Stress Wave E-Rating of Structural Timber—Size and Moisture Content Effects

Xiping Wang
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA, xwang@fs.fed.us

Abstract

The objectives of this study were to investigate the influence of cross-sectional size and moisture content on stress wave properties of structural timber in various sizes and evaluate the feasibility of using stress wave method to E-rate timber in green conditions. Four different sizes of Douglas-fir (*Pseudotsuga menziesii*) square timbers were tested using both stress wave and static bending methods at different moisture levels, ranging from green to dry conditions. As expected, stress wave velocity increased continuously as moisture content decreased through the whole moisture range studied. Master velocity–moisture relationships were established for Douglas-fir square timbers to convert stress wave velocity values from one moisture condition to any other moisture conditions. It was found that stress wave based dynamic MOE was generally higher than static bending MOE. However, the difference tended to be constant when moisture content was above the fiber saturation point (28%). This implied that green timber could still be sorted effectively based on dynamic MOE values even if there are moisture differences between individual pieces. The results also show that cross-sectional dimension of square timbers has a significant influence on dynamic MOE. As the cross-sectional size of square timbers increased, the MOE deviation increased also. This indicates that different sizes of timbers can not be graded together without making appropriate adjustments on dynamic MOE for size effect.

Keywords: Stress wave, structural timber, modulus of elasticity, moisture content, size

Introduction

Longitudinal stress wave technology has been widely used to evaluate the performance of various wood products in wood industry but more research is needed to enhance its application in timber grading. The fundamental wave theory used to evaluate the modulus of elasticity (MOE) of wood was developed for long slender rods of isotropic and elastic materials. Problems arise for wood with various cross-sectional sizes and high levels of moisture content (above fiber saturation point). Stress wave predicted MOE of wood in the forms of structural lumber (including dimensional lumber and structural timber) were significantly deviated from their static counterpart when the fundamental wave theory was applied. The objectives of this study were to investigate the influence of cross-sectional size and moisture content on stress wave properties of structural timber and evaluate the feasibility of using stress waves to E-rate timbers in green conditions.

Background

Predicting the MOE of structural lumber with longitudinal stress waves has received considerable research effort in recent years in terms of lumber grading or presorting. Typically, the MOE of a lumber is determined from the one-dimensional wave equation:

$$MOE_d = C^2 \rho \qquad (1)$$

where MOE_d is dynamic MOE (stress wave MOE), C is wave velocity, and ρ is gross density. This fundamental wave equation was developed for idealized elastic materials in the form of a long slender rod (Meyers 1994). Its application in wood materials can be affected by many factors, such as grain angle, knots, wood moisture content, and wood temperature, as well as dimensional size and geometrical form of a material.

Many investigations have dealt with the effects of moisture content, temperature, grain angle, and knots on stress wave behavior in wood. Stress wave velocity has been shown to decrease as either moisture content or temperature of wood is increased (James 1961; Burmester 1965; Gerhards 1975; Wang 1999; Han et al. 2006). Dynamic MOE calculated from wave velocity and wood density increases as moisture content increases above the fiber saturation point (FSP) (Galligan and Courteau 1965; Gerhards 1975; Sobue 1993). However, no attempt has been made to systematically investigate moisture influence on stress wave properties of structural lumber in different sizes and establish valid moisture adjustment on stress wave measures.

Gerhards (1982) studied the effects of knots on stress waves in lumber and found that wave velocity was slowed through knots and the curved grain around knots. Gerhards also suggested that, in lumber with cross grain and knots, the stress wave does not propagate with a normal wave front as supposed by the long slender rod theory but has a wave front that leads in the direction of the grain and lags across the grain or through knots. This non-normal wave front causes some problems in timing stress waves, particularly in large, short wood members.

The sizes (both cross section and length) and geometrical form of wood have also been recognized as critical factors to the application of the fundamental wave equation for wood property prediction (Wang et al. 2004). Theoretically, the one-dimensional wave Equation (1) is developed based on uniaxial stress. However, in a real case, there is radial inertia and a wave interaction with the external surfaces (free surfaces) of the material (Meyers 1994). Radial inertia is caused by the kinetic energy of the material flowing radially outward as the material is compressed. This effect, controlled by the dimensional size of materials, could have a significant bearing on the interpretation of stress-wave properties. Porter et al. (1972) first noted from experiments that stress-wave velocity could be affected by the dimensional size of the material in lumber testing. As a 51-mm by 305-mm (nominal 2- by 12-in.) lumber was cut down to 51 by 152 mm (nominal 2 by 6 in.) and 51 by 76 mm (nominal 2 by 3 in.), Porter et al. observed a continuous increase in wave velocity. Although the change in wave velocity may not be significant, it may introduce a significant change in dynamic MOE calculated from wave velocity and wood density since dynamic MOE is proportional to C^2. Wang (1999) investigated stress-wave behavior in red pine logs and found that high diameter to length ratio could cause significant changes in the wave propagation path with respect to longitudinal direction. Quantitative analyses of the effect of dimensional size on stress wave E-rating of structural lumber is still lacking.

Materials and Methods

Specimen preparation

The specimens used in this study were green Douglas-fir square timbers that were originally used for a heat sterilization study (Simpson et al 2003). After heat treatment (using steam with low wet-bulb depression), they were immediately stored under water spray for the purpose of this study. The specimens are 2.44-m long and included four size groups: 102 by 102 mm (4 by 4 in.), 152 by 152 mm (6 by 6 in.), 203 by 203 mm (8 by 8 in.), and 254 by 254 (10 by10 in.). Each size group included five specimens, which resulted in a total of 20 square timber specimens.

Experimental procedure

Table 1 shows the experimental matrix for testing square timber specimens. All timber specimens were first nondestructively (stress wave and static bending) tested in their initial green condition (MC_1). They were then stored in a condition room with 23 °C temperature and 65% relative humidity (RH) for air drying. During the drying process, stress wave and static bending tests were performed at four intermediate moisture levels (MC_2, MC_3, MC_4, and MC_5). The dimension, length, and weight of each specimen were also measured each time. At the end, all specimens were stored in a 32 °C and 25% RH condition room for about six months to allow each specimen conditioned to 5% equilibrium moisture content (EMC) (MC_6). Each specimen was then tested using the same procedure.

Table 1. Experimental matrix for examining the size and moisture effects on stress wave properties of structural lumber

Size of specimen	Moisture levels of specimen						Length-depth ratio
	Green	Intermediate moisture condition				5% EMC	
	MC_1	MC_2	MC_3	MC_4	MC_5	MC_6	
	Replicates						
102 by 102	5	5	5	5	5	5	24.0
152 by 152	5	5	5	5	5	5	15.3
203 by 203	5	5	5	5		5	11.2
254 by 254	5	5	5	5		5	8.8

Stress wave measurements

Stress wave measurement was conducted on each timber specimen to obtain the stress wave velocity. A stress wave was initiated by a hammer impact on one end of the timber. Stress wave propagation in the timber was sensed by a piezoelectric transducer mounted on the other end of the timber. Waveforms were displayed and analyzed using a personal computer through a data acquisition system and a software program. The program measured the time (Δt) between adjacent peaks in the waveform, which is the wave propagation time through a timber. Stress wave velocity can be determined by the equation

$$C = \frac{2L}{\Delta t} \tag{2}$$

where C is stress wave velocity in a specimen (m/s), L the length of the specimen (m), and Δt the stress wave propagation time (s). From stress wave velocity (C) and wood density (ρ) of the specimens, the dynamic modulus of elasticity (MOE_d) can be calculated using the fundamental wave Equation (1).

Static bending tests

Following stress wave measurements, all specimens were mechanically tested in bending with an Instron instrument to obtain the modulus of elasticity at various moisture levels. The static bending tests were conducted on each specimen within elastic limit using center-point loading (three replications for each specimen at each moisture condition) (ASTM 2003).

The square timbers were tested with center loading applied to the radial face with a test span of 2.13 m. The load-deflection data was recorded by the machine and the apparent modulus value was calculated using Instron's Merlin software, which is based the equation

$$\mathrm{MOE} = \frac{Pl^3}{48I\delta} \tag{3}$$

where P is the applied load (kgf), l the test span (cm), I moment of inertia (cm^4), and δ the midspan deflection (cm).

Density and moisture content determination

The dimension (cross section size and length) and weight of each specimen were measured at each moisture condition during the experimental process. Density of each specimen was calculated based on the weight and volume at each moisture level. After the stress wave and mechanical tests were completed, a moisture sample was cut from each specimen and its moisture content was determined using the oven dry method (ASTM D 4442-92, ASTM 2003). The size of moisture samples varied for different specimens, but generally was a 38-mm-thick slice cut from the location 152 to 305 mm from one end and contained no defects. The oven-dry determined MC of each moisture sample was then used to estimate the oven-dry weight of the corresponding specimen using the following equation:

$$W_{OD}^{\wedge} = \frac{W_0}{1 + MC_0} \tag{4}$$

where $W_{OD}^{\wedge}$ is the estimate of oven-dry weight of the specimen (g),; MC_0, the moisture content of the moisture sample at the equilibrium condition (%), and W_0, the weight of the specimen at equilibrium condition (g).

The moisture content of each specimen at each testing condition was then determined based on the weight measured at the time of testing and the estimated oven-dry weight of the specimen $W_{OD}^{\wedge}$

$$\mathrm{MC}_i = \frac{W_i - W_{OD}^{\wedge}}{W_{OD}^{\wedge}} \times 100\% \tag{5}$$

where MC_i is the moisture content of a specimen at moisture level i (%), and W_i, the weight of the specimen at moisture level i (g).

Results and Discussion

The initial moisture content of the timber specimens ranged from 32% to 63%. The specimens of 102 by 102 mm and 152 by 152 mms were tested at four intermediate moisture levels during drying process as originally planned (Table 1), but 203 by 203 mm and 254 by 264 mm specimens were tested at only three intermediate moisture levels because of limited machine time.

The nominal depth of the timber specimens ranged from 102 to 264 mm, which resulted in span-depth ratios ranging from 24 to 8.8. The small span-depth ratios for square timber specimens, especially for 203- by 203-mm and 264- by 264-mm timbers, could introduce a significant shear deflection to the beam in static bending testing.

The shear deflection, governed by the characteristics of the timber and the loading condition, can be estimated mathematically (Biblis 1965). For a simply supported beam loaded at midspan, the deflection due to shear is given by

$$\delta_s = \frac{0.3Pl}{AG} \tag{6}$$

Where P is the load (kgf), l is the span length (cm), A is the cross section area (cm^2), and G the shear modulus (Pa).

Assume that the ratio of E to G is constant, having a value of 16 for wood, the true modulus of elasticity (E) of the timber specimens can be calculated using the following equation (Bodig and Jayne 1982):

$$E = \left[1 + \frac{K}{(l/h)^2}\right]\text{MOE} \tag{7}$$

Where K is a constant controlled by the loading condition (K = 19.20 for concentrated load at the center), h is the depth of the timber specimens (cm).

The effect of span to depth ratio (*l/h*) for wood beams with concentrated load at the center is illustrated in Figure 1. As span-to-depth ratio decreases, shear deflection increases, thus the magnitude of error introduced by ignoring shear deflection gets bigger. To correct shear effect, true modulus of elasticity of each timber specimen was determined using Equation (12).

Figure 2 shows the relationship between stress wave velocity and moisture content for all timber specimens. The velocity–moisture relations for timber specimens were found analogous to what observed in dimension lumber specimens (Wang 2008). Stress wave velocity increased continuously as moisture content decreased. Stress wave velocity changed more rapidly in low moisture level (below FSP) than in high moisture level (above FSP). It was noted that all square timber specimens tend to have same type of velocity–moisture relationships. It is therefore possible that a master equation can be built to adjust stress wave velocity for moisture effect.

Table 2 shows the results of regression analysis for the relationships between stress wave velocity and moisture content of Douglas-fir timbers. A nonlinear regression analysis based on a backward selection procedure was performed to establish the empirical relationships. It was found that a second-order polynomial regression model fits the experimental data. By averaging the regression coefficients of individual models, a master velocity–moisture relationship was developed:

$$C = C_0 - 148.706(\text{MC}) + 1.4525(\text{MC}^2) \tag{8}$$

Where C_0 is a constant that depends on the properties of specific timber.

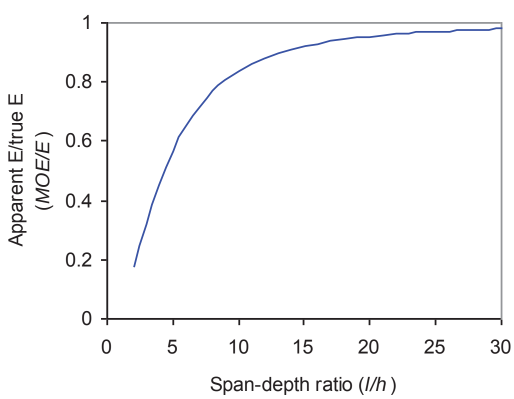

Figure 1. Effect of span to depth ratio (l/h) on the ratio of apparent to true modulus of elasticity for wood beams with concentrated load at the midspan.

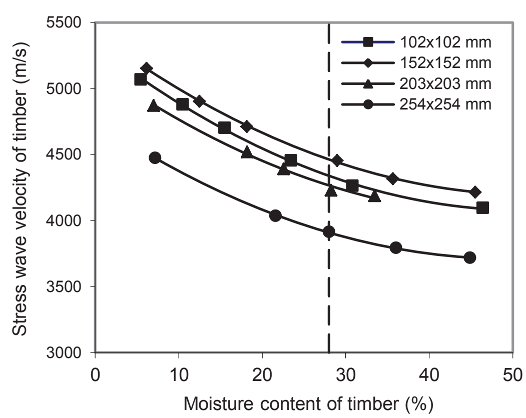

Figure 2. Relationship between stress wave velocity and moisture content of square timbers.

Table 2. Regression analysis of the relationships between stress wave velocity and moisture content of square timbers

Size group	Regression model: $C = a + b(MC) + c(MC^2)$				
	a	*b*	*c*	r^2	S_{xy}*
102 × 102	17472	–158.377	1.5290	0.999	53.3
152 × 152	17780	–152.731	1.4499	0.999	34.4
203 × 203	16949	–145.849	1.4419	0.994	94.8
254 × 254	15594	–137.867	1.3890	1.000	23.7

* S_{xy} - Standard error

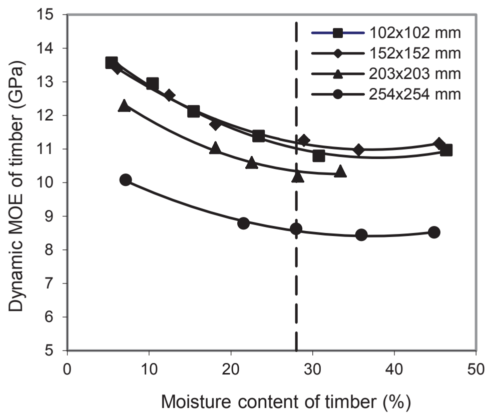

Figure 3. Relationship between dynamic modulus of elasticity and moisture content of Douglas-fir square timbers.

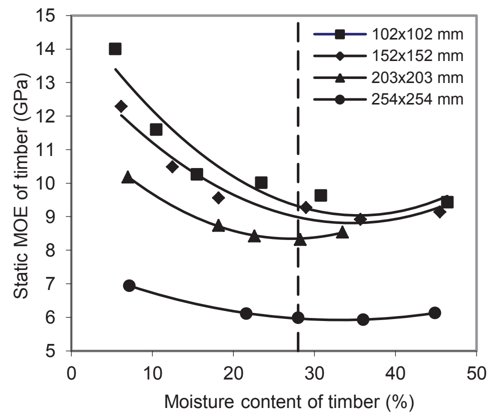

Figure 4. Relationship between static bending modulus of elasticity and moisture content of Douglas-fir square timbers.

For a given timber, if the stress wave velocity (C_1) is measured at moisture condition of MC_1, then the velocity can be converted to a value at any moisture content MC_2 (within the tested moisture range) using the following equation:

$$C_2 = C_1 - 148.706(\mathrm{MC}_2 - \mathrm{MC}_1) + 1.4525(\mathrm{MC}_2{}^2 - \mathrm{MC}_1{}^2) \quad (9)$$

Figure 3 and Figure 4 show the relationships between modulus of elasticity and moisture content for square timber specimens. Note that Figure 4 relates the true modulus of elasticity to MC. The results indicated that both dynamic modulus and static modulus decreased with increasing moisture content when MC was below FSP, but they remained relatively constant when MC was above FSP. This finding is consistent with what we observed in dimension lumber specimens (Wang 2008).

Figure 5 shows the comparison of dynamic MOE and static MOE at various moisture levels for the Douglas-fir timbers. The dynamic MOE of square timber were generally higher than their static counterpart. The deviation of dynamic MOE from static E (true value) was affected by the moisture content for 102- × 102-mm and 152- × 152-mm timbers when MC was below FSP, but the moisture effect on MOE diminished as timber size increased to 203 × 203 mm and 254 × 254 mm.

We also noticed that despite a significant deviation between dynamic and static MOE values, the dynamic MOE generally followed the same trend as static MOE. The MOE deviation in each size group was relatively constant when MC was above FSP. This implied that green timber could still be sorted effectively on the basis of dynamic MOE value even if there are moisture differences between individual pieces, as long as all timbers are in green condition.

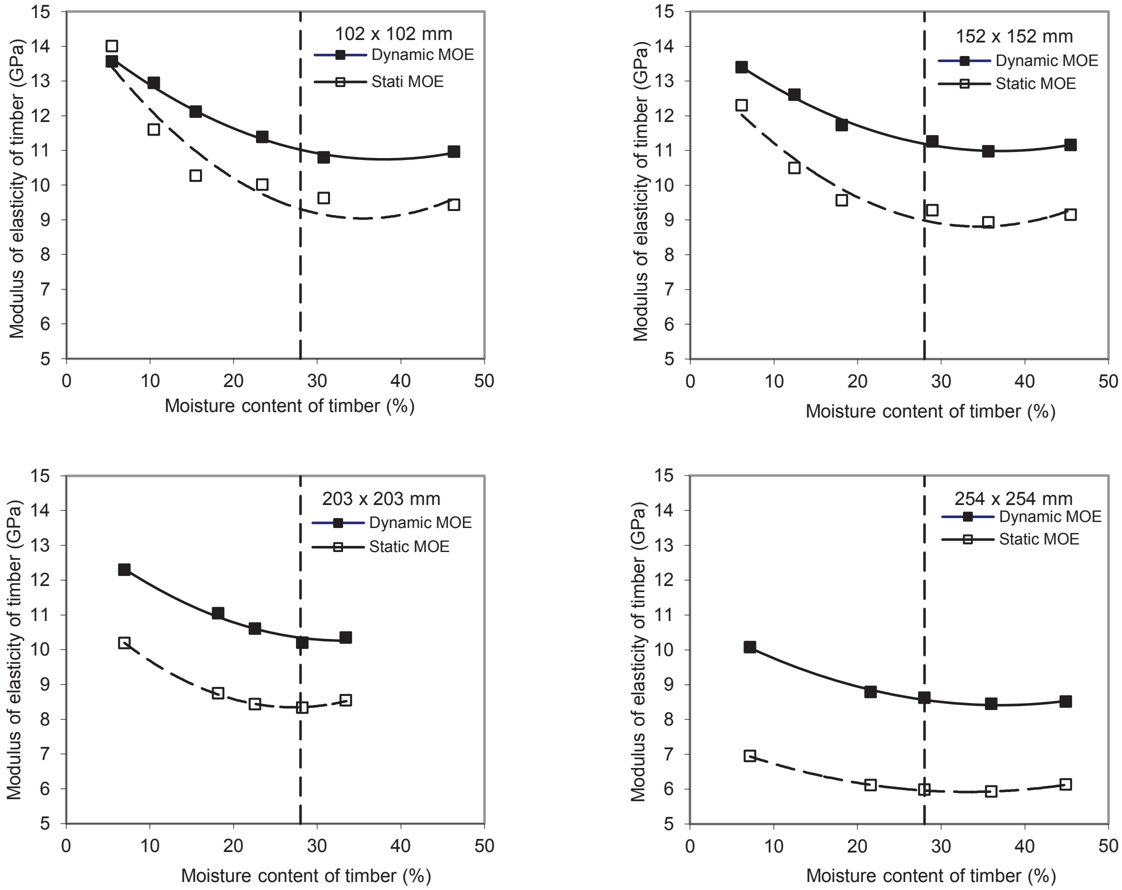

Figure 5. Comparison of dynamic MOE and static MOE at various moisture levels for square timber.

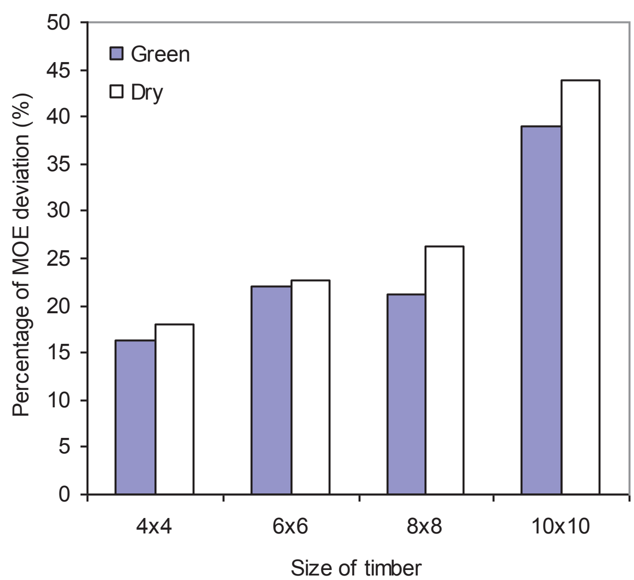

Figure 6. Average percentage of MOE deviation for each size group of square timber specimens at green (34%–46%) and dry (16%–22%) conditions.

Figure 6 is a histogram illustrating the average percentage of MOE deviation for each size group of timber specimens at green (34%–46%) and dry (16%–22%) conditions. Apparently, the size of timber has a significant impact on stress wave-E rating at both green and dry conditions. As the size of timbers increased, the MOE deviation increased. This implies that different sizes of timbers can not be graded together without making appropriate adjustments on dynamic MOE for size effect.

Conclusion

This study explored the effects of moisture content and cross-sectional dimension on stress wave E-rating of Douglas-fir timbers. From the results of the study, we conclude the following:

1. Stress wave velocity of Douglas-fir timbers increased continuously as moisture content decreased through the whole moisture range studied. Stress wave velocity changed at a much slower rate in high moisture levels (above fiber saturation point) than in low moisture levels (below FSP).

2. A master velocity–moisture relationship was formed for different size groups of the square timbers. This empirical model can be used to convert stress wave velocity values measured at one moisture condition to any other moisture conditions.

3. Below the fiber saturation point, dynamic modulus of elasticity increased continuously as moisture content decreased. Above the fiber saturation point, dynamic MOE remained relatively constant.

4. The dynamic modulus of elasticity of the square timbers was generally higher than the static bending modulus of elasticity. The deviation of dynamic MOE from its static counterpart was affected by the moisture content of the specimens when MC was below FSP. The MOE deviation were relatively constant when moisture level was above FSP. This implied that green timber could still be sorted effectively based on dynamic MOE values even if there are moisture differences between individual pieces.

5. We found that the cross-sectional dimension did have a significant influence on MOE deviation for Douglas-fir square timbers. As the cross-sectional size of the timber increased, the MOE deviation increased also. This indicates that different sizes of timbers can not be graded together without making appropriate adjustments on dynamic MOE for size effect.

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Proceedings
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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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