such as Tapping-tone technique, Fakopp and bending test. Using improved measuring method of Young’s modulus, it can be measured precisely for existing structures.

(a) Young’s modulus from Tapping-tone technique and Fakopp are related roughly with one from bending test. So, Fakopp is relatively stable method to find Young’s modulus of timbers.

(b) New measuring device which made of timber and steel bar is improved. It is very simple system based on Fakopp.

(c) With improved system, it is able to use in the existing wooden structures without even a slight wound.

(d) The rule of measuring is decided.

(e) Two measuring methods are proposed. One is that Young’s modulus is estimated by one measured value and the new corrective factor which is proposed every species of timber. Another is that Young’s modulus is estimated by the reminders of among more than two measured propagation time.

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