Chapter 10 — Nondestructive Evaluation of Green Materials—Recent Research and Development Activities

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Nondestructive evaluation (NDE) technologies are used in a variety of structural product grading programs. As presented in previous chapters, NDE is used to grade lumber and veneer and to assess timber in place. In recent years, there has been an increased emphasis by various research organizations to develop NDE techniques for assessing the potential structural quality of green materials. This chapter summerizes some recent research and developments in this area.

Trees

Property Assessment of Standing Trees

Sorting or grading trees has been an important procedure in improving the utilization of forest resources. The worldwide shift of wood supply from old-growth resources to intensively managed forest plantations increases the importance of assessing wood quality of standing trees. Traditionally, trees have been selected for harvest based on visual assessment of tree quality (diameter, height, observable defects) and stand characteristics (age, species composition, habitat type, presence of insects and diseases, and silvicultural objectives). These procedures do not incorporate estimates of the mechanical properties of wood in trees and thus do not adequately assess the potential quality of structural products that might be manufactured from the trees.

The applicability of using stress wave NDE techniques to assess the mechanical properties of wood in standing trees has been explored by a number of researchers in recent years **(Table 10.1). A** typical experimental setup

Table 10.1—Research summary on nondestructive evaluation of standing trees with stress wave methods.[a]

Reference	Tree species	NDE parameter	Reported properties	Comparison of NDE parameter of trees and reported properties (correlation coefficient r)
Nanami *et al.* (1992b)	Japanese cedar	ΔT	ΔT in logs	Good agreement (r was not reported)
Nanami *et al.* (1993)	Japanese cedar	C	MOE_d of trees	0.77
Nakamura (1996)	Todo-fir and larch	C^2	MOE_d of trees	0.94
Wang (1999), Wang *et al.* (2000b)	Western hemlock and Douglas-fir	C	C of small clear specimens	0.83
		MOE_d	MOE_d of small clear specimens	0.75
		MOE_d	MOE_s of small clear specimens	0.66
		MOE_d	MOR of small clear specimens	0.65 (western hemlock) 0.63 (Sitka spruce)
Huang (2000)	Loblolly pine	C	MOE_v of lumber	0.71
Ikeda and Kino (2000)	Japanese cedar	C	MOE_d of logs	0.56
Ikeda and Arima (2000)	Japanese cedar	C	MOE_d of log	0.61–0.68
		C	MOE_s of square timber	0.64
Ikeda *et al.* (2000b)	Japanese cedar	C	MOE_d of logs	0.56
		C	Mean MOE_d of logs	0.74–0.94
Ikeda *et al.* (2000a)	Hinoki	C	MOE_d of logs	0.64–0.80
Wu *et al.* (2000)	Douglas-fir	C_L	MOE_v of lumber	0.88
		C_R	MOE_v of lumber	0.62
		C_L^2 C_R^2	MOE_v of lumber	0.93

[a] ΔT, wave propagation time; C, C_L, stress wave speed in longitudinal direction; C_R, stress wave speed in radial direction; MOE_d, dynamic modulus of elasticity determined by stress wave method; MOE_v, modulus of elasticity determined by transverse vibration method; MOE_s, modulus of elasticity obtained from static bending tests; MOR, modulus of rupture obtained from static bending tests.

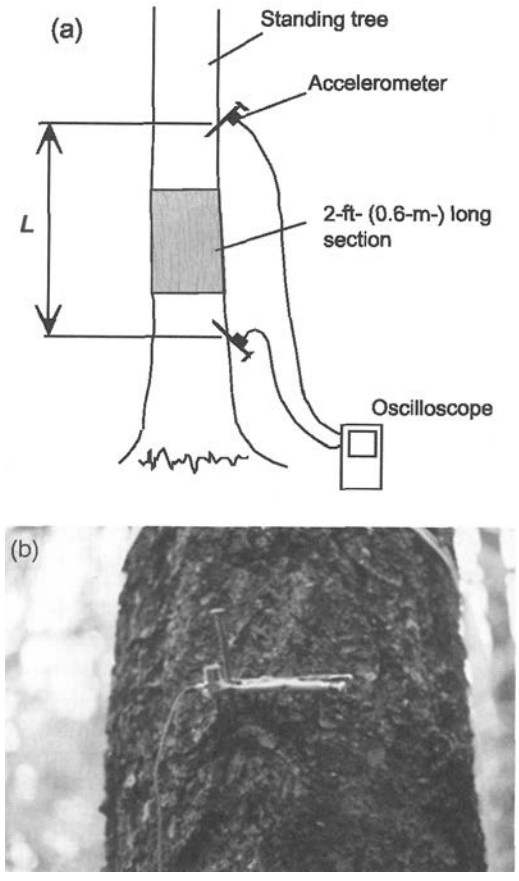

Figure 10.1 —*(a) A typical experimental setup used in the field test for tree quality evaluation (*L *is test span); (b) a transducer (upper) mounted on the trunk of a tree through a spike driven into the wood (Wang et al. 2000b).*

for conducting stress wave tests on trees is shown in **Figure 10.1.** With this setup, a stress wave is induced into the tree in such a manner that it flows primarily along the stem of the tree. Adaptations allow the measurement of stress wave transmission times in the longitudinal direction of the tree stem.

In such a setup, two accelerometers are attached to probes inserted into the tree stem. A stress wave is generated by impacting the exposed end of one probe. The resulting signals are received by start and stop accelerometers and recorded on an oscilloscope. The time it takes the stress wave to travel between the two sensors is determined and used to compute speed of wave propagation.

Nanami *et al.* (1992a,b; 1993) conducted several studies on Japanese cedar trees and found that stress wave propagation times obtained from such a setup correlated well with similar data obtained from logs cut from the trees **(Fig. 10.2).** Using a similar technique, Wang (1999) found that stress wave speeds determined from meassurements on western hemlock and Sitka spruce trees correlated well with speeds obtained from correspponding small clear speciments cur from the trees **(Fig. 10.3).**

Recent studies have focused on examining the relationships between various NDE parameters of trees and modulus of elasticity (MOE) of wood obtained from trees. Wang *et al.* (2000b) nondestrively evaluateed 168 western hemlock and Sitka spruce trees at several different stands and destructively sampled one-third of the tested trees. Stress-wave-determined MOE (MOE_d) values of trees were found to be in good agreement with those determined from small clear specimens cut from the trees. The authors also reported that stress wave properties (stress wave speed *C* and stress wave MOE) of trees correlated resonably well with static MOE and modulus of repture (MOR) of corresponding small clare specimens. Huang (2000) investigated the use of stress wave speed for predicting lumber stiffness of loblolly pine plantations and found that trees with the potential of produc-

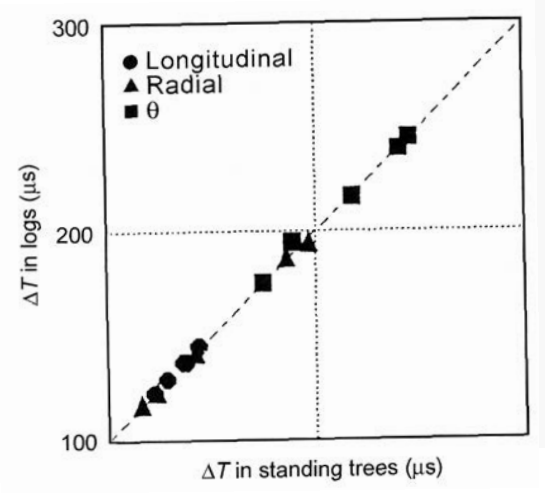

Figure 10.2—*Stress wave times* (ΔT) *measured in standing trees compared with those observed from corresponding logs (Nanami* et al. *1992b).*

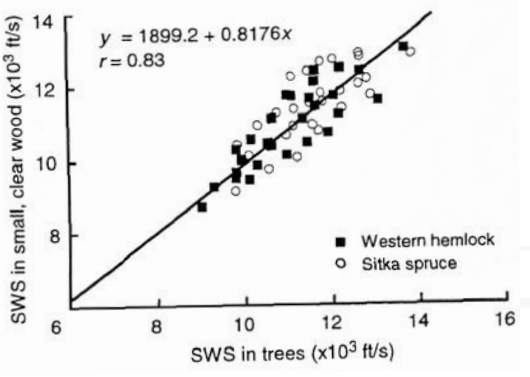

Figure 10.3 -*Relationship of stress wave speed (SWS) measured in standing trees to SWS measured in small clear specimens obtained from them (1 ft./s = 0.3408 m/s) (Wang 1999).*

ing lumber with high and low stiffness can be identified by stress wave speed alone. He concluded that the upper 15% and the lower quartile of the population could be sorted by high and low speeds, respectively.

The potential of stress wave speed of trees in both longitudinal and radial directions as a predictor of lumber MOE was explored by Wu *et al.* (2000). The results from testing six Douglas-fir trees showed that longitudinal stress wave speed C_L has a much better correlation with lumber MOE than does radial stress wave speed C. The authors also found that the correlation between the index C_L^2 C_R^2 and the average MOE of lumber was very high (r = 0.93).

Ikeda *et al.* (2000a,b) conducted a series of studies on standing trees using the stress wave propagation method with the aim of nondestructively evaluating the structural quality of trees. The stress wave speeds measured in trees (in the longitudinal direction) were compared with the dynamic and/or static properties of logs and square sawn timber obtained from the trees. The authors found highly significant correlations between MOE of logs and square sawn timbers and C of standing trees. They believe that stress wave propagation speed is an effective parameter to evaluate the mechanical properties of standing trees.

Silvicultural Practices

Quality and mechanical properties of wood are generally affected by silvicultural practices, especially stand density. Some silvicultural practices not only increase the biomass production of trees but also may improve the quality of the wood in trees. Nakamura (1996) used ultrasonically induced waves to assess Todo-fir and Larch trees. He observed significant differences in stress wave velocities and stress-wave-determined MOE for trees in forest stands at different locations and for trees of different ages. Wang

et al. (2000b) examined the effect of thinning treatments on both stress wave and static bending properties of western hemlock and Sitka spruce trees obtained from seven sites in Alaska. **Table 10.2** summarizes the results, with dynamic MOE (MOE_d) values for trees and static MOE (MOE_s) values for small clear specimens listed in decreasing order. The highest MOE values (dynamic and static) for both hemlock and Sitka spruce were found in the control stands and stands that received light thinning. The lowest MOE values (dynamic and static) were observed in stands that received heavy and medium thinning. A typical trend of stress wave and static bending characteristics as a factor of thinning regimes is illustrated in **Figure 10.4.** These results were encouraging and indicated that nondestructive stress wave techniques could be used to monitor wood property changes in trees and determine how forests could be managed to meet desired wood and fiber qualities.

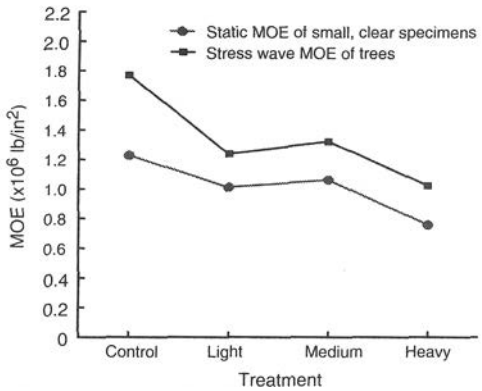

Figure 10.4 –*Modulus of elasticity (MOE) of Sitka spruce as a function of thinning treatment (control, light, medium, and heavy) (1 lb./in.^{2} = 6.894 kPa) (Wang* et al. *2000b).*

Deterioration Detection

The detection of deterioration in trees, particularly decay that does not have external indicators, is a concern to forest managers. An effective NDE method for detecting decay in standing trees would help forest managers improve stands, select cuts, make better sales, estimate volume losses, identify hazardous trees, and prevent the spread of decay.

Various techniques, based on different concepts, have been used to detect deterioration in trees. Sounding a tree by striking it with a tool can detect advanced decay or hollows inside the trunk, but this method is not effective on large thick-barked trees (Boyce 1948; McCracken 1985). X-ray and neutron radiography, computer tomography (CT), and magnetic resonance (MR) have been extensively investigated for imaging internal characteristics in logs and trees (Hailey and Morris 1987; Funt and Bryant 1987; Holoyen and Birkeland 1987; Oja *et al.* 2000). Although these techniques can supply one to three dimensional spatial locations of various defects and internal wood characteristics, their application to trees has been limited due to the high costs associated with their use.

Stress wave and ultrasonic techniques are simpler and less costly than imaging techniques. Because the propagation of stress waves or ultrasound is basically a mechanical phenomenon, it has been used frequently for detection of internal defects in wood. Stress wave transmission times or attenuation in wood has been proven to be an effective parameter to detect and estimate deterioration in wood members. Studies have shown that the presence of deterioration greatly affects stress wave transmission time in wood.

Table 10.2—Thinning effects on stress wave and static bending properties[a] (Wang *et al.* 2000b).

MOE ($\times 10^6$ lb./in.^{2})[b]													
Site 1		Site 2		Site 3		Site 4		Site 5		Site 6		Site 7	
MOE_d	MOE_s	MOE_d	MOE_s	MOE_d	MOE_s	MOE_d	MOE_s	MOE_d	MOE_s	MOE_d	MOE_s	MOE_d	MOE_s
Western hemlock													
1.39, C	1.1,C	1.32, C	1.16, C	1.98, C	1.22, C	1.51, L	1.45, L	1.66, C	1.17, C	2, L	1.22, L	1.33, L	0.9, C
1.23, M	1.09, L	1.31, M	1.15, M	1.56, L	1.16, L	1.43, C	1.12, C	1.42, L	1.15, L	1.63, C	1.15, C	1.2, M	0.9, L
1.09, L	1.08, M	1.27, L	1.11, H	1.38, M	1.15, M	1.2, H	1.05, M	1.37, M	1.05, H	1.63, C	1.1, H	1.16, C	0.79, H
1.07, H	0.87, H	1.1, H	0.9, L	1.14, H	0.98, H	1.07, M	0.96, H	1.36, H	0.97, M	1.57, H	1.07, M	1.04, H	0.75, M
Sitka spruce													
1.63, C	1.12, C	1.51, C	1.11, C	1.65, L	1.06, C	1.45, C	1.09, C	1.58, C	1.23, C	1.75, C	1.21, C	1.75, L	1.24, L
1.15, L	0.99, L	1.32, L	1.07, M	1.62, C	1.05, L	1.28, L	0.96, H	1.33, M	1.06, M	1.53, L	1.02, L	1.45, M	1.04, M
1.1, H	0.82, H	1.22, M	1.06, L	1.42, M	1.04, M	1.26, H	0.92, L	1.25, L	1.01, L	1.52, h	0.96, M	1.27, C	0.96, H
1.04, M	0.71, M	1.22, H	0.87, H	1.18, H	0.9, H	1.18, M	0.82, M	1.09, H	0.76, H	1.43, M	0.95, H	1.24, H	0.77, C

[a] MOE_d and MOE_s are tabulated in decreasing order for each site, with the letter after each entry indicating the level of thinning (C, control; L, light thinning; M, medium thinning; H, heavy thinning).

[b] 1 lb./in.^{2} = 6.894 kPa; MOE_d, dynamic modulus of elasticity of wood in a tree determined by the stress wave method; MOE_s, static modulus of elasticity of small, clear specimen determined by static bending test.

Mattheck and Bethge (1993) measured radial stress wave velocities in green and healthy trees using a commercially available stress wave timing unit. The equipment consisted of a hand-held hammer with a built-in accelerometer, a sensor with a second accelerometer, and an electronic clock. The hammer introduced a mechanical stress wave radially into the tree trunk and started the clock by triggering the first accelerometer. The clock stipped when the stress wave reached the second acclerometer at the opposite side of the trunk. To avoid large amounts of signal cushioning from the bark, two screws were turned into the trunk on both sides. The velocity was determined by dividing the distance between screw tips by the time measured. **Table 10.3** shows the values of radial stress wave velocities in standing softwood and hardwood trees. As a rule of thumb, stress wave velocity in softwoods is about 1,000 m/s and that in hardwoods about 1,500 m/s.

Table 10.3 - Radial stress wave velocities in healthy standing trees (Mattheck and Bethge 1993).

Species	Radial stress wave velocity (m/s)
Hardwoods	
Maple	1,006-1,600
Birch	967-1,150
Sweet chestnut	1,215-1,375
Oak	1,382-1,610
Ash	1,162-1,379
Lime	940-1,183
Plane	950-1,033
Pine poplar	967-1,144
Black locust	934-1,463
Red beech	1,206-1,412
Horse chestnut	873-1,557
Black poplar	869-1,057
Silver poplar	821-1,108
Willow	912-1,333
Softwoods	
Douglas-fir	905-1,323
Spruce	931-1,085
Pine	1,066-1,146
Larch	1,023-1,338
Fir	910-1,166

Bethge and Mattheck (1994) examined the effect of frost cracks, ring shakes, and hollow, loose tree rings on stress wave propagation through the tree stem. Drastic reductions of measured velocity were observed when the stress wave traveled across a crack or split. A radial crack reduces stress wave velocity significantly when waves travel perpendicular to it. When the stress wave was propagated parallel to the crack front, the measured velocity did not change. Bethge and Mattheck suggested that further investigation of the cross section should be conducted when stress wave velocity is less than 70% of the normal value of healthy trees.

Yamamoto *et al.* (1998) measured stress wave velocity in the radial direction across the stem of *Acacia mangium* trees. They found that stress wave velocity was much higher in sound stems than in stems hollowed by heart rot. Stress wave velocities ranged from 928 to 1,259 m/s in sound stems and from 357 to 876 m/s in decayed stems. The threshold velocity between sound and hollowed stems was around 800 m/s.

Lin *et al.* (2000) evaluated 68 Luanta China fir standing trees. About half of the tested trees had various amounts of wood deterioration caused by squirrel damage. Measurements were performed at 90° and 180° orientations in the cross section of the stem at breast height. The results were compared with transmission times of healthy trees in the radial direction, and the ratio of transmission times in the different orientations was examined as a predictor of decay degree. The ratio for severely deteriorated trees was between 0.21 and 0.52, which is significantly lower than the value for healthy trees (0.92).

at the research level for many years. Substantial research has been done in the United States, Japan, New Zealand, and Europe. Techniques include x-ray, radar, nuclear magnetic resonance (NMR), and longitudinal stress wave or longitudinal vibration-based technology. Stress wave or longitudinal vibration methods were found to be suitable and cost-effective for practical applications. Consequently, these methods have been extensively investigated. Research efforts are summarized in **Table 10.4.**

Prediction of Lumber Properties

Predicting the strength and stiffness of lumber that would be produced from a log has been studied extensively. Researchers have examined the relationships between stress wave parameters of logs and the mechanical properties of lumber obtained from the logs.

Aratake *et al.* (1992) and Aratake and Arima (1994) investigated the possibility of using the natural frequency of longitudinal vibration in a log to predict the strength (MOR) and stiffness (MOE) of scaffolding boards and square timbers cut from the log. The sample consisted of 89 Japanese cedar logs. One end of the log was hit with a hammer. A Fast Fourier Transform (FFT) spectrum analyzer was used to analyze the signals received from a microphone, which was located at the opposite end of the log. Aratake *et al.* found a close correlation between the fourth natural frequency of the logs and MOE and MOR of the scaffolding boards and square timbers obtained from the logs.

Ross *et al.* (1997) evaluated 193 balsam fir and eastern spruce logs using longitudinal stress wave techniques prior to processing into lumber. Longitudinal stress wave speed measured on logs was used to determine

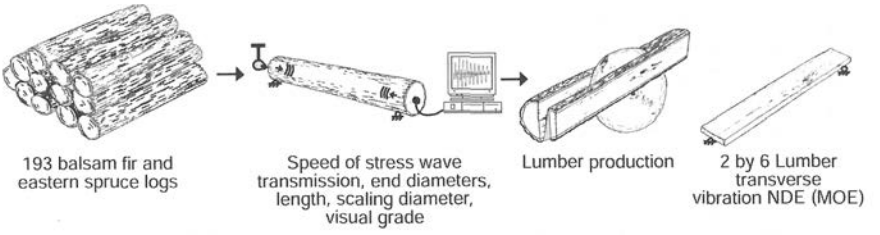

Figure 10.5 –*Experiment conducted to examine the relationship between log and lumber MOE (Ross* et al. *1997).*

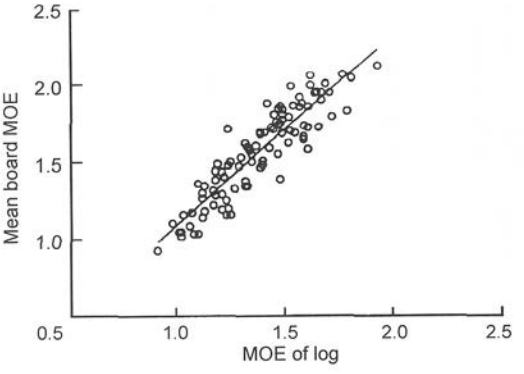

Figure 10.6 - *Mean board MOE as a function of MOE of logs for eastern spruce (1 lb./in.^{2} = 6.894 kPa) (Ross* et al. *1997).*

MOE_d for each log. The logs were then cut into nominal 2- by 6-in. (standard 38- by 140-mm) lumber. The flatwise MOE of each piece of lumber cut from logs was determined using a transverse vibration method. **Figure 10.5** shows the experimental protocol used in the study. The results of a linear regression analysis revealed that MOE of the log correlated reasonably well with MOE of the lumber **(Fig. 10.6).** Similar relationships between log and lumber properties were also reported by Sandoz and Lorin (1994), Iijima *et al.* (1997), and Wang (1999).

In an effort to validate the usefulness of longitudinal stress wave techniques for a practical log sorting process, Wang *et al.* (200a) conducted a study with 107 red maple logs. Using longitudinal stress wave techniques, they sorted the logs into four stress wave grades **(Table 10.5).** After drying and surfacing, the flatwise MOE of the lumber produced from the logs was determined using transverse vibration techniques. It was then sorted into four categories based on the MOE values. **Figure 10.7** shows the aberage lumber MOE for different log stress wave grades. Lumber produced from grade 1 logs had the highest average MOE (86×10^6 lb./in.^{2} (12.82 MPa)), followed by the lumber produced from grade 2 logs, with an average MOE of 1.79×10^6 lb./in.^{2} (12.34 MPa). The lumber from grade 3 logs had an average MOE of 1.60×10^6 lb./in.2 (11.03 MPa). The lumber obtained from grade 4 logs had the lowest average MOE (1.43×10^6 lb./in.^{2} (9.86 MPa)). Wang *et al.* (2000a) further compared log grades to lumber grades and found a good relationship between them. They concluded that longitudinal stress wave techniques could be used in sawmills to sort log for the production of high MOE products.

Prediction of Veneer Quality

Stress wave NDE of logs has also been successfully used to predict the performance of veneer obtained from a log. **Figure 10.8** shows the experimentsl procedure used by Ross *et al.* (1999) to examine the relationship between log

Table 10.4—Research summary on nondestructive evaluation of logs with longitudinal stress wave methods.[a]

Reference	Species	Material	NDE parameters of logs	Standard test	Reported properties	Comparison of NDE parameters of logs and reported properties (correlation coefficient *r*)
Aratake *et al.* (1992)	Japanese cedar	Logs, lumber	F_{c4}	Static bending	MOE_s of lumber	0.81–0.83 (green) 0.62–0.71 (dry)
					MOR of lumber	0.64–0.68 (green) 0.45–0.57 (dry)
Aratake and Arima (1994)	Japanese cedar	Logs, square timber	F_{c4}	Static bending	MOE_s of square timber MOR of square timber	0.87–0.89 0.38–0.62
Sandoz and Lorin (1994)	European spruce	Logs, lumber	MOE_{sw} (C, ρ)	Static bending	MOR of lumber	0.66
Ross *et al.* (1997)	Balsam fir Eastern spruce	Logs, lumber	MOE_{sw} (C, ρ)	Transverse vibration	MOE_v of lumber	0.57 0.90
Green and Ross (1997)	Southern Pine Douglas-fir Douglas-fir and western hemlock	Logs, lumber	MOE_{sw} (C, ρ)	Transverse vibration	MOE_v of lumber	0.79 0.71 0.86
Iijima *et al.* (1997)	Japanese cedar	Logs, lumber	MOE_{sw} (C, ρ)	Static bending	MOE_s of lumber	0.62

Table 10.4—(Cont.)

Wang (1999)	Douglas-fir and Southern Pine	Piles, lumber	MOE_{sw} (C, ρ)	Static bending	MOE_s of lumber	0.75
Ross *et al.* (1999)	Ponderosa pine	Logs, veneer	C	Stress wave	C of veneer	0.87
Rippy *et al.* (2000)	Douglas-fir	Logs, veneer	C	Stress wave	C of veneer	0.72
Wang *et al.* (2000a)	Red maple	Logs, cants, lumber	C	Stress wave	C of cant C of lumber	0.82 0.75
Wang *et al.* (2001b)	Jack pine	Logs	MOE_{sw} (C, ρ) MOE'_{sw} (C, ρ, D/L)	Static bending	MOE_s of logs MOE_s of logs	0.77 0.86
	Red pine	Logs	MOE_{sw} (C, ρ) MOE'_{sw} (C, ρ, D/L)	Static bending	MOE_s of logs MOE_s of logs	0.87 0.95

[a] C, stress wave speed; ρ, density; D/L, ratio of log diameter to log length; F_{c4}, the fourth natural frequency of logs; MOE_{sw}, modulus of elasticity of logs calculated from C and ρ; MOE'_{sw}, modulus of elasticity of logs calculated from C, ρ, and D/L; MOE_s, modulus of elasticity obtained from static bending tests; MOR, modulus of rupture obtained from static bending tests; MOE_v, modulus of elasticity obtained from transverse vibration tests.

Table 10.5 - Stress wave grades used to sort red maple logs (Wang *et al.* 200b).

Log grade	Stress wave transmission times (µs/ft.)[a]	(µs/m)
Grade 1	Less than 83	Less than 272
Grade 2	83 to 91	272 to 298
Grade 3	92 to 100	299 to 328
Grade 4	Greater than 100	Greater than 328

[a]1 µs/ft. = 3.281 µs/m.

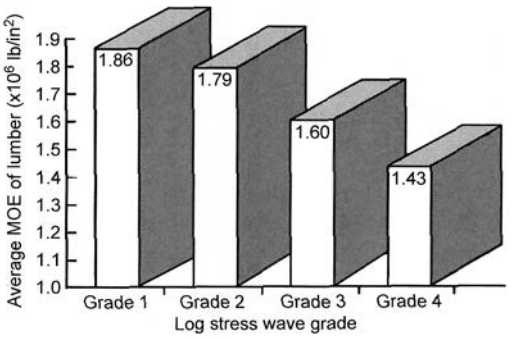

Figure 10.7 - *Average lumber MOE for different log stress wave grades (1 lb./in.^{2} = 6.894 kPa) (Wang* et al. *2000a).*

NDE measurements and the quality of veneer obtained from the log. Stress wave data were first taken from 62 ponderosa pine logs. The logs were then rotary peeled into 2.5-mm- (0.1-in.-) thick veneer, which was then dried. Special care was taken to ensure that each individual veneer sheet could be traced to the log from which it was peeled. Each full veneer sheet was then evaluated nondestructuvely in a commercially available veneer grader. In the grading machine, individual veneer sheets are fed through opposing ultrasocic rolling transducers that send and receive a wave that travels through the veneer along its length. The time it takes the wave to travel between the transducers is then determined. Average veneer transmission times for each log were compared with corresponding log values. **Figure 10.9** shows the relationship between stress wave transmission times for Ponderosa pine logs and corresponding veneer.

A similar procedure was used by Rippy *et al.* (2000) for evaluating Douglas-fir logs for veneer quality. Longitudinal stress wave transmission times were measured in twenty-five 35-ft. (10.7-m) Douglas-fir butt logs. The logs were then cut into 8-ft. (2.4-m) bolts plus trim and peeled into veneer. The veneer

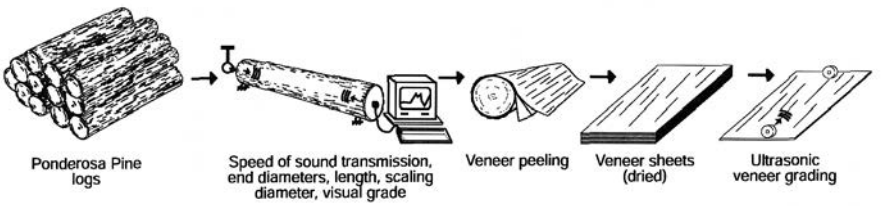

Figure 10.8 - Stress wave NDE of logs for assessing potential veneer quality (Ross et al. *1999).*

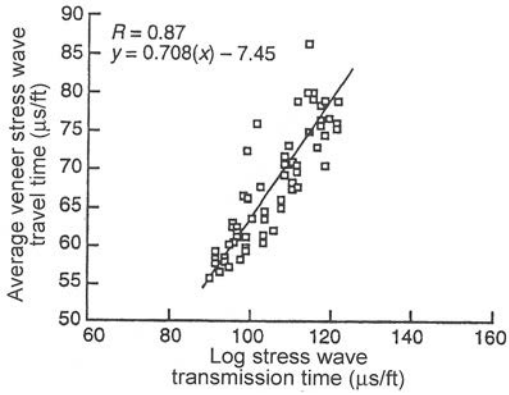

Figure 10.9 - *Stress wave transmission times for logs compared with those for the veneer obtained from them (1 µs/ft. = 3.281 µs/m) (Ross* et al. *1999).*

was dried and scanned using a commercial veneer grader, and the wave transmission times in the logs and veneers were compared. The results indicated that one-third of the veneer sample had wave transmission times lower than 58.3 µs/ft. (191.3 µs/m) (high MOE suitable for laminated veneer lumber (LVL)). Of this high MOE veneer, 83% came from the bottom two bolts of the log sample, indicating that the high-MOE veneer was often located near the base of the study tree. In addition, 43% of the veneer produced from logs with the lowest wave transmission times (≤82 µs/ft. (≤269µs/m)) had high MOE, and only 20% of the veneer produced from logs with the highest wave transmission times had high MOE. The results indicated that it would be possible to use log transmission times to predict the potential quality of veneer obtained from a given log.

Property Assessment of Round Timber

Recently, significant effort has been devoted to developing NDE methods to assess the potential performance characteristics of logs that will be used in round form (Wolfe 2000; Wang *et al*. 2001b). As an initial investication of predicting the performance of round timber, a study was conducted at USDA Forest Service, Forest Products Laboratory to examine the use of transverse vibration and longitudinal stress wave NDE techniques for assessing the stiffness and static MOE of logs. **Figure 10.10** illustrates the experimental procedure. One-hundred-fifty-nine jack and red pine logs were nondestructively evaluated and then statically tested. Typical results are illustratted in **Figure 10.11.** Useful relationships were found between dynamic MOE determined by these NDE techniques and static bending MOE. Two other findings were sig-

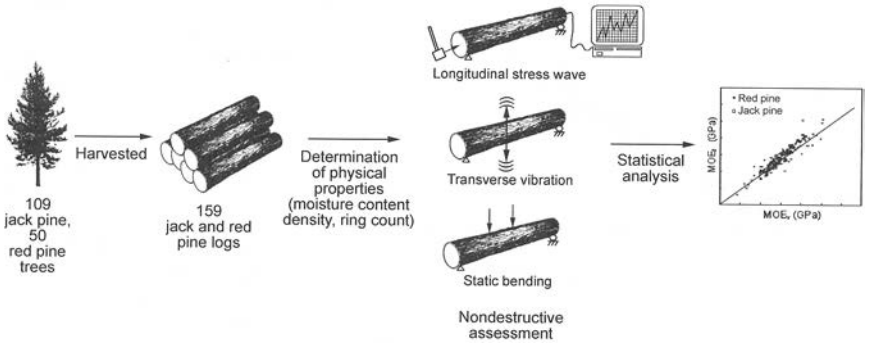

Figure 10.10 - *Experiment conducted to examine use of transverse vibration and longitudinal stress wave techniques to assess the stiffness and modulus of elasticity of logs (Wang* et al. *2001b).*

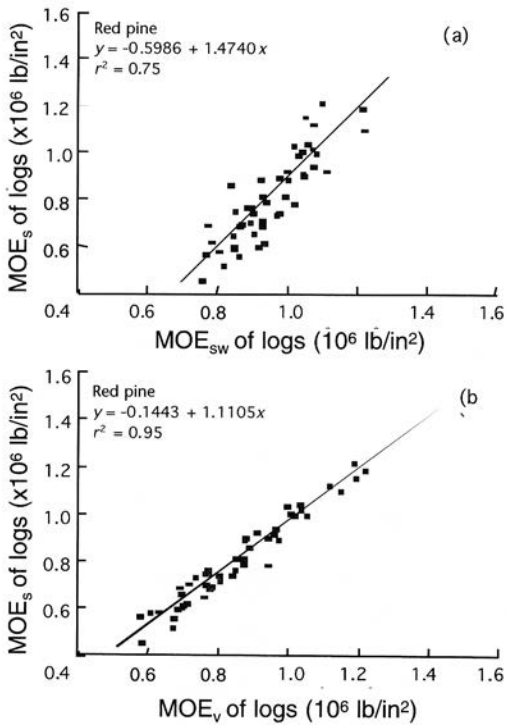

Figure 10.11 - *(a) Relationship of stress wave modulus of elasticity (MOE_{sw}) and (b) transverse vibration MOE (MOE_v) to static MOE (MOE_s) for red pine logs (1 lb./in.² = 6.894 kPa) (Wang et al. 2001b).*

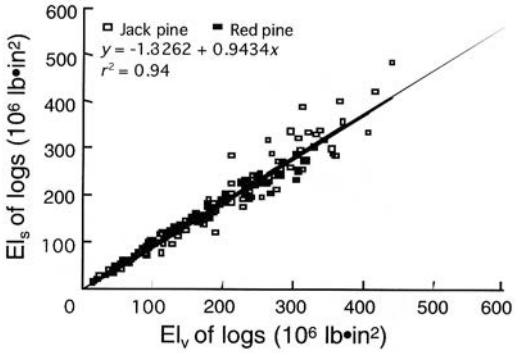

Figure 10.12 - *Vibration flexural stiffness (EI) compared with static EI (1 lb. •in.² = 0.00287 N•m) (Wang* et al. *2001b).*

nificant. First, an excellent relationship was found between transverse vibration and static stiffness values **(Fig. 10.12).** Second, incorporating information on the diameter to length ratio of the log significantly enhanced the correlative relationship between stress wave and static MOE values **(Fig. 10.13). Table 10.6** shows the results of regression analyses relating MOE_s to MOE_{sw} and diameter to length ratio.

Green Lumber and Green Veneer

The use of longitudinal stress wave techniques for grading structural lumber has been vigorously explored by a number of researchers (Galligan and Courteau 1965; Gerhards 1975, 1982a,b; Pellerin and Galligan 1973; Porter *et* al. 1972; Ross and Pellerin 1991). Many of these investigations have demonstrated good relationships between MOE_d and MOE_s for a variety of lumber species.

Typically, MOE_d was determined from the long slender rod wave equation:

$$MOE_d = C^2p \qquad [10.1]$$

where *C* is stress wave speed and p is mass density. This fundamental wave equation was developed for idealized elastic materials and was verified to be adequate for describing wave behavior in dry wood materials (Bertholf 1965; Kaiserlik and Pellerin 1977; Ross 1985). However, the effectiveness of its application for accurately predicting MOE_s at high wood moisture content levels has been questioned.

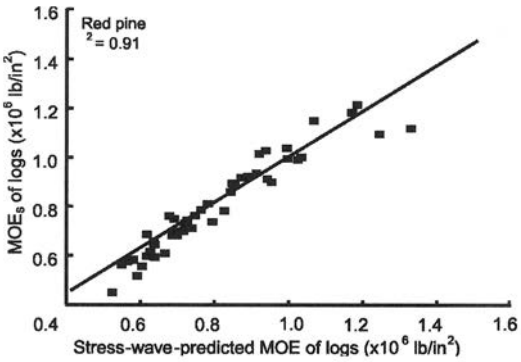

Figure 10.13 - *Relationship of MOE of logs predicted by a new stress wave model (shown in Table 10.6) to the static MOE (MOEs) of logs for red pine (1 lb./in.^{2} = 6.894 kPa) (Wang* et al *2001b).*

Ross and Pellerin (1991) investigated the hypothesis that a relationship might exist between MOE_d and MOE_s for green lumber. Both MOE_d and *C* are strongly correlated to MOE_s of dry wood materials, and Ross and Pellerin believed that a similar correlation might exist for wood with moisture content (MC) above the fiber saturation point (ESP). The MOE_s and MOE_d of 113 green Douglas-fir specimens (nominal 2 in. by 4 in. by 12 ft. (standard 38 mm by 89 mm by 3.7 m)) were determined. Results of linear regression analyses between MOE_s and *C* revealed a useful relationship. The regression analyses accounted for 60% of the observed behavior (r = 0.78). A strong relationship (r = 0.95) was evident between MOE_s and MOE_d. The regression model using MOE_d to predict MOE_s accounted for 90% of the observed behavior. Although good relationships were observed between MOE_s ande $MOOE_d$ for green materials, significant deviations were found in MOE_d compared with MOE_s as a result of the presence of moisture (Galligan and Courteau 1965; Gerhards 1975; Sobue 1993). The effect of MC on stress wave properties and adjustment of MOEd for moisture effect is discussed in detail later in this chapter.

In the United States, stress wave or ultrasonic techniques are also used by many manufacturers to sort veneer for LVL production. Commercially, stress wave or ultrasonic techniques have allowed LVL manufacturers to translate individual veneer quality (that is, veneer stiffness and strength) into structural LVL material with low variability and predictable strength properties. After the veneer is dried, a commercial veneer grader ultrasonically transmits stress waves longitudinally through the veneer. The average wave velocity *C* is calculated for each veneer and is then categorized into predetermined strength and stiffness classes that correspond to the mean *C* of each piece. The strength classes are determined by reported empirical relationships between C and the stiffness of the veneer and final LVL mechanical properties.

The present application of stress wave or ultrasonic methods to sort veneer for LVL manufacturer is restricted to dry veneer. By the time the veneer is sorted into stress grades, significant drying costs have been incurred. If a similar sorting procedure for green veneer could be determined, it would be possible to dry material with similar strength and stiffness together in customized drying schedules. These custom drying cycles, based on veneer strength and stiffness, could lead to increased efficiency, energy savings, and lower costs by reducing or eliminating veneer redrying.

Laboratory investigations of the use of stress-wave-based NDE methods for assessing the quality of green veneer have yielded promising results. Brashww *et al.* (1996) evaluated the potential of using stress wave techniques

Table 10.6—Results of regression analyses relating static bending modulus of elasticity (MOE_s) to stress wave MOE (MOE_{sw}) and ratio of log diameter to log length (D/L)[a] (Wang *et al.* 2001b).

	Regression model: $y = a\,x_1^{\,b}\,x_2^{\,c}$								
Species	y	x_1	x_2	a	b	c	r^2	r	S_{yx}
Red pine	MOE_s	MOE_{sw}	D/L	0.0968	0.9078	−0.7326	0.91	0.95	0.055
Jack pine	MOE_s	MOE_{sw}	D/L	1.7826	1.1957	−0.5060	0.74	0.86	0.120

[a] MOE_{sw}, modulus of elasticity of logs obtained from stress wave tests; MOE_s, modulus of elasticity of logs obtained from static bending tests; *D/L*, ratio of log diameter to log length; *a, b, c* = empirical constants; r^2, coefficient of determination; *r*, correlation coefficient; S_{yx}, standard error of estimate.

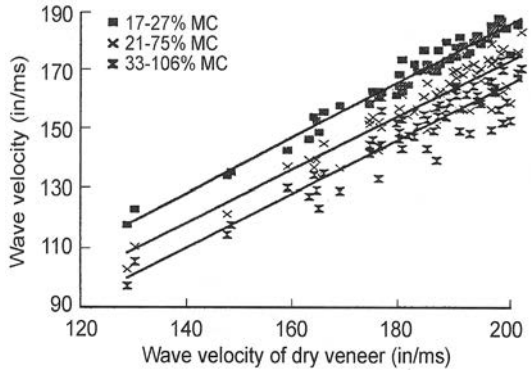

Figure 10.14 - *Stress wave velocities of southern yellow pine veneer at several moisture content (MC) ranges compared with stress wave velocity of dry veneer measured with a digital oscilloscope (1 in./ms = 25.4 m/s) (Brashaw* et al. *1996).*

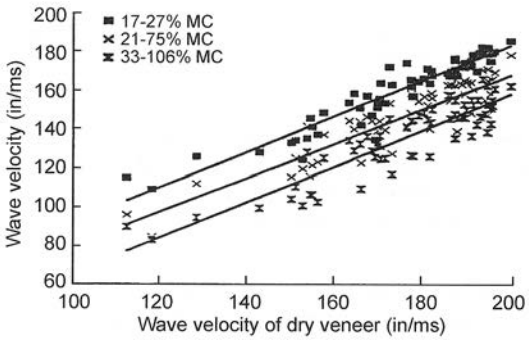

Figure 10.15 - Stress wave velocities of southern yellow pine veneer at several moisture content (MC) *ranges compared with stress wave velocity of dry veneer measured with a stress wave timer (1 in./ms = 25.4 m/s) (Brashaw et al. 1996a).*

to sort green southern yellow pine and Douglas-fir veneer into stress grades. Stress wave NDE was used to separate green veneer into several grades for use in manufacturing engineered wood composites, most notably LVL. Stress wave transit times were measured in a sample of veneer using both a digital oscilloscope and a commercial grading device. The stress wave transmission times were measured in both green (wet) and dry conditions. Brashaw *et al.* (1996) found that stress wave velocities in green and dry veneers were strongly correlated. **Figure 10.14** compares longitudinal stress wave velocities of southern yellow pine veneer at several moisture content ranges to the velocity of dry veneer measured with an oscilloscope. **Figure 10.15** shows longitudinal stress wave velocities of southern yellow pine veneer at several moisture content ranges compared with the velocity of dry veneer as measured with a commercial stress wave timer. This research effort indicates that it may be possible to sort green veneer prior to drying, which could result in significant savings for manufacturers of LVL materials.

Effect of Moisture Content on Stress Wave Properties

Wood is hygroscopic and hydrophilic in nature. Its MC changes as relative. humidity changes. Moisture in wood affects both wave speed and density. According to Equation [10.1], the effect of moisture on MOE_d depends on how wave speed and wood density change with MC. Generally, chemically bound water in wood cells slows down the speed of the wave traveling through the wood in proportion to the decreace in MOE and increases gross density of wood. Equation [10.1] shows that decrease of wave speed and increase of wood density have opposite effects on MOE_d; that is, as wave speed decreases with increasing MC, MOEd decreases. On the other hand, increase of gross density caused by increasing moisture above fiber saturation

could yield a higher computed value of MOE_d. Studies show that Equation [10.1] generally yields high estimates of MOE_s in both dry and green conditions (Galligan and Courteau 1965; Gerhards 1975; Sobue 1993). In addition, MOEd calculated from the wave speed and wood density increases as MC increases above FSP (about 30%). This observation contradicts the general relationship between mechanical properties of wood and MC (wood properties usually remain constant as moisture raises above the FSP). Consequently, MOE_d determined by the longitudinal stress wave technique requires adjustment for MC above fiber saturation.

The nature of the response of wave speed to MC changes also suggests that moisture gradients in wood could have a significant influence on stress wave propagation. For green lumber, the surface wood is usually drier than the interior wood. In a typical sensor arrangement of longitudinal stress wave measurement, the dry shell and the wet core wave propagation. **Figure 10.16** shows the electrical circuit analog of parallel arrangements of wet and dry zones. Therefore, as the wave travels through lumber in the longitudinal direction, a dry shell may have a dominating effect on measured speed (Simpson 1998). If used for stress grading, the logitudinal stress wave technique may overestimate the MOE_s of green lumber when there is a moisture gradient in lumber.

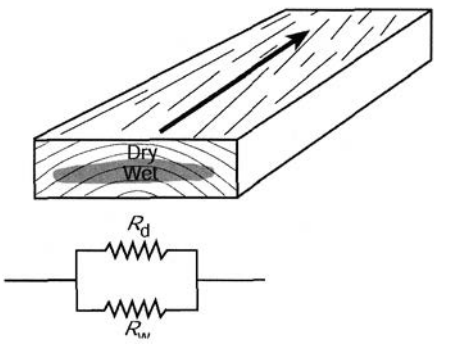

Figure 10.16 - *Electrial analog of parallel arrangement of wet (Rw) and dry (Rd) wood (Simpson 1998).*

Several studies have made progress in sharpening our understanding of the effect of moisture content on stress wave properties of wood. James (1961) evaluated moisture effect within the hygroscopic range (from 0% to about 30%) on the speed of longitudinal stress waves. Speed decreased as MC increased, as would be expected from the known effect of moisture on MOE_s of wood. Burmester (1965) developed data on the effect of MC on stress wave speed in pine within the hygroscopic range and at the water-soaked condition (152%). Below FSP, Burmester and James agree very closely, with respective reductions in stress wave speed of 15% for an increase of 27 percentage units in fiber moisture. For an additional 125 percentage units increase, Burmester observed 14% more reduction in speed. One limitation of their studies was lack of data between FPS and the water-soaked condition.

Gerhards (1975) studied the effect of MC in the range of 15% to 150% on both stress wave speed and MOE_d in five 8-ft.- (2.4-m-) long nominal 2- by 4-in. (standard 38- by 89-mm) clear sweetgum sapwood samples. His results for wave speeds agreed with James and Burmester's results on a relative basis. Gerhards also found that the MOE_d calculated from the fundamental wave equation was highly dependent on wood MC across the whole range studied. Above FSP, MOEd yielded a value much higher than that of static bending **(Fig. 10.17).** For example, at 27% MC, MOE_d was 2.05×10^6 lb./in.^{2} (14.13 MPa), which is about 16% higher than its static counterpart. As moisture

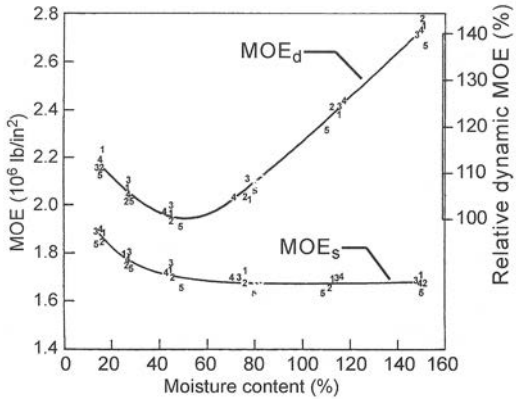

Figure 10.17 - *Comparison of stress-wave-determined dynamic MOE (MOE_d) and static bending MOE (MOE_s) in the range of 15% to 150% moisture content (1 lb./in.^{2} = 6.894 kPa) (Gerhards 1975).*

increased to 150%, MOE_d increased dramatically resulting in a value of 2.72 × 10^6 lb./in.^{2} (18.75 MPa), which was 63% higher than the static value. Gerhards concluded that static modulus is substantially overestimated by the longitudinal stress waave technique if MOEd is not adjusted to account for moisture effect, particularly when MC is greater than 50%. Therefore, it is obvious that a correction factor for MC above fiber saturation is necessary.

In an effort to make adjustments to MOE_d for moisture effect. Sobue (1993) conducted a simulation study to examine the influence of free water on MOE_d of wood. Above FSP, he suggested a new concept - mobility of free water (k) - which is defined as the ratio of the weight of free water that vibrates in the same phase with wood cell walls to the total weight of free water. The assumption was that the free water, which vibrates in the opposite phase with wood cell walls, does not contribute to the propagation of waves in the wood and should not be included in the calculation of MOE_d. Sobue therefore introduced an effective density p_{eff} that is related to the gross density of wood p and the mobility of free water k:

$$\rho_{\text{eff}} = \rho \left\{ 1 - \frac{(1-k)(\text{MC} - \text{MC}_{\text{FSP}})}{(100 + \text{MC})} \right\} \qquad [10.2]$$

where MC_{FSP} is moisture content at FSP. A true MOE_d was then determined from measured stress wave speed C and effective density of wood p_{eff} by the equation

$$\text{MOE}_{\text{d}} = C^2 \rho_{\text{eff}} \qquad [10.3]$$

Sobue hypothesized that MOE_d calculated from Equation [10.3] remains constant (same with MOE_s) when MC is above FSP. **Figure 10.18** shows Sobue's simulation results of the relationships between wave speed and MC with different k values. A coefficient k increases (more free water vib rates in the same phase with the wood cell wall), wave speed decreases. From a comparison of simulation results and actual data published by Kodama (1992), Sobue estimated that the mobility of free water k is 0.78 for ultrasonic waves at 200 kHz and 0.12 for ultrasonic waves at 1 MHz. This means that about 78% and 12% of free water vibrates in the same phase with the wood cell wall as 200 kHz and 1 MHz ultrasonic waves, respectively, are applied. Sobue further concluded that mobility of free water is wave frequency dependent and low frequency waves should correspond to high k values. Although these

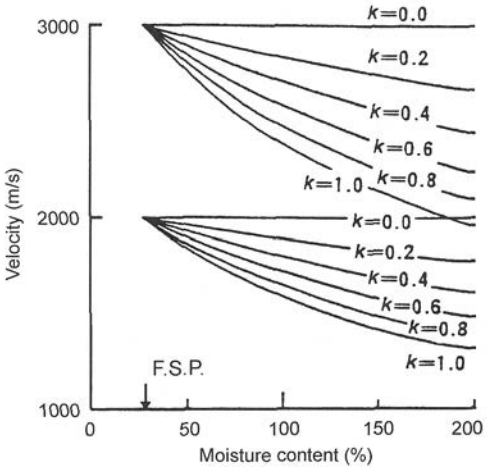

Figure 10.18 - *Effect of mobility of free water (k) on relationship between stress wave velocity and moisture content (FSP, fiber saturation point) (Sobue 1993).*

results are limited to high frequency ultrasonic waves, they appear to provide useful guidelines for stress grading of green material with longitudinal stress wave techniques.

Wang and Chuang (2000) applied a similar simulation procedure to estimate the coefficient *k* for both stress wave and ultrasonic wave evaluation of Japanese cedar using small clear specimens (30 by 30 by 500 mm). They reported a coefficient *k* of 0.6 for stress waves and 0.7 for ultrasonic waves at 16 kHz. Their result for ultrasonic waves is generally in agreement with Sobue's estimation, but the *k* value stress waves is much lower than that Sobue predicted, considering the fact that stress waves have a much lower frequency than that of ultrasonic waves. Another limitation of the study is that the results obtained from small clear wood may not apply to dimension lumber, in which the moisture gradient may have an effect in addition to moisture content level.

Mishiro (1995, 1996) conducted several studies on the relationship between wave speed and MC. Some model specimens he used were assembled from woods with different known MCs to simulate moisture gradients. Mishiro found that when a moisture gradient exists in the transverse direction, wave speed is more dependent on the wood zone with lower MC. This phenomenon can also lead to an overestimation of static modulus when Equation [10.1] or [10.3] is used to calculate true MOE_d of lumber.

The effect of MC and moisture gradient on stress wave properties can be further complicated by the dimensional size (slenderness) of lumber. Porter *et al.* (1 972) first noted that stress wave speed can be affected by lumber width. As a 2 by 12 was cut into 2 by 6's and 2 by 3's, the authors observed a continuous increase in wave speed (5,029, 5,090, and 5,121 m/s). Although the change in wave speed may not be significant, it may introduce a significant change in MOE_d calculated from wave speed and wood density since MOE_d is proportional to C^2.

Currently, information is still limited on making moisture corrections to MOE_d to accurately predict MOE_s of wood at different moisture conditions, especially above FSP. Research in this area would considerably advance state-of-the-art stress wave techniques.

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Nondestructive Evaluation of Wood

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