Effect of Temperature and Moisture State Changes on Modulus of Elasticity of Red Pine Small Clear Wood

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Abstract

This study examined the response of dynamic and static modulus of elasticity (MOE) of red pine small clear wood to a temperature change from -40 to 40 °C. The 25.4×25.4×407 mm red pine specimens used in this study were selected from those used in a previous laboratory investigation of acoustic properties. The moisture content (MC) of the specimens ranged from 0% to 118.3%. The dynamic MOE was calculated based on measured acoustic velocity and the wood density at the time of acoustic measurement. The static MOE was measured by conducting a static bending test in a laboratory-controlled environment chamber with wood temperature changing from -40 to 40 °C. Our results indicated that both static and dynamic MOE of wood were affected by temperature and the state of moisture in wood. Above freezing point, MOE decreased linearly at a slow rate as wood temperature increased. Below freezing point, MOE increased at a rapid rate as wood temperature dropped. We found that MC of wood had a significant compounding effect on the MOE-temperature relationships. Temperature effect was much more significant in green wood than in dry wood. Mathematical models were developed to predict the percentage change of MOE relative to the standard temperature of 20 °C for wood temperature below and above freezing point. It is concluded that dynamic MOE of wood based on acoustic measurements can be used as a good predictor of static MOE for nondestructive evaluation of wood under a range of wood temperatures.

Key words: Acoustic velocity, dynamic modulus of elasticity (MOE), static MOE, small clear wood, temperature, moisture content, freezing point.

Introduction

Past research has proven the concept of acoustic measurement on standing trees and logs as a nondestructive evaluation method to evaluate wood quality through the value chains of forest operation and wood products manufacture (Wang et al 2007). Acoustic velocity is now recognized as a measure for predicting the stiffness or modulus of elasticity of wood and wood products derived from measured logs or standing trees. As acoustic measurements are increasingly being conducted on tree stems and logs in forests and log yards, the effects of wood moisture content and environmental condition on acoustic measures has received considerable attention. In a recent laboratory investigation, we studied how acoustic velocity and energy loss response to wood temperature changes on small clear wood samples, especially around freezing point. We found that wood temperature has a significant effect on acoustic velocity in frozen wood. Below the freezing point, acoustic velocity increased as wood tem-
perature decreased. When wood temperature was well above freezing, velocity in green wood was not significantly affected by temperature change. It was also found that wood moisture content had a significant compounding effect on the velocity-temperature relationships. Temperature effect was much more significant in green wood than in dry wood.

When acoustic velocity measure of trees and logs are used to predict the stiffness of wood, a similar temperature and moisture content effect is expected to be seen in dynamic MOE. But how does the dynamic MOE response differently to the changes of temperature and moisture content than static MOE is not clear yet. The objectives of this study were to further investigate the effects of temperature and moisture content/state on dynamic and static MOE of red pine small clear specimens and develop analytical models for adjusting predicted MOE to account for temperature differences when acoustic measurements are performed in different climates or different seasons.

Background

A series of studies have reported the effect of temperature on mechanical properties of wood. Gehrards (1982) summarized the studies on the immediate effects of moisture content and temperature on several mechanical properties of clear wood. Comben (1964) investigated the effect of temperature on strength and elasticity of ash, balsa, and Douglas-fir under 12%, 18%, 20%, and green conditions. He found that as wood temperature decreased from 17 to -73°C, the static MOE increased 32% under 12% MC and 78% for green wood.

Sellevold et al. (1975) examined the response of dynamic MOE and internal friction of beech wood beams at a various equilibrium moisture contents from 0 to 96% to the temperature changing from 25 to -130°C. A marked transition was found on the curve of the percentage change of MOE relative to 25°C with the temperature at around -90°C and around 0°C for the wood of moisture contents at or above the FSP. The magnitude of the transition decreased with the decreasing moisture content. They reported a 23% increase in MOE with the decreasing temperature from 25 to -70°C for wood of 15% MC and 55% for wood of 98% MC.

Mishiro and Asano (1984a, b) investigated the effects of temperature and moisture content on bending properties of spruce in the temperature range -180 to 60°C with moisture content below FSP (0% to 28.5%) and above FSP (50 to 210%). Both MOE and bending strength were found to increase as temperature decreased. They noticed that the relationships between bending properties and temperature were apparently influenced by the wood moisture content. For green wood, the property-temperature relations were characterized as segmented linear relationships with distinctively different slopes in three temperature ranges: -140 to -20°C, -20 to 0°C and 0 to 60°C. Above 0°C, MC above fiber saturation point did not significantly influence the properties-temperature relations; but below 0°C, MC showed a strong compounding effect on the bending properties.

Fridly et al. (1992) evaluated the mechanical properties of 38 by 89 mm structural Douglas-fir lumber in several hygrothermal states and found about 14% loss in median modulus of rupture (MOR) but little change in MOE when the lumber specimens were heated form 23 to 55°C.

DeGeer and Bach (1995) conducted static bending tests on different grades of 38 by 89 mm spruce-pine-fir (SPF) lumber at 20°C, -15°C and -30°C with MC from 15% to 17%. They reported a fast increase in MOE for the temperature change from 20 to -15°C, while a much smaller change observed for the temperature change from -15 to -30°C. They attributed the change in MOE and MOR with changing temperature to the phase change of the moisture in the lumber.

Green and Evans (2008) evaluated the immediate effect of temperature on flexural MOE of green and dry structural lumber from 66 to -26°C. They observed an increase in MOE with decreasing temperature for both green and dry lumber. For lumber at 4 and 12% MC levels, a linear relationship was used to relate the increase in MOE to decrease in temperature. For green lumber, a segmented linear re-
gression was developed to describe the change in MOE of green lumber with changing temperature. The slope of the MOE-temperature relationship was steeper below 0°C than above.

Chan et al (2010) performed acoustic wave measurements on 200 × 80 × 55 mm radiata pine sapwood boards at a temperature range of -71 to 58°C and a MC range of 17% to 159%. Acoustic velocity decreased linearly with increasing temperature and an abrupt discontinuity occurred around freezing point of water for the wood with MC above FPS. A similar relationship was also found between calculated dynamic MOE and temperature.

**Materials and Methods**

**Materials**

The materials used in this study were selected from the small clear red pine specimens (25.4 × 25.4 × 407 mm) that were used for a previous laboratory investigation on acoustic properties (Gao et al. 2012). The entire set of the specimens were in different moisture levels: Group 1 was green condition (fresh-cut and stored in a freezer before test); Group 2 and 3 were conditioned to 24 and 12% equilibrium moisture content (EMC); and Group 3 was oven-dried to 0% MC. We initially selected 12 specimens for this study, 3 from each group. The specific MC of three green specimens was 118.3%, 91.4% and 78.6% respectively. These specimens were wrapped with plastic film individually and stored in a refrigerator at –20°C before test.

**Ultrasonic measurement**

A Sylvatest Duo (CBS-CBT, Les Ecorces, France) unit was used to measure the ultrasonic velocity in the selected wood samples at a temperature range of -40 to 40 °C. A sealed foam box was constructed and used as an environmental chamber throughout the testing process. Dry ice and hot water were used as a cooling and heating source during testing. A detailed procedure for controlling wood temperature is described in Gao et al. 2012.

**Static bending test**

To perform static bending tests over a wide range of temperature conditions, we built a special environmental chamber which was mounted on the universal testing machine (Figure 1). The chamber was constructed with a sealed foam box which fitted into the center-point loading setup on the machine, with the wood specimen, end supports, and the loading head enclosed into the chamber. A wood specimen wrapped with plastic film was supported over a 35.6-cm span by two metal supporting plates (51 by 51 mm) which were resting on two wood blocks. A liquid carbon dioxide tank was used as a cooling source to provide low temperature carbon dioxide gas into the chamber. Two 30W light bulbs were used as a heating source to heat the wood specimen inside the chamber. The temperature of specimen was controlled by regulating air circulation using two small electric fans running at the opposite corners of the chamber. Two thermocouples (TC) were inserted into the wood specimen at different position to monitor the wood temperature change. TC No. 1 was fixed at the mid-span and center depth and TC No.2 at the quarter span and quarter depth. TC No. 3 was placed in the chamber to measure the air temperature. During the testing process, a microprocessor thermometer (Omega Model HH23, OMEGA Engineering, Inc., Stamford, CT) was used to monitor the wood temperatures (TC No.1 and No.2) and the air temperature in the lower chamber (TC No.3). A solenoid connected CO2 cylinder was used to control the flow of liquid CO2 gas from cylinder to specimen chamber through a copper tube line. A temperature controller (Chromalox) was used to control CO2 gas circulation to keep the desired wood temperatures.

Static bending test was conducted on each specimen under a center-point loading according to ASTM 143-94 (ASTM, 2006). The modulus of elastic of wood was calculated from the following equation (1):
Where $L$ is the span length, $b$ and $h$ are the base and height of the specimen respectively, $\Delta P$ is the load increment and $\Delta D$ is the deflection increment under $\Delta P$.

![Diagram of the static bending test setup equipped with a temperature control system.](image1)

![Diagram of the environmental chamber with a temperature control system.](image2)

Figure 1—Schematic of the bending test system for measuring MOE of red pine at various temperatures (1-Environmental chamber; 2-Wood specimen; 3-End supports; 4-Electronic fan; 5-Temperature controller; 6-Microprocessor thermometer; 7-Liquid carbon dioxide cylinder; 8-Copper tube; 9-Cross-head; 10-Instron machine; 11-Thermocouple wire; 12-Heating bulb)

Testing process was started by releasing the liquid CO$_2$ gas from the cylinder to the chamber till the wood temperature reached -40°C. Static bending test was conducted at a wood temperature of -40°C first and then repeated at every 10°C increment till the wood temperature increased to 40°C. When the chamber temperature reached the room temperature, the electronic heaters (light bulbs) were turned on to gradually raise the wood temperature up to about 40°C. During each testing cycle, two electric fans were manually control the air circulation so that the targeted temperatures were reached with uniformity, which was indicated by close readings of three thermocouples (TC No.1, No.2 and No.3). After the testing process was completed, we re-measured the dimension and the weight of each specimen to calculate the wood density, and monitored MC change during testing.

Results and Discussion

Response of static MOE to temperature change

Table 1 summarizes the physical characteristics of the red pine specimens tested. Due to system break-down and limited machine time available, we tested six specimens in total: three in group 1, each had distinctively different MC; one for each other groups. The MC of the specimens was in a range of 0.3% and 112.9%. The time used to complete one test cycle was about 8 to 10 hours. No noticeable change was observed in weight and dimension for each specimen. Wood moisture loss during the test cycle was minimal (0.9-1.2 % for Group 1, 0.7 – 1.4% for Group 2, 0.1 – 2.1% for Group 3, and 0.2% for Group 4). Wood density was derived based on the weight and dimension of the specimen at the beginning of static bending test.

Figure 2 shows the load-deflection curves of a green specimen (No.1) obtained at a wood temperature range from -40 to 40 °C, with a 10°C increment. It is apparent that the slope of the linear curves (within the elastic region), which indicates the stiffness of the specimen, increased as wood temperature dropped from 40 °C to -40 °C. We also observed a significant shift on the slope of the load-deflection curve between 0 °C and -10 °C. This was consistent with what we observed on acoustic velocity shift for the same specimen around the freezing point (Gao et al. 2012).
Figure 2—Load-deflection relationships of a green wood specimen (No. 1) at various temperatures.

Figure 3—Effects of temperature and moisture content on static modulus of elasticity.

Table 1—Physical properties of the red pine small clear specimens selected for static bending test.

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Specimen No.</th>
<th>MC (%)</th>
<th>Density (kg/m³)</th>
<th>Dimension (Height mm)</th>
<th>Weight (g)</th>
<th>Oven-dry Weight (g)</th>
<th>Ring count (no./mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>112.9</td>
<td>858.28</td>
<td>25.68</td>
<td>407.02</td>
<td>225.35</td>
<td>105.85</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>90.1</td>
<td>730.91</td>
<td>25.30</td>
<td>407.12</td>
<td>194.27</td>
<td>102.19</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>76.4</td>
<td>723.18</td>
<td>25.20</td>
<td>407.10</td>
<td>189.55</td>
<td>107.47</td>
</tr>
<tr>
<td>II</td>
<td>4</td>
<td>24.5</td>
<td>517.90</td>
<td>26.16</td>
<td>407.00</td>
<td>138.39</td>
<td>111.19</td>
</tr>
<tr>
<td>III</td>
<td>5</td>
<td>15.2</td>
<td>463.27</td>
<td>29.08</td>
<td>407.00</td>
<td>140.26</td>
<td>121.75</td>
</tr>
<tr>
<td>IV</td>
<td>6</td>
<td>0.3</td>
<td>465.69</td>
<td>23.93</td>
<td>407.14</td>
<td>108.66</td>
<td>107.95</td>
</tr>
</tbody>
</table>

Figure 3 shows the response of static MOE of the specimens with different MC to the wood temperature changes. The static MOE increased continuously as wood temperature dropped from 40 °C to -40 °C. The change rate of static MOE was different at different temperature zones (above 0°C, -10 to 0°C, and -10 to -40 °C) and affected by the wood moisture condition. The freezing point of water (0°C) was clearly a turning point for the trends of static MOE-temperature relationships in green wood. As wood temperature changed from 40 °C to -40 °C, the percentage increase in static MOE was from 92.34 to 149.56 % for green specimens, 30% for specimen of 24% MC, 26.8% for specimen of 12%MC, and 11.3% for specimen of 0%MC.

With respect of moisture effect, 24% MC (FSP of red pine) presented as a demarcation point in the static MOE-MC relationships. For dry wood (below FSP), the static MOE decreased dramatically with increase of MC. This trend was generally same for the entire temperature range tested. For green wood (above FSP), the static MOE decreased slightly with the increasing MC when wood temperature was above freezing, but it stayed relatively constant when wood was below freezing.

Overall, our results indicated that wood temperature, moisture content, and moisture state (frozen or non-frozen) had a compounding effect on the static MOE of wood. The effect of temperature on static MOE was most prominent for green wood and below freezing point. Our findings are basically in agreement with those reported by Mishiro and Asano (1984a, b). The sudden raise in MOE around freezing point was attributable to the phase transformation of the free water in wood cells. Mishiro and Asano (1984a, b) used the rule of mixtures to explain their results and predicted wood properties by considering the percentage of water in saturated cell wall and air voids and frozen water in the cell lumen. In addition, our experimental data showed that temperature changes contributed more to the static MOE change when wood temperature was below freezing, and moisture content changes con-
tributed more to the static MOE change when wood temperature was above freezing.

Analytical models

Relative static MOE and dynamic MOE

To examine the significance of the temperature impact on MOE and minimize the difference in prediction across percentile levels of the property distribution, an analytical model based on the percentage of change in MOE relative to the MOE at a base temperature of 20 °C was used to describe the relationship between MOE and temperature. The percentage of change in MOE is defined as

$$\Delta \text{MOE} = \left( \frac{\text{MOE}_T - \text{MOE}_0}{\text{MOE}_0} \right) \times 100 \quad (2)$$

where \( \text{MOE}_T \) is MOE at the temperature \( T \) and \( \text{MOE}_0 \) is the MOE at 20 °C (Barrett et al. 1989; Green and Evans, 2008; Gao et al., 2012, 2013).

Figure 4 illustrates the percentage of change in measured static MOE relative to 20°C (relative static MOE) at different temperatures. A significant change in relative static MOE with temperature was observed below freezing point for green wood. Above freezing, the relative static MOE increased gradually as the wood temperature decreased. An abrupt increase in relative static MOE occurred when wood temperature dropped just below the freezing point. Then the change became slow as the temperature fell below -10°C. For wood specimens with a MC below the FSP, the relative static MOE was not significantly affected by temperature.

Our previous study has demonstrated that temperature has significant effect on acoustic velocity of small wood specimen. The mathematic models were developed to describe the relationship between acoustic velocity and temperature (Gao et al. 2012). Based on the acoustic velocity and density of the specimens, the corresponding dynamic modulus of elasticity was derived and the percentage of change in dynamic MOE relative to 20°C with temperature was illustrated in the Figure 5. The relative dynamic MOE showed a similar changing trend with temperature as the relative static MOE. This further proved the hypothesis initiated by Jayne (1959) that the energy storage and dissipation properties of wood materials in a stress wave test are controlled by the same mechanisms that determine the static behavior of such material.

Prediction models of relative static and dynamic MOE

The relative MOE and temperature relationships can be characterized by the following segmented linear regression models at two different temperature ranges:

$$\Delta \text{MOE} = k_1T + h_1 \quad (\% ) \quad (-40^\circ \text{C} \leq T \leq 10^\circ \text{C} \quad \text{or} \quad 0^\circ \text{C} \leq T \leq 40^\circ \text{C}) \quad (4)$$

Figure 4—Relationship between relative static MOE and temperature.

Figure 5—Relationship between relative dynamic MOE and temperature.
Table 2—Coefficients of regression models of relative MOE–temperature

<table>
<thead>
<tr>
<th>MC</th>
<th>$T \leq -10^\circ C$</th>
<th>$T \geq 0^\circ C$</th>
<th>MC</th>
<th>$T \leq -10^\circ C$</th>
<th>$T \geq 0^\circ C$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_d$</td>
<td>$h_d$</td>
<td>$k_d$</td>
<td>$h_d$</td>
<td>$k_s$</td>
</tr>
<tr>
<td>118.3%</td>
<td>-0.400</td>
<td>28.94</td>
<td>-0.054</td>
<td>2.267</td>
<td>112.9%</td>
</tr>
<tr>
<td>91.4%</td>
<td>-0.295</td>
<td>22.17</td>
<td>-0.056</td>
<td>2.390</td>
<td>90.1%</td>
</tr>
<tr>
<td>78.6%</td>
<td>-0.347</td>
<td>10.83</td>
<td>-0.084</td>
<td>1.117</td>
<td>76.4%</td>
</tr>
<tr>
<td>24.9%</td>
<td>-0.257</td>
<td>1.221</td>
<td>-0.097</td>
<td>1.749</td>
<td>24.5%</td>
</tr>
<tr>
<td>15.2%</td>
<td>-0.261</td>
<td>2.257</td>
<td>-0.107</td>
<td>2.368</td>
<td>15.2%</td>
</tr>
<tr>
<td>0.2%</td>
<td>-0.185</td>
<td>0.264</td>
<td>-0.165</td>
<td>0.084</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

Figure 6 shows the linear regression lines for relative static and dynamic MOE and temperature relationships at two temperature zones: $-40^\circ C \leq T \leq -10^\circ C$ and $0^\circ C \leq T \leq 40^\circ C$. The straight line between $0^\circ C$ and $-10^\circ C$ simply represents the transition of relative MOE and no statistical regression line can be obtained because of limited data points.

The regression coefficients of the linear models for relative static and dynamic MOE versus temperature at different MC levels are listed in Table 2. The coefficient of determination for the static $\Delta$ MOE ranged from 0.91 to 0.99 in the temperature range of $-40$ to $-10^\circ C$ and from 0.90 to 0.99 in the temperature range of $0$ to $40^\circ C$. The coefficients of determination for the dynamic $\Delta$ MOE ranged from 0.95 to 0.99 in the temperature range of $-40$ to $-10^\circ C$ and from 0.22 to 0.95 in the temperature range of $0$ to $40^\circ C$.

Figure 6—Linear regressions demonstrating the effect of temperature on percentage of change in static and dynamic MOE relative to $20^\circ C$.

Figure 7—Relationships between relative dynamic MOE and relative static MOE of red pine specimens.
Figure 7 shows comparisons between relative static MOE and relative dynamic MOE of the red pine specimens. Very good linear relationships existed between measured changes in dynamic MOE and static MOE, with a coefficient of determination of 0.92 (Figure 8a) and between predicated changes in dynamic MOE and static MOE, with a coefficient of determination of 0.946 (Figure 8b). Therefore it is logical that the dynamic MOE based on acoustic velocity can be used as a good predictor of the static MOE for nondestructive evaluation of wood at a range of wood temperatures.

Conclusions

This study examined the response of dynamic and static modulus of elasticity (MOE) of red pine small clear wood to a temperature change from -40 to 40 °C and developed analytical models to predict the percentage of changes in MOE at different temperatures relative to a standard temperature (20°C). Based on the results, we conclude the following:

1. Modulus of elasticity of wood was affected by temperature and the state of moisture in wood. Above the freezing point, MOE of wood (non-frozen) decreased linearly at a slow rate as wood temperature increased. Below freezing point, MOE increased at a rapid rate as wood temperature dropped.

2. Moisture content of wood had a significant compounding effect on the MOE-temperature relationships. Temperature effect was much more significant in green wood than in dry wood. MOE of green wood changed abruptly around the freezing point, due to the phase transformation of free water in the cell lumens.

3. Mathematical models were developed to predict the percentage change of MOE relative to standard temperature of 20°C in two temperature zones: -40°C ≤ T ≤ -10°C and 0°C ≤ T ≤ 40°C.

4. The relative dynamic MOE showed a similar changing trend with temperature as the relative static MOE. Dynamic MOE can be used as a good predictor of the static MOE for nondestructive evaluation of wood at a range of wood temperatures.

Acknowledgement

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Abstract
The 18th International Nondestructive Testing and Evaluation of Wood Symposium was hosted by the USDA Forest Service’s Forest Products Laboratory (FPL) in Madison, Wisconsin, on September 24–27, 2013. This Symposium was a forum for those involved in nondestructive testing and evaluation (NDT/NDE) of wood and brought together many NDT/NDE users, suppliers, international researchers, representatives from various government agencies, and other groups to share research results, products, and technology for evaluating a wide range of wood products, including standing trees, logs, lumber, and wood structures. Networking among participants encouraged international collaborative efforts and fostered the implementation of NDT/NDE technologies around the world. The technical content of the 18th Symposium is captured in this proceedings.

Keywords: International Nondestructive Testing and Evaluation of Wood Symposium, nondestructive testing, nondestructive evaluation, wood, wood products

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