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Nondestructive Testing for Assessing Wood Members in Structures

A Review

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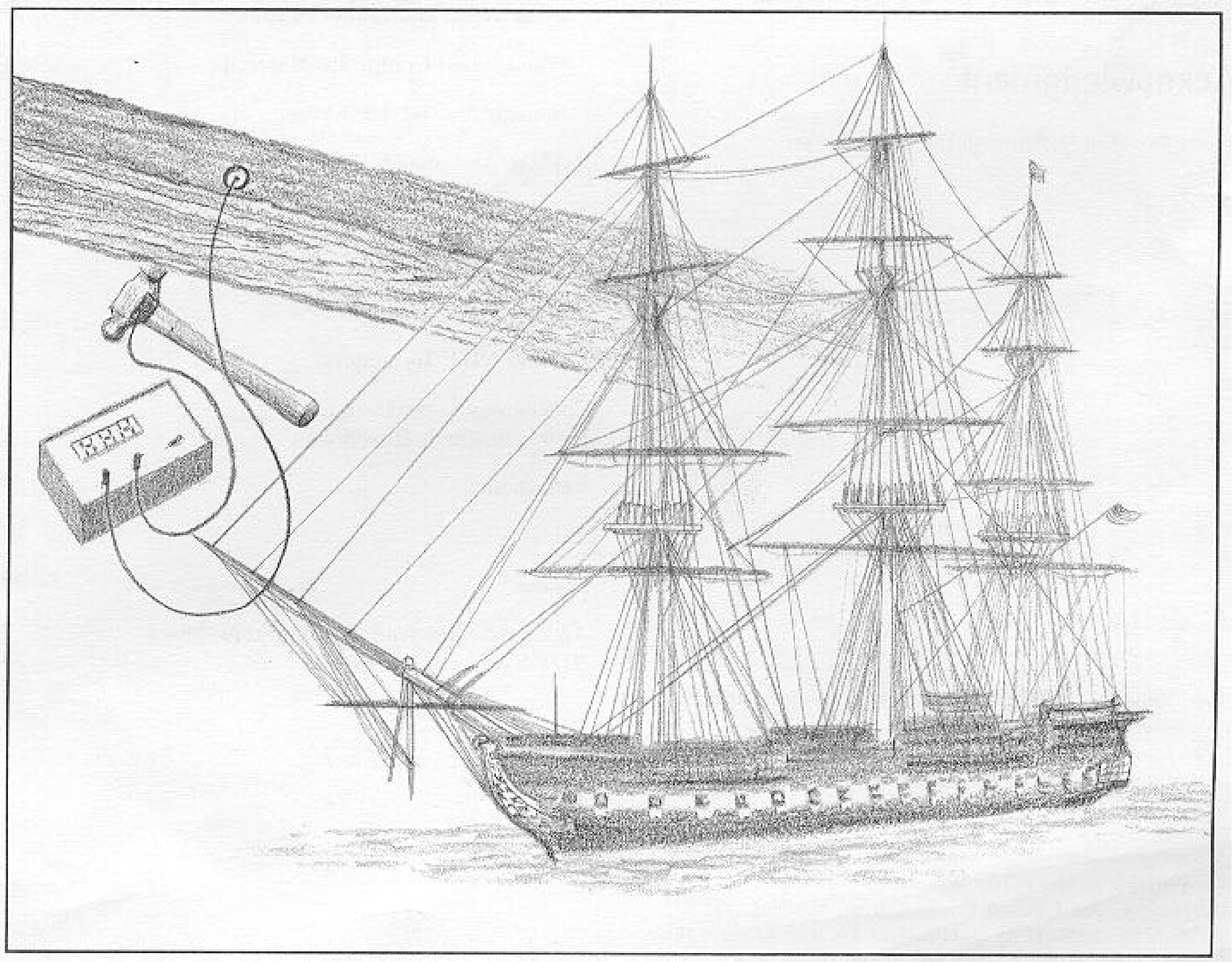

Abstract

Numerous organizations have conducted research to develop nondestructive testing (NDT) techniques for assessing the condition of wood members in structures. A review of this research was published in 1991. This is an update of the 1991 report. It presents a comprehensive review of published research on the development and use of NDT tools for in-place assessment of wood members. It examines the fundamental hypothesis behind NDT of wood, reviews several widely used NDT techniques, and summarizes results of projects that focused on laboratory verification of the fundamental hypothesis. Results obtained from projects that used NDT techniques for in-place evaluation of wood members are presented. In addition, recommendations are given for future in-place assessment NDT research.

Keywords: Nondestructive testing, structures, literature review, wood

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A Review

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Executive Summary

The USDA Forest Service, Forest Products Laboratory (FPL), and Washington State University (WSU) have been actively developing nondestructive testing (NDT) techniques for wood products for more than 30 years. Their individual and combined efforts of research and technology transfer activities have yielded a variety of NDT tools and techniques that are commonly used by manufacturers and users of forest products throughout the world.

Recently, individuals and organizations have shown considerable interest in the use of NDT for assessing the performance of wood members in structures. Both the FPL and WSU have received numerous requests for background information that illustrates use of NDT techniques for in-place member assessment. Questions are frequently asked about fundamental NDT concepts and about previous NDT research that might be extended to a particular application.

We prepared this updated report to provide a synthesized information base to aid in addressing such requests. This report is a compilation of various published research and application efforts that have focussed on NDT of wood products. The report begins by examining fundamental concepts for NDT of wood. It then reviews pertinent laboratory investigations designed to explore fundamental concepts and presents several examples of how to apply these concepts to in-place assessment of wood members. Recommendations are also given for future in-place assessment NDT research.

Introduction

By definition, nondestructive materials evaluation is the science of identifying physical and mechanical properties of a piece of material without altering its end-use capabilities. Such evaluations rely upon nondestructive testing (NDT) techniques to provide accurate information pertaining to the properties, performance, or condition of the material in question.

Historically, the wood products community has developed and used NDT techniques almost exclusively for sorting or grading structural products. Two excellent examples are machine stress rating (MSR) of lumber and ultrasonic grading of veneer. As currently practiced in North America, MSR couples visual sorting criteria with nondestructive measurements of the stiffness of a piece of lumber to assign it to an established grade (Galligan and others 1977). Similarly, laminated veneer manufacturing facilities use stress wave NDT techniques to sort incoming veneer into strength classes prior to processing into finished products. Veneers are assigned to strength categories, which are established through empirical relationships between stress wave velocity and strength, based on the velocity at which an induced stress wave travels through the veneer (Sharp 1985).

However, a need also exists for NDT techniques to be used in the evaluation of wood in structures. This need is expanding because an increasing amount of resources are being devoted to repair and rehabilitation of existing structures rather than to new construction. As more resources are devoted to repair, an increasing emphasis must be placed on the in-place assessment of structures. This, in turn, requires accurate, cost-effective NDT techniques.

This updated report presents a review of literature on NDT techniques used for in-place evaluation of wood in structures. Reports of work utilizing NDT techniques for in-place evaluation of wood in structures are also discussed. The Appendix contains a reference listing from the Nondestructive Testing of Wood Symposium Series.

Fundamental Hypothesis

Nondestructive testing techniques for wood differ greatly from those for homogeneous, isotropic materials such as metals, plastics, and ceramics. In such nonwood-based materials, whose mechanical properties are known and tightly controlled by manufacturing processes, NDT techniques are used only to detect the presence of discontinuities, voids, or inclusions. However, in wood, these irregularities occur naturally and may be further induced by degradative agents in the environment. Therefore, NDT techniques for wood are used to measure how natural and environmentally induced irregularities interact in a wood member to determine its mechanical properties.

This concept led researchers to vigorously examine several NDT techniques for grading structural lumber and evaluating the quality of laminated materials (Bell and others 1950; Galiginaitis and others 1954; Jayne 1955, 1959; James 1959; Hoyle 1961b; McKean and Hoyle 1962; Senft and others 1962). Two significant developments evolved from their efforts: MSR of lumber, and perhaps more significant, the evolution of a hypothesis based on fundamental material properties for establishing relationships between measurable NDT parameters and static mechanical properties.

The fundamental hypothesis for NDT of wood materials was initiated by Jayne (1959). He proposed that the energy storage and dissipation properties of wood materials, which can be measured nondestructively by using a number of NDT techniques, are controlled by the same mechanisms that determine the static behavior of such material. As a consequence, useful mathematical relationships between these properties and static elastic and strength behavior should be attainable through statistical regression analysis.

To elaborate on Jayne's (1959) hypothesis, consider how the microscopic structure of clear wood affects its static mechanical behavior and energy storage and dissipation properties. Clear wood is a composite material composed of many tube-like cells cemented together. At the microscopic level, energy storage properties are controlled by orientation of the cells and structural composition, factors that contribute to static elasticity and strength. Such properties are observable as frequency of oscillation in vibration or speed-of-sound transmission. Conversely, energy dissipation properties are controlled by internal friction characteristics, which bonding behavior between constituents contributes to significantly. Rate of decay of free vibration or acoustic wave attenuation measurements are frequently used to observe energy dissipation properties in wood and other materials.

Statistical regression analysis methods are used to establish mathematical relationships between NDT parameters and performance characteristics. As shown in Figure 1, the closer data are grouped around the regression line and the lower the variability, the more successful an NDT parameter is at predicting performance. In the literature we reviewed, most researchers reported on the quality of an NDT parameter in terms of a correlation coefficient r. Correlation coefficients can range from -1 to 1. A correlation coefficient nearing 1 suggests a strong positive relationship, and a coefficient near 0.7 indicates a positive relationship. A correlation coefficient of zero reveals that no relationship exists, positive or negative.

NDT Techniques

The following sections briefly describe several techniques used to nondestructively evaluate wood-based materials.

Static Bending Techniques

Measuring modulus of elasticity (MOE) of a member by static bending techniques is the foundation of MSR of lumber. As currently employed for MSR, this relatively simple measurement involves utilizing the load-deflection relationship of a simply supported beam loaded at its midspan (Fig. 2). Modulus of elasticity can be computed directly by using equations derived from fundamental mechanics of materials and used to infer strength.

Transverse Vibration Techniques

Transverse vibration techniques have received considerable attention for NDT applications. To illustrate these methods, an analogy can be drawn between the behavior of a vibrating beam and the vibration of a mass that is attached to a weightless spring and internal damping force (Fig. 3). In Figure 3, mass M is supported from a rigid body by a weightless spring whose stiffness is denoted by K. Internal friction or damping is represented by the dashpot D. A forcing function equaling P_0 sin wt 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:

$$M\left(\frac{d^2x}{dt^2}\right) + D\left(\frac{dx}{dt}\right) + Kx = P_0 \sin \omega t \qquad (1)$$

Equation (1) can be solved for either K or D.

A solution for K will lead to an expression for MOE where

$$\text{MOE} = \frac{f_r^2 W L^3}{12.65 I g} \tag{2}$$

for a beam freely supported at two nodal points and

$$\text{MOE} = \frac{f_r^2 W L^3}{2.46 I g} \tag{3}$$

for a beam simply supported at its ends

In Equations (2) and (3),

MOE is dynamic modulus of elasticity (lb/in^2 (Pa)),
f_r resonant frequency (Hz),
W beam weight (lb (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 (1) for D leads to an expression of the internal friction or damping component. The logarithmic decrement of vibrational decay d is a measure of internal friction and can be expressed in the form (for free vibrations)

$$\delta = \frac{1}{(n-1)} \ln \frac{A_1}{A_n} \tag{4}$$

where A_1 and A_n are the amplitudes of two oscillations $n - 1$ cycles apart (Fig. 4)

For forced vibrations,

$$\delta = \frac{\pi \Delta f}{f_r} \frac{1}{\sqrt{(A_r/A)^2 - 1}} \tag{5}$$

where

Δf is the difference in frequency of two points of amplitude A on each side of a resonance curve,
f_r the frequency at resonance, and
A_r the amplitude at resonance (Fig. 4b).

Sharpness of resonance Q is frequently used to measure damping capacity; Q is defined as the ratio of f_r/f. Note that if the value $0.707A_r$ (half-power point method) is substituted for A in Equation (5), the equation reduces to

$$\delta = \frac{\pi \Delta f}{f_r} \tag{6}$$

and

$$Q = \frac{\pi}{\delta} \tag{7}$$

Stress Wave Techniques

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

To illustrate these techniques, consider application of one-dimensional wave theory to the homogeneous viscoelastic bar (Fig. 5). After an impact hits the end of the bar, a 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 of the wave come to rest. 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, is reflected, and begins traveling back down the bar.

Energy is dissipated as the wave travels through the bar; therefore, although the speed of the wave remains constant, movement of particles diminishes 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 a propagating stress wave results in waveforms that consist of a series of equally spaced pulses whose magnitude decreases exponentially with time (Fig. 6). The propagation speed C of such a wave can be determined by coupling measurements of the time between pulses At and the length of the bar L by

$$C = \frac{2L}{\Delta t} \tag{8}$$

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

$$\text{MOE} = C^2 \rho \tag{9}$$

Wave attenuation can be determined for the rate of decay of the amplitude of pulses using Equation (4) for logarithmic decrement.

Note that wave attenuation calculated using 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. As their results show, energy loss characteristics as measured by stress wave techniques provide useful information pertaining to 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 loss of energy. 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 and others 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 and also verified 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 also 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 commonly used technique that employs stress wave NDT technology utilizes simple time-of-flight-type measurement systems to determine speed-of-wave propagation (Figs. 7,8). 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 it takes for the wave to travel between sensors is measured and used to compute wave propagation speed.

Several research projects designed to examine application of one-dimensional theory to wave propagation in clear wood, lumber, and veneer have been conducted using this type of measurement. These projects examined relationships between MOE values obtained from stress wave measurements and those measured using static testing techniques. Note the strong correlative MOE relationships found in these research projects (Table 1).

Considerable research activity has focused on development of techniques to measure stress wave attenuation in wood products. For example, Ross and Pellerin (1988) used an inexpensive velocity meter to measure wave attenuation. Others (Beall 1987, Patton-Mallory and De Groot 1989, Biernacki and Beall 1993) examined coupling acoustic emission (AE) and ultrasonic techniques to measure wave attenuation.

Acoustic emission techniques have also been extensively researched for application to wood-based materials. These techniques rely upon the application of stress to a member to generate a stress wave. An excellent review of AE techniques and research related to their application to wood-based materials is presented by Beall (1987).

Other Techniques

Several other NDT techniques have been investigated for use with wood. For example, the attenuation of x-rays has been investigated for detecting internal voids in wood (Mothershead and Stacey 1965) and for inspecting utility poles and trees (Monro and others 1990).

Screw withdrawal (Talbot 1982) and pick- or probing-types tests have also been examined. These inexpensive techniques provide information about a member at a point and are consequently of limited value for inferring strength for large members. However, they are useful for detecting surface damage of members.

The Pilodyn test is also used to detect surface damage. The Pilodyn instrument consists of a spring-loaded pin device that drives a hardened steel pin into the wood. Depth of pin penetration is used as a measure of degree of degradation (Hoffmeyer 1978).

Laboratory Verification of Fundamental Hypothesis

Several research organizations have examined application of fundamental concepts under laboratory conditions. The following sections summarize results presented by these organizations.

Clear Wood and Lumber Products

Initial laboratory studies to verify the fundamental hypothesis were conducted with clear wood and lumber products using a variety of NDT techniques. For example, considerable research activity was conducted in the early 1960s to examine relationships between the static bending MOE and ultimate strength of softwood dimension lumber. Results obtained from various projects designed to examine this relationship are summarized in Tables 2 to 4. Note that useful correlative relationships were found between MOE and the bending, compressive, and tensile strengths of dimension lumber obtained from various softwood species. Recently, these relationships have been shown to exist for hardwood structural lumber (Table 5) (Green and McDonald 1993a,b).

Research coupling noncontact scanning technology with other NDT techniques has also yielded encouraging results. Results indicate that an increase of accuracy estimates of the strength of lumber products can be achieved when measurements of slope-of-grain are incorporated into strength predictive equations (Bechtel and Allen 1987, Cramer and McDonald 1989).

Research using transverse vibration and stress wave techniques is summarized in Table 6. Jayne (1959) designed and conducted one of the first studies that utilized transverse vibration NDT 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. He utilized an experimental setup similar to that illustrated in Figure 9. With this setup, 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. Pellerin (1965a,b) verified the hypothesis using free transverse vibration techniques on dimension lumber and glulam timbers with the apparatus shown in Figure 10. After obtaining a damped sine waveform for a specimen (Fig. 3), he analyzed it utilizing equations 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 and others (1993) used a variety of stress wave and transverse vibration techniques to evaluate the static bending MOE of structural lumber. Recently, Ross and others (1991) coupled relatively inexpensive personal computer technologies and transverse vibration NDT techniques and obtained comparable results.

Kaiserlik and Pellerin (1977) furthered the hypothesis by using stress wave techniques to evaluate the tensile strength of a small sample of clear lumber containing varying degrees of slope of grain (Fig. 11). They utilized the one-dimensional wave Equation (9) to compute MOE and the equation presented by Pellerin (1965b) for logarithmic decrement.

Laboratory research has also been conducted to examine the validity of using fundamental concepts to evaluate the quality of green or wet materials (Ross and Pellerin 1991). Results from this research revealed that stress wave NDE techniques may be useful for evaluating the structural performance of wet materials.

Wood-Based Composite Materials

The fundamental hypothesis was verified using stress wave techniques on wood-based composites (Suddarth 1965, Pellerin and Morschauser 1974, Ross 1984, Fagan and Bodig 1985, Vogt 1985, and Ross and Pellerin 1988) (Table 7). Pellerin and Morschauser (1974) used the setup in Figure 7 to show that stress wave speed, a measure of energy storage properties, could be used to predict the flexural behavior of underlayment grade particleboard. Ross (1984) and Ross and Pellerin (1988) revealed that wave attenuation, a measure of energy dissipation properties, is sensitive to bonding characteristics and is a valuable NDT parameter that contributes significantly to the prediction of tensile and flexural mechanical behavior of wood-based particle composites. Vogt (1985) furthered the application of the hypothesis to 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. Suddarth (1965) verified the hypothesis by using forced transverse vibration techniques to locate poorly bonded or debonded areas in wood components for missiles.

Biologically Degraded Wood

Verification of the hypothesis with wood subjected to different levels of deterioration by decay fungi, which adversely effect the mechanical properties of wood and are frequently found in wood structures, has been limited to studies that have employed only energy storage parameters (Table 8). Wang and others (1980) found that wood decay significantly affected the frequency of oscillation of small, eastern pine, sapwood, cantilever bending specimens (Fig. 12). Pellerin and others (1985) showed that stress wave speed could be successfully used to monitor the degradation of small clear-wood specimens exposed to brown-rot fungi. They showed a strong correlative relationship between stress wave speed and parallel-to-grain compressive strength of exposed wood. Rutherford and others (1987) showed similar results. They also revealed that MOE perpendicular to the grain, measured using stress wave NDT techniques, was significantly affected by degradation from brown-rot decay and could be used to detect incipient decay. Chudnoff and others (1984) reported similar results from experiments that utilized an ultrasonic measurement system (Fig. 8) 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 (Fig. 13). Their results showed that energy loss parameters may provide useful additional information pertaining to early strength loss from incipient decay caused by brown-rot fungi.

Verkasalo and others (1993) and Ross and others (1992) have shown 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.

Acoustic emission techniques were also investigated for use in decay detection. Utilizing a small sample of clear, white fir specimens infected with brown-rot fungi, Beall and Wilcox (1986) were able to show a relationship between selected AE parameters and radial compressive strength (Fig. 14).

In-Place Assessment of Wood Members

Several organizations have published research results on the use of NDT techniques for in-place evaluation of wood members (Table 9). The following summarizes research conducted on the use of several NDT techniques for such evaluations.

Static Bending Techniques

Measuring flexural MOE by static bending techniques has been successfully employed to grade lumber by using machines that approximate simply supported boundary conditions. Such machines consistently maintain these conditions. However, an in-place environment yields boundary conditions that may vary considerably in even the simplest structure. Consequently, application of this technique for in-place assessment of wood members has been limited.

Abbott and Elcock (1987) developed an in-place NDT technique for measuring the stiffness of in-service poles (Fig. 15). A bending load was applied to individual poles above the ground line. Load and resulting deflections were recorded and used to compute flexural stiffness. From these measurements, inferences pertaining to pole strength were made, and predicted and actual values were compared.

Transverse Vibration Techniques

Transverse vibration techniques are also significantly influenced by boundary conditions. Most researchers conducting laboratory studies with this technique devote considerable time to ensuring that simple end conditions are attained. As discussed previously, such conditions frequently do not exist with wood members in structures. Consequently, use of this technique has also been limited for in-place evaluations.

Murphy and others (1987) developed a technique based on transverse vibration NDT techniques for evaluating wood poles. Their technique involved measuring the vibrational response of a pole after it is tapped by a rubber mallet. Resonant frequency of the pole was identified and used to infer pole strength.

Stress Wave Techniques

Longitudinal stress wave NDT techniques have also been investigated by researchers for assessing wood members in structures. The influence that boundary conditions have on speed-of-sound transmission measurements has been shown to be significantly less than that for static bending or transverse vibration techniques. Thus, many researchers have examined longitudinal stress wave NDT techniques for in-place assessment of wood members. The following briefly describes stress wave NDT techniques that have been used in projects.

Eighteenth Century Mansion

Lee (1965) was one of the first to examine use of stress wave techniques for in-place evaluation. He assessed the roof structure of an 18th century mansion, using an ultrasonic impact and measurement system similar to that illustrated in Figure 8. He measured propagation speed of stress waves in wood members both parallel and perpendicular to the grain. To obtain an estimate of strength loss, sections from purlins were evaluated statically in a laboratory, and a chart relating stress wave velocity and strength was prepared. Strength of the remaining timbers was then inferred.

University Football Stadium

Washington State University's football stadium, Pullman, Washington, was also inspected using stress wave NDT techniques. This stadium was originally constructed in the 1930s; the north and south grandstands were replaced after a fire in the 1960s. The portion of the stadium that was inspected for its structural integrity in the early 1980s was the horseshoe section that joined the north and south grandstands. This horseshoe section was part of the original stadium and was constructed from large solid-sawn timbers. An informal inspection by graduate students enrolled in a NDT wood course revealed that the structural members in the horseshoe section were badly decayed and probably would not be able to carry the load from the anticipated crowd. Further evaluation using stress wave equipment (Fig. 16) showed that speed-of-sound transmission was significantly lower in decayed members than in sound wood. Subsequent probing of those areas indicated that the decay was so extensive that only a thin shell of sound wood remained. These results led to the dismantling of the horseshoe section of the stadium. The decay of the timbers was so advanced that when the stress-skin effect of the seating was removed, the substructure collapsed under its own weight.

School Gymnasium

Another structure evaluated with stress wave NDT techniques was a school gymnasium, constructed with laminated barrel arches (Hoyle and Pellerin 1978). These laminated arches were the main support structure for the gymnasium (Fig. 17). Each arch end was exposed to the weather and rested in a metal stirrup fastened to a concrete pier foundation. These conditions and the heavy nonbreathing paint that was used on the exposed portions of the arches created an environment that would support the growth of decay fungi. Cracking and peeling of paint were the first indications that decay was present in the arch ends. When the condition of the gymnasium was realized by school personnel, the problem was one of determining where decay was present and where the wood was sound and did not require replacement. It was not necessary to pinpoint the decayed areas with great precision but to establish how far in from the arch ends that the decay had progressed. The repair procedure was then to replace those ends of the arches with structurally sound material.

The method of inspection was the same as described for the football stadium. To ensure that the stress wave travel times were measured in straight, lines through individual laminates, a paper, on the third arch from the near end of the gymnasium, containing a grid of 1.5-in. (38-mm) squares, was fastened to each side of the arch and used as a map for taking stress wave time measurements (Fig. 18). The recorded times were then used to determine the extent of the decay (Fig. 19).

Piers

Stress wave techniques were also used to inspect the structural integrity of several piers. Currently limited to inspection of structural components that are above the water line, stress wave techniques were used to inspect a Seattle, Washington, pier that is owned and operated by the U.S. Coast Guard. The pier is constructed of large wood beams and stringers supported on wood piling. Although details of the inspection are not published, NDT techniques similar to those described previously were used.

Bridges

A report by Hoyle and Rutherford (1987) describes the evaluation of wood bridges for the Washington State Department of Transportation using speed-of-sound transmission as an index of deterioration. Previously described stress wave NDT techniques were used. About 12 bridges were evaluated and only one revealed signs of decay. Similarly, Aggour and others (1986) used ultrasonic techniques to evaluate the residual compression strength of timber bridge piles. Relationships between speed-of-sound transmission and residual compressive strength showed excellent correlation.

TRESTLE

TRESTLE was constructed between July 1976 and February 1979 and is one of the largest known glue-laminated structures in the world. It is located at Kirkland Air Force Base, New Mexico. TRESTLE was built as a test stand for aircraft that weigh 550,000 lb (250,000 kg). It has a 50- by 394-ft (15- by 120-m) access ramp and a 200- by 200-ft (61- by 61-m) test platform, and the top surface is 118 ft (36 m) above the ground (Fig. 20).

In the early 1980s, the U.S. Air Force wanted to test aircraft that were considerably heavier than had previously been tested, so they requested a structural evaluation of TRESTLE. One evaluation method relied upon speed-of-sound transmission measurements. Figure 21 shows one stress wave technique that was used. Measurements were taken both longitudinally and transversely to the length of the laminated beams. Neal (1985) and Browne and

Kuchar (1985) reported that a total of 484 glulam members (representing approximately 5 percent of the structural members) were evaluated. They concluded that the structural framework of TRESTLE had not measurably degraded, but the exposed deck system was significantly degraded.

Barn Structure

Stress wave techniques were also used to evaluate the wood members of a barn, constructed in 1925 for the College of Agriculture, Washington State University, Pullman, Washington (Lanius and others 1981). The structure evaluated was primarily used as an animal shelter on the ground floor and for hay storage on the second floor. The inspection was confined to the nominal 2- by 12-in. (standard 38- by 286-mm) floor joists in the south bay of the barn where hay storage was believed to be the primary use. Speed-of-sound propagation parallel to the grain was measured on 50 percent of the members of the structure. These values were then related to an allowable extreme fiber stress in bending and used to judge remaining strength.

Water Cooling Towers

Stewart and others (1986) used stress wave techniques to evaluate the wood members of several water cooling towers. Using the instrumentation illustrated in Figure 22, approximately 7,700 4-ft- (1.2-m-) long nominal 2- by 4-in. (standard 38- by 89-mm) redwood columns were evaluated. Using the information obtained from a correlation between stress wave parameters and column strength of 74 test specimens and that obtained from the in-place evaluation, individual column strengths were predicted. Columns not meeting desired reliability limits were identified for replacement. This effort resulted in salvaging a substantial portion of the columns that would have otherwise required replacement.

Wood Utility Poles

Anthony and Bodig (1989) reported on the use of sonic stress wave spectral analysis techniques that they had developed and used for inspection of wood structures. Their equipment was designed on the concept that stress waves propagate at different speeds and attenuate differently at various frequencies in wood-based products. Anthony and Bodig collected a time record of a wave propagating through a member, converted it to a frequency spectrum, and then correlated various characteristics to strength using multiple regression analysis techniques (Fig. 23).

Dunlop (1983) utilized an electronic system (Fig. 24), sweeping through a selected range of excitation frequencies, to develop an acoustic signature of a pole. Resonant frequencies were examined for use as NDT parameters.

USS Constitution

The USS Constitution is the oldest commissioned ship in the U.S. Navy. Stress wave techniques were used to locate decayed sections within its hull and support structure (Witherall and others 1992). Speed of sound transmission was significantly reduced in decayed sections.

Other NDT Techniques

Simple mechanical tests are frequently used for in-service inspection of wood members in structures. For example, sounding-, pick-, or probing-type tests are used by inspectors of wood structures to indicate the condition of a structural member. The underlying premise for the use of such tests is that degraded wood is relatively soft and will have a low resistance to probe penetration.

A quantitative test based on the same underlying premise was developed by Talbot (1982). His test differed from the probing-type test in that instead of evaluating probe penetration resistance, Talbot examined withdrawal resistance of a threaded probe, similar to a wood screw, inserted into a member. Talbot believed that a correlative relationship between withdrawal resistance and residual strength should exist and would be relatively easy to implement. To determine if such a relationship existed, he conducted an experiment using several small Douglas-fir beams that were in various stages of degradation as a result of exposure to decay fungi. Prior to testing to failure in bending, probe withdrawal resistance was measured at the neutral axis of the beams. Bending strength and corresponding probe resistance values were then compared. Talbot's results revealed that a relationship does exist (Fig. 25). He used this test in conjunction with stress wave techniques to assess the extent of damage to the solid-sawn timbers of Washington State University's football stadium. Ross and others (1991) developed a similar test for inspecting fire-retardant-treated panel products.

Concluding Remarks and Future Research Directions

Considerable effort has been devoted to developing NDT techniques for assessing the performance of wood structural members. This report reviewed literature pertaining to NDT of wood, with an emphasis on techniques used for in-place assessment. Based on our review, we conclude the following:

1. A fundamental hypothesis for establishing relationships between NDT parameters and performance of wood members has been established and verified

using a wide range of wood-based materials and a variety of NDT techniques.

2. Laboratory investigations on validity of the fundamental hypothesis for establishing predictive relationships for biologically degraded wood, as is sometimes found in structures, have been limited in regards to both the NDT techniques employed and the biological agents of deterioration studied.

3. In-place assessment efforts have focused primarily on adaptations of stress wave NDT techniques. These techniques have shown considerable promise, are relatively easy to use, and have low equipment costs.

Future in-place assessment NDT research should focus on furthering the application of stress wave techniques. Stress wave NDT techniques have been extensively investigated under laboratory conditions and used by inspection professionals on a limited basis. However, many questions remain unanswered regarding the effectiveness of stress wave NDT techniques to evaluate members in complicated structures. No published work documents how wave behavior is affected by the varied boundary conditions found in wood structures. In addition, little information has been published on the relationship between excitation system characteristics and wave behavior. Research efforts in these two areas would advance state-of-the-art inspection techniques considerably.

References

Abbott, A.R.; Elcock, G. 1987. Pole testing in the European context. In: Proceedings, 6th nondestructive testing of wood symposium; 1987 September 14-16; Pullman, WA. Pullman, WA: Washington State University: 277–302.

Aggour, M.S.; Hachichi, A.; Meyer, M.A. 1986. Nondestructive evaluation of timber bridge piles. In: Proceedings of the American Society of Civil Engineers structures congress. Special publication on evaluation and upgrading of wood structures, Structures Congress '86; 1986 September 15-18; New Orleans, LA. New York, NY: American Society of Civil Engineers: 82–95.

Anthony, R.W.; Bodig, J. 1989. Nondestructive evaluation of timber structures for reliable performance. In: Proceedings, 2d Pacific timber engineering conference; 1989 August 28831; Auckland, New Zealand.

Beall, F.C. 1987. Fundamentals of acoustic emission and acoustic-ultrasonics. In: Proceedings, 6th nondestructive testing of wood symposium; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 3–28.

Beall, F.C.; Wilcox, W.W. 1987. Relationship of acoustic emission during radial compression to mass loss from decay. Forest Products Journal. 37(4): 38–42.

Bechtel, F.K.; Allen, J.R. 1987. Methods of implementing grain angle measurements in the machine stress rating process. Proceedings, 6th international symposium on nondestructive testing of wood; 1987 September 14-16; Pullman, WA. Pullman, WA: Washington State University: 303–353.

Bell, E.R.; Peck, E.C.; Krueger, N.T. 1950. Youngs modulus of wood determined by a dynamic method. Report 1775. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Bell, E.R.; Peck, E.C.; Krueger, N.T. 1954. Modulus of elasticity of wood determined by dynamic methods. Report 1977. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Bertholf, L.D. 1965. Use of elementary stress wave theory for prediction of dynamic strain in wood. Bulletin 291. Pullman, WA: Washington State University, College of Engineering.

Biernacki, J.M.; Beall, F.C. 1993. Development of an acousto-ultrasonic scanning system for nondestructive evaluation of wood and wood laminates. Wood and Fiber Science. 25(3): 289–297.

Browne, C.M.; Kuchar, W.E. 1985. Determination of material properties for structural evaluation of TRESTLE. In: Proceedings, 5th international nondestructive testing of wood symposium; 1985 September 9–11; Pullman, WA. Pullman, Wa: Washington State University: 361–384.

Chudnoff, M.; Eslyn, W.E.; McKeever, D.B. 1984. Decay in mine timbers: Part III, Species-independent stress grading. Forest Products Journal. 34(3): 43–50.

Corder, S.E. 1965. Localized deflection related to bending strength of lumber. In: Proceedings, 2d nondestructive testing of wood symposium; 1965 April; Spokane, WA. Pullman, WA: Washington State University: 461–472.

Cramer, S.M.; McDonald, K.A. 1989. Predicting lumber tensile stiffness and strength with local grain angle measurements and failure analysis. Wood and Fiber Science. 21(4): 393-410.

Doyle, D.V.; Markwardt, L.J. 1966. Properties of Southern Pine in relation to strength grading of dimension lumber. Res. Pap. FPL-RP-64. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Dunlop, J.I. 1983. Testing of poles by acoustic resonance. Wood Science Technology. 17: 31-38.

Fagan, G.B.; Bodig, J. 1985. Computer simulation as a nondestructive evaluation tool. In: Proceedings, 5th nondestructive testing of wood symposium; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 3–37.

Galiginaitis, S.V.; Bell, E.R.; Fine, A.M. [and others]. 1954. Nondestructive testing of wood laminates. Final Report. Louisville, KY: Office of Naval Research, Institute of Industrial Research, University of Louisville.

Galligan, W.L.; Courteau, R.W. 1965. Measurement of elasticity of lumber with longitudinal stress waves and the piezo-electric effect of wood. In: Proceedings, 2d nondestructive testing of wood symposium; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 223–244.

Galligan, W.L.; Snodgrass, D.V.; Crow, G.W. 1977. Machine stress rating: practical concerns for lumber producers. Gen. Tech. Rep. FPL–GTR–7. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Gerhards, C.C. 1981. Effect of cross grain on stress waves in lumber. Res. Pap. FPL–RP–368. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Gerhards, C.C. 1982. Effect of knots on stress waves in lumber. Res. Paper FPL–RP–384. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Green, D.W.; McDonald, K.A. 1993a. Investigation of the mechanical properties of red oak 2 by 4's. Wood and Fiber Science. 25(1): 35–45.

Green, D.W.; McDonald, K.A. 1993b. Mechanical properties of red maple structural lumber. Wood and Fiber Science. 25(4): 365–374.

Harris, D.O.; Tetleman, AS.; Darwish, F.A.I. 1972. Detection of fiber cracking by acoustic emission. Acoustic Emission. ASTM 505. Philadelphia, PA: American Society for Testing and Materials. 11 p.

Hoerber, G.F. 1962. A study of modulus of elasticity and modulus of rupture in Douglas Fir dimension lumber. Lewiston, ID: Potlatch Forests, Inc.

Hoffmeyer, P. 1978. The Pilodyn instrument as a nondestructive tester of the shock resistance of wood. In: Proceedings, 4th nondestructive testing of wood symposium; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 47–66.

Hofstrand, A.D.; Howe, J.P. 1963. Relationship between modulus of elasticity and compression strength of white fir. Lewiston, ID: Potlatch Forests, Inc.

Hoyle, R.J. 1961a. Comparison of modulus of elasticity and modulus of rupture of four types of western softwood dimension lumber. Lewiston, ID: Potlatch Forests, Inc.

Hoyle, R.J. 1961b. A nondestructive test for stiffness of structural lumber. Forest Products Journal. 11(6): 251–254.

Hoyle, R.J. 1962. Analysis of relationship between stiffness and strength of 2" x 8" white fir (*Abies grandis*) used as joist and plank. Lewiston, ID: Potlatch Forests, Inc.

Hoyle, R.J. 1964. Research results on machine stress rated Southern Pine lumber. Lewiston, ID: Potlatch Forests, Inc.

Hoyle, R.J. 1968. Background to machine stress rating Forest Products Journal. 18(4): 87–97.

Hoyle, R.J.; Pellerin, R.F. 1978. Stress wave inspection of a wood structure. In: Proceedings, 4th nondestructive testing of wood symposium; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 33–45.

Hoyle, R.J.; Rutherford, P.S. 1987. Stress wave inspection of bridge timbers and decking. Final report for Research Project Y–3400. Pullman, WA: Department of Civil and Environmental Engineering, Washington State University.

James, W.L. 1959. A method for rapid measurement of the rate of decay of free vibrations. Bull. 2154. Madison,, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Jayne, B.A. 1955. A nondestructive test of glue bond quality. Forest Products Journal. 5(5): 294–301.

Jayne, B.A. 1959. Vibrational properties of wood as indices of quality. Forest Products Journal. 9(11): 413–-416.

Johnson, J.W. 1965. Relationships among moduli of elasticity and rupture. In: Proceedings, 2d nondestructive testing of wood symposium; 1965 April; Pullman, WA. Spokane, WA: Washington State University: 419–457.

Kaiserlik, J.H.; Pellerin, R.F. 1977. Stress wave attenuation as an indicator of lumber strength. Forest Products Journal. 27(6): 39–43.

Koch, P.; Woodson, G.E. 1968. Laminating butt-jointed, log-run southern pine veneers into long beams of uniform high strength. Forest Products Journal. 18(10): 45–51.

Kolsky, H. 1963. Stress waves in solids. New York: Dover Publications, Inc.

Kramer, P.R. 1964. Correlation of bending strength and stiffness of Southern Pine. Forest Products Journal. 14: 495–496.

Lanius, R.M.; Tichy, R.; Bulleit, W.M. 1981. Strength of old wood joists. In: Journal of the Structural Division: Proceedings, American Society of Civil Engineers; 1981 December. New York, NY: American Society of Civil Engineers, Vol. 107, No. ST12: 2349–2363.

Lee, I.D.G. 1965. Ultrasonic pulse velocity testing considered as a safety measure for timber structures. In: Proceedings, 2d nondestructive testing of wood symposium; 1965 April; Spokane, WA. Pullman, WA: Washington State University: 185–203.

Littleford, T.W. 1965. Mechanical stress-rating of western Canadian species. In: Proceedings, 2d nondestructive testing of wood symposium; 1965 April; Spokane, WA. Pullman, WA: Washington State University: 475–485.

McAlister, R.H. 1976. Modulus of elasticity distribution of loblolly pine veneer as related to location within the stem and specific gravity. Forest Products Journal. 26(10): 37–40.

McKean, H.B.; Hoyle, R.J. 1962. Stress grading method for dimension lumber. Special Tech. Pub. 353. Philadelphia, PA: American Society for Testing Materials.

Miller, D.G. [Comments on Littleford (1965)]. In: Proceedings, 2d nondestructive testing of wood symposium; 1965 April; Spokane, WA. Pullman, WA: Washington State University: 485–491.

Mothershead, J.S.; Stacey, S.S. 1965. Applicability of radiography to inspection of wood products. In: Proceedings, 2d nondestructive testing of wood symposium; 1965 April; Spokane, WA. Pullman, WA: Washington State University: 307–331.

Monro, J.J.; McNulty, R.E.; Ling, R.; [and others]. 1990. Mobile computed tomography systems for industrial applications. Materials Evaluation. 48(5): 568–572.

Murphy, M.W.; Franklin, D.E.; Palylyk, R.A. 1987 A nondestructive testing technique for wood poles. Surrey, British Columbia: British Columbia Hydro Research and Development.

Neal, D.W. 1985. Establishment of elastic properties for in-place timber structures. In: Proceedings, 5th nondestructive testing of wood symposium; 1985 September 9911; Pullman, WA. Pullman, WA: Washington State University: 353–359.

O'Halloran, M.R. 1969. Nondestructive parameters for lodgepole pine dimension lumber. Fort Collins, CO: Colorado State University. M.S. thesis.

Patton-Mallory, M.; De Groot, R.C. 1989. Acousto-ultrasonics for evaluating decayed wood products. In: Proceedings, 2d Pacific timber engineering conference; 1989 August 28-29; Auckland, New Zealand.

Pellerin, R.F. 1963a. Compression parallel to grain versus modulus of elasticity for Douglas Fir dimension lumber. Washington State University, Division of Industrial Research. Lewiston, ID: Potlatch Forests, Inc.

Pellerin, R.F. 1963b. Correlation of strength properties of l-inch lumber. Washington State University, Division of Industrial Research. Lewiston, ID: Potlatch Forests, Inc.

Pellerin, R.F. 1965a. The contributions of transverse vibration grading to design and evaluation of 55-foot laminated beams. In: Proceedings, 2d nondestructive testing of wood symposium; 1965 April; Spokane, WA. Pullman, WA: Washington State University: 337–347.

Pellerin, R.F. 1965b. A vibrational approach to nondestructive testing of structural lumber. Forest Products Journal. 15(3): 93–101.

Pellerin, R.F. 1989. Inspection of wood structures for decay using stress waves. In: Proceedings, 2d Pacific timber engineering conference; 1989 August 28–31; Auckland, New Zealand.

Pellerin, R.F.; Galligan, W.L. 1973. Nondestructive method of grading wood materials. Canadian Patent 918286.

Pellerin, R.F.; Morschauser, C.R. 1974. Nondestructive testing of particleboard. In: Proceedings, 7th international particleboard symposium; 1973 March; Pullman, WA. Pullman, WA: Washington State University.

Pellerin, R.F.; De Groot, R.C.; Esenther, G.R. 1985. Nondestructive stress wave measurements of decay and termite attack in experimental wood units. In: Proceedings, 5th nondestructive testing of wood symposium; 1985 September 9911; Pullman, WA. Pullman, WA: Washington State University: 319–352.

Porter, A.W.; Kusec, D.J.; Olson, S.L. 1972. Digital computer for determining modulus of elasticity of structural lumber. WFPL Info. Rep. VP–X–99. Vancouver, B.C.: Department of Environment, Canadian Forest Service.

Ross, R.J. 1984. Stress wave speed and attenuation as predictors of the tensile and flexural properties of wood-based particle composites. Pullman, WA: Washington State University. Ph.D. dissertation.

Ross, R.J. 1985. Stress wave propagation in wood products. In: Proceedings, 5th nondestructive testing of wood symposium; 1985 September 9911; Pullman, WA. Pullman, WA: Washington State University: 291–318.

Ross, R.J.; Pellerin, R.F. 1988. NDE of wood-based composites with longitudinal stress waves. Forest Products Journal. 38(5): 39–45.

Ross, R.J.; Pellerin, R.F. 1991. Stress wave evaluation of green material: preliminary results using dimension lumber. Forest Products Journal. 41(6): 57–59.

Ross, R.J.; Cooper, J.; Wang, Z. 1991. In-place evaluation of fire retardant treated wood products. Proceedings, 8th international nondestructive testing of wood symposium. Pullman, WA: Washington State University: 247–252.

Ross, R.J.; Geske, E.A.; Larson, G.L.; Murphy, J.F. 1991. Transverse vibration nondestructive testing using a personal computer. Res. Pap. FPL–RP–502. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Ross, R.J.; Ward, J.C.: TenWolde, A. 1992. Identifying bacterially infected oak by stress wave nondestructive evaluation. Res. Pap. FPL–RP–512. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Rutherford, P.S. 1987. Nondestructive stress wave measurement of incipient decay in Douglas-fir. Pullman, WA: Washington State University. M.S. thesis.

Rutherford, P.S.; Hoyle, R.J.; De Groot, R.C.; Pellerin, R.F. 1987. Dynamic vs. static MOE in the transverse direction in wood. In: Proceedings, 6th nondestructive testing of wood symposium; 1987 September 14-16; Pullman, WA. Pullman, WA: Washington State University: 67–80.

Senft, J.F.; Suddarth, S.K.; Angleton, H.D. 1962. A new approach to stress grading of lumber. Forest Products Journal. 12(4): 183–186.

Sharp, D.J. 1985. Nondestructive testing techniques for manufacturing LVL and predicting performance. In: Proceedings, 5th nondestructive testing of wood symposium; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 99–108

Stewart, A.H.; Brunette, T.L.; Goodman, J.R. 1986. Use of nondestructive testing in rehabilitation of wood cooling towers. In: Gopu, Vijay K.A., ed. Evaluation and upgrading of wood structures: case studies: Proceedings of the American Society of Civil Engineers structures congress; 1986 September 15–18; New Orleans, LA. New York, NY: American Society of Civil Engineers.

Suddarth, S.K. 1965. Detection of adhesive bond defects in the Polaris missile nose fairing through mechanical impedance measurements. In: Proceedings, 2d nondestructive testing of wood symposium; 1965 April; Spokane, WA. Pullman, WA: Washington State University: 267–285.

Sunley, J.G.; Hudson, W.M. 1964. Machine-grading lumber in Britain. Forest Products Journal. 14: 155–158.

Talbot, J.W. 1982. Unpublished research. Pullman, WA: Washington State University.

Verkasalo, E.; Ross, R.J.; TenWolde, A.; Youngs, R.L. 1993. Properties related to drying defects in red oak wetwood. Res. Pap. FPL–RP–516. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Vogt, J.J. 1985. Evaluation of the tensile and flexural properties and internal bond of medium density fiberboard using stress wave speed and attenuation. Pullman, WA: Washington State University. M.S. thesis.

Vogt, J.J. 1986. Longitudinal stress waves as predictors of internal bond strength. In: Proceedings, 12th international particleboard/composite materials symposium; 1986 March; Pullman, WA. Pullman, WA: Washington State University.

Wang, S.C.; Suchsland, O.; Hart, J.H. 1980. Dynamic test for evaluating decay in wood. Forest Products Journal. 30(7): 35–37.

Wang, Z.; Ross, R.J.; Murphy, J.F. 1993. A comparison of several NDE techniques for determining the modulus of elasticity of lumber. World Forestry Research. 6(4): 86–88. (In Chinese.)

Witherall, P.W.; Ross, R.J.; Farris, W.R. 1992. Using today's technology to help preserve USS Constitution. Naval Engineers Journal. 104(3): 124–134.

Table 1–Research summary on the correlation between stress wave modulus of elasticity values obtained from time-of-flight-type measurements and static modulus of elasticity of various wood materials

Reference	Material	Static loading mode	Correlation coefficient, *r*
Bell and others (1954)	Clear wood	Compression	0.98
		Bending	0.98
Galligan and Courteau (1965)	Lumber	Bending	0.96
Koch and Woodson (1968)	Veneer	Tension	0.96 – 0.94
Porter and others (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

Table 2–Research summary on the correlation between modulus of elasticity (tested flatwise) and flatwise bending strength of softwood dimension lumber

Reference	Species	Nominal moisture content (percent)	Grade[a]	Nominal width (in.)[b]	Growth location	Correlation coefficient, *r*
Hoyle (1961b)	Douglas-fir	12	SS,C,U	4,6,10	Western Oregon, Washington	0.79
					Idaho, Washington	0.72
	Western hemlock	12	SS,C,U	4,6,10	Western Oregon, Washington	0.74
	Western larch	12	SS,C,U	4,6,8	Idaho, Washington	0.70
Hoyle (1962)	Grand fir	12	C,S,U	8	Idaho	0.72
Hofstrand and Howe (1963)	Grand fir	12	C,S	4,6,8	Idaho	0.75
Pellerin (1963b)	Douglas-fir	12	Combination of visual grades	4,8	Idaho	0.76
Hoyle (1964)	Southern Pine	12	1D,1,2D,2,3	4,6,8	Southeastern United States	0.76
Kramer (1964)	Southern Pine	12	1D,2,3	4,6,10	Southeastern United States	0.88
Johnson (1965)	Douglas-fir	10	SS,C,U	6	Western Oregon, Washington	0.85
	Western hemlock	10	SS,C,U	6	Western Oregon, Washington	0.86

[a] Grades are by regional rules in use at time of research. Western Products Association and West Coast Lumber Inspection Bureau Grades: SS = Select Structural, C = Construction, S = Standard, U = Utility. Western Wood Products Association grades: 1, 2, 3. Southern Pine Inspection Bureau Grades: 1D = No. 1 Dense, 1 = No. 1, 2D = No. 2 Dense, 2 = No. 2, 3 = No. 3.

[b] 1 in. = 25.4 mm.

Table 3–Research summary on the correlation between modulus of elasticity (tested flatwise and on edge) and edgewise bending strength of softwood dimension lumber

Reference	Species	Nominal moisture content (percent)	Grade[a]	Nominal width (in.)[b]	Growth location	Correlation coefficient, r
Hoerber (1962)	Douglas-fir	12	SS,C,U	4,6,8	Idaho, Eastern Washington	0.65
Hoyle (1962)	Grand fir	12	C,S,U,SS	8	Idaho	0.59 - 0.70
Hoyle (1964)	Southern Pine	12	1D,1,2D,2,3	4,6,8	Southeastern United States	0.57
Sunley and Hudson (1964)	Norway spruce and Scots pine (pooled)			4,7	Great Britain	0.68
Corder (1965)	Douglas-fir	12	SS,C,S	4,6,10	Inland Northwestern, United States	0.64
Johnson (1965)	Douglas-fir	10	SS,C,U	6	Western Oregon, Washington	0.80 - 0.87
	Western hemlock	10	SS,C,U	6		0.84
Littleford (1965)	Douglas-fir	10	—	6	British Columbia, Canada	0.74
	Western hemlock	12	—	6		0.70 - 0.77
	Noble fir	12	—	6		0.66
	Western white spruce	12	—	6		0.79
	Lodgepole pine	17	—	6		0.80
Miller (1965)	White spruce	12	—	6	Eastern Canada	0.78 - 0.84
	Jack pine	12	—	6		0.69 - 0.73
Doyle and Markwardt (1966)	Southern Pine	12	1D,1,2D,2,3	4,6, 8,10	Southeastern United States	
Hoyle (1968)	Southern Pine	12	1D,1,2D,2,3	4,6,8	Southeastern United States	0.67

[a] Grades are by regional rules in use at time of research. Western Products Association and West Coast Lumber Inspection Bureau Grades: SS = Select Structural, C = Construction, S = Standard, U = Utility. Western Wood Products Association grades: 1, 2, 3. Southern Pine Inspection Bureau Grades: 1D = No. 1 Dense, 1 = No. 1, 2D = No. 2 Dense, 2 = No. 2, 3 = No. 3.

[b] 1 in. = 25.4 mm.

Table 4—Research summary on the correlation between modulus of elasticity (tested flatwise) and the compressive and tensile strength of softwood dimension lumber.

Strength property	Reference	Species	Nominal moisture content (percent)	Grade[a]	Nominal width (in.)[b]	Growth location	Correlation coefficient, r
Compressive	Hofstrand and Howe (1963)	Grand fir	12	Ungraded	4,8	Idaho	0.84
	Pellerin (1963a)	Douglas-fir	12	SS,S,E	4,8	Idaho	0.78
	Hoyle (1968)	Southern Pine	12	1,2,3	4,8	Southeastern United States	0.67
Tensile	Hoyle (1968)	Douglas-fir	13	1.0,1.4,1.8,2,2	4,8	Idaho	0.74
		White fir	14			Idaho	0.75
		Western hemlock	15			Western Oregon, Washington	0.81

[a] Grades are by regional rules in use at time of research. Western Products Association and West Coast Lumber Inspection Bureau Grades: SS = Select Structural, S = Standard, E = Economy.

Western Wood Products Association grades: 1, 2, 3. Machine Stress Grades: 1.0, 1.4, 1.8, 2.2.

[b] 1 in. = 25.4 mm.

Table 5—Research summary on the correlation between modulus of elasticity and other mechanical properties of hardwood lumber

Reference	Species/group	Nominal moisture content (percent)	Grade[a]	Nominal width (in.)	Growth location	NDT technique	Static property	Correlation coefficient, r
Green and McDonald (1993a)	Northern red oak (*Quercus velutina*, *Quercus rubra*)	12	SS, 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 obtained from transverse vibration measurements.
E_{sB} = Modulus of elasticity obtained from static bending test.
MOR = Modulus of rupture.
UTS = Ultimate tensile stress.
UCS = Ultimate compressive stress.
1 lb/in^2 = 6.9×10^3 Pa.

[a] Grades by procedures given in the National Grading Rule performed by a quality supervisor of Southern Pine Inspection Bureau. SS = Select Structural.

Table 6—Summary of results that verify the fundamental hypothesis that used transverse vibration and stress wave nondestructive testing (NDT) techniques on clear wood and lumber products’

Reference	NDT technique	Material	NDT parameters measured	Static test	Reported properties	Comparison of NDT parameters and static 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 amd 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 glue-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
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 and δ — 0.90
Wang and others (1993)	Free transverse vibration and longitudinal stress wave	Spruce-Pine-Fir dimension lumber	E_d	Bending	E_{sB}	E_{sB} and E_d 0.96 — 0.99
Ross and others (1991)	Free transverse vibration	Spruce-Pine-Fir dimension lumber	E_d	Bending	E_{sB}	E_d and E_{sB} — 0.99
Ross and Pellerin (1991)	Longitudinal stress wave	Green Douglas-fir dimension lumber	C, E_d	Bending	E_{sB}	C and E_{sB} — 0.78 E_d and E_{sB} — 0.95

[a] C = Speed of sound.
δ = Logarithmic decrement.
E_d = Dynamic modulus of elasticity obtained from either transverse vibration or stress wave measurements.
E_{sB} = Modulus of elasticity obtained from static bending test.
MOE = Modulus of elasticity.
MOR = Modulus of rupture.
Q = Sharpness of resonance.
UTS = Ultimate tensile stress.
1 lb/in^2 = 6.9 × 10^3 Pa.
[b] Correlation coefficients were not reported by Jayne. However, he did report 95 percent confidence intervals.

Table 7—Summary of results that verify the fundamental hypothesis using wood-based composites[a]

Reference	NDT technique	Material	NDT parameters measured	Static test	Reported properties	Comparison of NDT parameters and static properties (correlation coefficient, r, unless noted)
Suddarth (1965)	Forced transverse vibration	Laminated wood (missile noise fairing)	E_d, d			Mapped out debonded or poorly bonded areas.
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,d	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/d — 0.63 UTS and combination of E_d, 1/d — 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/d — 0.70 MOR and combination of E_d, 1/d — 0.97
				Internal bond	IB	IB and combination — 0.79
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,d	Tension	E_{sT}, UTS	E_{sT} and C^2 — 0.90 E_{sT} and E_d — 0.88 UTS and C^2 — 0.81 UTS and E_d — 0.88 Combination — 0.88
				Bending	E_{sB}, 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 — 0.92 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.
d = Logarithmic decrement.
E_d = Dynamic modulus of elasticity obtained from either transverse vibration or stress wave measurements.
E_{dt} = Dynamic modulus of elasticity, through the thickness orientation.
E_{sB} = Modulus of elasticity obtained from a static bending test.
E_{sT} = Modulus of elasticity obtained from a static tension test.
MOR = Modulus of rupture.
UTS = Ultimate tensile stress.

Table 8—Research summary of correlation between nondestructive testing (NDT) parameters and properties of degraded wood[a]

Reference	NDT technique	Material	Degradation agent	NDT parameters measured	Static test	Reported properties	Comparison of NDT parameters and static properties (correlation coefficient, *r*, unless noted)
Wang and others (1970)	Free transverse vibration (cantilever bending)	Small, clear eastern white pine sapwood specimens	Brown-rot fungi (Poria placenta Murr.)	Natural frequency	None		Significant loss in frequency as early as 7 days after inoculation.
Chudnoff and others (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 and others (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 (controls) 0.73 (exposed) 0.80 (control and exposed) UCS and E_d: 0.86 (controls) 0.86–0.89 (exposed) 0.94 (control and exposed)
			Termites (subterranean)	C, E_d			UCS and C: 0.65 (controls) 0.21 (exposed) 0.28 (control and exposed) UCS and E_d: 0.90 (controls) 0.79 (exposed) 0.80 (control and exposed)

Table 8—Research summary of correlation between nondestructive testing (NDT) parameters and properties of degraded wood[a]—con

Reference	NDT technique	Material	Degradation agent	NDT parameters measured	Static test	Reported properties	Comparison of NDT parameters and static properties (correlation coefficient, *r*, unless noted)
Beall and Wilcox (1986)	Acoustic	Small, clear white fir specimens	Brown-rot fungi (Poria placenta)	AE	Compression	Stress at various levels	AE events were very sensitive to degree of mass loss and stress level.
Rutherford and others (1987a,b)	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	C decreased in a linear fashion with increasing decay degradation. Signal strength decreased with increasing decay degradation. High-frequency components of signal were attenuated with very early stages of decay degradation.
Ross and others (1992)	Longitudinal stress wave (perpendicular to grain)	Red and white oak lumber	Clastridium and Erwinia sp.	C	None	Presence of infection	C decreased with presence of infection.
Verkasalo and others (1993)	Longitudinal stress wave (perpendicular to grain)	Red oak lumber	Clastridium and Erwinia sp.	C	Tension perpendicular to grain	UTS, presence of infection	C, UTS decreased with presence of infection.

[a] AE = Acoustic emission.
C = Speed of sound.
E_c = Modulus of elasticity obtained from a static compression test.
E_d = Dynamic modulus of elasticity obtained from either transverse vibration or stress wave measurements.
MOE = Modulas of elasticity.
MOR = Modulus of rupture.
UCS = Ultimate compressive stress.
UTS = Ultimate tensile stress.

Table 9—Research summary of nondestructive testing (NDT) concepts for in-place evaluation of wood structures[a]

Reference	NDT technique	Type of structure	Location	Material	NDT parameters measured	Analysis performed-conclusions
Lee (1965)	Longitudinal stress wave	Eighteenth century mansion roof	United Kindgom	Solid-sawn timber	C	Developed empirical relationship between speed-of-sound transmission and residual strength.
Hoyle and Pellerin (1978)	Longitudinal stress wave (perpendicular to grain)	School building	Idaho	Curved glulam arches (span 120 ft, rise 33 ft)	C	Detected decay in exposed ends of arches. Mapped out areas of decay.
Lanius and others (1981)	Longitudinal stress wave	Barn	Washington	2- by 12-in. joists	C, E_d	Estimated residual strength of members.
Dunlop (1983)	Acoustic resonance	Wood poles	Australia	Wood utility poles	Resonant frequencies	Test diagnosed large percentage of poles in sample set correctly.
Browne and Kuchar (1985)	Longitudinal stress wave	Dielectric support stand for testing large aircraft in a simulated flight situation	New Mexico	Glulam, structural timbers	C, E_d	MOE determined, strength properties inferred.
Neal (1985)	Longitudinal stress wave (parallel and perpendicular to grain)	Large military test stand (TRESTLE)	New Mexico	Glulam	E_d	Structural framework was not degraded; exposed deck system was degraded.
		Small military test stand	New Mexico	Glulam	E_d	Structural framework and decks were degraded.
		Large military test stand	Arizona	Glulam, solid-sawn timber	E_d	Accessible structural degradation had not occurred.
Aggour and others (1986)	Longitudinal stress wave (perdendicular to grain)	Bridge piling	Maryland	Piling	C, density	Correlation of density and C to compressive strength of pile (r = 0.98).
Abbott and Elcock (1987)	Full-size static MOE test	Wood poles	United Kingdom	Wood utility poles	Bending MOE	Correlative relationship between MOE and residual strength of poles (r = 0.68).

Table 9—Research summary of nondestructive testing (NDT) concepts for in-place evaluation of wood structures[a]—con

Reference	NDT technique	Type of structure	Location	Material	NDT parameters measured	Analysis performed-conclusions
Hoyle and Rutherford (1987)	Longitudinal stress wave (parallel and perpendicular to grain)	Timber bridges	Northwestern United States	Solid-sawn timber	C, E_d	Revealed signs of decay in 1 of 12 bridges; reevaluation every 3 years.
Murphy and others (1987)	Vibration	Wood poles	Western Canada	Wood utility poles (Douglas-fir cedar)	Resonant frequencies	Comparison to pole stiffness (r = 0.82).
Anthony and Bodig (1989)	Stress wave	Wood cooling tower, poles	Texas, Western United States	Solid-sawn timber, poles	C, δ, phase shifts	Determined rate of strength degradation.
Pellerin (1989)	Longitudinal stress wave	University football stadium	Washington	Solid-sawn timber	C	Found severe decay degradation; structure. was dismantled. Substructure collapsed under its own weight.
		Piers	Washington	Large wood beam, stringers supported by wood pilings		Replaced structural members containing decay.
Ross and others (1991)	Probe resistance, bending proof load	Residential dwelling	Eastern United States	Fire-retardant-treated roof sheathing	Probe withdrawal resistance, proof load	Many panels degraded; replaced.
Witherall and others (1992)	Longitudinal stress wave	Wooden ship	Boston, Massachusetts	Ribs, hull, and cross members	C	Found decay degradation on several members. Replaced members containing decay.

[a] C = Speed of sound.
δ = Logarithmic decrement.
E_d = Dynamic modulus of elasticity obtained from either transverse vibration or stress wave measurements.
MOE = Modulus of elasticity.
r = correlation coefficient.
1 ft = 0.3 m, 1 in. = 25.4 mm.

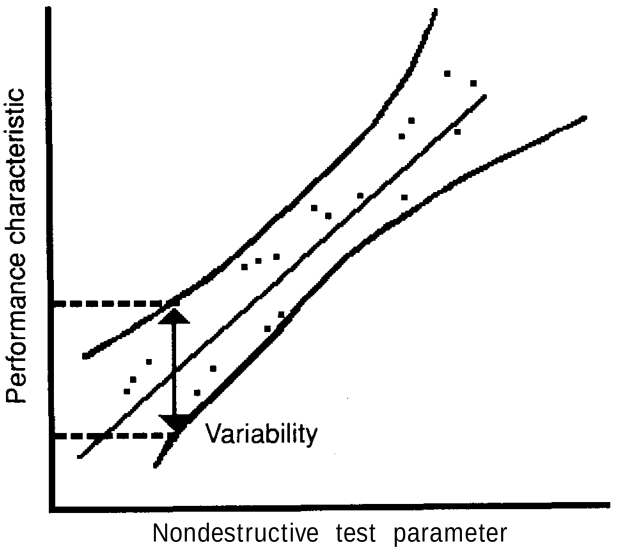

Figure 1—Typical relationship between nondestructive testing parameter and performance.

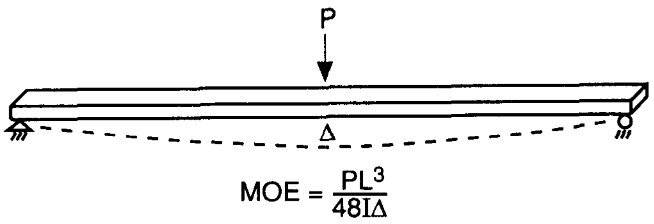

Figure 2—A simply supported beam loaded at its midspan and the mathematical equation relating modulus of elasticity to load and deflection.

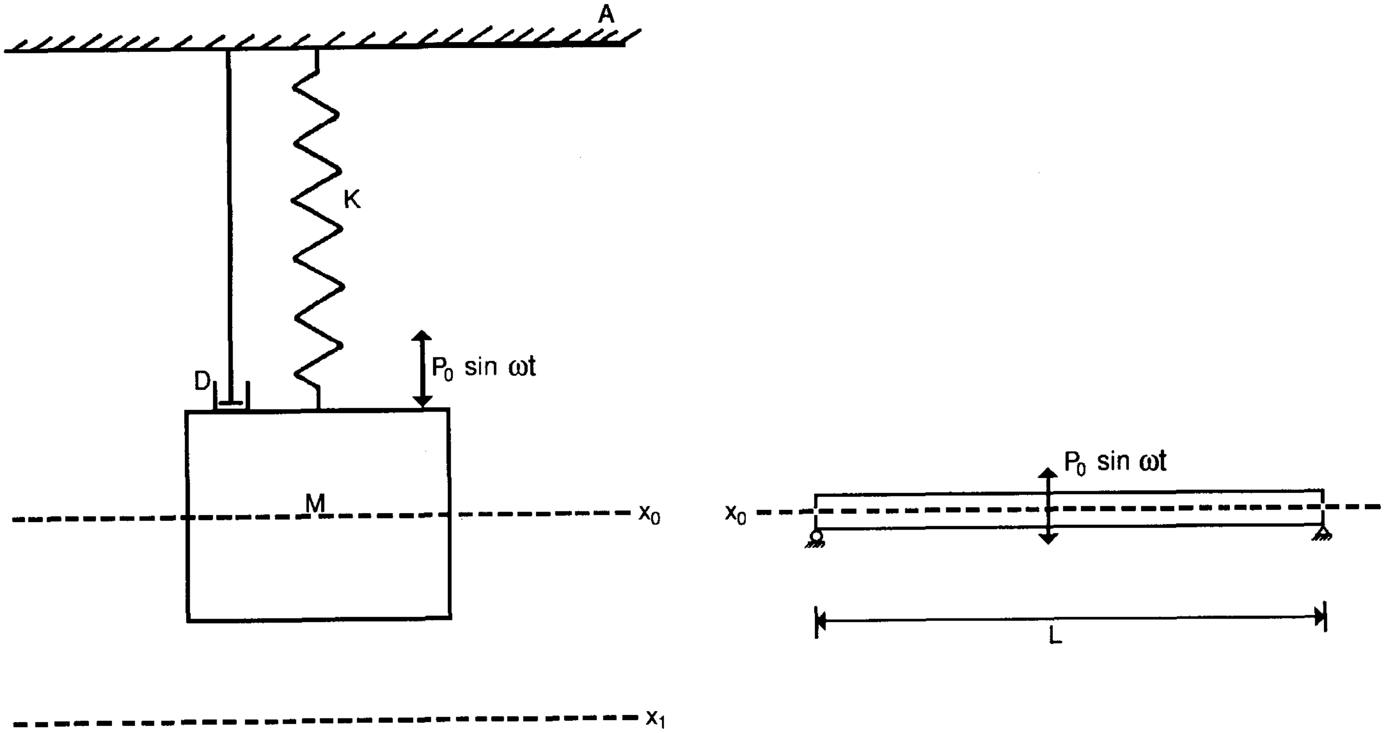

Figure 3—Mass-spring dashpot vibration model (left) and transversely vibrating beam (right).

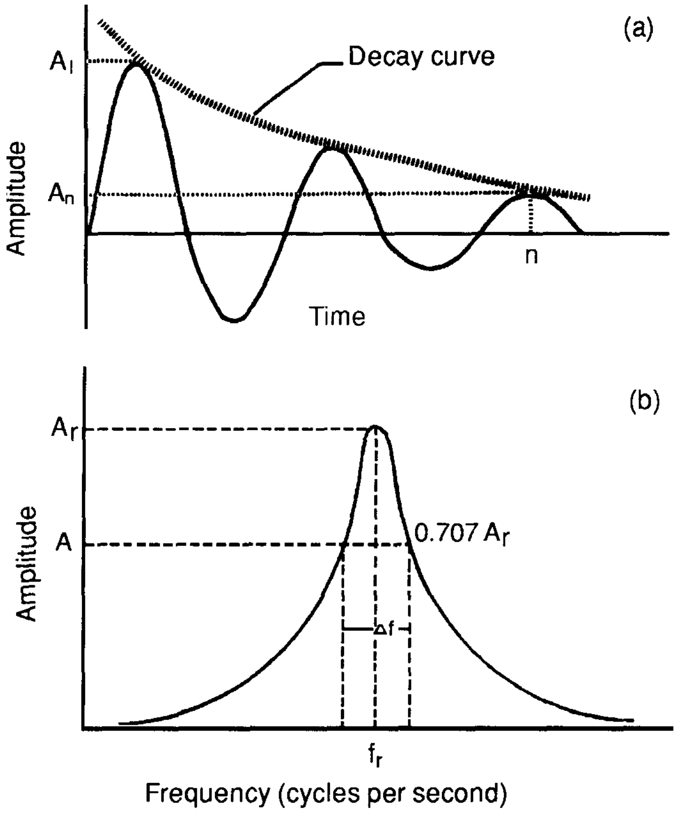

Figure 4—Free vibration of a beam: (a) damped sine wave, (b) frequency response curve.

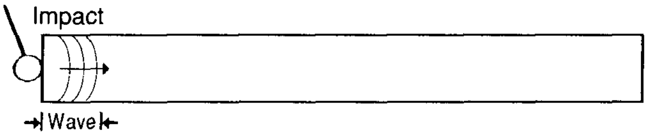

Figure 5—Viscoelastic bar of length L subjected to an impact.

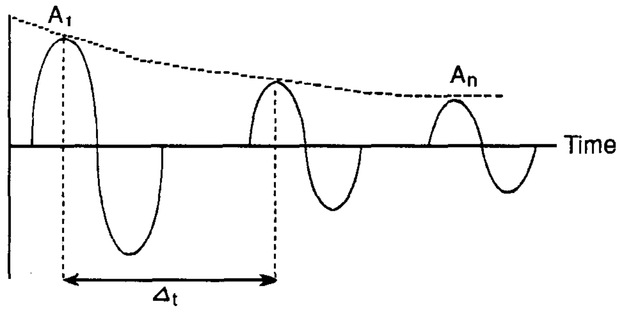

Figure 6—Theoretical response of the end of a viscoelastic bar in response to a propagating stress wave.

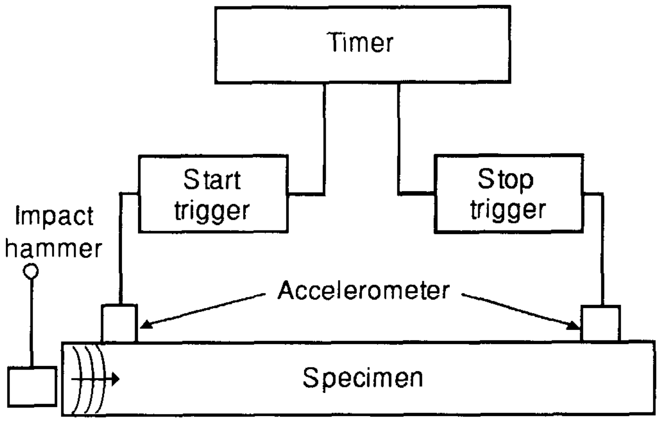

Figure 7—Technique utilized to measure impact-induced stress wave propagation speed in various wood products.

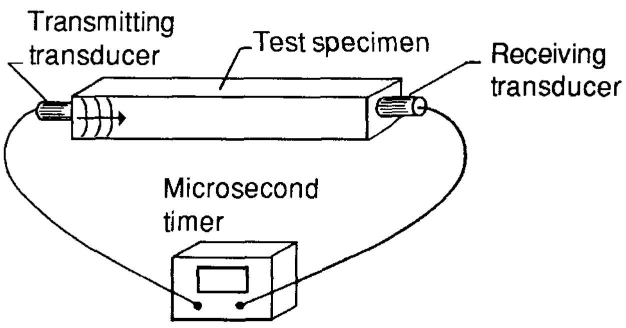

Figure 8—Ultrasonic measurement system used to measure speed-of-sound transmission in various wood products.

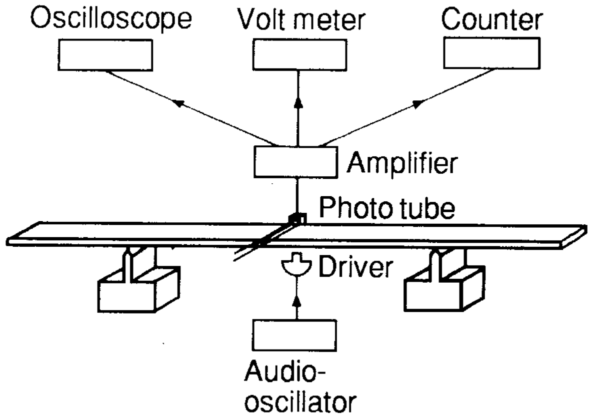

Figure 9—Experimental setup utilized to measure the response of wood beams to forced transverse vibration.

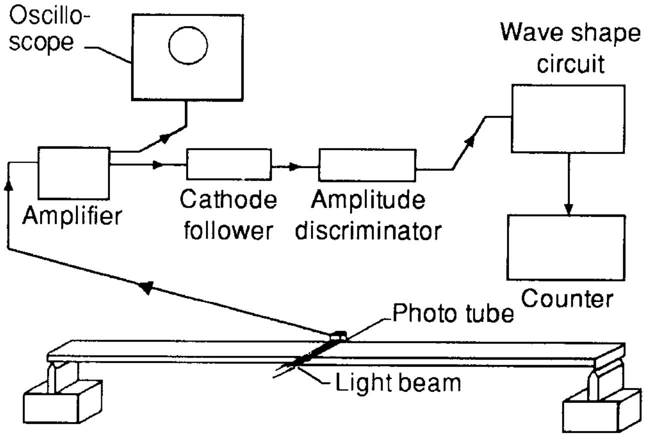

Figure 10—Apparatus used to examine free transverse vibration characteristics of lumber specimens (Pellerin 1965a.b).

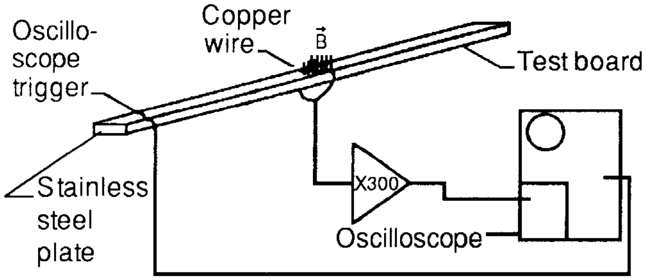

Figure 11—Instrumentation developed to observe stress wave behavior in lumber (Kaiserlik and Pellerin 1977).

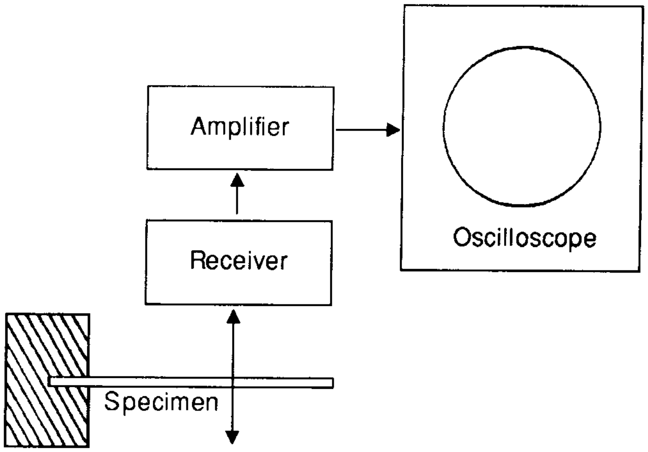

Figure 12—Experimental setup developed to observe free vibration response of decayed specimens.

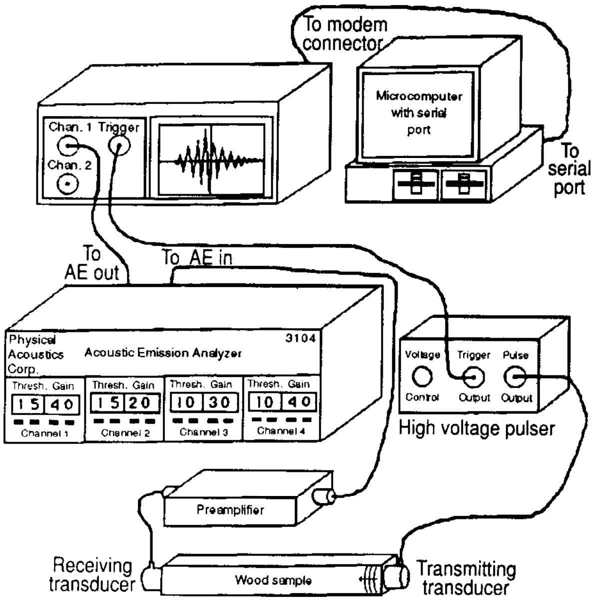

Figure 13—Acousto-ultrasonic equipment (Patton-Mallory and De Groot 1989).

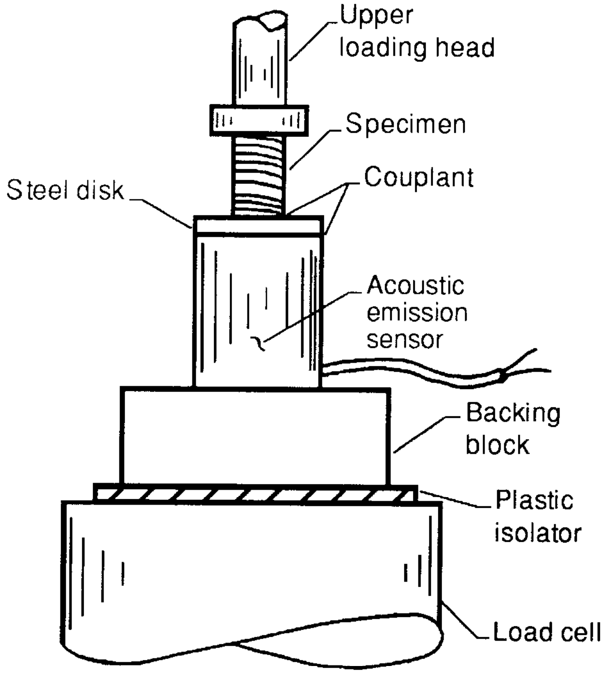

Figure 14—Experimental setup to monitor acoustic emissions from decayed specimens subjected to a compressive force.

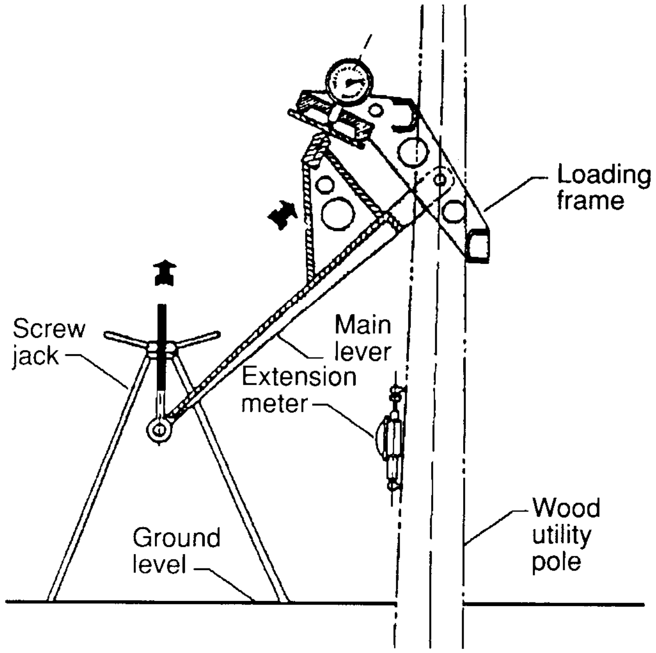

Figure 15—Setup developed to evaluate poles

Figure 16—Stress wave equipment used to evaluate university football stadium.

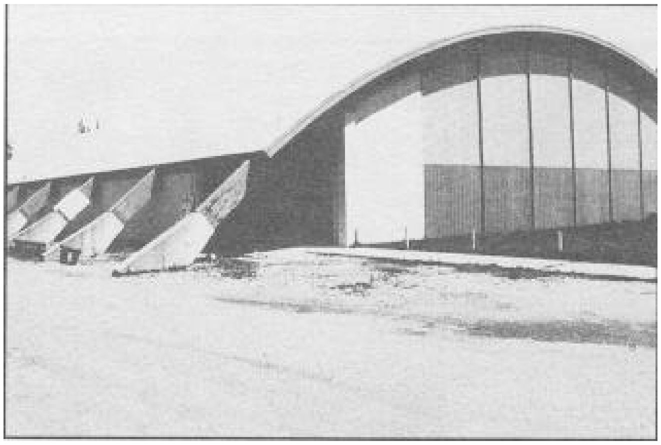

Figure I7—School gymnasium evaluated by Hoyle and Pellerin (1978).

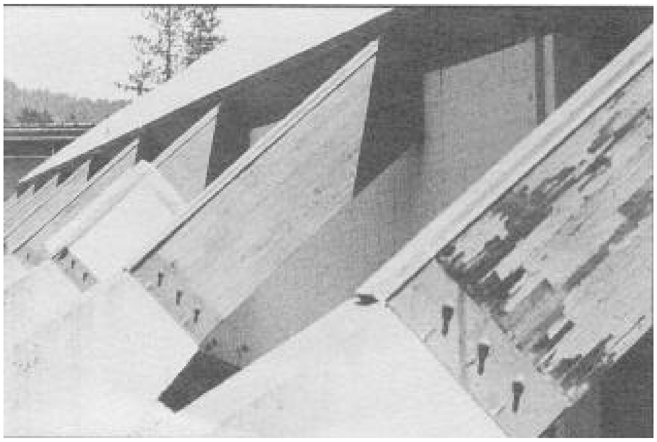

Figure 18—Third barrel arch contains map for stress wave reading.

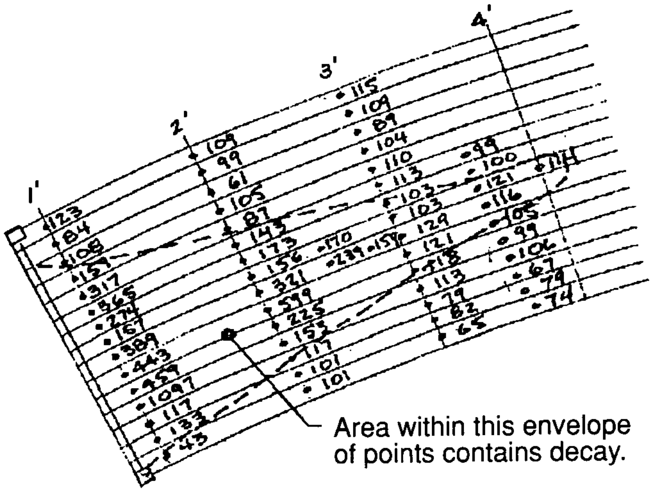

Figure 19—Inspection diagram showing stress wave travel time (ms).

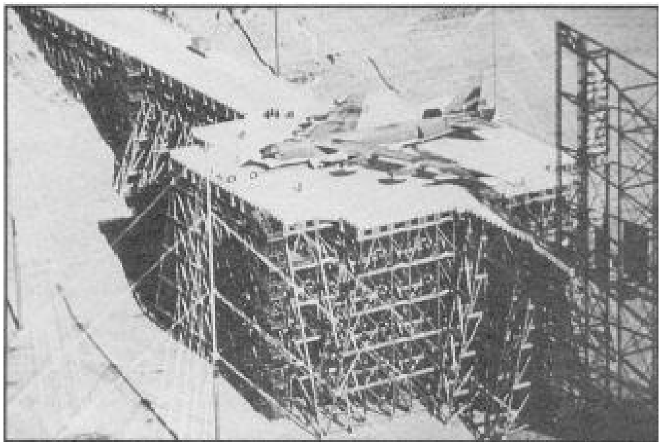

Figure 20—TRESTLE test stand for aircraft

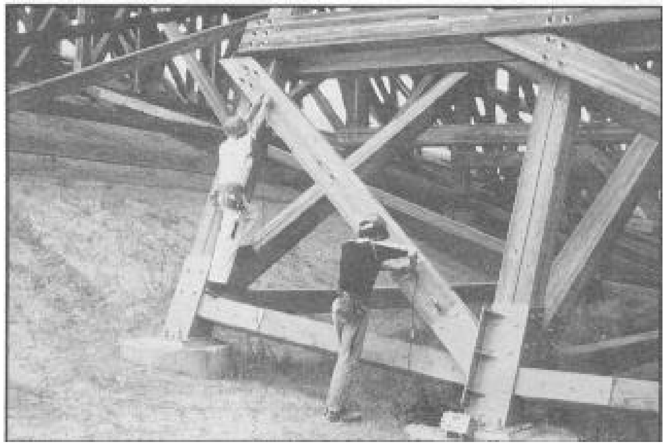

Figure 21—Stress wave evaluation of wood members of TRESTLE.

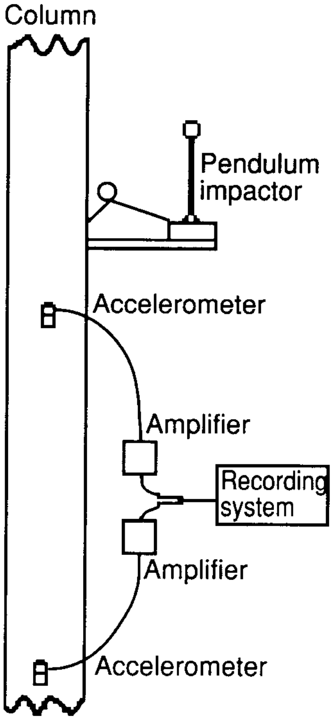

Figure 22—Instrumentation utilized to test wood members in water cooling tower.

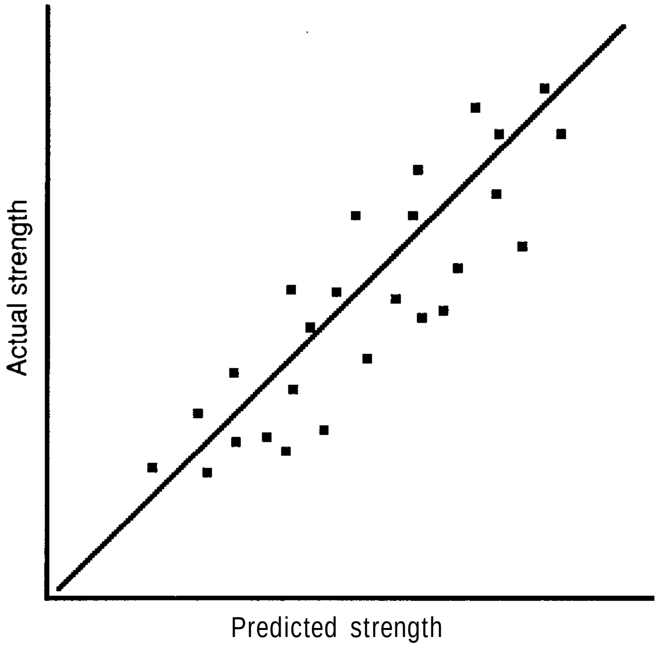

Figure 23—Relationship between predicted and actual strength of utility poles.

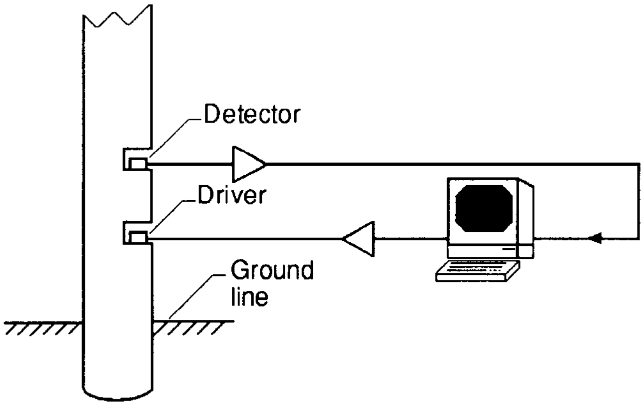

Figure 24—Electronic system to analyze poles

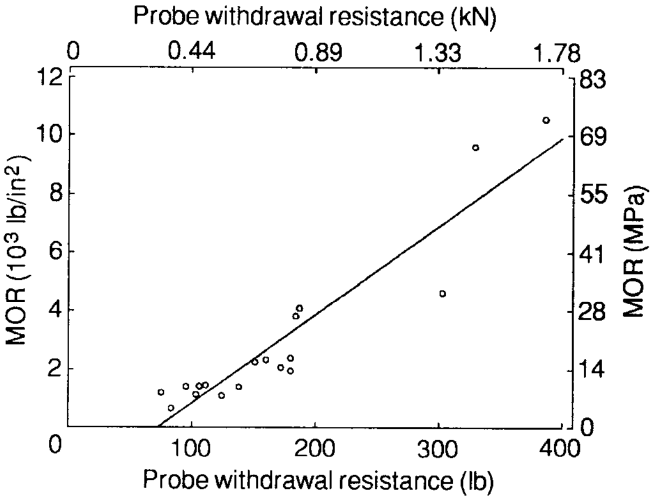

Figure 25—Relationship between probe withdrawal resistance and residual bending strength of Douglas-fir specimens.

Appendix-Reference Listing From the NDT of Wood Symposium Series

Degradation

4th symposium

Kaiserlik, Joseph H. 1978. Selected methods for quantifying strength in degraded wood. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 95–117.

5th symposium

Pellerin, Roy F.; De Groot, Rodney C.; Esenther, Glenn E. 1985. Nondestructive stress wave measurements of decay and termite attack in experimental wood units. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 319–352.

6th symposium

Patton-Mallory, Marcia; Anderson, Kent D.; De Groot, Rodney C. 1987. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 167–189.

Rutherford, Paul S.; Hoyle, Robert J., Jr.; De Groot, Rodney C.; Pellerin, Roy F. 1987. Dynamic versus static MOE in the transverse direction in wood. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 67–80.

Smith, Kevin T. 1987. Electrical resistance and previsual decay detection. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 125–135.

7th symposium

Lemaster, Richard L.; Beall, Frank C. 1990. The monitoring of degradation in wood and wood-based products with acousto-ultrasonics. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 295.

Patton-Mallory, Marcia; De Groot, Rodney C. 1990. Detecting brown-rot decay in southern yellow pine by acousto-ultrasonics. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 29–44.

General

2d symposium

Bethel, J.S. 1965. Science, symposia and technological advancement. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 175–178.

Calvin, L.D.; Snodgrass, J.D. 1965. Statistical inference in wood testing. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 13–23.

Ethington, R.L. 1965. Research objectives for the nondestructive evaluation of wood and wood products. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 519–527.

Fukada, E. 1965. Piezoelectric effect in wood and other crystalline polymers. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 143–172.

Galligan, W.L. 1965. Opening remarks. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 499–500.

Hearmon, R.F.S. 1965. The assessment of wood properties by vibrations and high frequency acoustic waves. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 49–67.

Hovland, H. 1965. Plugging the melon. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 291–293.

Jayne, B.A. 1965. The concept of mechanical impedance and its application to nondestructive testing. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 245–266.

Kotok, E.S. 1965. Summary of second symposium. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 503–506.

Marra, G.G. 1965. The promise of nondestructive testing. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 1–4.

McKean, H.B. 1965. Summary of second symposium. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 507–509.

Narayanamurti, D. 1965. Some aspects of the nondestructive testing of wood. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 95–142.

Newell, D.W. 1965. Summary of second symposium. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 515–517.

Pentoney, R.E. 1965. Basic science as it relates to the nondestructive testing of wood. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 7–12.

Pevey, C.V. 1965. Future objectives of nondestructive testing for wood. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 529–532.

Werren, F. 1965. Summary of second symposium. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 511–513.

Youngs, R.L. 1965. Needs for nondestructive testing in the forest products industries. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 25–35.

3d symposium

Hoyle, Robert J., Jr. 1970. A summary of the short course. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 163.

Marra, G.G. 1970. Concluding remarks. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 160.

Marra, G.G. 1970. Introductory remarks. MSR: A solution in search of a problem. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April-May; Vancouver, WA. Pullman, WA: Washington State University: 5–6.

Rysdorp, John H. 1970. Concluding remarks. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April-May; Vancouver, WA. Pullman, WA: Washington State University: 160.

Tayelor, F. Alan; Thebault, Gary. 1970. Short course appraisal and discussion. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 157–161.

4th symposium

Baker, David E.; Carlson, David C. 1978. On-line product inspection by non-contact ultrasonics. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 233–237.

Bechtel, Friend K. 1978. Some quality control considerations for the forest products industry. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 141–153.

Bucur, Voichita. 1978. Wood failure testing in ultrasonic methods. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 223–226.

Hoffmeyer, Preben. 1978. The pilodyn instrument as a non-destructive tester of the shock resistance of wood. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 47–66.

King, Edward A. 1978. Laser scanning. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 15–25.

King, Ray J. 1978. Microwave electromagnetic nondestructive testing of wood. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 121–134.

Marra, George C. 1978. Progress in nondestructive testing in the wood industry. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 5.

Maxey, Carl. 1978. Sonic spectral response. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 135–139.

Tayelor, F. Alan. 1978. Now that we've got it, what do we do with it? In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 307–308.

Warren, W.G. 1978. Recent developments in statistical quality-control procedures for MSR. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 193–213.

5th symposium

Fyan, Robert E. 1985. Performance-based quality assurance. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 645–657.

Galligan, William L. 1985. Reflections on model-based QC for MSR lumber. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 613–644.

Gibson, Ronald F. 1985. Frequency domain testing of materials. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 385–406.

Hailey, J.R.T.; Menon, R.S.; Mackay, A.; Burgess, A.E.; Swanson, J.S. 1985. Nuclear magnetic resonance scanning for wood characterization. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 175–191.

McKimmy, M.D. 1985. The effect of intra-ring microcharacteristics on mechanical properties of young-growth Douglas fir wood. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 161–174.

Ross, Robert J. 1985. Stress wave propagation in wood products. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9-11; Pullman, WA. Pullman, WA: Washington State University: 291–318.

Sebelius, John A. 1985. Matching quality control to NDE requirements. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9911; Pullman, WA. Pullman, WA: Washington State University: 591–612.

Shelley, Bradley E. 1985. Calibrating a NDT process to an existing market using QC procedures. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 561–577.

Snodgrass, Delos V. 1985. Statistical quality control-questions about its use in monitoring materials strength characteristics. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 579–590.

Suddarth, Stanley K. 1985. Improved strength performance of I-beams built with proof tested lumber. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 549–559.

6th symposium

Beall, Frank C. 1987. Fundamentals of acoustic emission and acousto-ultrasonics. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 3–28.

Beall, Frank C. 1987. Future applications of acoustic emission and acousto-ultrasonics, In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 369–375.

Galligan, William L. 1987. Future needs in the NDE of lumber. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 377–388

Humphrey, Philip E.; Irving, David; Butler, David A. 1987. Micro-strain mappings within structural members during flexural loading using computerised optical scanning. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 237–244.

Humphrey, Philip E.; Morrell, Jeffrey J. 1987. Distinguishing between refractory and permeable wood at mill production speeds: A possible approach. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14-16; Pullman, WA. Pullman, WA: Washington State University: 269–276.

Maloney, Thomas M.; Pellerin, Roy F. 1987. Industrial and consumer needs in NDE of panel products. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 387–392.

Quarles, Stephen L.; Zhou, Lei. 1987. Use of acoustic emissions to detect drying defects: A preliminary

report. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 95–111.

Soest, Jon F. 1987. Potential of future technologies in lasers. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14-16; Pullman, WA. Pullman, WA: Washington State University: 357–368.

Soest, Jon F. 1987. Principles of laser technology for evaluation of wood. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14-16; Pullman, WA. Pullman, WA: Washington State University: 29–48.

7th symposium

Beall, Frank C. 1990. Nondestructive evaluation center. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 131.

Birkeland, Rolf. 1990. NDE facilities and research program in Norway. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27-29; Madison, WI. Pullman, WA: Washington State University: 57–62.

Bucur, Voichita. 1990. Mode conversion technique for the determination of non-diagonal terms of stiffness matrix wood. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 291.

Carino, Nicholas J. 1990. NDE research and facilities at National Institute of Standards and Technology. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI Pullman, WA: Washington State University: 137.

Choi, D.; Thorpe, J.L.; Cote, W.A.; Hanna, R.B. 1990. Image analysis to measure strain in wood and wood products. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 287.

Davis, John R.; Ilic, Jugo. 1990. Gamma-ray densitometry study of moisture content in wood during drying. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 285.

Davis, John R.; Wells, Peter; Morgan, Michael; Shadbolt, Pam. 1990. Wood research applications of computerized tomography. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 73–77.

Davis, John R.; Wells, Peter; Morgan, Michael, J.; Shadbolt, Pam; Suendermann, Brigitta. 1990. X-ray microtomography for wood science studies. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 305.

Green, Robert E., Jr. 1990. Center for nondestructive evaluation, The Johns Hopkins University. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 79.

Humphrey, Philip E.; Ethington, Robert L. 1990. Nondestructive testing research at Oregon State University, Department of Forest Products. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 125–129.

Kucera, Ladislav J. 1990. Current use of the NMR tomography on wood at the Swiss Federal Institute of Technology: Overview and outlook. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 71–72.

Lindgren, Owe. 1990. The accuracy of a medical cat-scanner for nondestructive wood density measurements in small volume elements. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 277.

Madsen, Bo; Adelhoej, John. 1990. Testing of wooden construction in buildings. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 63–70.

Murray, A.; Green, R.E.; Mecklenburg, M.F. 1990. NDE applied to the conservation of wooden art objects. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 297.

Palka, L.C. 1990. Nondestructive evaluation of wood and wood-based materials at Forintek Canada Corporation. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 133–135.

Portala, Jean-Francois; Ciccotelli, Joseph. 1990. NDT techniques for evaluating wood characteristics. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI Pullman, WA: Washington State University: 97–124.

Scalzi, John B.; Chong, Ken P.; Dillon, Oscar W. 1990. Overview of nondestructive evaluation projects at NSF. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27729; Madison, WI. Pullman, WA: Washington State University: 81–88.

Schaffer, Erwin L. 1990. NDE programs at the Forest Products Laboratory. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 89–96.

8th symposium

Butkovic, George; Babunovic, Krecimir. 1992. Optimization of furniture parts production based on computer program simulation. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23325; Vancouver, WA. Pullman, WA: Washington State University: 263.

Chazelas, Jean-Louis; Vergne, Alain. 1992. Two technics for the analysis of local properties of wood. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State Universit,y: 9–20.

Davis, John R.; Wells, Peter; Lindgren, Owe; Ilic, Jugo. 1992. Microstructure of wood using high resolution x-ray computed tomography. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 91–103.

Groom, Leslie H. 1992. Determination of truss-plate joint integrity using acousto-ultrasonics. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman WA: Washington State University: 143–161.

Jayne, Benjamin A. 1992. World forests, wood products and non-destructive evaluation in century twenty one. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 3–5.

Kawamoto, Sumire; Noguchi, Masami. 1992. Propagation properties of AE waves in wood. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 270.

Kenway, D.J.; Flatman, C.F.; Bauer, W.N. 1992. The architecture of the VisionSmart 3000 MIPS Industrial Supercomputer. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 265.

Lemaster, Richard L.; DeVries, Warren R. 1992. Non-contact measurement and signal processing methods for surface roughness of wood. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 203–218.

Lindgren, Owe. 1992. Medical CAT-scanning: X-ray absorption coefficients; CT-numbers and their relation to wood density. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 266.

Lindgren, Owe; Davis, John; Wells, Peter; Shadbolt, Pam. 1992. Nondestructive wood density distribution measurements using computed tomography: A comparison between two scanners. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 267.

Glued Products and Composites

2d symposium

Pellerin, R.F. 1965. The contributions of transverse vibration grading to design and evaluation of 55-foot laminated beams. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 337–348.

Suddarth, S.K. 1965. Detection of adhesive bond defects in the polaris missile nose fairing through mechanical impedance measurements. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 267–287.

4th symposium

Fox, Selwyn P. 1978. Recent changes in manufacturing specifications for Canadian glued-laminated timber. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 263–274.

Prentice, Mayo S. 1978. Proof loading finger end joints for structural purposes. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 227–232.

Szabo, Ted. 1978. Use of ultrasonics to evaluate or characterize wood composites. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 239–260.

5th symposium

Adkins, D.; Lyngcoln, K. 1985. Stress grading to Australian standards. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 39–74.

Bach, Lars. 1985. Machine stress-rating panel products. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 75–97.

Faero, Oscar. 1985. Proof loading to establish integrity of structural finger joints. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 465–475.

Fagan, G. Brent; Bodig, Jozsef. 1985. Computer simulation as a nondestructive evaluation tool. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 3–37.

Ross, Robert J.; Vogt, James J. 1985. Nondestructive evaluation of wood-based particle and fiber composites with longitudinal stress waves. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 121–157.

Sharp, Donald J. 1985. Nondestructive testing techniques for manufacturing LVL and predicting performance. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 99–108.

6th symposium

Bo-Zhang, Shi. 1987. Form of stress waves in various types and sizes of wood products. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 49–65.

Maloney, Thomas M.; Pellerin, Roy F. 1987. Industrial and consumer needs in NDE of panel products. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 387–392.

7th symposium

Beall, Frank C. 1990. Use of AE/AU for evaluation of adhesively bonded wood base materials. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 45–53.

Lemaster, Richard L.; Pugel, Anton D. 1990. Measurement of density profiles of wood products materials using acoustic emission. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 1–28.

8th symposium

Anthony, Ronald W.; Phillips, Gregory E. 1992. Process control of finger joint strength using acousto-ultrasonics. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 45–56.

Beall, Frank C.; Biernacki, Jacek M. 1992. An approach to the evaluation of glulam beams through acousto-ultrasonics. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 73–88.

King, Ray J.; Basuel, Jesse C. 1992. Measurement of basis weight and moisture content of composite boards using microwaves. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 21–32.

Petit, Marie H.; Bucur, Voichita; Viriot, C. 1992. Aging monitoring of structural flakeboards by ultrasound. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 191–201.

Sato, Keiichi; Fushitani, Masami. 1992. Development of nondestructive testing system for wood-based materials utilizing acoustic emission technique. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 33–43.

In-place Assessment

2d symposium

Jensen, L.C. 1965. Sonic detection of internal decay in wood poles. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 207–221.

Lee, I.D.G. 1965. Ultrasonic pulse velocity testing considered as a safety measure for timber structures. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 185–205.

Stieda, C.K.A. 1965. Photostress analysis of timber structures. In: Proceedings of the 2d symposium on

nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 349–385.

4th symposium

Agi, J.J. 1978. Nondestructive testing and structural analysis of in-place wood marine piling. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 83–93.

Graham, R.D. 1978. Inspecting and treating western redcedar and Douglas Fir poles in service. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 29–32.

Hoyle, Robert J., Jr.; Pellerin, Roy F. 1978. Stress wave inspection of a wood structure. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 33–45.

5th symposium

Browne, Craig M.; Kuchar, Wayne E. 1985. Determination of material properties for structural evaluation of TRESTLE. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 361–384.

Enochson, Loren D. 1985. Examples of structural model analysis. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 407–421.

Neal, Donald W. 1985. Establishment of elastic properties for in-place timber structures. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 353–359.

7th symposium

Bickert, William G.; Harrigan, Timothy M.; Stowell, Richard L. 1990. Moisture related deterioration of the wood frame and metal fasteners in Michigan free stall dairy barns. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 293.

Chui, Y.H. 1990. Vibration testing of wood and wooden structures practical difficulties and possible sources of errors. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 173–188.

Ross, Robert J.; LeVan, Susan L.; Winandy, Jerrold. 1990. Fire retardant wood inspection. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 283.

8th symposium

Brooks, Robert T.; Phillips, Gregory E. 1992. Nondestructive strength assessment of wood cooling tower columns. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23-25; Vancouver, WA. Pullman, WA: Washington State University: 219–233.

Cooper, John L.; Reilly, Jack. 1992. Evaluation of wood products during the building inspection process. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 253–260.

Petit, Marie H.; Bucur, Voichita; Viriot, C. 1992. Aging monitoring of structural flakeboards by ultrasound. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 191–201.

Ross, Robert J.; Cooper, John; Wang, Zhitong. 1992. In place evaluation of fire-retardant treated products. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23-25; Vancouver, WA. Pullman, WA: Washington State University: 247–252.

Volny, Norbert J. 1992. Timber bridge inspection-Case studies in use of stress wave velocity. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 235–246.

Logs, Trees

2d symposium

Mothershead, J.S.; Stacey, S.S. 1965. Applicability of radiography to inspection of wood products. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 307–336.

5th symposium

Birkland, Rolf. 1985. The status of tomographic scanning as a tool for detecting internal log defects. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 231–237.

Johansson, Lars Gote. 1985. Experiences from using x-ray tomography, isotope-based nontomographic measuring, and NMR for testing logs before sawing. In: Proceedings of the 5th symposium on nondestructive

testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 205–229.

Lindgen, Owe. 1985. On the relationship between density/moisture content in wood and x-ray attenuation in computer tomography. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 193–204.

McCracken, Francis I. 1985. Using sound to detect decay in standing hardwood trees. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 281–287.

Wagner, Francis G.; Taylor, Fred W. 1985. Economic returns from internal log scanning. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9-11; Pullman, WA. Pullman, WA: Washington State University: 267–280.

6th symposium

Swanson, James S.; Hailey, Joseph R.T. 1987. Scanning and imaging techniques for assessing decay and wood quality in logs and standing trees. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 83–93.

7th symposium

Conners, Richard; Zhu, Doug Ping; Araman, Philip. 1990. The automatic analysis of computer tomography images of logs. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 281.

Davis, John R.; Wells, Peter; Morgan, Michael; Shadbolt, Pam. 1990. A field portable x-ray CT pole scanner and CT log scanning. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 251–262.

Haack, Robert A. 1990. Acoustic emissions from drought-stressed trees: Implications for forest insects. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 279.

Kucera, Ladislav J.; Bucher, Hans Peter. 1990. Vitamat: Non-destructive testing of the internal condition of trees and timber by measuring AC impedance. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 303.

Miller, W. Prank; Doolittle, James A. 1990. The application of ground-penetrating radar to detection of internal defect in standing trees. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 263–274.

Steele, Philip H.; Harless, Thomas E.G.; Wagner, Francis G.; Taylor, Fred W. 1990. Potential dollar increases from internal log information. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 231–250.

Wagner, Francis; Taylor, Fred; Ladd, Douglas; McMillin, Charles; Roder, Fredrick. 1990. Ultrafast CT scanning of logs for internal defects. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 221–229.

Wang, Paul C.; Chang, Sun Joseph; Olsen, James R. 1990. Scanning logs with an NMR scanner. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 209–219.

8th symposium

Carlyle, John M. 1992. Use of acoustic emission to detect water stress in woody plants. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 264.

Han, Wei; Birkeland, Rolf. 1992. Log scanning through combination of ultrasonics and artificial intelligence. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 163–187.

Steele, Phil; Araman, Philip; Kumar, Lalit; Wagner, Fran. 1992. The influence of volume maximization on value maximization of lumber sawn from hardwood logs. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 268.

Lumber

2d symposium

Corder, S.E. 1965. Localized deflection related to bending strength of lumber. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 461–473.

Galligan, W.L.; Courteau, R.W. 1965. Measurement of the elasticity of lumber with longitudinal stress waves and the piezoelectric effect of wood. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 223–244.

Hoyle, R.J., Jr. 1965. Marketing experiences with machine stress rated lumber. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 37–43.

Johnson, J.W. 1965. Relationships among moduli of elasticity and rupture: Seasoned and unseasoned coast-type Douglas-fir and seasoned western hemlock. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 419–459.

Kollmann, K. 1965. Relationship between elasticity and bending strength of wood. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 69–93.

Littleford, T.W. 1965. Mechanical stress-rating of western Canadian species. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 475–496.

Nemeth, L.J. 1965. Correlation between tensile strength and modulus of elasticity for dimension lumber. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 391–418.

Perry, W.D. 1965. A non-contact moisture meter for lumber. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 297–305.

3d symposium

Angleton, Hugh. 1970. MSR lumber in research houses. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April-May; Vancouver, WA. Pullman, WA: Washington State University: 141–145.

Bollerslev, Karl. 1970. Boise Cascade Corporation's experience. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April-May; Vancouver, WA. Pullman,, WA: Washington State University: 87–88.

Bollerslev, Karl. 1970. What production people want from machine-stress-rating. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 9–13.

Countryman, David. 1970. MSR lumber uses in plywood systems. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 69–71.

Ethington, Robert L. 1970. Machine-stress-ratings and new lumber standards. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April-May; Vancouver, WA. Pullman, WA: Washington State University: 101–113.

Galligan, William L. 1970. Frank Lumber Company's experience. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April-May; Vancouver, WA. Pullman, WA: Washington State University: 81–84.

Galligan, William L. 1970. Planning for an MSR grading operation. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April-May; Vancouver, WA. Pullman, WA: Washington State University: 125–133.

Hoyle, Robert J., Jr. 1970. Estimating profits from MSR grading. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April-May; Vancouver, WA. Pullman, WA: Washington State University: 117–124.

Hoyle, Robert J., Jr. 1970. Experiences with MSR grading in other countries. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 89–99.

Hoyle, Robert J., Jr. 1970. A summary of the short course. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 163.

Hoyle, Robert J., Jr. 1970. The big E. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 17–34.

Johnson, J.W. 1970. Using MSR lumber in laminated beams. Digest of remarks. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April-May; Vancouver, WA. Pullman, WA: Washington State University: 57–63.

Knudson, Myron. 1970. Commercial grading machines. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April-May; Vancouver, WA. Pullman, WA: Washington State University: 135–140.

Marra, G.G. 1970. Concluding remarks. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 160.

Mills, Zimri I. 1970. Using MSR lumber in a structural specialty. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 147–150.

Rysdorp, John H. 1970. Concluding remarks. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 160.

Rysdorp, John H. 1970. What salesmen and distributors want from machine-stress-rating. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 1–8.

Snodgrass, Delos V. 1970. Simpson Timber Company's experience. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 85–86.

Snodgrass, Delos V. 1970. Using MSR lumber to frame apartments. In: Commercial machine-stress-rating for profit,: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 151–153.

Steida, C.K.A. 1970. Some problems in the optimum utilization of MSR. joists. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 41–56.

Tayelor, F. Alan; Thebault, Gary. 1970. Short course appraisal and discussion. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 157.

Thomas, Harold. 1970. MSR lumber uses–A customer's viewpoint. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 73–78.

Todd, R.L. 1970. An association technical director's viewpoint. In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 65–67.

Williston, E.M. 1970. MSR lumber grades-are they too technically complex? In: Commercial machine-stress-rating for profit: 3d Washington State University short course on nondestructive testing of wood; 1970 April–May; Vancouver, WA. Pullman, WA: Washington State University: 35–40.

4th symposium

Bechtel, Friend K. 1978. Some quality control considerations for the forest products industry. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 141–153.

Logan, James D. 1978. Machine stress rating. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 285–303.

McDonald, Kent A. 1978. Lumber quality evaluation using ultrasonics. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 5–13.

McLauchlan, T.A.; Kusec, D.J. 1978. Continuous noncontact slope-of-grain detection. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 67–76.

Schmidt, Torbjorn. 1978. Scanning/computing methods for measuring knots and other defects in lumber and veneers. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 23–25.

Snodgrass, D.V. 1978. Development of a proof loading machine for quality control of MSR lumber. In:

Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 215–221

Todd, Ray L. 1978. Development of markets for MSR lumber. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 279–281.

Tory, J.R. 1978. Machine stress grading in the United Kingdom: Theory into practice. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 77–82.

Warren, W.G. 1978. Recent developments in statistical quality-control procedures for MSR. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 193–213.

5th symposium

Cramer, Steven M.; Goodman, James R. 1985. Predicting tensile strength of lumber. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 525–545.

DeBonis, Albert L. 1985. A new generation MSR machine from Accutech, Inc. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 491–508.

Kharadly, Mos. 1985. Microwave diagnostics for stress-rating of dimension lumber. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 445–464.

McDonald, Kent A.; Bendtsen, B. Alan. 1985. Localized slope of grain-its importance and measurement. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 477–489.

Samson, Marcel. 1985. Model for predicting modulus of elasticity of lumber measured by stress-grading machines. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9-11; Pullman, WA. Pullman, WA: Washington State University: 425–443.

Snodgrass, Delos V. 1985. Improvements on a long span E-tester. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 509–524.

Suddarth, Stanley K. 1985. End use evaluation of proof loading of lumber. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 109–120.

6th symposium

Bechtel, Friend K.; Allen, James R. 1987. Methods of implementing grain angle measurements in the machine stress rating process. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 303–353.

Hamm, E.A.; Lam, F. 1987. Compression wood detection using ultrasonics. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 137–165.

McDonald, K.A.; Cramer, S.M.; Bendtsen, B.A. 1987. Research progress in modeling tensile strength of lumber from localized slope of gram. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 113–123.

Palka, L.C. 1987. Automatic lumber grading. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA Pullman, WA: Washington State University: 247–267.

7th symposium

Chazelas, Jean-Louis; Bucur, Voichita; Vergnes, Alain. 1990. Local physical properties of wood around knots. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 289.

Chui, Y.H. 1990. Vibration testing of wood and wooden structures practical difficulties and possible sources of errors. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 173–188.

Geske, Earl A.; Ross, Robert J.; Larson, Gary R.; Murphy, Joseph F. 1990. PC–based E measurement. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 299.

Kenway, Daniel J.; Stewart, Sherry C. 1990. Computer aided lumber grading. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 189–206.

Samson, Marcel; Huot, Bernard. 1990. Machine stress-rating nonuniform lumber at high speed. In:

Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 153–171.

Smith, Ian. 1990. A direct derivation of machine settings in machine controlled stress grading of softwood lumber. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 141–151.

Smulski, Stephen J. 1990. Relationship of stress wave- and static bending-determined properties of four Northeastern hardwoods. In: Proceedings of the 7th symposium on nondestructive testing of wood; 1989 September 27–29; Madison, WI. Pullman, WA: Washington State University: 301.

8th symposium

Divos, F.; Csupor, K.; Broker, F.W. 1992. Ultrasonic and stress wave-based nondestructive testing of wood. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 272.

Hamm, Ernie A.; Lum, Conroy. 1992. Application of ultrasonics and a slope of grain indicator to detection of compression wood in lumber. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 105–130.

Ohlsson, Sven; Perstorper, Mikael. 1992. Elastic wood properties from dynamic tests and computer modelling. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 269.

Sandoz, Jean Luc. 1992. Nondestructive evaluation of building timber by ultrasound. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 131–142.

Sato, Keiichi; Fushitani, Masami. 1992. Development of nondestructive testing system for wood-based materials utilizing acoustic emission technique. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 33–43.

Steele, Phil; Araman, Philip; Kumar, Lalit; Wagner, Fran. 1992. The influence of volume maximization on value maximization of lumber sawn from hardwood logs. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 268.

Tanaka, Toshinari; Nagao, Hirofumi; Nakai, Takashi. 1992. Nondestructive evaluation of bending and tensile strength by longitudinal and transverse vibration of lumber. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 57–72.

Verkasalo, Erkki; TenWolde, Antoni; Ross, Robert J.; Youngs, Robert. 1992. Stress wave NDE of bacterially infected red oak lumber. In: Proceedings of the 8th symposium on nondestructive testing of wood; 1991 September 23–25; Vancouver, WA. Pullman, WA: Washington State University: 271.

Poles, Pilings

2d symposium

Jensen, L.C. 1965. Sonic detection of internal decay in wood poles. In: Proceedings of the 2d symposium on nondestructive testing of wood; 1965 April; Pullman, WA. Pullman, WA: Washington State University: 207–221.

4th symposium

Agi, J.J. 1978. Nondestructive testing of marine piling. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 187.

Frederickson, Larry. 1978. Specifications for the restoration of deteriorated piling utilizing the patented sea form method. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 177–181.

Graham, R.D. 1978. Inspecting and treating western redcedar and Douglas Fir poles in service. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 29–31.

Kennedy, John. 1978. Ultrasonic testing of wood and wood products. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 185.

Knannlein, James R. 1978. Piling inspection visual and core sampling. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 175.

Pellerin, Roy F. 1978. Nondestructive testing of wood-a possible method for timber piling. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 169–174

Roe, Thorndyke, Jr. 1978. The timber piling problem (Navy viewpoint). In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 165–168.

Smith, Charles E. 1978. Timber piling problem (Coast guard and harbor viewpoint), some solutions. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 163.

Test, Gerald W. 1978. Bridge piling problems. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 161–162.

5th symposium

Anthony, Ronald W.; Bodig, Jozsef. 1985. Reliability of pole strength prediction methods. In: Proceedings of the 5th symposium on nondestructive testing of wood; 1985 September 9–11; Pullman, WA. Pullman, WA: Washington State University: 239–265.

6th symposium

Abbott, A.R.; Elcock, G. 1987. Pole testing in the European context. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 277–302.

Arsenault, Robert D. 1987. Stress wave analysis of compression strength of new wood piles. In: Proceedings of the 6th symposium on nondestructive testing of wood; 1987 September 14–16; Pullman, WA. Pullman, WA: Washington State University: 191–236.

Veneer

4th symposium

Kunesh, Robert H. 1978. Using ultrasonic energy to grade veneer. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 275–278.

Logan, James D. 1978. Machine stress rating. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 285–303.

Schmidt, Torbjorn. 1978. Scanning/computing methods for measuring knots and other defects in lumber and veneers. In: Proceedings of the 4th symposium on nondestructive testing of wood; 1978 August 28830; Vancouver, WA. Pullman, WA: Washington State University: 23-25.