Chapter 2 - Transverse Vibration and Longitudinal Stress Wave Nondestructive Evaluation Methods

Roy F. Pellerin
Professor Emeritus
Washington State University, Pullman, Washington

Robert J. Ross
Project Leader
Forest Products Laboratory, Madison, Wisconsin

Transverse Vibrational Techniques

Transverse vibration techniques have received considerable attention for nondestructive evaluation (NDE) applications. To illustrate these methods, an analogy can be drawn between the vibration of a mass that is attached to a weightless spring and internal damping force and the behavior of a vibrating beam (Fig. 2.1). in Figure 2.1, mass M is supported from a rigid body by a weightless spring whose stiffness is denoted by K. Internal friction or damp-

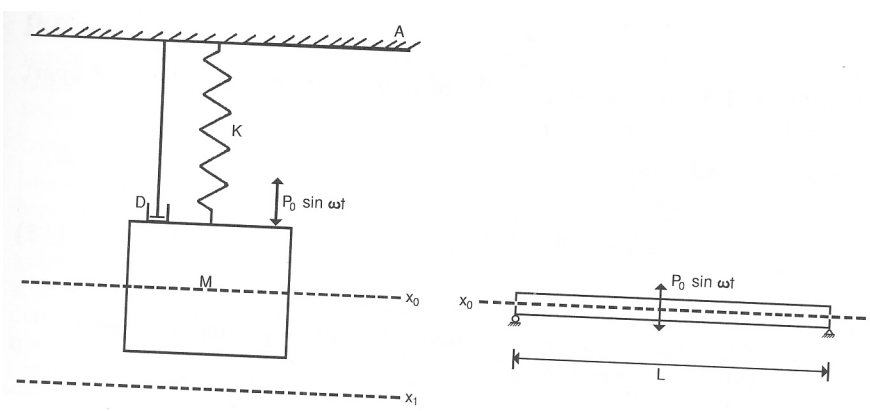

Figure 2.1 - *Mass-spring dashpot vibration model (left) and transversely vibrating beam(right).*

ing is represented by the dashpot *D*. A forcing function equaling $P_0 \sin\omega t$ or zero is applied for forced and free vibration, respectively. When *M* is set into vibration, its equation of motion can be expressed by the following:

$$M\left(\frac{d^2x}{dt^2}\right) + D\left(\frac{dx}{dt}\right) + Kx = P_0 \sin \omega t \qquad [2.1]$$

Equation [2.1] can be solved for either *K* or *D*. A solution for K will lead to an expression for modulus of elasticity (MOE) where for a beam freely supported at two nodal points

$$\text{MOE} = \frac{f_r^2 WL^3}{12.65Ig} \qquad [2.2]$$

and for a beam simply supported at its ends

$$\text{MOE} = \frac{f_r^2 WL^3}{2.46Ig} \qquad [2.3]$$

In Equations [2.2] and [2.3],

MOE = dynamic modulus of elasticity (lb./in.^{2}, Pa),

f_r = resonant frequency (Hz),

W = beam weight (lv., kg.g),

L = beam span (in., m),

I = beam moment of inertia (in.^{4}, m^4), and

g = acceleration due to gravity (386 in./s^2, 9.8 m/s^2).

Solving Equation [2.1] for *D* leads to an expression of the internal friction or damping component. The logarithmic decrement of vibrational decay δ is a measure of internal friction and can be expressed in the form (for free vibrations)

$$\delta = \frac{1}{(n-1)} \ln \frac{A_1}{A_n} \qquad [2.4]$$

where A_1 and A_n are the amplitudes of two oscillations n - 1 cycles apart (**Fig. 2.2**).

For forced vibrations,

$$\delta = \frac{\pi \Delta f}{f_r} \frac{1}{\sqrt{(A_r/A)^2 - 1}} \qquad [2.5]$$

where:

Δf = difference in frequency of two points of amplitude *A* on each side of a resonance curve,

f_r = frequency at resonance, and

A_r = amplitude at resonance (**Fig. 2.2b**).

Sharpness of resonance Q is frequently used to measure damping capacity; Q is defined as the ratio $f_r/\Delta f$. Note that if the value $0.707A_r$ (half-power point method) is substituted for A in Equation [2.5], the equation reduces to

$$\delta = \frac{\pi \Delta f}{f_r} \qquad [2.6]$$

and

$$Q = \frac{\pi}{\delta} \qquad [2.7]$$

Research and Development

Table 2.1 summarizes research on the use of transverse vibration NDE techniques. Jayne (1959) designed and conducted one of the first studies that utilized these techniques for evaluating the strength of wood. He was successful in demonstrating a relationship between energy storage and dissipation properties, measured by forced transverse vibration techniques, and the static bending properties of small clear wood specimens. Using an experimental setup similar to that illustrated in **Figure 2.3,** Jayne was able to determine the resonant frequency of a specimen from a frequency response curve. In addition, sharpness of resonance (energy loss) was obtained using the half-power point method.

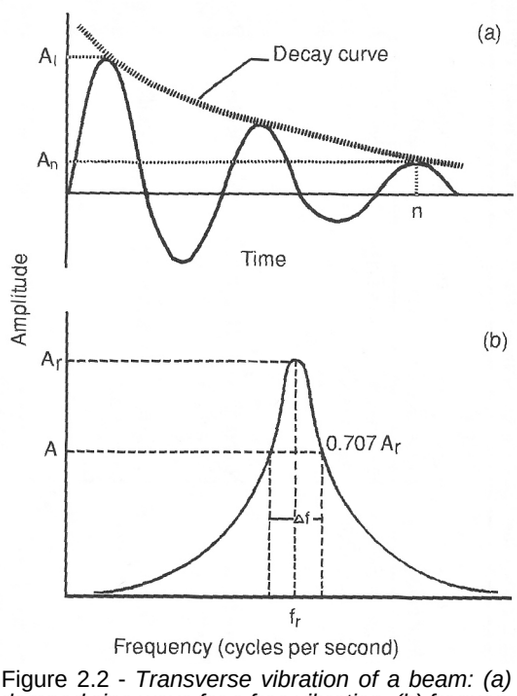

Figure 2.2 - *Transverse vibration of a beam: (a) damped sine wave for a free vibration, (b) frequency response curve for a forced vibration.*

Pellerin (1965a,b) used the apparatus shown in **Figure 2.4** to examine the free transverse vibration characteristics of dimension lumber and glulam timbers. After obtaining a damped sine waveform for a specimen, he analyzed it utilizing equationa for MOE and logarithmic decrement. Measured values of MOE and logarithmic decrement were then compared to static MOE and strength values. O'Halloran (1969) used a similar apparatus and obtained comparable results with softwood dimension lumber. Wang *et al.* (1993) used transverse vibration techniques to evaluate the static bending MOE of structural lumber. Ross *et al.* (1991) obtained comparable results through coupling relatively inexpensive personal computer technologies and transverse vibration NDE techniques. Research on the use of transverse vibration techniques

Table 2.1—Summary of research using transverse vibration nondestructive evaluation techniques.[a]

Reference	NDE technique	Material	NDE parameter measured	Static test	Reported properties	Comparison of NDE parameters and properties (correlation coefficient *r*, unless noted)
Jayne (1959)[b]	Forced transverse vibration	Small clear Sitka spruce specimens	Resonant frequency, E_d, Q	Bending	E_{SB}, MOR	E_{SB} and E_d, 100,000 lb./in.^{2} MOR and E_d, 1,000 lb./in.^{2} MOR and E_d, 1,000 lb./in.^{2} MOR and density/Q, ±1,000 lb./in.^{2} MOR and E_d/δ, ±900 lb./in.^{2}
Pellerin (1965a)	Free transverse vibration	Douglas-fir glulam	Natural frequency, E_d, δ	Bending	E_{SB}, MOR	Predicted relative strength of three glued-laminated members
Pellerin (1965b)	Free transverse vibration	Inland Douglas-fir dimension lumber	Natural frequency, E_d, δ	Bending	E_{SB}, MOR	E_{SB} and E_d, 0.98 MOR and E_d, 0.67–0.93 MOR and $1/\delta$, 0.46–0.88 MOR and E_d/δ, 0.68–0.92
O'Halloran (1969)	Free transverse vibration	Lodgepole pine dimension lumber	Natural frequency, E_d, δ	Bending	E_{SB}, MOR	E_{SB} and E_d, 0.98 MOR and E_d, 0.89 MOR and $1/\delta$, 0.82 MOR and E_d/δ, 0.91
Wang *et al.* (1993)	Free transverse vibration	Spruce–Pine–Fir dimension lumber	E_d	Bending	E_{SB}	E_{SB} and E_d, 0.96–0.99
Ross *et al.* (1991)	Free transverse vibration	Spruce–Pine–Fir dimension lumber	E_d	Bending	E_{SB}	E_d and E_{SB}, 0.99

[a] δ, logarithmic decrement; E_d, dynamic modulus of elasticity (MOE); E_{SB}, MOE obtained from static bending test; MOR, modulus of rupture; Q, sharpness of resonance. 1 lb./in.^{2} = 6.9 kPa.

[b] Correlation coefficients were not reported by Jayne. However, he did report 95% confidence intervals.

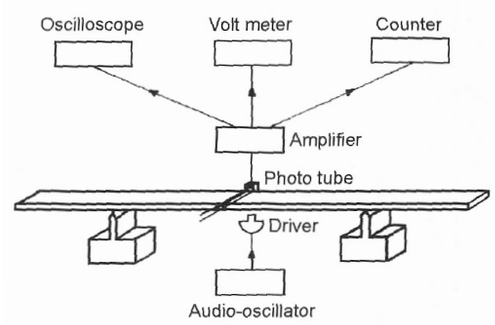

Figure 2.3 - *Experimental setup used to measure response of wood beams to forced transverse vibration.*

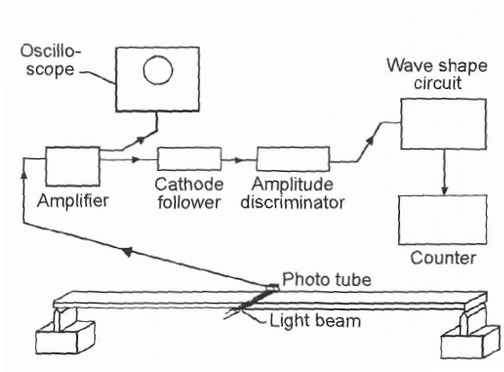

Figure 2.4 - *Apparatus used to examine free transverse vibration characteristics of lumber specimens (Pellerin 1965a,b).*

to assess the potential of hardwood lumber for structural applications is summarized in **Table 2.2.**

The use of transverse vibration techniques has evolved considerably, especially in the past several years. Two firms have developed excellent equipment that utilizes free transverse vibration techniques (**Table 2.3**). Both pieces of equipment utilize relatively low-cost personal computer technologies as part of their data acquisition and computing package. This equipment is used by lumber grading agencies and research organizations worldwide to assist in assessing the potential yield of structural lumber that can be obtained from a given wood species or species group.

Essential Laboratory Testing Procedures and Key Information

Figure 2.5 illustrates a typical free transverse vibration test setup. The specimen is simply supported at both ends. A slight deflection is introduced at the midspan of the specimen. The specimen is then allowed to freely oscillate in the vertical (transverse) direction. Frequency of oscillation is determined and, along with the specimen weight and dimensions, used to compute MOE. The MOE is calculated from the following formula:

$$\text{MOE} = \frac{f^2 W S^3}{2.46 I g} \qquad [2.8]$$

where:

f = resonant frequency (Hz),

W = weight of specimen (lb.),

S = span (in.),

I = moment of inertia (in.^{4}), and

g = acceleration due to gravity (386 in./s^2).

Table 2.2—Summary of research on the correlation between modulus of elasticity and other mechanical properties of hardwood lumber.[a]

Reference	Species group	Nominal moisture content (%)	Grade[b]	Nominal width (in.)	Growth location	NDE technique	Static property	Correlation coefficient r
Green and McDonald (1993a)	Northern red oak *(Quercus velutina, Quercus rubra)*	12	1, 2, 3	4	Central Wisconsin	Transverse vibration (flatwise)	E_{SB}, UCS, UTS, MOR	E_{SB} and E_d, 0.92 MOR and E_d, 0.58 UTS and E_d, 0.54 UCS and E_d, 0.70
Green and McDonald (1993b)	Red maple *(Acer rubra)*	12	SS, 2, 3	4	Central Vermont	Transverse vibration (flatwise)	E_{SB}, UCS, UTS, MOR	E_{SB} and E_d, 0.85 MOR and E_d, 0.42 UTS and E_d, 0.46 UCS and E_d, 0.60

E_d, dynamic modulus of elasticity (MOE) obtained from transverse vibration measurements; E_{SB}, MOE obtained from static bending test; MOR, modulus of rupture; UTS, ultimate tensile stress; UCS, ultimate compressive stress. 1 lb./in.^{2} = 6.9 kPa.
Grades by procedures given in the National Grading Rule performed by a quality supervisor of Southern Pine Inspection Bureau. SS, Select Structural.

Table 2.3 - Equipment for free transverse vibration techniques.

Manufacturer	Description of equipment
Qualtim, Inc. 5937 Meadwood Dr., Suite 7 Madison, WI 53711-4125 USA Telephone: (608) 271-1176 Fax: (978) 285-7693 E-mail: info@qualtim.com	E-Wave - Measures modulus of elasticity, weight, specific gravity, and damping ratio from transverse vibration of simply supported specimens.
Metriguard, Inc. 1120 SE Latah, P.O. Box 399 Pullman, WA 99163 USA Telephone: (509) 332-7526 Fax: (509) 332-0485 E-mail: sales@metriguard.com	Model 340 Transverse Vibration E Computer-Measures modulus of elasticity, weight, specific gravity, and damping ratio from transverse vibration of simply supported specimens.

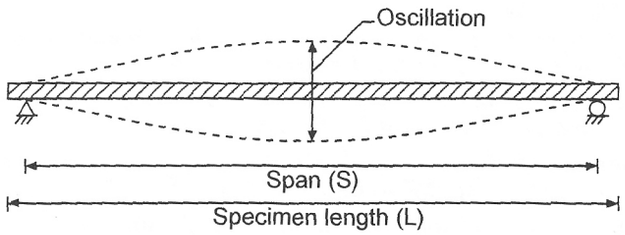

Figure 2.5 - *Schematic of typical free transverse vibration test setup.*

Three elements are essential to the test setup: a support apparatus, an escitation system, and a measurement system.

Support apparatus

- The apparatus should provide vertical support to the ends of the specimen yet permit rotation.
- The specimen should be supported so as to prevent damage at the point of contact between the specimen and the reaction support. The reactions shouold be such that shortening and rotation of the specimen about the reaction resulting from deflection are not restricted.
- Provisions shold be made at the reactions to allow for initial twist in the length of the specimen. If the bearing surfaces of the specimen at its reaction are not parallel, the specimen should be shimmed or the bearing surfaces rotated about an axis parallel to the span to provide adequate bearing across the width of the specimen.
- No lateral support should be applied. Specimens unstable in this mode should not be tested.

- The specimen should be positioned such that an equal portion of the length overhangs each support. Excessive overhang may alter results. If Equation [2.8] is used, the span to length (S/L) ratio of the specimen should exceed 0.98. Other S/L ratios may be used, but a more exacting analysis and equation are needed (Murphy **1997).** An overhang of approximately 1 in. (25.4 mm) on each end is often used in tests of dimension lumber. The amount of overhang may be influenced by the convenience of handling and positioning, but it should be kept uniform from specimen to specimen.

Excitation system

- The member should be excited so as to produce a vertical oscillation in a reproducible manner in the fundamental mode.
- Manual deflection of the specimen will provide sufficient impetus for oscillation for many products. The deflection should be vertical with an effort to exclude lateral components; neither excessive impact nor prolonged contact with the specimen is recommended. For example, a manual tap on a 16-ft. (4.8-m) nominal 2- by 12-in. (standard 38- by 286-mm) piece of lumber with MOE of 2.0×10^6 lb./in.^{2} (13.8 GPa) and supported flatwise will result in a vertical oscillation of 3 to 4 Hz.
- Specimens with very high stiffness require mechanical excitation by a high force or carefully regulated impact/release.

Measurement system

- Measurement of the frequency of oscillation should be obtained by either a force or displacement measuring device.
- Changes in force in response to the vibration at one or both supports are used to obtain frequency of oscillation.
- Frequency of oscillation can also be determined by measuring midspan displacement in response to initial displacement.
- It is critical that only the frequency associated with the fundamental vertical oscillation mode be used. Immediately after the specimen is excited, many vibration modes appear. The modes associated with higher frequencies than the fundamental bending frequency usually dissipate rapidly. Therefore, a short delay is necessary before acquiring the data to ensure that the data are related only to the fundamental vertical mode. This is an effective way to filter undesired modes from the data.
- The span-to-depth ratio should be greater than 60 unless special precautions are taken to permit higher frequency measurements. With small span-to-depth ratios, it is difficult to verify that the specimen is oscillating in a bending mode. Best results are obtained when the frequency of oscillation is less than 30 Hz.

Stress Wave Techniques

Several techniques that employ stress wave propagation have been researched for use as NDE tools. Speed-of-sound transmission and attenuation of induced stress waves in a material are frequently used as NDE parameters.

To illustrate stress wave techniques, consider application of one-dimensional wave theory to a homogeneous viscoelastic bar **(Fig. 2.6).** After an impact hits the end of the bar, a compression wave is generated. This wave immediately begins moving down the bar as particles at the leading edge of the wave become excited, while particles at the trailing edge come to rest. The

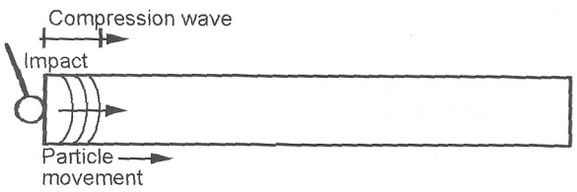

Figure 2.6 - *Viscoelastic bar of length* L *subjected to an impact.*

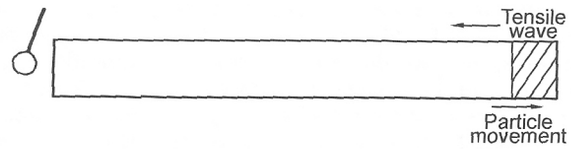

Figure 2.7 - *Travel of compression wave along bar. The forward-moving wave impinges on the free end of the bar, is reflected as a tensile wave, and begins to travel back down the bar.*

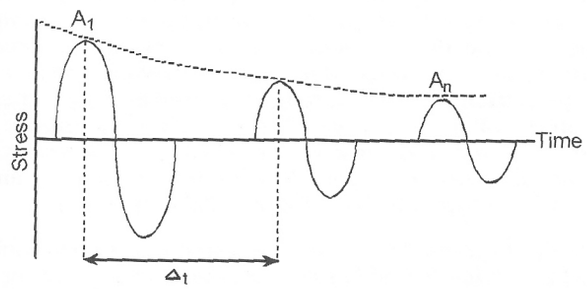

Figure 2.8 - *Waveforms consist of a series of equally spaced pulses whose magnitude decreases exponentially with time.*

wave depth or the distance between the leading and trailing edges of the wave is controlled by the length of the impactor and the velocity of propagation of the material that makes up the impactor. The wave moves along the bar at a constant speed, but its individual particles have only small longitudinal movements as a result of the wave passing over them. After traveling the length of the bar; this forward-moving wave impinges on the free end of the bar and is reflected as a tensile wave traveling back down the bar (**Fig. 2.7**) the velocity of the wave is independent of the intensity of the impact.

Energy is dissipated as the wave travels through the bar; therefore, although the speed of the wave remains constant, movement of particles diminish with each successive passing of the wave. Eventually all particles of the bar come to rest. Monitoring the movement of a cross section near the end of such a bar in response to propagating stress wave results in waveform that consists of a series of equally spaced pulses whose magnitude decreases expotentially with time (**Fig. 2.8**).

The propagation speed C of such a stress wave can be determined by coupling measurements of the time between pulses, Δt, and the length of the bar L by

$$C = \frac{2L}{\Delta t} \qquad [2.9]$$

The MOE can be computed using C and the mass density of the bar p:

$$\text{MOE} = C^2 \rho \qquad [2.10]$$

Wave attenuation can be determined from the rate of decay of the amplitude of pulses using Equation [2.4] for logarithmic decrement.

Note that wave attenuation calculated by this formula is highly dependent upon characteristics of the excitation system used. Thus, results reported by various researchers cannot be directly compared because several excitation systems were employed. Nonetheless, these results show that energy loss characteristics as measured by stress wave techniques provide useful information on the performance of wood-based materials.

A more rigorous treatise on the measurement of energy loss by stress wave techniques is presented by Kolsky (1963). In general, a more appropriate method for evaluating energy loss would be to determine the quantity of energy imparted into a member and the corresponding rate of energy loss. Loss of energy would be calculated using an integral of a waveform, as is done for determining the energy emitted during acoustic emission testing of materials (Harris *et al.* 1972). This is defined as the root mean square (RMS) value.

Wood is neither homogeneous nor isotropic; therefore, the usefulness of one-dimensional wave theory for describing stress wave behavior in wood could be considered dubious. However, several researchers have explored application of the theory by examining actual waveforms resulting from propagating waves in wood and wood products and have found that one-dimensional wave theory is adequate for describing wave behavior. For example, Bertholf (1965) found that the theory could be used to accurately predict dynamic strain patterns in small wood specimens. He verified predicted stress wave behavior with actual strain wave measurements as well as dependence of propagation velocity on the MOE of clear wood. Ross (1985) examined wave behavior in both clear wood and wood-based composites and observed excellent agreement with one-dimensional theory. Similar results were obtained with clear lumber in tests conducted by Kaiserlik and Pellerin (1977).

An interesting series of experiments designed to explore wave behavior in lumber was conducted by Gerhards (1981, 1982). He observed changes in the shape of a wave front in lumber containing knots and cross grain by measuring the change in wave speed in the vicinity of such defects. He concluded that a stress wave traveling in lumber containing knots and cross grain does not maintain a planar wave front.

One common technique that employs stress wave NDE technology uses simple time-of-flight type measurement systems to determine stress wave propagation speed **(Figs. 2.9 and 2.10).** In these measurement systems, a mechanical or ultrasonic impact is used to impart a longitudinal wave into a member. Piezoelectric sensors are placed at two points on the member and used to sense passing of the wave. The time required for the wave to travel between sensors is measured and used to compute wave propagation speed.

Stress wave transmission times on a per length basis for various wood species are summarized in **Table 2.4.** Note that stress wave transmission times are shortest along the grain (parallel to fiber) and longest across the grain (perpendicular to fiber). Note that for Douglas-fir and Southern Pine, stress wave transmission times parallel to the grain are approximately

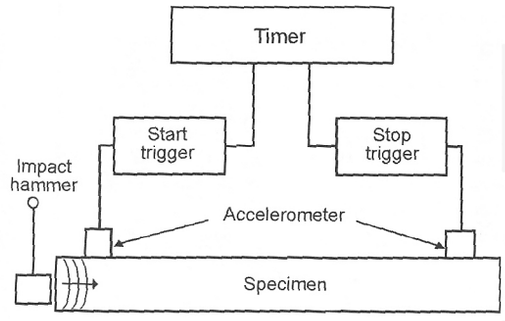

Figure 2.9 –*System used to measure impact-induced stress wave propagation speed in various wood products.*

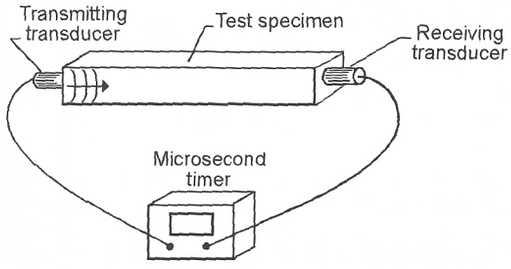

Figure 2.10 - *Ultrasonic measurement system used to measure speed-of-sound transmission in various wood products.*

200 µs/m (60 µs/ft.). Stress wave transmission times perpendicular to the grain range from 850 to 1,000 µs/m (259 to 305 µs/ft.).

Several research projects have been conducted on the use of one-dimensional wave theory for assessing the MOE of clear wood, lumber, and veneer. These studies have examined relationships between MOE values obtained from stress wave measurements and those obtained by static testing techniques. The strong correlative relationships found in these studies are shown in **Table 2.5.**

Table 2.6 summarizes research on the use of stress wave techniques for assessing the strength properties of lumber and composite products. Kaiserlik and Pellerin (1977), for example, used stress wave techniques to evaluate the tensile strength of a small sample of clear lumber containing varying degrees of slope of grain. They used the one-dimensional wave equation, Equation [2.9], to compute MOE and the equation presented by Pellerin (1965b) for logarithmic decrement.

Extensive research has been conducted on the use of stress wave techniques for assessing the mechanical properties of wood composites (Fagan and Bodig 1985; Pellerin and Morschauser 1974; Ross 1984; Ross and Pellerin 1988; Vogt 1985). Pellerin and Morschauser (1974) used the setup in **Figure 2.11** to show that stress wave speed could be used to predict the flexural behavior of underlayment-grade particleboard. Ross (1984) and Ross and Pellerin (1988) showed that wave attenuation is sensitive to bonding characteristics and is a valuable NDE parameter that contributes significantly to the prediction of tensile and flexural mechanical behavior of wood-based particle composites. Vogt (1985) examined the use of stress wave techniques with wood-based fiber composites. In an additional study, Vogt (1986) found a strong relationship between internal bond and stress wave parameters of particle and fiber composites.

The use of stress wave techniques with wood subjected to different levels of biodeterioration, which adversely affects mechanical properties, has been limited to studies that have employed only energy storage parameters **(Table 2.7).** For example, Pellerin *et al.* (1985) showed that stress wave speed could used to monitor the degradation of small, clear wood specimens exposed to brown-rot fungi. They showed a strong correlative rela-

Table 2.4—Summary of research on stress wave transmission times for various wood species.

Reference	Species	Moisture content (% ovendry)	Stress wave transmission time (μs/m (μs/ft.))	
			Parallel to grain	Perpendicular to grain
Smulski (1991)	Sugar maple	12	256–194 (78–59)	—
	Yellow birch	11	230–180 (70–55)	—
	White ash	12	252–197 (77–60)	—
	Red oak	11	262–200 (80–61)	—
Armstrong *et al.* (1991)	Birch	4–6	213–174 (65–53)	715–676 (218–206)
	Yellow-poplar	4–6	194–174 (59–53)	715–676 (218–206)
	Black cherry	4–6	207–184 (63–56)	689–620 (210–189)
	Red oak	4–6	226–177 (69–54)	646–571 (197–174)
Elvery and Nwokoye (1970)	Several	11	203–167 (62–51)	—
Jung (1979)	Red oak	12	302–226 (92–69)	—
Ihlseng (1878, 1879)	Several	—	272–190 (83–58)	—
Gerhards (1978)	Sitka spruce	10	170 (52)	—
	Southern Pine	9	197 (60)	—
Gerhards (1980)	Douglas-fir	10	203 (62)	—
Gerhards (1982)	Southern Pine	10	197–194 (60–59)	—
Rutherford (1987)	Douglas-fir	12	—	1,092–623 (333–190)
Ross (1982)	Douglas-fir	11	—	850–597 (259–182)
Hoyle and Pellerin (1978)	Douglas-fir	—	—	1,073 (327)
Pellerin *et al.* (1985)	Southern Pine	9	200–170 (61–52)	—
Soltis *et al.* (1992)	Live oak	12	—	613–1,594 (187–486)
Ross *et al.* (1994)	Northern red and white oak	green	—	795 (242)

Table 2.5—Summaryof research on correlation between stress wave and static modulus of elasticity of clear wood, lumber, and veneer.

Reference	Material	Static loading mode	Correlation coefficient *r*
Bell *et al.* (1954)	Clear wood	Compression	0.98
	Clear wood	Bending	0.98
Galligan and Courteau (1965)	Lumber	Bending	0.96
Koch and Woodson (1968)	Veneer	Tension	0.96–0.94
Porter *et al.* (1972)	Lumber	Bending	0.90-0.92
Pellerin and Galligan(1973)	Lumber	Bending	0.96
	Veneer	Tension	0.96
McAlister (1976)	Veneer	Tension	0.99
Gerhards (1982)	Knotty lumber	Bending	0.87
	Clear lumber	Bending	0.95

tionship between stress wave speed and parallel-to-grain compressive strength of exposed wood. Rutherford *et al.* (1987) showed similar results. These authors also revealed that MOE perpendicular to the grain, measured using stress wave NDE techniques, was significantly affected by degradation from brown-rot decay and could be used to detect incipient decay. Chudnoff *et al.* (1984) reported similar results from experiments that utilized an ultrasonic measurement system and several hardwood and softwood species. Patton-Mallory and De Groot (1989) reported encouraging results from a fundamental study dealing with the application of acousto-ultrasonic techniques. Their results showed that energy loss parameters may provide useful additional information on early strength loss from incipient decay caused by brown-rot fungi.

Verkasalo *et al.* (1 993) and Ross *et al.* (1992) obtained encouraging results when using stress wave techniques to identify bacterially infected red oak. They found that speed of sound transmission perpendicular to the grain was significantly slower in sections of wood containing bacterial infection.

Stress wave techniques, especially those relying on measurement of transmission times, are used worldwide. Current manufacturers of stress wave timing equipment are listed in **Table 2.8.**

Essential Laboratory Testing Procedures and Key Information

The following text describes essential laboratory testing procedures and additional key information for using stress wave measurements in a laboratory environment.

Pulse Echo Test Setup

Figure 2.11 illustrates a typical pulse echo test setup. An impact or "pulse" on one end of the specimen induces a wave to flow along the length

Table 2.6—Summary of results from studies using nondestructive stress wave testing techniques on lumber and wood composite products.[a]

Reference	NDE technique	Material	NDE parameter measured	Static test	Reported properties	Comparison of NDE parameters and static properties (correlation coefficient r, unless noted)
Kaiserlik and Pellerin (1977)	Longitudinal stress wave	Douglas-fir boards	C, E_d, δ	Tension	UTS	UTS and E_d,0.84; UTS and combination of E_d, δ, 0.90
Pellerin and Morschauser (1974)	Longitudinal stress wave	Underlayment particleboard	C	Bending	E_{SB}, MOR	E_{SB}, and C^2, 0.93–0.95 MOR and C^2, 0.87–0.93
Ross (1984), Ross and Pellerin (1988)	Longitudinal stress wave	Underlayment and industrial particleboard, structural panel products	C, E_d, δ	Tension	E_{ST}, UTS	E_{ST} and C^2, 0.98 E_{ST} and E_d, 0.98 UTS and C^2, 0.91 UTS and E_d, 0.93 UTS and $1/\delta$, 0.63 UTS and combination of E_d, $1/\delta$, 0.95
				Bending	E_{SB}, MOR	E_{SB}, and C^2, 0.97 E_{SB}, and E_d, 0.96 MOR and C^2, 0.93 MOR and E_d, 0.92 MOR and $1/\delta$, 0.70 MOR and combination of E_d, $1/\delta$, 0.97
				Internal bond	IB	IB and combination, 0.79

Table 2.6—(Cont.)

Fagan and Bodig (1985)	Longitudinal stress wave	Wide range of wood composites	C	Bending	MOR	Simulated and actual MOR distributions were similar
Vogt (1985)	Longitudinal stress wave	Medium-density fiberboard	C, E_d, δ	Tension	E_{ST}, UTS	E_{ST} and C^2, 0.90 EST and E_d, 0.88 UTS and C^2, 0.81 UTS and E_d, 0.88 Combination, 0.88
				Bending	ESB, MOR	E_{SB}, and C^2, 0.76 E_{SB}, and E_d, 0.72 MOR and C^2, 0.96 MOR and C^2, 10.92 Combination, 0.97
Vogt (1986)	Stress wave (through transmission)	Underlayment and industrial particleboard, structural panel products	C_t, E_{dt}	Internal bond	IB	IB and C_t^2, 0.70–0.72 IB and E_{dt}, 0.80–0.99

[a] C, speed of sound; C_t, speed-of-sound transmission through thickness; δ, logarithmic decrement; E_d, dynamic modulus of elasticity (MOE) from transverse vibration or stress wave measurements; E_{dt}, dynamic MOE through thickness orientation; E_{SB}, MOE from static bending test; E_{ST}, MOE from static tension test; IB, internal bond; MOR, modulus of rupture; UTS, ultimate tensile stress.

Table 2.7—Research summary of correlation between nondestructive testing parameters and properties of degraded wood.

Reference	NDE technique	Material	Degradation agent	NDE parameter measured	Static test	Reported properties	Comparison of NDE parameters and static properties (correlation coefficient *r*, unless noted)
Chudnoff *et al.* (1984)	Longitudinal stress wave (parallel to grain)	Decayed and sound mine props; 26 species or species groupings	—	E_d	Compression parallel to grain	E_c, UCS	E_c and E_d, 0.84–0.97 (all species combined, hardwoods, maple, and oaks) E_c and E_d, 0.73–0.81 (all species combined, southern pines, lodgepole pine) UCS and E_d, 0.85–0.95 (all species combined, hardwoods, maple, and oaks)
Pellerin *et al.* (1985)	Longitudinal stress wave (parallel to grain)	Small clear southern yellow pine specimens	Brown-rot fungi *(Gloeophyllum trabeum)*	C, E_d	Compression parallel to grain	UCS	UCS and C: 0.47 (control) 0.73 (exposed) 0.80 (control and exposed) UCS and E_d: 0.86 (control) 0.86–0.89 (exposed) 0.94 (control and exposed)
			Termites (subterranean)	C, E_d			UCS and C: 0.65 (control) 0.21 (exposed) 0.28 (control and exposed) UCS and E_d: 0.90 (control) 0.79 (exposed) 0.80 (control and exposed)

Table 2.7—(Cont.)

Rutherford (1987), Rutherford *et al.* (1987)	Longitudinal stress wave (perpendicular to grain)	Small, clear Douglas-fir specimens	Brown-rot fungi *(Gloeophyllum trabeum)*	C, E_d	Compression perpendicular to grain	E_c, UCS	E_c and C, 0.91 E_c and E_d, 0 94 UCS and C, 0.67–0.70 UCS and E_d, 0 79 UCS and MOE, 0.80
Patton-Mallory and De Groot (1989)	Longitudinal stress wave	Small, clear southern yellow pine specimens	Brown-rot fungi *(Gloeophyllum trabeum)*	C, root mean square voltage frequency content of received signal	Bending	Maximum moment, alkali solubility	Linear decrease in C and decrease in signal strength with increased wood degradation. High-frequency components of signal attenuated in very early stages of decay.
Ross *et al.* (1992)	Longitudinal stress wave (perpendicular to grain)	Red and white oak lumber	Bacteria *(Clostridium* and *Erwinia* sp.*)*	C	None	Presence of infection	Decrease in C with presence of infection.
Verkasalo *et al.* (1993)	Longitudinal stress wave (perpendicular to grain)	Red oak lumber	Bacteria *(Clostridium* and *Erwinia* sp.*)*	C	Tension perpendicular to grain	UTS, presence of infection	Decrease in C and UTS with presence of infection.

[a] AE, acoustic emission; C, speed of sound; E_c, modulus of elasticity (MOE) from static compression test; E_d, dynamic MOE from transverse vibration or stress wave measurements; MOR, modulus of rupture; UCS, ultimate compressive stress; UTS, ultimate tensile stress.

Table 2.8—Manufacturers of stress wave timing equipment.

Manufacturer	Description of equipment
James Instruments, Inc. 3727 North Kedzie Ave. Chicago, IL 60618 USA Telephone: (773) 463–6565 Fax: (773) 463–0009 E-mail: info@ndtjames.com	James "V" meter—Utilizes an ultrasonic pulse generator to impart a stress wave into a member. Measures transmission times.
Metriguard, Inc. 1120 SE Latah P.O. Box 399 Pullman, WA 99163 USA Telephone: (509) 332–7526 Fax: (509) 332–0485 E-mail: sales@metriguard.com	Model 239A Stress Wave Timer—Utilizes a mechanical impact to induce a stress wave. Measures transmission times.
Concept Bois Technologie 40 Rue de Jordils CH-1025 Saint Sulpice, Switzerland Telephone: (41) 21–697–0850 Fax: (41) 21–697–0852 www.chs-cht.com	Sylvatest Duo—Utilizes an ultrasonic pulse generator to impart a stress wave into a member. Measures transmission times and attenuation.
IML, Inc. 1950 Barrett Lakes Blvd. Suite 2212 Kennesaw, GA 30144 Telephone: (888) 514–8851 Fax: (770) 514–8351 www.imlusa.com	Impulse hammer–electronic hammer—Utilizes a mechanical impact to induce a stress wave. Measures transmission times.

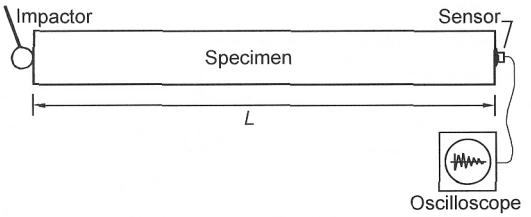

Figure 2.11—*Typical pulse echo test setup.*

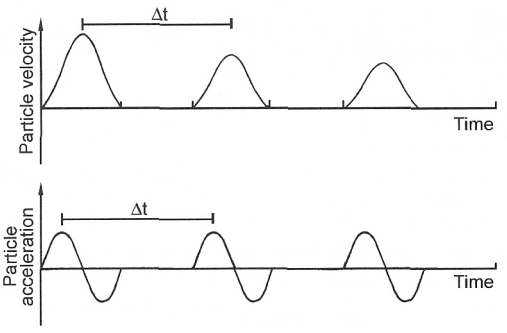

Figure 2.12 - *Example waveforms obtained by transducers that measure particle velocity and acceleration.*

of a specimen. The pulse is "echoed from the opposite end of the specimen, hence the term pulse echo. Characteristics of waveforms observed when using the pulse echo technique are highly dependent upon the type of sensor used. Various types of sensors, including those that measure particle displacement, particle velocity, and particle acceleration or strain, can be used with this type of test setup. **Figure 2.12** illustrates example waveforms obtained by transducers that measure particle velocity and acceleration. Note that the time required for a pulse to travel a round trip through the specimen can be obtained by using any of these transducers. The formula for transmission time is

$$Transmission \quad time \ = \frac{At}{2L}$$

where *At* is time between pulses and *L* is specimen length. Note that this technique, as described, requires that both ends of the specimen are freely supported. A fixed end support condition will yield waveforms with different characteristics.

Pitch and Catch Test Setup

Figure 2.13 illustrates a typical pitch and catch test setup. A pulse is introduced in the specimen, sensed by a transducer, and then allowed to flow through the specimen. The leading edge of the pulse is then sensed by a second transducer located further down the specimen. A pitch and catch test setup yields an electronic signal similar to that illustrated in **Figure 2.14.** The time required for the wave or pulse to travel between the sensors can be calculated by the following equation:

$$Transmission \quad time \ = \frac{At}{L}$$

where *At* is time between pulses and *L* is distance between transducers.

There are two key points to consider when using the pitch and catch test setup:

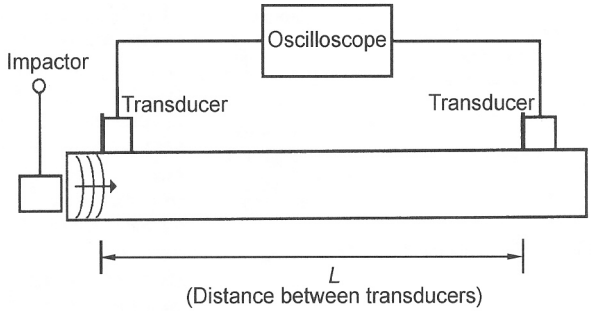

Figure 2.13 — *Typical pitch and catch test setup. Pulse is introduced in specimen, sensed by transducer, and allowed to flow through specimen.*

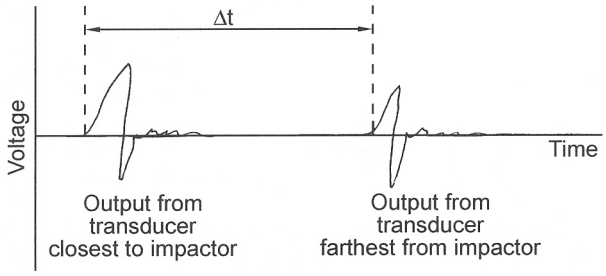

Figure 2.14 — *Electronic signal yielded by pitch and catch test setup.*

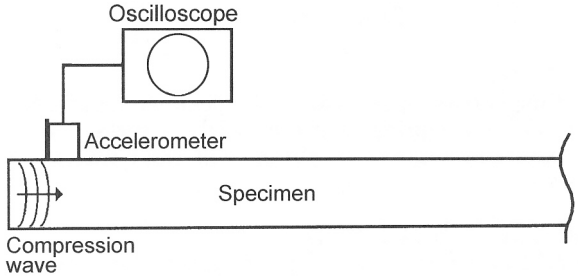

Figure 2.15 — *Accelerometer positioned so that its base faces away from approaching compressive wave. Orientation of accelerometer influences characteristics of waveform.*

1. The transducers must be in line with each other.
2. Many transducers are sensitive to the manner in which they are installed. For example, commonly used accelerometers yield wave forms that are strongly dependent upon which direction they sense the pulse. Note that in **Figure 2.15,** the base of the accelerometer directly faces an approaching compressive wave. Simply turning the accelerometer so that its base faces away from the approaching compressive wave changes the characteristics of the waveform.

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Compiled and Edited by
Roy F. Pellerin and
Robert J. Ross

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