Effects of Size and Moisture on Stress Wave E-rating of Structural Lumber

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Summary

This paper discusses the effects of size and moisture content on stress wave properties of wood and evaluates the feasibility of using stress waves to E-rate Douglas-fir dimension lumber in green condition. Six size groups of Douglas-fir lumber were tested using both stress wave and static bending methods at different moisture levels, ranging from green to dry conditions. Stress wave speed increased continuously as moisture content decreased through the whole moisture range studied. General speed-moisture relationships were developed to adjust stress wave speed values from one moisture condition to any other moisture conditions. It was found that stress wave based dynamic modulus of elasticity (MOE) is generally higher than static bending MOE. However, the difference tends to be constant when moisture content is above fiber saturation point. This suggests that green lumber can be sorted effectively based on dynamic MOE values even if there are moisture differences between individual pieces.

1. Introduction

Longitudinal stress waves have great potential to be implemented as a quality control tool through the operation value chain but more research is needed to enhance its application. The fundamental wave theory used to evaluate the modulus of elasticity 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 (FSP)). Stress wave predicted MOE of wood in the forms of structural lumber often deviates from their static counterpart when the fundamental wave theory is applied (Galligan and Courteau 1965, Gerhards 1975, Sobue 1993, Wang 1999, Wang et al. 2004). The objectives of this study are to investigate the influence of cross sectional size and moisture content on stress wave properties of wood and evaluate the feasibility of using stress waves to E-rate Douglas-fir dimension lumber in green condition.

2. Materials and Methods

2.1 Specimen Preparation

The lumber specimens used in this study were cut from green Douglas-fir timber that had undergone a heat sterilization treatment in a previous project. After heat treatment with saturated steam (dry bulb temperature: 71 ºC), they were immediately stored under water spray to maintain green condition. All lumber specimens were 2.44-m (8 ft.) long and 51-mm (nominal 2 in.) thick. The specimens were prepared to include six size groups based on width: 1) 51×51 mm (nominal 2×2 in.); 2) 51×102 mm (nominal 2×4 in.); 3) 51×152 mm (nominal 2×6 in.); 4) 51×203 mm (nominal 2×8 in.); 5) 51×254 mm (nominal 2×10 in.); and 6) 51×305 mm (nominal 2×12 in.). Each group has five specimens, which resulted in a total of thirty lumber specimens.

2.2 Experimental Procedure

All lumber specimens were first nondestructively tested in their initial green condition using stress wave and static bending methods. They were then stored in a condition room with 23.3° 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. The cross sectional size (width and thickness), length, and weight of each specimen were measured each time. At the end, all specimens were stored in a 32.2° C and 25% RH condition room for six months to allow each specimen to be conditioned to 5% equilibrium moisture content (EMC). Each specimen was then tested using the same procedure.

2.2.1 Stress Wave Measurement

Stress wave measurement was conducted on each specimen while it lay on the top of the wood stack. A stress wave was initiated by a hammer impact on one end of the lumber. Stress wave propagation in the lumber was detected and monitored through a piezoelectric transducer mounted on the other end of the lumber. Stress wave speed was determined by measuring the wave propagation time and lumber length. Dynamic modulus of elasticity of each lumber was calculated using the fundamental wave equation:

$$MOE_d = C^2 \rho \tag{1}$$

Where MOE_d is dynamic modulus of elasticity (GPa), C is stress wave speed (m/s), and ρ is gross density (kg/m^3).

2.2.2 Static Bending Test

Following stress wave measurement, all lumber specimens were mechanically tested in flatwise bending to obtain static MOE at various moisture levels (ASTM 2003a). The static bending tests were conducted on each specimen within elastic limit using center-point loading. The load-deflection data was recorded by the Instron machine and static MOE was calculated using Instron’s Merlin software, which is based on the formula:

$$MOE = \frac{Pl^3}{48I\delta} \tag{2}$$

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

2.2.3 Density and Moisture Content Determination

The dimension (width, thickness, 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 static bending tests were completed, a moisture sample was cut from each lumber specimen and its moisture content was determined using the oven dry method (ASTM D 2003b). The MC value of each moisture sample was then used to estimate the oven-dry weight of the corresponding lumber specimen using the following equation:

$$W_{OD}^{\wedge} = \frac{W_0}{1 + MC_0} \qquad (3)$$

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

The moisture contents of the lumber specimens at each testing condition were then determined based on the weight measured at the time of testing and the estimated oven-dry weight $W_{OD}^{\wedge}$:

$$MC_i = \frac{W_i - W_{OD}^{\wedge}}{W_{OD}^{\wedge}} x100\% \qquad (4)$$

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

3. Results and Discussion

The initial moisture content of the specimens ranged from 34% to 126% on individual basis and from 44.5% to 79.2% on group basis. The moisture range of the specimens was in agreement with the moisture content values of green Douglas-fir wood (heartwood: 37%, sapwood: 115%) given in the Wood Handbook (Forest Products Laboratory 1999).

Figure 1 shows the relationships between stress wave speed and moisture content for six size groups of Douglas-fir lumber. It was noted that the stress wave speed varied from group to group, with 51×254 mm (2×10 in.) group having the lowest speed and 51×51 mm (2×2 in.) group having the highest speed. This is presumably due to wood property difference between the groups. For all size groups, stress wave speed increased continuously as moisture content decreased. Stress wave speed changed more rapidly in low moisture level (below FSP) than in high moisture level (above FSP). These results are consistent with the findings from previous studies (James 1961, Burmester 1965, Gerhards 1975, Wang 1999). It is also found that all size groups have similar speed-moisture relations in low moisture levels (below FSP), but this is not the case in high moisture levels (above FSP). The slopes of the speed-moisture curves for 51×203 mm (2×8 in.), 51×254 mm (2×10 in.), and 51×305 mm (2×12 in.) are much smaller than those for the 51×51 mm (2×2 in.), 51×102 mm (2×4 in.), and 51×152 mm (2×6 in.) when MC is above FSP. This implies that lumber width has certain effects on speed-moisture relations. One possible contributing factor could be the moisture gradient caused by uneven drying in wider pieces of lumber.

Table 1. Regression analysis of the relationships between stress wave speed and moisture content of Douglas-fir dimension lumber [a].

Size group	Regression model: C = a + b(MC) + c(MC^2)				
	a	b	C	r^2	S_{xy}
51 × 51 mm	18306	-89.376	0.3464	0.993	179.0
51 × 102 mm	17853	-100.086	0.4971	0.995	155.1
51 × 152 mm	17771	-104.174	0.5641	0.999	82.9
51 × 203 mm	17277	-134.191	1.2751	0.996	88.5
51 × 254 mm	15214	-102.614	0.7345	0.987	180.2
51 × 305 mm	17342	-121.382	0.8727	0.989	179.8

[a] C- ft/s, 1 ft/s = 0.3048 m/s; S_{xy} - Standard error

Table 1 shows the results from regression analysis of relationships between stress wave speed and moisture content for Douglas-fir lumber. 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 sufficiently:

$$C = a + b(MC) + c(MC^2) \tag{5}$$

From the regression analysis, it appeared that the Douglas-fir lumber may be separated into two size groupings: 1) 51×51 mm (2×2 in.), 51×102 mm (2×4 in.), and 51×152 mm (2×6 in.); 2) 51×203 mm (2×8 in.), 51×254 mm (2×10 in.), and 51×305 mm (2×12 in.). A general equation relating stress wave speed to moisture content can be developed for each size grouping as follows:

$$C = C_0 - 97.879(MC) + 0.4692(MC^2) \tag{6}$$

for 51×51 mm, 51×102 mm, and 51×152 mm lumber.

$$C = C_0 - 119.396(MC) + 0.9608(MC^2) \tag{7}$$

for 51×203 mm, 51×254 mm, and 51×305 mm lumber.

Where, C_0 is a constant. Note that equations (6) and (7) are only valid in the tested moisture ranges. With above equations, for a given piece of Douglas-fir lumber, if stress wave speed is measured at a moisture condition of MC_1, then the speed value can be adjusted to any moisture condition level (MC_2) using the following equations:

$$C_2 = C_1 - 97.879(MC_2 - MC_1) + 0.4692(MC_2{}^2 - MC_1{}^2) \tag{8}$$

for 51×51 mm, 51×102 mm, and 51×152 mm lumber.

$$C_2 = C_1 - 119.396(MC_2 - MC_1) + 0.9608(MC_2{}^2 - MC_1{}^2) \tag{9}$$

for 51×203 mm, 51×254 mm, and 51×305 mm lumber.

Figure 2 and Figure 3 show the relationships between dynamic and static MOE and moisture content of Douglas-fir lumber. Similar to static MOE, the dynamic MOE increases as MC decreases when MC is below FSP. However, the dynamic MOE appears not to be affected by moisture content when MC is above FSP. For example, as MC of 51×152 mm (2×6 in.) lumber increased from 32% to 66% and 79%, the dynamic MOE changed from 12.00 to 11.58 and 11.79 MPa (1.74 to 1.68 and 1.71 $\times 10^6$ lb/in^2), only 2 to 3 percent fluctuation. Over the same moisture range, the static MOE changed from 10.96 to 10.41 and 10.55 MPa (1.59 to 1.51 and 1.53 $\times 10^6$ lb/in^2), indicating a 4 to 5 percent fluctuation. It is evident from these results that dynamic MOE follows the same trend as static MOE when moisture changes from green to dry condition. These findings are similar to the results reported by Wang (1999), but quite different from the results reported by Gerhards (1975). It has been noticed that, in Gerhards' study, the targeted moisture contents of the 51×102 mm (2×4 in.) lumber were obtained through kiln drying, which could have caused greater moisture gradient across the board width. The uneven drying between the inner core and the out-layer of a specimen could potentially affect stress wave speed measurement. Since the stress waves tend to seek drier portion of the board for their path, stress wave speed measured on unevenly dried boards could be biased towards high end, and consequently the dynamic MOE could be dramatically overestimated due to the power function relationship between dynamic MOE and stress wave speed as indicated by equation (1).

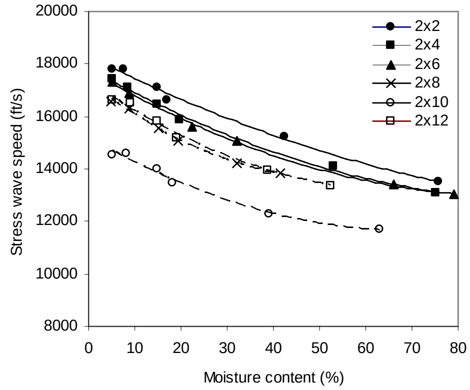


Figure 1. Relationships between stress wave speed and moisture content of Douglas-fir lumber (1 ft/s=0.3048m/s).

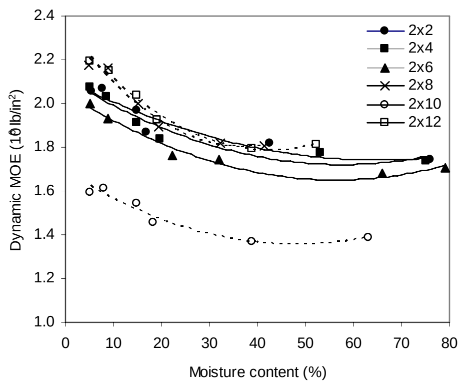


Figure 2. Relationships between dynamic MOE and moisture content of Douglas-fir lumber (1 lb/in^2 = 6.894 Pa).

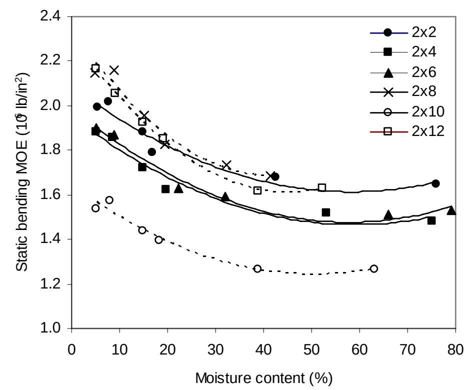
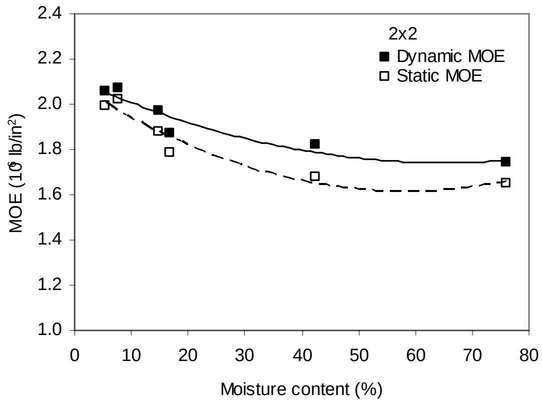


Figure 3. Relationships between static MOE and moisture content of Douglas-fir lumber (1 lb/in^2 = 6.894 Pa).

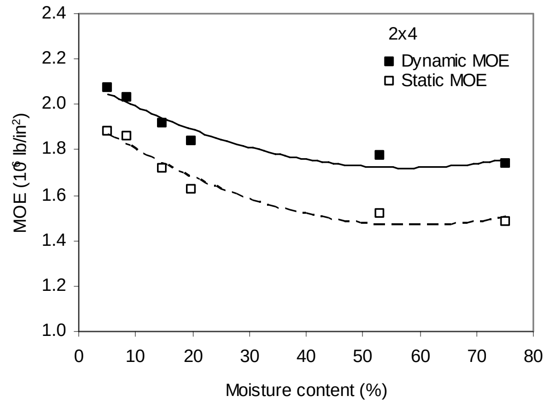
Figure 4 shows the comparison of dynamic MOE and static MOE at various moisture levels for each size group of Douglas-fir lumber. Dynamic MOE of the lumber specimens were generally higher than their static counterpart. The deviation of dynamic MOE from static MOE is apparently affected by the moisture level of the specimens.

Figure 5 shows the percentage of MOE deviation in relation to moisture content. As moisture content of the specimens decreased, the MOE deviation decreased. This indicates that stress wave E-rating of structural lumber is more accurate in low moisture levels than in high moisture levels. It was also noticed that the MOE deviation tended to be relatively constant when moisture level was above 40% to 50%. This implied that green lumber could still be sorted effectively based on dynamic MOE value even if there are moisture differences between individual pieces of lumber, as long as all lumber are in green condition.

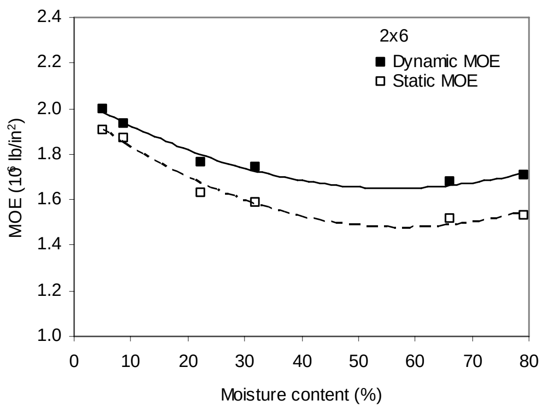
Figure 6 is a histogram illustrating the average percentage of MOE deviation for each size group of Douglas-fir lumber at green (42% – 79%) and dry (15% – 22%) conditions. Of all specimens tested, 51×102 mm (2×4 in.) lumber has the largest MOE deviation (17.1% in green and 11.4% in dry) and 51×51 mm (2×2 in.) lumber has the smallest MOE deviation (5.7% in green and 4.8% in dry). No distinct relationship was found between size and MOE deviation for Douglas-fir lumber.



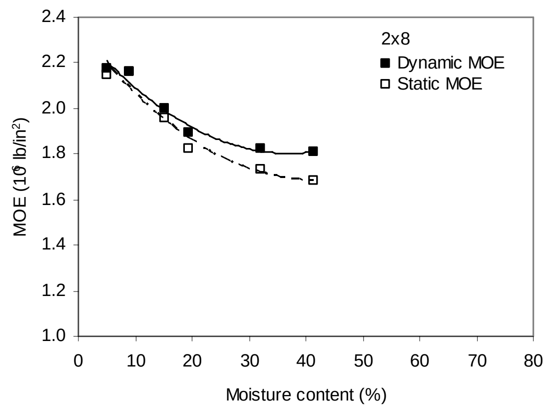
(a) 51×51 mm (2×2 in.)



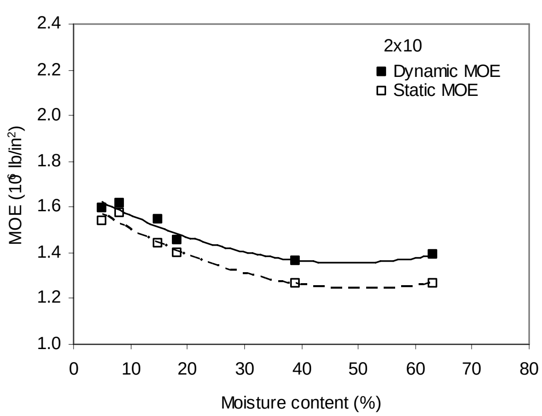
(b) 51×102 mm (2×4 in.)



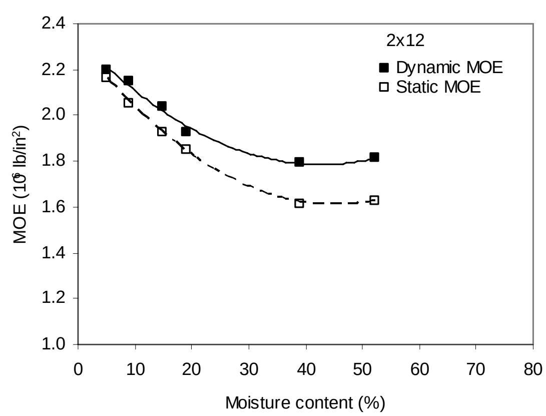
(c) 51×152 mm (2×6 in.)



(d) 51×203 mm (2×8 in.)



(e) 51×254 mm (2×10 in.)



(f) 51×305 mm (2×12 in.)

Figure 4. Comparison of dynamic MOE and static MOE of Douglas-fir lumber at various moisture levels (1 lb/in^2 = 6.894 Pa).

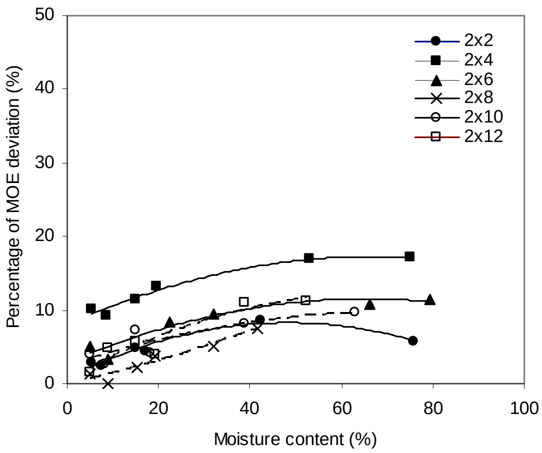


Figure 5. MOE deviation in relation to moisture content.

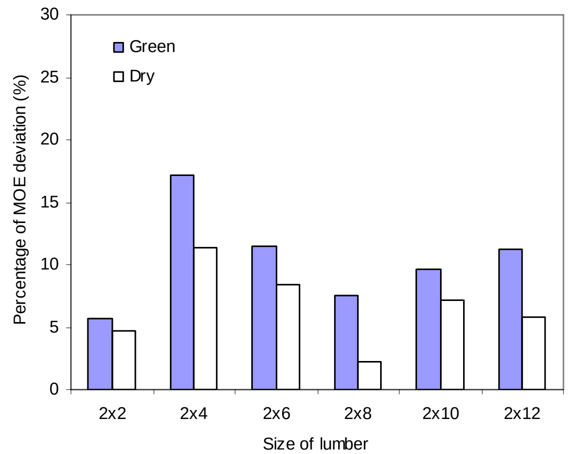


Figure 6. Average MOE deviation versus size of lumber at green and dry conditions.

4. Conclusion

This study investigated the effects of moisture content and lumber size on stress wave speed and stress wave based dynamic MOE of Douglas-fir dimension lumber. From the results of this study, we conclude the following:

1. Stress wave speed increases continuously as moisture content decreases through the whole moisture range studied. Stress wave speed changes less dramatically in high moisture levels (above fiber saturation point) than in low moisture levels (below FSP).

2. General speed-moisture relationships were developed for Douglas-fir lumber. These empirical speed-moisture models can be used to adjust stress wave speed values from one moisture condition to any other moisture conditions.

3. Below fiber saturation point, dynamic MOE of Douglas-fir lumber increases continuously as moisture content decreases. Above fiber saturation point, dynamic MOE remains relatively constant.

4. The dynamic MOE of Douglas-fir lumber is generally higher than the static bending MOE. The deviation of dynamic MOE from its static counterpart is affected by the moisture content of the specimens when MC is below FSP. The MOE deviation tends to be relatively constant when moisture level is above FSP. This indicates that green Douglas-fir lumber can be sorted effectively based on dynamic MOE values even if there are moisture differences between individual pieces of lumber.

5. No distinct relationship was found between lumber width and MOE deviation for Douglas-fir dimension lumber.

5. References

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