Vibrational Properties of Japanese Cedar Juvenile Wood at High Temperature

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The vibrational properties of Japanese cedar wood at high temperature were measured. The specimen, its support system, a magnetic driver, and a deflection sensor were placed in an electric drying oven, where vibration tests were conducted. The heating temperatures ranged from 25 ºC to 200 ºC in 25 ºC increments. The resonance frequency decreased with higher heating temperature and decreased most dramatically in the temperature range of 150 ºC to 200 ºC. The loss tangent had a minimum value at 100 ºC and changed more in the temperature range from 150 ºC to 200 ºC than in the range from 25 ºC to 150 ºC. The changes in the resonance frequency and loss tangent of the specimens with larger distance from the pith (*d*) were smaller than those around the pith. These tendencies are believed to have occurred because the portion with a larger *d* had a smaller number of intercellular layers than the portion around the pith.

Keywords: High temperature; Juvenile wood; Loss tangent; Real-time measurement; Specific Young's modulus; Vibration test

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INTRODUCTION

Currently, an increasing number of conifer plantations in Japan are being left alone without thinning (Chiba 1999). The reason for doing so may be attributed to the inferior quality of thinned timber and a lack of suitable applications being developed for such timber.

Given that thinned timber has a high ratio of juvenile wood and a small diameter, such qualities as tensile strength, specific compressive strength, specific compressive Young's modulus, and dynamic flexural Young's modulus are lower than those of mature wood. There are also large variations in the properties of the juvenile wood (Ohta *et al*. 1968a, b; Ohta 1972; Panshin *et al*. 1964).

Laminas for glued laminated timber have been developed from thinned timber to make use of small-diameter timber. Sufficient strength against compression, bending, and shearing has been obtained using laminas with high strength properties for the outer layers and laminas with low qualities for the inner layers (Ido *et al*. 2007; Tansho *et al*. 2007). However, serious defects such as twisting, bending, and checking may occur in kiln-dried juvenile wood (Nara *et al*. 1977). Therefore, the basic properties of juvenile wood must be determined before processing.

In our previous study (Kubojima *et al*. 2010), the relationship between the temporal changes in vibrational properties and the distance from the pith of Japanese cedar during heating was investigated. It was concluded that the larger number of intercellular layers of the juvenile wood could result in decreased resonance frequency and increased loss tangent during heating. In other words, the larger variation in vibrational properties in juvenile wood as compared to mature wood can be attributed to the juvenile wood properties, as well as the radial variation in initial moisture content.

This result includes the effects of temperature and moisture content. In this study, the effect of temperature on the vibrational properties of both oven-dried juvenile wood and mature wood were investigated.

EXPERIMENTAL

Specimens

Japanese cedar (*Cryptomeria japonica* D. Don) green wood with red-heart and black-heart were used for this study. The specimens measured 180 mm in length (longitudinal direction: L), 20 mm in width (radial direction: R), and 10 mm in thickness (tangential direction: T). The specimens used for measuring temperature, weight, dimensions, and vibrational properties were matched in the L-direction. Specimens were cut from a plank containing the pith, and directions 1 and 2 were determined for the sake of convenience (Fig. 1). The specimens were oven dried at 105 ºC and were then allowed to cool to below 20 ºC at 0% relative humidity.

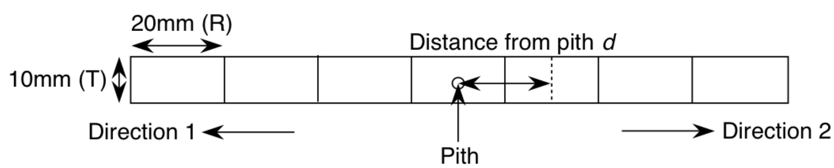

Fig. 1. Schematic diagram of specimens used for measuring temperature and weight and for the vibration test

Tracheid Length

After conducting the vibration tests mentioned below, small chips cut from the latewood of the specimens that were subjected to vibration testing were macerated in a solution of acetic acid and hydrogen peroxide at 70 ºC (Franklin 1945). The lengths of 50 tracheids per annual ring were measured, and their mean was calculated as the tracheid length for each annual ring. The tracheid length of the specimens used for vibration testing was obtained by averaging the tracheid length of all annual rings in each specimen (Kubojima *et al*. 2010).

Vibration Test

To obtain the resonance frequency and loss tangent, a free-free flexural vibration test was conducted. The same apparatus for high-temperature testing was used as was used in a previous study (Kubojima *et al*. 2001) (Fig. 2). A test beam was suspended by two wires (0.12 mm in diameter) at the nodal positions of the free-free vibration corresponding to its first resonance mode. The beam was excited in the direction of thickness at one end by a magnetic driver, with the beam's motion in the frequency range of 200 Hz (resonance frequency ± 100 Hz) being detected as voltage by a deflection sensor at the other end. The output signal was then processed through a fast Fourier transform (FFT) digital signal analyzer.

The resonance frequency (f) was obtained and the loss tangent ($\tan\delta$) was calculated from the width at –6 dB of the peak of the resonance curve (Δf) using the following equation:

$$\tan\delta = \frac{\Delta f}{\sqrt{3} f}. \tag{1}$$

It took 100 s to create a resonance curve.

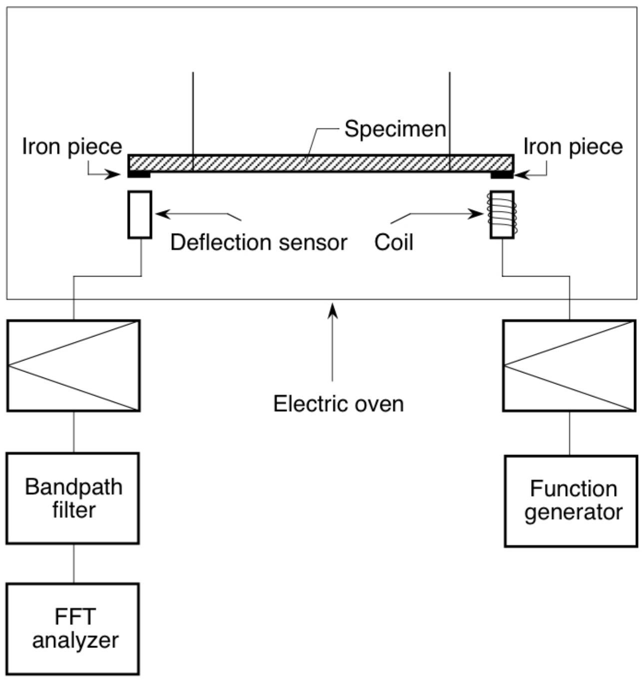

Fig. 2. Apparatus for the vibration test

Measurement of Wood Properties during Heating

The specimens used for vibration testing, those used for measuring specimen temperature, and those used for measuring dimensions and weight were heated in an electric oven. In the vibration tests, a specimen, its support system, the magnetic driver, and the deflection sensor were placed in an oven as shown in Fig. 2. After vibration testing at room temperature (of about 25 ºC), the temperature was increased from 50 ºC to 200 ºC in 25 ºC intervals.

Temperatures were held at each designated level for 30 min before conducting a vibration test. On the other hand, the specimens were taken out of the oven immediately after reaching constant temperature for measuring the dimensions and weight. A type-T thermocouple was inserted in the L-direction to a depth of 30 mm from the central point of the RT plane. The temperature changed at a rate of about 5 ºC/min. Figure 3 shows an example of the temporal change in temperature.

The measuring system was not sealed and humidity in the oven was not adjusted during heating because there were small openings for the cables of the magnetic driver and deflection sensor.

RESULTS AND DISCUSSION

Figure 4 shows the radial distribution of the tracheid length (*TL*). The value of *TL* increased with increasing distance from the pith (*d*). Whether *TL* became constant was not clear, thus making it difficult to determine the boundary between the juvenile and mature wood.

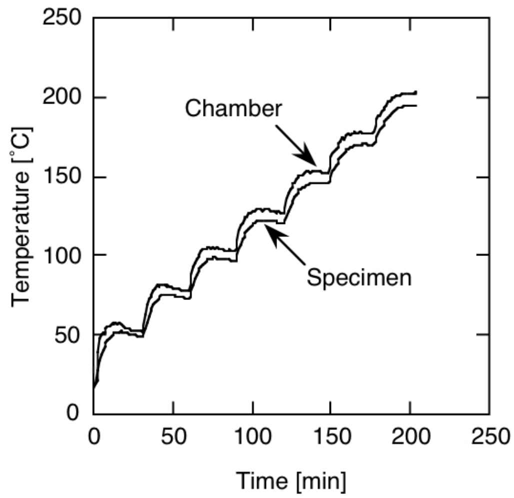

Fig. 3. Example of the temporal change in temperature

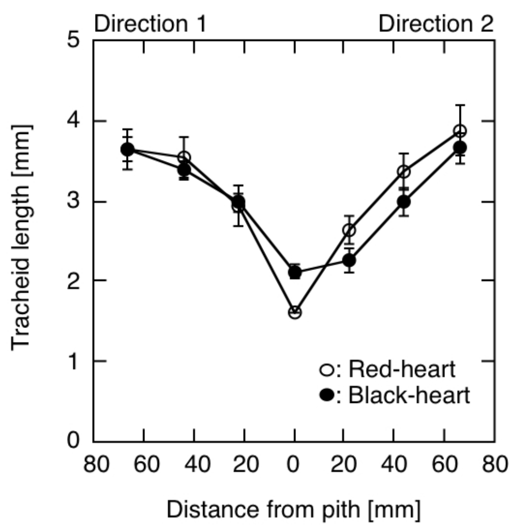

Fig. 4. Radial variation of the tracheid length of specimens for the vibration test. *d* denotes distance from the pith

Table 1 lists the resonance frequency and loss tangent after oven drying at 105 ºC before heating measured at 20 ºC.

The resonance frequency can be expressed as follows,

$$f = \frac{ik^2}{2\pi l^2}\sqrt{\frac{E}{\rho}}, \tag{2}$$

where i denotes the radius of gyration of a cross section, k is 4.73, E is the Young's modulus, l is the length, and ρ is the density. Given the small dimensional changes during heating, the changes in i and l were also small. Hence, the change in resonance frequency corresponded to that in the specific Young's modulus.

Figure 5 shows the change in resonance frequency. The change was expressed by using a ratio based on the value measured after oven drying at 105 ºC before heating (f/f_0).

Table 1. Resonance Frequency and Loss Tangent after Oven Drying at 105 ºC Before Heating Measured at 20 ºC

d [mm]	*f* [Hz]		tanδ [10^{-3}]	
	Direction 1	Direction 2	Direction 1	Direction 2
Red-heart				
0	1039		11.90	
22	1311	1305	8.87	8.92
44	1540	1502	6.07	7.10
66	1580	1517	6.65	6.29
Black-heart				
0	1049		10.62	
22	1186	1101	7.58	9.44
44	1342	1182	8.05	7.52
66	1335	1278	8.99	8.32

d: distance from the pith, *f*: resonance frequency, tanδ: loss tangent

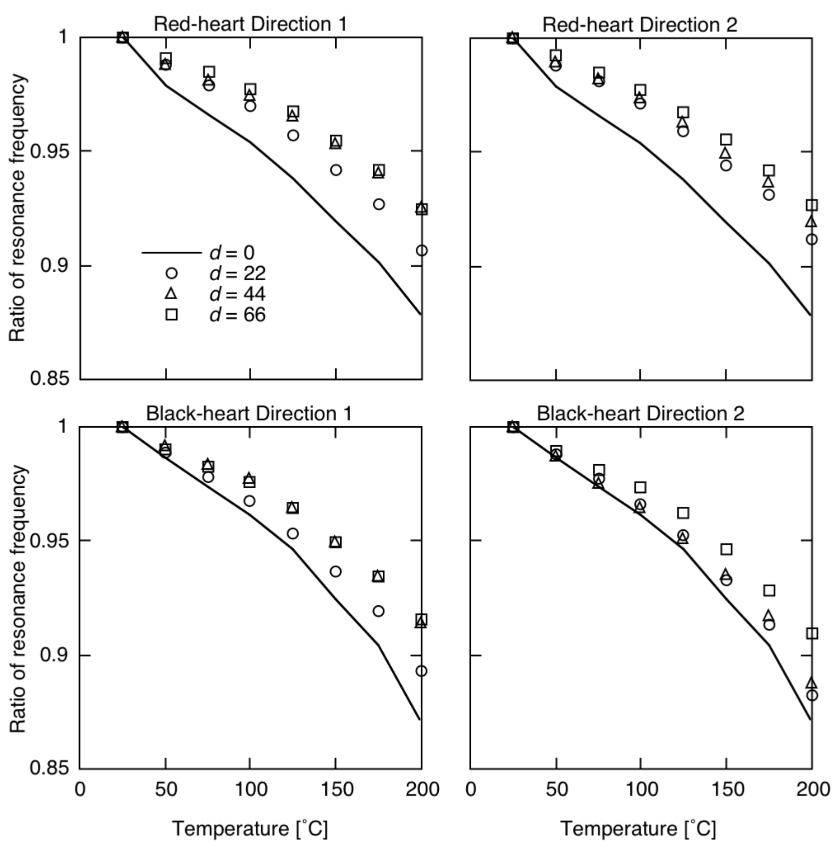

Fig. 5. Temperature dependence of the resonance frequency

The resonance frequency decreased with higher temperature, most dramatically in the temperature range from 150 ºC to 200 ºC in the cases of red-heart and black-heart. This tendency was similar to that of Young's modulus reported in other works (Fukada 1951; James 1961; Suzuki and Nakato 1964; Bernier and Kline 1968; Sellevold *et al*. 1975; Chen *et al*. 1999; Kitahara and Matsumoto 1968; Handa *et al*. 1978; Hirai *et al*. 1990; Sugiyama and Norimoto 1996; Kubojima *et al*. 2001). According to Sawabe (1970), the thermal softening point of wood dried at 105 ºC measured by a bending creep test was 151 to 156 ºC. Changes in the resonance frequency of specimens with a larger *d* were larger than those around the pith.

Figure 6 shows the change in the loss tangent. The change was expressed using a ratio based on the value measured after oven drying at 105 ºC before heating ($\tan\delta/\tan\delta_0$).

The loss tangent had a minimum value at 100 ºC and showed a larger change in the temperature range from 150 ºC to 200 ºC than from 25 ºC to 150 ºC in the cases of red-heart and black-heart. Other studies also found this tendency (Fukada 1951; James 1961; Suzuki and Nakato 1964; Bernier and Kline 1968; Sellevold *et al*. 1975; Chen *et al*. 1999; Kubojima *et al*. 2001), which may be related to the thermal softening point of the oven-dried wood mentioned above (Sawabe 1970). Changes in the loss tangent of specimens with a larger *d* were smaller than those around the pith.

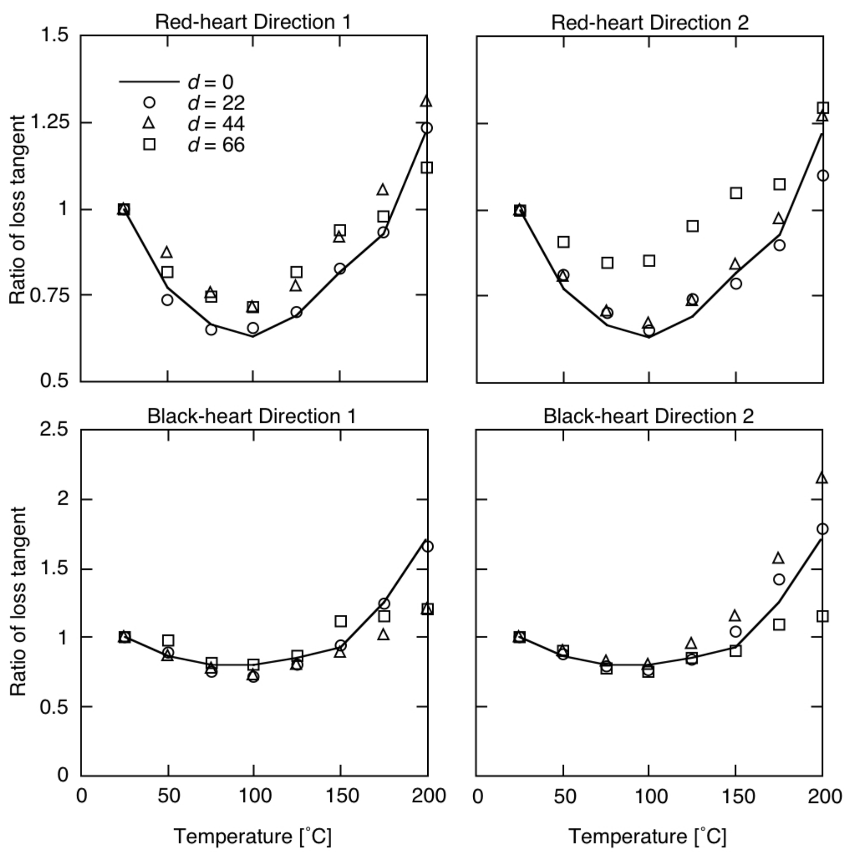

Fig. 6. Temperature dependence of the loss tangent

The results showing smaller changes in the resonance frequency and loss tangent of specimens with a larger *d* than those around the pith can be explained as follows: The increase in *TL* with the increase in *d* (Fig. 3) means that the number of tracheids (*i.e.*, number of intercellular layers) decreased with an increase in *d*. Most of the compound middle lamella consists of amorphous material (Panshin *et al*. 1964; Saiki *et al*. 1958). The amorphous material can cause a decrease in the resonance frequency and an increase in the loss tangent at higher temperatures. Hence, the intercellular layer will cause a further decrease in the resonance frequency and a further increase in the loss tangent under high temperatures.

In this study, the changes in the resonance frequency (f/f_0) and loss tangent ($\tan\delta/\tan\delta_0$) were 0.87 to 1.00 and 0.63 to 2.15, respectively, while f/f_0 and $\tan\delta/\tan\delta_0$ were 0.61 to 0.97 and 0.73 to 4.33, respectively, when drying green wood at 120 ºC (Kubojima *et al*. 2010). Although the softening temperature of cellulose is not strongly influenced by moisture content, the softening temperatures of hemicelluloses and lignin are significantly lowered by water (Goring 1963; Takamura 1968). Therefore, the extent of changes in the resonance frequency (specific Young's modulus) and loss tangent in our previous study (Kubojima *et al*. 2010) was significant because high temperature affected wood that contained water.

CONCLUSIONS

1. The resonance frequency decreased with higher heating temperature and decreased most dramatically in the temperature range from 150 ºC to 200 ºC.
2. The loss tangent had a minimum value at 100 ºC and changed more in the temperature range from 150 ºC to 200 ºC than in the range from 25 ºC to 150 ºC.
3. Changes in the resonance frequency and loss tangent of specimens with a larger *d* were smaller than those around the pith. These tendencies presumably occurred because the portion with a larger *d* had a smaller number of intercellular layers than those with a smaller *d*.
4. The extent of decrease in the resonance frequency and the increase in the loss tangent was significantly increased by water in the wood.

ACKNOWLEDGMENTS

The authors would like to thank Ms. Emiko Okada of the Forestry and Forest Products Research Institute for her help in conducting our experiments.

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Article submitted: July 8, 2013; Peer review completed: Aug. 20, 2013; Revised version received and accepted: August 28, 2013; Published: September 6, 2013.