Shan Gao*, Xiping Wang and Lihai Wang

Modeling temperature effect on dynamic modulus of elasticity of red pine (*Pinus resinosa*) in frozen and non-frozen states

Abstract: The response of dynamic and static modulus of elasticity (MOE_{dyn} and MOE_{sta}) of red pine small clear wood (25.4×25.4×407 mm^3) within the temperature range -40 to 40°C has been investigated. The moisture content (MC) of the specimens ranged from 0 to 118%. The MOE_{dyn} was calculated based on measured ultrasonic velocity (*V*) and wood density. The MOE_{sta} was measured by static bending tests in a climate chamber between -40 and 40°C. The results indicate that both MOE_{dyn} and MOE_{sta} were affected by temperature and the MC. Above freezing point, MOE decreased linearly at a slow rate with increasing temperature. Below freezing point, MOE increased at a rapid rate with decreasing temperature. The MC-level had a significant effect on the MOE-temperature relationships. Temperature effect was much more significant in green wood than in dry wood. Analytical models were developed to predict the change of MOE_{dyn} relative to that at 20°C in the case of acoustic measurements under different temperature conditions.

Keywords: freezing point, ice formation, modulus of elasticity, moisture content, ultrasonic velocity

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Introduction

Acoustic measurement on standing trees and logs is a useful nondestructive method for wood quality assessment (Wang et al. 2007; Zhang et al. 2011). The method is well suited for predicting the stiffness or modulus of elasticity (MOE) of wood and wood products and frequently applied in forests and log yards (Wang et al. 2007). Gao et al. (2012) found that velocity (*V*) and energy loss of longitudinal acoustic waves were dependent on temperature (*T*) changes on small clear wood samples, especially around freezing point. Below freezing, acoustic *V* increased with decreasing *T*. Above freezing, however, the *V* in green wood was not significantly affected by *T* change. Moisture content (MC) in wood has a significant effect on the *V*–*T* relationships. Temperature effect is more pronounced in green wood than in dry wood. This is also true for green logs and standing trees monitored in forest for 12 consecutive months (Gao et al. 2013).

Accordingly, for the prediction of wood stiffness, the interactive effect of *T* and MC must be considered when determining the dynamic modulus of elasticity (MOE_{dyn}). Typically, the MOE_{dyn} can be predicted from the one-dimensional (1D) wave equation:

$$MOE_{dyn}=V^2\rho \tag{1}$$

where *V* is acoustic velocity (m s^{-1}) and ρ is wood density (kg m^{-3}).

Intuitively, changes in wood temperature (T_{wood}) and MC will be reflected in ρ (as a function of MC) and *V* (as a function of MC and *T*). However, the complex relationships are not fully understood in the context of dynamic modulus of elasticity. The literature gives little information with this regard. In previous studies, we examined the effect of *T* changes on acoustic *V* of trees and green logs (Gao et al. 2013), but no results were reported concerning MOE prediction by means of the 1D wave theory. Chan et al. (2010) studied radiata pine sapwood boards and provided some useful data on the effects of MC and *T* on the MOE_{dyn} of the boards. However, the relationships were found not straightforward.

The objectives of the present study were to investigate the effect of *T* on MOE_{dyn} of red pine in frozen and non-frozen states and develop analytical models for adjusting MOE_{dyn} to account for *T* differences in the case of acoustic measurements under different temperature conditions.

***Corresponding author: Shan Gao,** PhD, College of Engineering and Technology, Northeast Forestry University, Harbin 150040, China, Phone: +86-0451-82191248, e-mail: sgao.nefu@gmail.com
Xiping Wang: U.S. Forest Service, Forest Product Laboratory, Madison, WI, USA
Lihai Wang: College of Engineering and Technology, Northeast Forestry University, Harbin, China

Materials and methods

Small clear red pine (*Pinus resinosa* Ait.) specimens were cut (ca. 25.4×25.4×407 mm^3) from 1-m-long green log sections. The logs were from a 45-year-old red pine tree harvested from a plantation stand located in Arena, Wisconsin, USA. Twelve freshly-cut sapwood (SW) specimens were selected and divided into four groups (I–IV) consisting of three specimens in each group. Three green specimens in Group I were immediately wrapped in thin plastic film and moved to a cold room (-18°C) to maintain their green condition. Groups II and III were placed into climate chambers with equilibrium moisture contents (EMC) of 24 and 12%, respectively. Specimens of Group IV were oven-dried to 0% MC. After the target MC was reached, specimens of Groups II, III and IV were also wrapped individually in thin plastic film and kept cold until tested.

The ultrasonic *V* in the wood specimens in a *T*-range of -40 to 40°C was measured using a Sylvatest Duo (CBS-CBT, Les Ecorces, France) device operating at a frequency of 22 kHz. A sealed foam box served as a climate chamber throughout the testing process (Figure 1). A detailed procedure for controlling T_{wood} was described in Gao et al. 2012.

Dimensions and weight of each specimen were measured before placement into the climate chamber and each measurement began with T_{wood} of -40°C and was repeated with 10°C increments up to 40°C, except when T_{wood} was close to 0°C, where *V* measurement was performed with 2–3°C increments. During each measurement cycle, the transmitter probe and the receiver probe were positioned at the center of the specimen ends. A constant pressure of 207 kPa was applied to the probes through controlled compressed air. For each *V* measurement, the transmitter probe emitted five consecutive pulses through the specimen. An average ultrasound propagation time (UPT) was recorded after each measurement. The ultrasonic velocity (*V*) of the specimen was calculated based on the average UPT value and the length of the specimen (*L*):

$$V(\mathrm{ms}^{-1})=L/\mathrm{UPT} \tag{2}$$

After each measurement cycle, the specimens were weighted again. MC loss of the specimens during the test was found minimal (1.1–3.1% for Group I, 0.7–1.4% for Group II, 0.1–2.1% for Group III and 0.2% for Group IV).

Static bending test was conducted on each specimen in the *T*-range of -40 to 40°C. Another environmental chamber was built and mounted on a universal testing machine for conducting this test (Figure 2). The testing chamber was constructed with a sealed foam box that fitted into the center point loading setup on the machine, with the wood specimen, end supports and loading head enclosed into the chamber. A wood specimen wrapped in plastic film was supported over a 356 mm span by two metal supporting plates (51×51 mm) which were resting on two hardwood blocks. A liquid CO_2 cylinder served as a cooling source to provide low temperature CO_2 gas into the chamber. Two 30 W light bulbs served as a heating source inside the chamber. The T_{wood} was controlled by regulating air circulation by means of two small electric fans placed at the opposite corners of the chamber. Two thermocouples (TC) were inserted into the specimens at different position for monitoring *T*-change. Thermocouple no. 1 was fixed at the mid span and center depth and thermocouple no. 2 at the quarter span and quarter depth. Thermocouple no. 3 was placed in the chamber to measure the air temperature. Monitoring T_{wood} (thermocouples no. 1 and no. 2) and T_{air} in the chamber (thermocouple no. 3) was performed by a microprocessor thermometer (Omega Model HH23, Omega Engineering, Incorporated, Stamford, CT, USA). The flow of liquid CO_2 gas from cylinder to specimen chamber through a copper tube line was controlled by a solenoid connected to the CO_2 cylinder. A T-controller (Chromalox) was used to control CO_2 gas circulation.

Static bending test was conducted on each specimen under a center-point loading with a constant loading rate of 1.3 mm min^{-1} (ASTM 2009). The load-deflection data were collected at a constant load level (670 N) within the elastic region. An individual static bending test was completed within 1.5–4 min. The static bending MOE (GPa) was calculated:

$$\mathrm{MOE}_{sta}=PL^3/48\Delta I \tag{3}$$

where *P* is the load applied within the proportional limit (N), *L* is the span length (mm), Δ is the deflection measured at the mid span (mm), and *I* is the moment of inertia (mm^4).

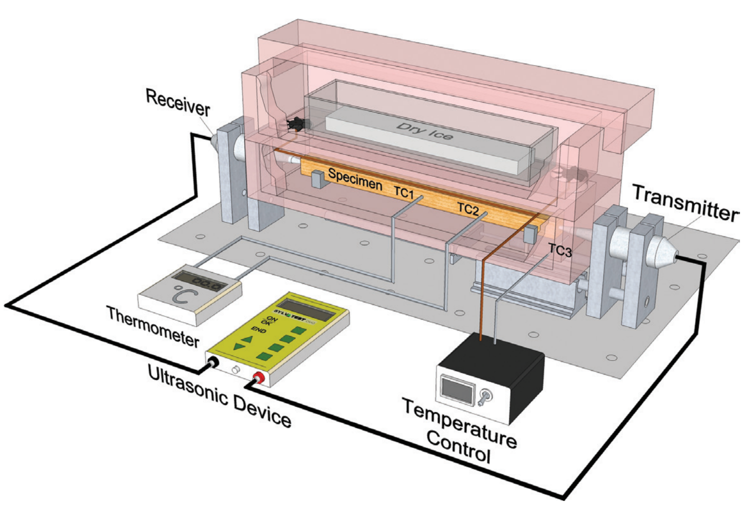

Figure 1 Schematic of the laboratory test system for measuring ultrasonic velocity of red pine specimens in a climate chamber.

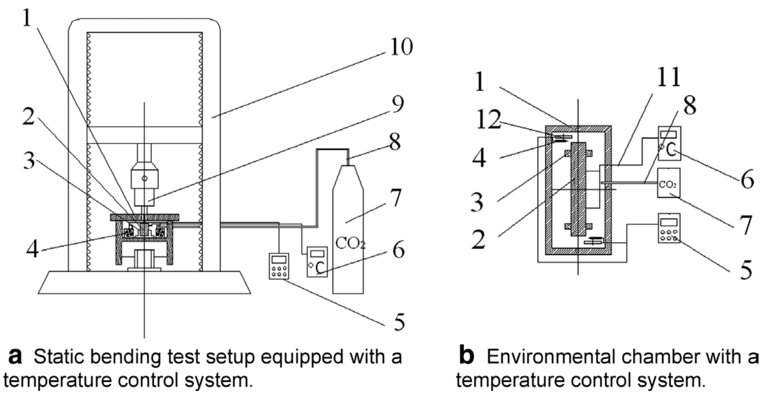

Figure 2 Schematic of the static bending test system for measuring MOE of red pine at various temperatures: 1) Climate chamber; 2) wood specimen; 3) end support; 4) electronic fan; 5) temperature controller; 6) microprocessor thermometer; 7) liquid carbon dioxide cylinder; 8) copper tube; 9) cross-head; 10) Instron machine; 11) thermocouple wire measuring wood temperature; 12) thermocouple wire measuring air temperature of the chamber.

Testing process was started by releasing the liquid CO_2 gas from the cylinder to the chamber till the T_{wood} reached -40°C. Static bending test was conducted at a T_{wood} of -40°C first and then repeated at every 10°C increment till the T_{wood} became 40°C. When the climate chamber reached room temperature, the electronic heaters (light bulbs) were turned on to raise the T_{wood} up to 40°C gradually. During each testing cycle, two electric fans were manually controlled to regulate the air circulation so that the target temperatures were reached with uniformity, which was indicated by close readings of three thermocouples. The time needed to complete the cyclic bending test on one specimen was about 8–10 h. After the testing process was completed, the dimension and the weight of each specimen were determined again but no noticeable change was observed in this regard.

Results and discussion

Ultrasonic velocity versus temperature

Moisture contents of three green specimens in Group I was 79, 91, and 118%, respectively, based on the MC determination of the moisture blocks cut adjacent to the specimens. MC of other groups was relatively uniform. Average EMC of Groups II, III and IV was 25, 13 and 0% with a standard deviation of 0.9, 2.1 and 0.1%, respectively.

For comparison analysis, we chose 20°C as a base temperature. At 20°C, the measured *V* ranged from 3757 to 6187 m s^{-1} with a coefficient of variation (COV) of 14.4%. This wide *V*-range was attributed to both wood property variation and MC differences of the specimens. The velocity difference between frozen and non-frozen states was considerable. When T_{wood} decreased from 20°C to -40°C, *V* increased for all specimens but at different rates for different MC levels. Percentage change of *V* (ΔV) from 20°C to -40°C was proportional to MC, and was highest for the specimen of highest MC and decreased with decreasing MC-levels. A regression analysis indicated a linear relationship between ΔV (%) and MC as illustrated in Figure 3a. It is clear that MC of wood plays an important role in *V* measurements. The influence of *T* on *V* is greater at higher MC-levels.

Figure 4a shows the plots of *V* and T_{wood} at various MC-levels. The overall trend of *V* change is similar for all dry wood specimens, i.e., *V* decreased gradually with increasing *T* and *vice versa*. The *V*–*T* trend flattened progressively as MC changed from 24 to 0%. However, for green wood (Group I), the *V*–*T* trend was different, i.e., *V* changed abruptly around the freezing point (-2.5°C to 2.5°C). *V*–*T* relations were characterized based on three *T* zones: below freezing point, ultrasonic *V* decreased as T_{wood} increased; around freezing point (-2.5°C to 2.5°C), *V* changed abruptly as T_{wood} changed, and above freezing point, ultrasonic *V* decreased slightly as T_{wood} increased. The dramatic shift in *V* around the freezing point is attributed to the phase transformation of free water in wood cells into ice crystals (Gao et al. 2012).

Dynamic MOE versus temperature

Dynamic modulus of elasticity (MOE_{dyn}) of the specimens was calculated based on Equation 1. Wood density value for calculation was derived based on the weight and dimension of the specimen measured at the beginning of ultrasonic test. When *T* is below 0°C, free water in green specimens (MC>FSP) freezes and expands, and thus may cause increases in dimension of the specimens. Mishiro

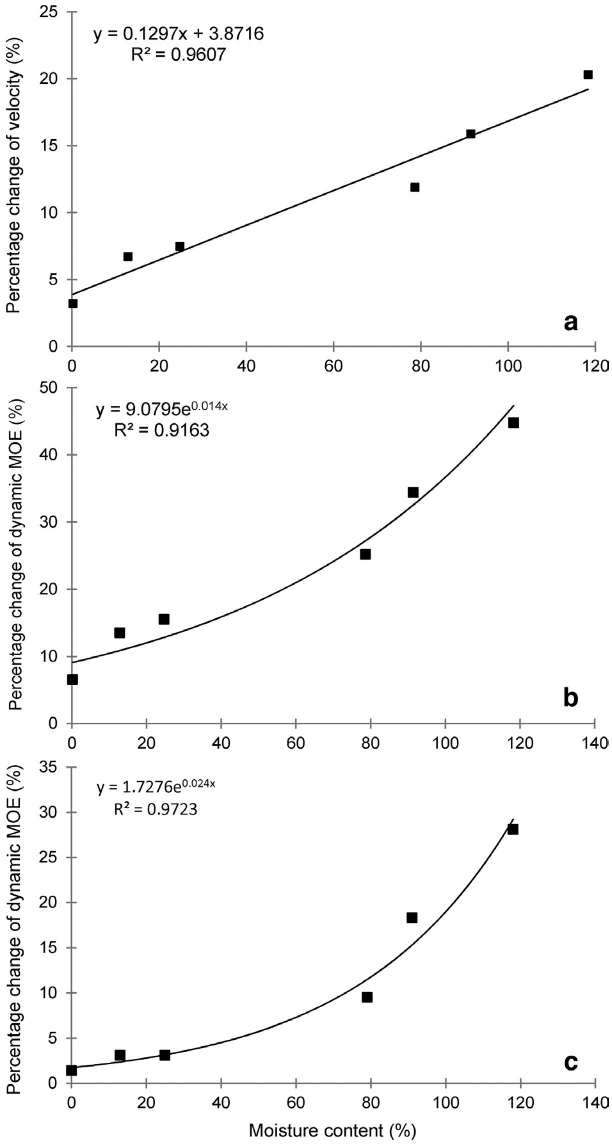

Figure 3 Effect of wood moisture content on percentage change of ultrasonic velocity and dynamic MOE of red pine resulting from a temperature change: a) Percentage change of ultrasonic velocity from 20 to -40°C; b) percentage change of dynamic MOE from 20 to -40°C; c) percentage change of dynamic MOE from 20 to -2.5°C.

and Asano (1984b) observed that the dimension of wood specimen increased with MC above 110%, but no *T*-effect was found within the *T* range of -140°C and -10°C. In our experiments, no noticeable change was observed in weight and MC after a complete testing cycle within -40°C to 40°C. The dimensional changes were not monitored during each testing cycle because such changes were not expected based on the results of Mishiro and Asano (1984b). Therefore, the density of each specimen was regarded as constant during testing and any changes of MOE_{dyn} with *T* were caused by *V* changes that were measured.

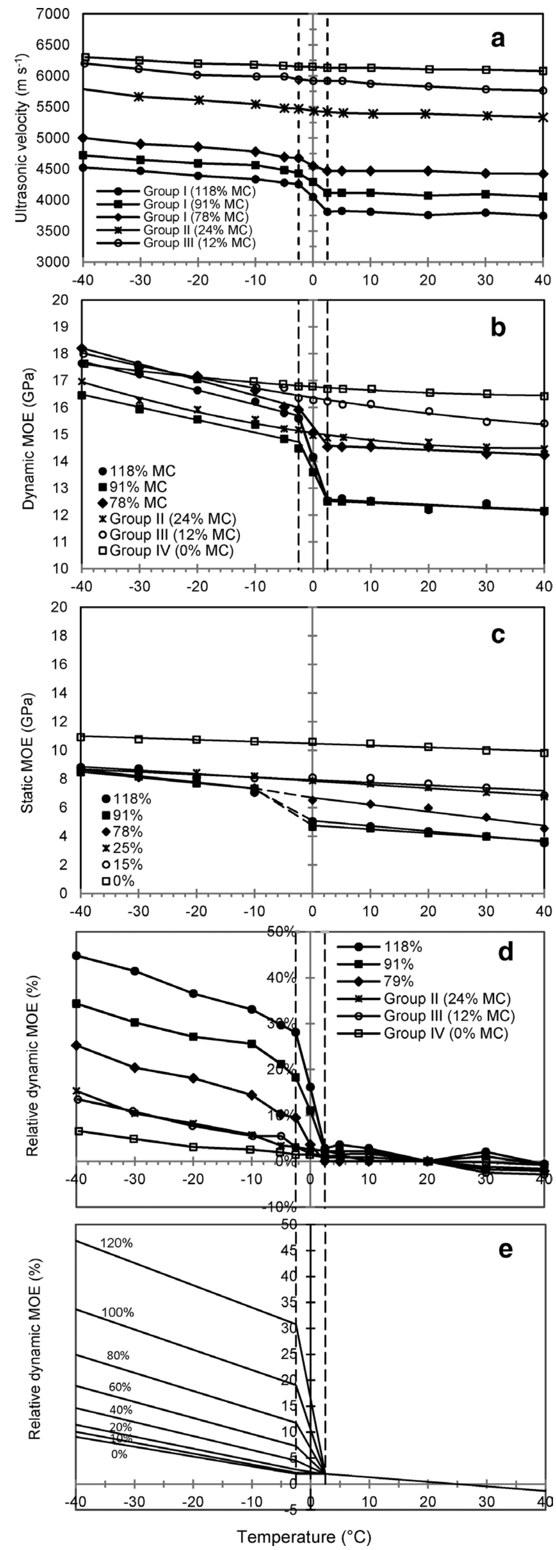

Figure 4 Ultrasonic velocity and modulus of elasticity of red pine in relation to wood temperature: a) Ultrasonic velocity vs. temperature; b) dynamic MOE vs. temperature; c) Static MOE vs. temperature; d) relative dynamic MOE (change relative to 20°C) vs. temperature; e) predicted relative dynamic MOE (change relative to 20°C) vs. temperature at various moisture levels.

At the base T of 20°C, the MOE_{dyn} derived from V measurement ranged from 12.2 GPa to 17.3 GPa with a mean value of 15 GPa. When T_{wood} dropped to -40°C, the MOE_{dyn} changed to 16.0–18.6 GPa with a mean value of 17.5 GPa, which is a 16.5% increase. When analyzing the MOE_{dyn} with respect to MC of the specimens, percentage change of MOE_{dyn} (ΔMOE_{dyn}, %) was directly affected by the MC-levels. There is an exponential relationship between ΔMOE_{dyn} and MC (Figure 3b). This implies that T-effect is magnified at MC-levels higher than FSP. Interestingly, the variation of MOE_{dyn} of the specimens was reduced significantly as T_{wood} decreased from 20°C to -40°C. The COV of MOE_{dyn} was 11.2% at 20°C and 5.2% at -40°C. This was due to ice-effect and it can greatly impair the ability of the acoustic wave method in predicting wood properties under frozen conditions.

Figure 4b shows the relationships between MOE_{dyn} at various MC-levels and T_{wood} between -40°C to 40°C. The trends of MOE_{dyn} reflect the variation in V with respect to T_{wood}. For dry wood specimens, MOE_{dyn} increased continuously with decreasing T_{wood}. No apparent discontinuity in MOE_{dyn} was observed around the freezing point (-2.5°C to 2.5°C). The MOE_{dyn}–T trend flattened as MC changed from 25% to 0%. Mathematically, the MOE_{dyn}–T relationships can be best characterized by polynomial regression equations given in Table 1. From practical point of view, the T-effect can be modeled by linear regressions. Under these conditions, MOE_{dyn} increased on average by 0.03 GPa per °C for specimens of 25 and 13% MC and 0.01 GPa per °C for specimens of 0% MC as T_{wood} decreased. This result is comparable to the value reported by Chan et al. (2010) on radiata pine (0.02 GPa per °C for wood at 19 and 24% MC).

For green wood specimens, a sharp discontinuity in MOE_{dyn} occurred between -2.5 and 2.5°C as a result of abrupt V changes. The MOE_{dyn} increment from 2.5 to -2.5°C was 3.2, 2.2, and 1.4 GPa for the specimens with MC of 118, 91, and 79%, respectively, which means 25, 18 and 10% MOE_{dyn} increase, respectively. The MOE_{dyn} increment below freezing is related to ice formation, which begins below 0°C. The ice formation can be calculated according to Cudinov et al. (1978):

$$\text{Ice}\,(\%) = 1 - \frac{12 + 18e^{0.0567(T+2)}}{\text{MC}} \tag{4}$$

where, ice (%) is the proportion of ice in water, and T (°C) is $-50°C \le T \le -2°C$.

For the green red pine specimens with 118, 91, and 79% MC, the proportion of water that turned into ice at -2.5°C was estimated to be 75, 68, and 63%, respectively. This explains the higher magnitude of MOE_{dyn} increment with increasing MC. This finding is consistent with the results reported by Sellevold et al. (1975) for beech and Chan et al. (2010) for radiata pine.

Below -2.5°C, MOE_{dyn} change is inversely proportional to T_{wood} and the slope of linear correlation line between -2.5 and -40°C is similar for the green specimens at different MC levels (Table 1). On average, MOE_{dyn} increased by 0.053 GPa per °C as a function of T decrement. Chan et al. (2010) found MOE_{dyn} increment of 0.051 GPa per °C for radiata pine with 84% MC.

Above freezing point, MOE_{dyn} shows nearly no change with T, i.e., between 2.5 and 40°C a 0.01 GPa MOE_{dyn} decrement per °C increase is observable. The corresponding

Table 1 Regression equations characterizing the relationships between dynamic MOE and temperature for red pine specimens.

Group no.	MC (%)	$MOE_{dyn}=a+bT$			$MOE_{dyn}=a+bT+cT^2$			
		a	b	R^2	a	b	c	R^2
			$T<-2.5°C$					
I	118	15.560	-0.0538	0.99				
	91	14.628	-0.0469	0.94				
	78	15.847	-0.0591	0.98				
			$T>2.5°C$					
I	118	12.568	-0.0092	0.76				
	91	12.600	-0.0111	0.64				
	78	14.604	-0.009	0.82				
			$-40\le T\le 40°C$			$-40\le T\le 40°C$		
II	24	15.260	-0.0307	0.87	15.056	-0.0307	0.0004	0.99
III	12	16.460	-0.0332	0.96	16.360	-0.0332	0.0002	0.99
IV	0	16.847	-0.0146	0.91	16.772	-0.0146	0.0002	0.99

MOE_{dyn}, dynamic modulus of elasticity (GPa); MC, moisture content (%); T, temperature (°C); V, velocity (m s^{-1}); a, b, c, d, regression coefficients; R^2, coefficient of determination.

data of Chan et al. (2010) were around 0.02 GPa MOE_{dyn} decrement per °C.

Static MOE versus temperature

The clusters of load-deflection curves of green and dry specimens (Figure 5), obtained from static bending tests in the range of -40 to 40°C, shows the changes of MOE_{sta} (indicated by the slops of the curve within elastic region) with temperature. The influence of T on load-deflection curves is more prominent in green wood than in dry wood. There is a big change of the slope of the load-deflection curve between 0 and -10°C in green wood which is in agreement with the observation of MOE_{dyn} shifts around the freezing point (Figure 4b).

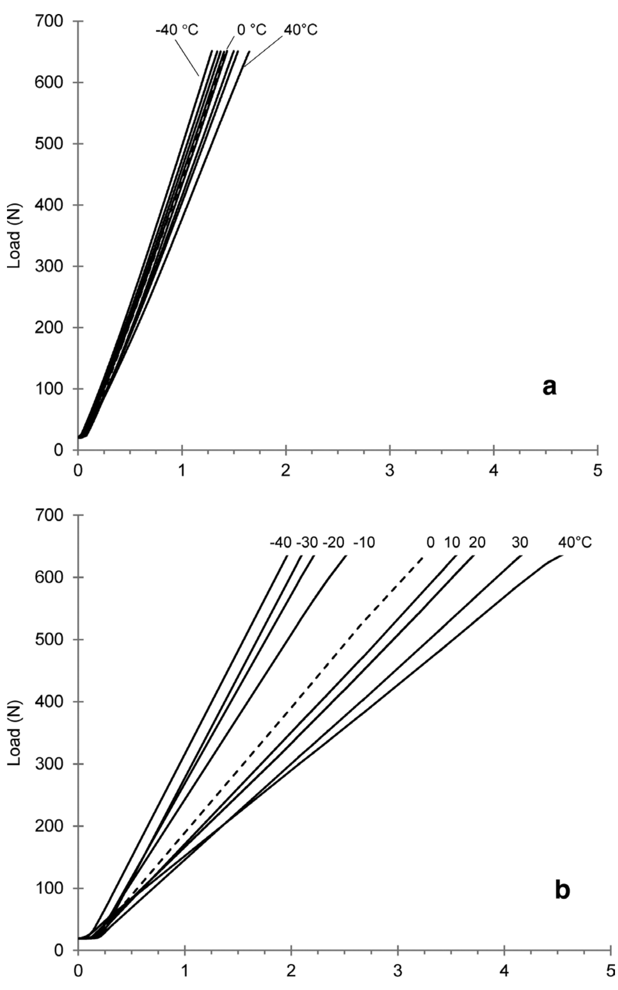

Figure 5 Load-deflection curves obtained from static bending tests on red pine specimens: a) Dry wood specimen (12% MC); b) green wood specimen (118% MC).

Due to limited machine time available, only six specimens out of 12 were tested: three in Group I, each had distinctively different MC; one in each other groups (Group II, III and IV). The MOE_{sta} measured at 20°C ranged from 4.5 to 10.2 GPa. After adjusting for the MC effect, the MOE_{sta} (12% MC) ranged from 5.3 to 9.4 GPa with a mean value of 7.3 GPa. The measured MOE_{sta} of the red pine specimens was apparently lower than the values given in Wood Handbook (11.2 GPa for dry wood of 12% MC) (FPL 2010). This is likely caused by the creep deflection produced during the cyclic loading of each specimen. The repeated removal and application of load during bending test resulted in a slope of load-deflection curve that could include delayed elastic and viscous deformation components. When measured at 20°C (the seventh measurement within the testing cycle), the MOE_{sta} calculated from Equation 3 was lower than the value defined by the true elastic behavior. The other possible reason is that the specimens tested in this study came from young fast growing plantations that had a relatively low specific gravity (average 0.40 g cm^{-3}).

The observed 36% MOE_{sta} increment at -40°C compared to 20°C is much higher than the MOE_{dyn} increment (16.2%). Moreover, there is a large MOE_{sta} difference between dry and green wood if compared with the frozen and non-frozen states: i.e., 46→101% (green wood) and 7→18% (dry wood). In frozen states during cooling, moisture diffuses out of the saturated cell walls and condenses as ice crystals in the cell cavities, resulting in a significant MOE increment as compared with that in non-frozen state (Comben 1964; Sellevold et al. 1975; Mishiro and Asano 1984a,b; DeGeer and Bach 1995; Green and Evans 2008).

The relationships between MOE_{sta} and T_{wood} (Figure 4c) are similar to that published by Gerhards (1982) and Green et al. (1999). For all specimens of different MC (0–118% MC), the MOE_{sta} increased continuously as T_{wood} decreased from 40 to -40°C. The change rate of MOE_{sta} was clearly affected by the MC levels. For dry wood specimens, the effect of T was uniform below and above 0°C. MOE_{sta} was a linear function of T through the whole T range (-40 to 40°C). The slope of the regression line shows a lowering tendency with decreasing MC. For green specimens, the freezing point of water (0°C) was clearly a turning point for the trends of MOE_{sta}–T relationships and the abrupt shift in MOE_{sta} between 0 and -10°C is in agreement with the patterns of MOE_{dyn} discussed above. The MOE_{sta} increment from 0°C to -10°C was 2.2, 2.6, and 0.6 GPa for the specimens with 118, 91, and 78% MC, respectively, which means 43, 54 and 10% MOE_{sta} increase, respectively. These results were consistent with the results reported by Sellevold et al. (1975) and Mishiro and Asano (1984b).

Change in dynamic MOE relative to that at 20°C

The percentage of change in MOE_{dyn} relative to that at 20°C (hereafter referred to as relative MOE_{dyn}) is defined as

$$\Delta MOE_{dyn}(\%)=\left(\frac{MOE_{dynT}\text{-}MOE_{dyn0}}{MOE_{dyn0}}\right)\times 100 \quad (5)$$

where MOE_{dynT} is dynamic modulus of elasticity at a certain T and MOE_{dyn0} is dynamic modulus of elasticity at 20°C.

Figure 4d illustrates this concerning relative MOE_{dyn} in relation to T. Above freezing T (2.5–40°C), increasing MC from 0 to 118% changed MOE_{dyn} only by -3 to 4%. This result is similar to that of Chan et al. (2010). The magnitude of the fluctuation in MOE_{dyn} is considered minimal and could be attributed to measurement errors in ultrasonic testing. For practical application, MOE_{dyn} can be considered constant and T adjustment is not needed.

Below freezing T (-2.5 to -40°C), a significant change in relative MOE_{dyn} was observed for green wood, for example at -2.5°C the changes in MOE_{dyn} relative to 20°C were 9, 19, and 28% for specimens with 79, 91, and 118% MC, respectively. In comparison, changes in MOE_{dyn} for dry specimens were only 1–3%.

For dry wood specimens (0–25% MC), relative MOE_{dyn} continuously increased with decreasing T from -2.5 to -40°C. For every 10°C T decrement, there was a further 1.8–2.2% increase in MOE_{dyn}. There was no discontinuity around freezing point (Figure 4d).

For green wood specimens (79–118% MC), after the abrupt increase around freezing point, the relative MOE_{dyn} continuously increased from -2.5 to -40°C, but at a slower rate. For every 10°C decrement, there was a further 3.8–4.4% MOE_{dyn} increment.

Models for predicting relative dynamic MOE

The relationships between relative MOE_{dyn} and temperature can be characterized by the following segmented linear regression models at two different T ranges:

$$\Delta MOE_{dyn}=a+bT\ (\%)\begin{cases}-40\leq T\leq -2.5°C\\ 2.5\leq T\leq 40°C\end{cases} \quad (6)$$

In the T range $2.5\leq T\leq 40$°C, the change of MOE_{dyn} was relatively small for all the specimens, ranging from -2.9 to 2.8%, but overall it showed a slight decreasing trend with increasing T. The following model describes this observation:

$$\Delta MOE_{dyn}=2.1679\text{-}0.088T \quad (R^2=0.97) \quad 2.5\leq T\leq 40°C. \quad (7)$$

In the T range $-40\leq T\leq -2.5$°C, the MOE_{dyn} change was dependent on both MC and T and the T dependency can be expressed as:

$$\Delta MOE_{dyn}=\Delta MOE_{dyn@-25°C}+b(T+2.5)(\%) \quad (8)$$

where $\Delta MOE_{dyn@-2.5°C}$ represents the change of MOE_{dyn} at -2.5°C relative to that at 20°C.

Figure 3c shows the empirical relationship between relative MOE_{dyn} at -2.5°C ($\Delta MOE_{dyn@-2.5°C}$) and MC of wood specimens, which can be expressed using the following exponential model:

$$\Delta MOE_{dyn@-2.5°C}=1.7276e^{0.024MC}\ (R^2=0.97) \quad (9)$$

Our data analysis indicated that the correlation coefficient b in Equation 8, which represents the relative MOE_{dyn} change, was MC dependent below -2.5°C. Correlation coefficient b was found to have the following linear relationship with MC:

$$b=\text{-}0.19\text{-}0.002MC \quad (R^2=0.96) \quad (10)$$

By integrating Equations 8, 9 and 10, the following general empirical model is valid below freezing point:

$$\Delta MOE_{dyn}=1.7276e^{0.024MC}\text{-}(0.19+0.002MC)(T+2.5) \quad (-40\leq T\leq -2.5°C) \quad (11)$$

Figure 4e demonstrates the predicted relationships between relative MOE_{dyn} and T at various MC levels. The straight lines between 2.5 and -2.5°C simply represent the transition of relative MOE_{dyn} around freezing point. From a practical point of view, MOE_{dyn} may be considered constant when T_{wood} is above freezing, therefore no T adjustment is needed. When wood is measured below freezing, the MOE_{dyn} can be adjusted for T for woods with various MCs. As an illustration, Table 2 shows the predicted values of relative MOE_{dyn} for red pine in the frozen state with MC from 10 to 120%.

Conclusions

MOE_{dyn} of frozen wood is heavily influenced by temperature, i.e., below the freezing point, MOE_{dyn} increased continuously with decreasing temperature. In non-frozen state this effect is not perceptible. MC had a significant effect on the $MOE_{dyn}-T$ relationships, especially above FSP. The trends of MOE_{dyn} changes were well reflected by variation of ultrasound velocity in terms of temperature.

Table 2 Predicted percentage of change in MOE_{dyn} relative to that at 20°C for frozen red pine with various MC levels.

Temp. (°C)	Percentage of change in MOE_{dyn} (%) at the MCs (%) indicated											
	10	20	30	40	50	60	70	80	90	100	110	120
-2.5	2.2	2.8	3.5	4.5	5.7	7.3	9.3	11.8	15.0	19.0	24.2	30.8
-5	2.7	3.4	4.2	5.2	6.5	8.1	10.1	12.7	15.9	20.0	25.2	31.9
-10	3.8	4.5	5.4	6.5	7.9	9.6	11.7	14.4	17.8	22.0	27.3	34.0
-15	4.8	5.7	6.7	7.9	9.4	11.2	13.4	16.2	19.6	23.9	29.3	36.2
-20	5.9	6.8	7.9	9.2	10.8	12.7	15.0	17.9	21.5	25.9	31.4	38.3
-25	6.9	8.0	9.2	10.6	12.3	14.3	16.7	19.7	23.3	27.8	33.4	40.5
-30	8.0	9.1	10.4	11.9	13.7	15.8	18.3	21.4	25.2	29.8	35.5	42.6
-35	9.0	10.3	11.7	13.3	15.2	17.4	20.0	23.2	27.0	31.7	37.5	44.8
-40	10.1	11.4	12.9	14.6	16.6	18.9	21.6	24.9	28.9	33.7	39.6	46.9

MOE_{dyn}, dynamic modulus of elasticity (GPa); MC, moisture content (%).

MOE_{dyn} changes in dry wood were slow and continuous but for green wood, a sharp discontinuity in MOE_{dyn} occured around the freezing point due to ice formation. MOE_{sta} was influenced by temperature in a similar manner as in the case of MOE_{dyn}. However, the relative change of MOE_{dyn} in the frozen condition was less pronounced than in the case of MOE_{sta}. Analytical models were developed to predict the percentage of change in MOE_{dyn} relative to that obtained at 20°C in the case of acoustic measurements under different temperature conditions. The experimental data in this study are limited and thus more experimental work is needed to test the temperature adjustment hypothesis.

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