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Assessing Biological Deterioration in Wood with Acoustic-Based Techniques—A Review

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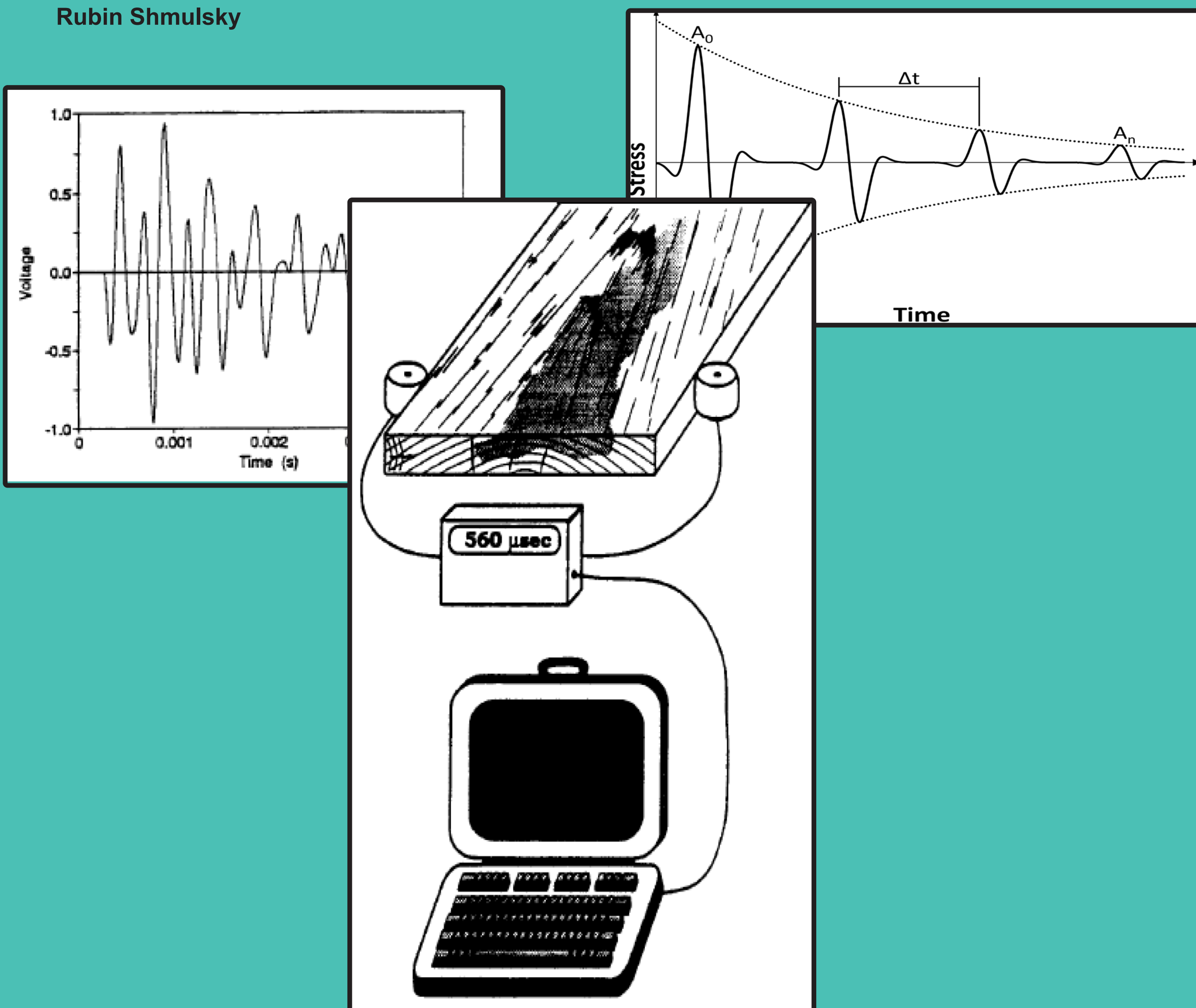

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Abstract

Acoustic inspection is a reliable tool for assessing biological deterioration in wood. As wood decays, several mechanical properties are negatively affected. A variety of acoustic techniques have been developed to identify, and in some cases quantify, the extent to which the presence of decay has altered the wood. Knowledge of the extent of decay allows an inspector to estimate strength loss of the wood structure. This report serves as an introduction to acoustic inspection of biologically deteriorated wood. Basic acoustic techniques are described. Percentage reductions of wood mechanical properties as a function of wood mass reduction from decay are collected from references spanning nine decades. Common data analysis methods used in assessing acoustic data are presented. Finally, a model of wood material strength is given.

Keywords: wood; nondestructive testing; deterioration; acoustic

Contents

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Introduction

Wood is used extensively for both interior and exterior applications in the construction of a variety of structures (residential, agricultural, commercial, government, religious, etc.). The deterioration of an in-service wood member may result from a variety of causes during the life of a structure. Periodically assessing the condition of wood used in structures is important to determine the extent of the deterioration, which gives the knowledge necessary to determine if degraded members need to be replaced or repaired to avoid structural failure. An assessment is especially critical for buildings in municipalities affected by catastrophic events.

Assessment of the condition of wood in a building or other structure can be conducted for a variety of reasons. Code compliance, historic preservation, or alternative uses of a structure are frequently cited reasons for conducting a condition assessment. A structural condition assessment consists of the following: (1) a systematic collection and analysis of data pertaining to the physical and mechanical properties of materials in use, (2) evaluation of the data collected, and (3) providing recommendations, based on evaluation of the collected data, regarding portions of an existing structure that affect its current or proposed use. Such an assessment relies upon an in-depth inspection of the wood members in the structure. A wide variety of techniques are used to assess the condition of wood in structures. Visual inspection, resistance drilling, probing, and stress wave or ultra-sound-based techniques are all used either individually or in combination to evaluate the condition of in-service members (Ross and others 2004, White and Ross 2014, Franca and others 2015). Chemical and chemical-change analyses can also be important for inspections and condition assessment. These, however, are covered elsewhere (Winandy and Morrell 1993) and are beyond the scope of this review.

Inspections of wood structures focus on areas that have the highest probability of deterioration, specifically areas in members that are exposed to moisture intrusion and reduced drying ability. These areas are usually where end-grain is exposed and where two or more members are joined. Some examples of these areas or situations include window joinery, exterior or exposed molding and millwork, outdoor deck framing and rail assemblies, wood foundation piles that are subjected to changes in the water table level (for example, those in Venice, Italy), crane mats, electrical generation cooling tower components that spend their service lives in air along with warm cascading water, timber bridge components, grade beams and sills, etc. When these types of items fail, an estimation of their residual strength and/or stiffness at the time of failure is often required.

Most connections in wood structures were originally designed to minimize tension-perpendicular-to-the-grain (tension perp) stresses. Despite best design attempts, the state of stress at connections in timber structures still results in stressing the wood in tension perpendicular to the grain. Gordon (1976) wrote “Properly made knots and splices in rope are from forty to eighty percent efficient…Nailed, bolted, screwed, pegged or dovetailed joints in wood are far less efficient than this…” Despite advances since that time, stress concentrations and weaknesses associated with fasteners and joinery remain difficult to overcome. Thus, knowledge of the deleterious effects that decay has on properties related to tension perpendicular to the grain is important.

Effect of Biological Deterioration on Wood Physical and Mechanical Properties

Deterioration of wood fibers caused by decay has a significant effect on various properties of structural timber. The following sections summarize the effect of decay on various strength properties of wood. Table 1 summarizes estimated strength losses at early stages of decay in softwoods and hardwoods from scientific literature on the topic (Ross and others 2018).

Table 1—Estimated values for strength losses in softwoods and hardwoods at early stages of decay (indicated by weight loss) by brown-rot and white-rot fungi as a percentage of value for nondecayed samples[a,b]

	Strength property loss (%)										
			Static bending								
Approx. weight loss (%)	Toughness	Impact bending	General bending strength	Work to max. load	MOR[c]	MOE[c]	Compression perpendicular (radial)	Compression parallel	Tension parallel	Shear parallel	Tangential hardness
						Brown-rot					
Softwoods											
1	57	20–38	—	—	—	—	—	—	—	2	—
2	—	20–50	5	27	13–50	4–55	18–24	10	23–40	—	—
4	75	25–55	—	—	—	—	25–35	—	—	6	7
6	—	62–72	16	—	61	66	48	25	60	—	—
8	—	78	—	—	—	—	48–60	—	50	15	21
10	—	85	36	—	70	—	66	45	—	20	—
Hardwoods											
1	—	6–27	—	—	—	—	—	—	—	—	—
2	36	31–50	—	54	32	—	6–10	—	56	—	—
4	—	60–70	—	69	49	—	—	—	—	—	—
6	—	80	—	75	61	—	16–25	—	—	—	—
8	—	9–89	13–34	—	—	—	19	—	82	—	—
10	60	70–92	—	—	—	—	—	—	—	—	—
						White-rot					
Softwoods											
1	55	—	—	—	—	—	—	—	—	—	—
2	—	—	—	—	—	—	10–20	—	4–38	—	—
4	—	—	—	—	—	—	—	—	8–43	—	—
6	75	—	—	—	—	—	32–61	—	10–49	—	—
8	—	—	—	—	—	—	—	—	14–58	—	—
10	85	—	—	—	—	—	—	—	20–63	—	—
Hardwoods											
1	—	21	—	—	—	—	4	—	—	—	—
2	—	26	—	28–35	13–14	4	5	—	22–42	—	—
4	70	44	—	38	20	—	—	—	17–44	—	—
6	75	50	—	45–53	20–27	10	12–27	14	12–58	—	18
8	—	—	—	—	—	—	—	—	14–49	—	—
10	85	60	—	58	24	14	35	20	20–50	—	25

[a]From Wilcox (1978). Values obtained from published experimental results and adjusted to equivalent weight loss levels.
[b]Sources: Brown (1963), Cartwright and others (1931), Gillwald and Michalak (1963), Hartley (1958), Henningsson (1967), Kennedy (1958), Kennedy and Ifju (1962), Kubiak and Kerner (1963), Mizumoto (1966), Mulholland (1954), Pechmann and Schaile (1950), Richards (1954), Scheffer (1936), Toole (1971), Wilcox (1968).
[c]MOR, modulus of rupture; MOE, modulus of elasticity.

Loss of mass in wood has been considered the most reliable variable for determining changes in quality resulting from decay (Wilcox 1978). Mass loss can be used to judge variability across experimental studies and can be used as the basis of comparisons. Strength properties are therefore reported most often as a function of mass loss. A summary of some key strength properties used in inspections and assessments continues in the following subsections.

Toughness

Toughness (the ability of a wood member to withstand shock loading) is generally considered to be the strength property most affected in early stages of decay (Wilcox 1978). Research dating to 1954 indicates a decrease in toughness of 50% with a corresponding loss of only 1% in weight (Table 1). Although both brown- and white-rot fungi have impacts on toughness in softwoods and hardwoods at low levels of mass loss, there is greater variability in the decrease of toughness after mass loss is greater than 10% (Wilcox 1978). Therefore, in this area of research, it is vital to cite not only the conditions under which the decay was performed but also to indicate an accurate percentage of mass loss so that accurate models may be developed.

Static Bending

Static bending tests are one method of determining strength properties of wood, particularly modulus of elasticity (MOE) and modulus of rupture (MOR) (Shmulsky and Jones 2019). Research dating back to the 1930s has been conducted on MOE, MOR, and work to maximum load, and the impact of decay on these properties has long been known. Reported results, such as those summarized in Table 1, indicate a significant loss in MOR (maximum bending strength) with decayed wood. The combination of decay organism, conditions, anatomical characteristics of wood, and time of exposure all contribute to the broadly ranging effects on static bending.

Other Strength Properties

Research has shown that compression perpendicular to the grain, compression parallel to the grain, tension parallel to the grain, shear parallel to the grain, and tangential hardness are also impacted by deterioration caused by decay. However, the effect of decay on these properties has been investigated less often than the more frequently measured static bending properties. It is important that we understand the entirety of decay impacts on wood properties so that we can predict with greater accuracy the likelihood of failures and develop more precise design values.

To develop improved methods for detecting and quantifying the effect of decay fungi on wood products, Janzen and Nicholas (2016) developed a soil-block decay test that used perpendicular-to-grain compression properties (MOE and strength). They found that early stages of decay were detected in both radial and tangential loading directions.

Acoustic-Based Nondestructive Evaluation Techniques

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

Wave Motion through Wood

To illustrate acoustic techniques, consider the application of one-dimensional wave theory to a wood specimen (Fig. 1). After an impact hits the end of the specimen, a compression wave is generated. This wave immediately begins moving down the specimen as particles at the leading edge of the wave become excited, while particles at the trailing edge come to rest. The wave depth or the distance between the leading and trailing edges of the wave is controlled by the length of the impactor and the velocity of propagation of the material that makes up the impactor. The wave moves along the specimen 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 specimen, this forward-moving wave impinges on the free end of the specimen and is reflected as a tensile wave traveling back down the specimen. The velocity of the wave is independent of the intensity of the impact.

Data Collection Techniques

Two common methods of data collection using wave motion are pitch and catch and pulse-echo (Senalik and others 2014). In pitch and catch, simple time-of-flight type measurement systems are used to determine stress wave propagation speed (Figs. 2 and 3). In these measurement systems, a mechanical impact or piezoelectric transducer is used to impart a longitudinal wave into a member. Piezoelectric transducers are placed at two points on the member and used to sense passing of the wave. If a mechanical impactor is used, then both transducers are used as receiving sensors to detect the passing wave. Alternatively, one transducer can be used as a transmitter with a second transducer used as a receiver. The time required for the wave to travel between transducers is measured and used to compute wave propagation speed. Several types of instruments are available for conducting pitch and catch tests on structural timbers and trees. Most of

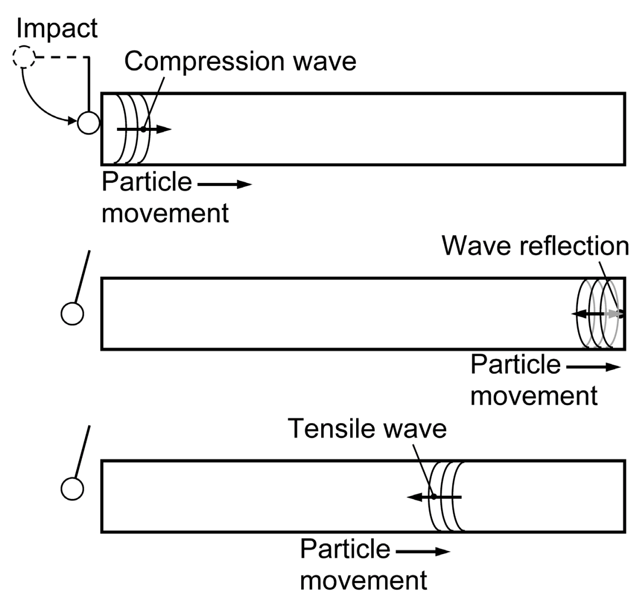

Figure 1. Idealized viscoelastic bar subjected to an impact.

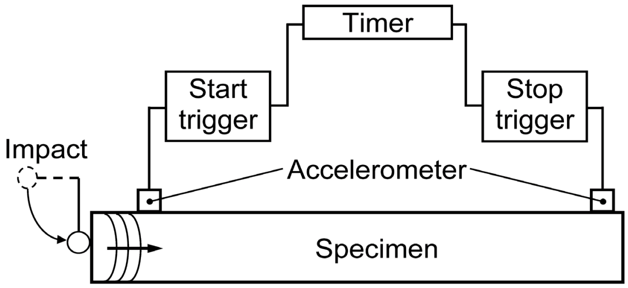

Figure 2. System used to measure impact-induced stress wave propagation speed in various wood products.

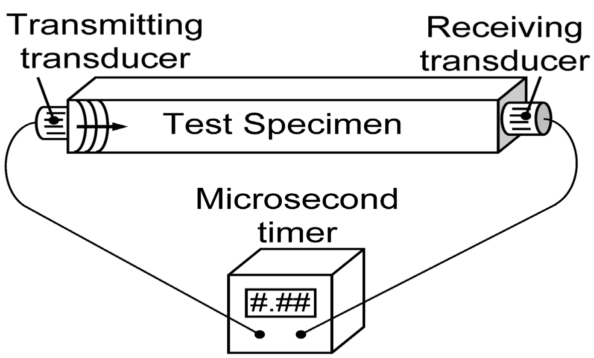

Figure 3. Ultrasonic measurement system used to measure speed-of-sound transmission in various wood products.

these instruments measure the time it takes a wave to traverse a fixed distance and report a transmission time. Many users report this number on a per length basis. The advantage of this method is that signal noise from internal reflections within the specimen is normally low at the leading edge of the wave, which is used to calculate the time-of-flight. This technique requires multiple transducers. In addition, physical limitations (access, distance, etc.) may prevent the receiving transducer from being placed as desired.

The pulse-echo technique is similar to pitch-and-catch but uses only one transducer. As with pitch and catch, the wave source can be a separate mechanical impactor or the transducer itself. In most cases, the receiving transducer is located near the wave source. The wave travels through the specimen and is reflected by both internal features (cracks, splits, knots, etc.) and external features (sides of the specimen). The receiving transducer senses the wave reflections. The main advantages of the pulse-echo technique compared with pitch and catch are less equipment (one transducer versus two or more) and reduced requirement for access on all sides of the specimen. It is not uncommon to be unable to access the far side of a beam or wall. In that case, pulse-echo can be used. The disadvantages of pulse-echo are greater likelihood of signal noise and size constraints of the tested specimen. Unlike pitch and catch, the first wave sensed in pulse-echo is not necessarily from the far side of the specimen; the reflection could be from an internal feature. The inspector must have knowledge of the specimen dimensions and be able to determine which reflections are from the extents of the specimen and which are from internal features. In addition, sensing of wave reflections cannot begin until after the source wave fully passes the sensing transducer. The source wave occurs during a brief but finite time. During the brief period of time after the source is triggered, the sensing transducer will detect the wave generated by the source itself rather than from reflectors within the specimen. Any reflections that arrive while the source wave is passing the transducer will probably be masked by the source wave. After the initial source wave has passed, normal reflection sensing begins. In some cases, the transducer itself can be both the source and the receiver. In this configuration, sensing of reflections cannot begin until after the transducer has finished generating the source wave. Any reflections that arrive while the transducer is generating the source wave will not be sensed.

Data Analysis Techniques

Energy is dissipated as the wave travels through the specimen; therefore, although the speed of the wave remains constant, movement of particles diminish with each successive passing of the wave. Eventually all particles of the specimen come to rest. Monitoring the movement of a cross section near the end of a specimen 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. 4). Depending on the design of the measurement used to monitor movement of the cross section in response to the wave, the shape of the individual pulses can appear to be different. Of critical importance is the fact that the speed at which the wave traverses the specimen and its attenuation are not influenced by the measurement system used.

The propagation speed of such a stress wave, C, can be determined by coupling measurements of the time between pulses, Δt, and the travel distance between the source and receiver, L, by the time-of-flight (ToF) equation given in Table 2. The dynamic MOE, E_D, can be computed using C and the mass density of the specimen, ρ, using the elastic constants determination equation in Table 2. Wave attenuation can be determined from the pulse amplitude during successive reflections and the time between pulses using the wave attenuation equation in Table 2.

Table 2 contains several common analysis techniques that are applied to acoustic measurements and recorded signals obtained during testing. Descriptions of techniques and the mathematical expressions for each are also given (Senalik and others 2014).

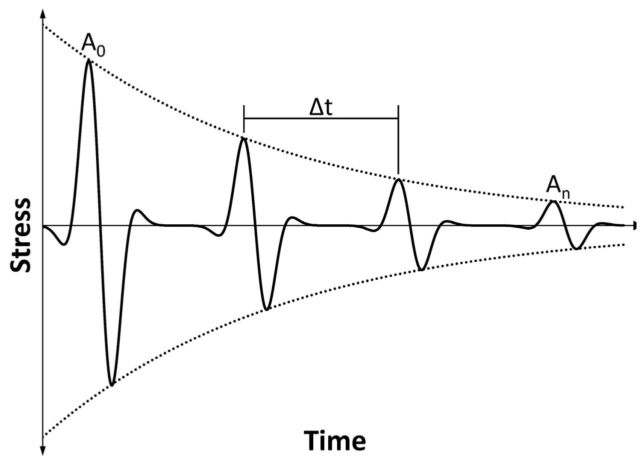

Figure 4. Waveforms consist of a series of equally spaced pulses for which magnitude decreases exponentially with time.

Fundamental Relationships between Acoustic Parameters and Strength of Deteriorated Wood

Parallel-to-Grain Compressive Strength

Pellerin and others (1985) were the first to report on a systematic examination of the effect of biological attack on the acoustic properties of clear wood and its relationship to compressive strength. They used small, clear Southern Pine specimens in a laboratory study designed to examine the effect brown-rot decay fungi and termite attack had on acoustic velocity and static strength. Time-of-flight measurements, parallel to the fiber axis, were made using a pitch and catch system on specimens after various exposure times. They observed a considerable change in acoustic ToF with exposure time. More importantly, they were able to conclude the following:

Table 2—Several common analysis techniques that are applied to acoustic measurements and to recorded signals obtained during testing

Ultrasonic technique	Description	Mathematical expression
Time of flight (ToF)	Measure of the time required for an ultrasonic packet of energy to travel through the material. Usually expressed as per unit length.	$\text{ToF} = \frac{t_2 - t_1}{L} = \frac{\Delta t}{L} = \frac{1}{C}$ t_2 is arrival time t_1 is initiation time L is travel distance between source and receiver
Pulse length (PL)	Measure of spreading of received waveform with respect to a standard waveform. Influenced by differences in path length and sound speed that tend to spread waveform.	$PL = Kt_r \int v(t)^2\, dt$ K is a constant t_r is time required for received wave energy integral from 10% to 90% of its final value v is signal voltage as a function of time t is time
Insertion loss (IL)	Ratio of energy received, after transmission through material, to energy input.	$\text{IL} = 10 \log\left(G \frac{P_r}{P_t}\right)$ P_r is received power P_t is transmitted power G is receiver gain
Elastic constants determination	Relates longitudinal and shear wave velocities to Poisson's ratio and dynamic MOE.	$E_D = \rho C_L^2 G_D = \rho C_\tau^2$ C_L is longitudinal wave velocity C_τ is shear wave velocity ρ is mass density E_D is dynamic MOE G_D is dynamic shear elastic modulus
Wave attenuation	Ratio of pulse magnitude during successive pulses of an exponentially decaying signal. Shown using variables in Figure 4.	$\delta = \frac{1}{n} \ln \frac{A_0}{A_n}$ δ is logarithmic decrement A_0 is amplitude of first pulse A_n is amplitude of n^{th} pulse n is number of peaks examined

- Changes in ToF occurred well before measurable weight loss (density) and before strength loss was observed.
- A significant correlation was observed between residual strength and acoustic ToF.
- Because termite attack was preferential to the early wood sections of the specimens, ToF measurements parallel to the fiber axis were not useful for monitoring corresponding changes in strength.

DeGroot and others (1994, 1995, 1998) reported on a follow-up study they performed to examine both energy storage and loss parameters for monitoring the deterioration of clear wood when exposed to natural populations of decay fungi and subterranean termites. They used a pulse-echo test setup (Ross and others 1994) to measure speed of sound transmission and wave attenuation, parallel to the fiber axis, in small clear Southern Pine specimens in field exposure conditions, and they developed empirical models using both parameters that could predict residual compressive strength with a high level of accuracy (Ross and others 1996a, 1996b, 1997).

Perpendicular-to-Grain Tensile and Compressive Strength

Verkasalo and others (1993) investigated the effect anaerobic bacterial infection, specifically infection by *Clostridium* and *Erwinia* spp., had on various properties of red oak wood. Anaerobic bacteria secrete enzymes that can degrade pectic substances of the compound middle lamella as well as starch, tannins, and possibly monomeric wood sugars (Schink and Ward 1984, Ward and Zeikus 1980). Consequently, chemical bonds between wood cells are weakened. The degradation is indicated by destroyed pit membranes and microcracks between the cell walls. Thus, although the secondary cell walls appear to remain intact and the wood maintains its original density, the wood's ability to withstand drying stresses is decreased (Ward and Pong 1980). Verkasalo and others (1993) found that the presence of anaerobic bacteria significantly decreased several physical and mechanical properties.

Rutherford and others (1987) examined the relationship between compressive dynamic and static MOE values of Douglas-fir samples exposed to brown-rot decay fungi (*Gloeophyllum trabeum*) for exposure times between 2 and 12 weeks. A strong statistical relationship was found to exist.

Ross and others (2001) used pitch and catch techniques to estimate the compressive properties of several eastern white pine timbers removed from service (Table 3). A strong relationship was observed between transmission times and compression properties. The timber specimens were originally part of a heavy timber truss system of a blacksmith shop in northern Michigan, USA. After the acoustic transmission times were measured and recorded, each specimen was tested to failure in compression perpendicular to the grain. Compressive stress at proportional limit and maximum compressive stress were determined for each specimen.

Modeling of Foundation Relationships

The foundation for most applications of acoustic-based nondestructive testing techniques is based on the relationships among energy storage and loss characteristics, speed of sound transmission and logarithmic decrement (acoustic wave attenuation rate), and the strength of wood and wood products. Early research and development efforts focused on using speed of sound transmission for assessing lumber stiffness and strength and identifying deteriorated sections of large, in-place timbers (Ross 2015).

Kaiserlik and Pellerin (1977) were the first to incorporate an energy loss parameter into a model to predict a wood product's strength. The hypothesis of a relationship between this parameter and strength assumed the following:

- Fiber alignment (grain angle) strongly influences MOE and speed of sound transmission, exhibited as a linear relationship (speed of sound transmission increases with increasing MOE values), and
- Fiber alignment, the presence of strength-reducing natural defects, and the strength of the bond between constituents strongly influence logarithmic decrement. Also, they believed strength was inversely related to logarithmic decrement.

Based on their hypothesis and subsequent modeling work by Ross and Pellerin (1988) with layered and random orientation wood composites, a multivariable linear regression analysis is used to examine the relationships between measured NDE parameters and strength. The NDE parameters include specific gravity, speed of stress wave transmission, and logarithmic decrement of the wave as it traverses through a specimen. The following multiplicative model is used:

$$P = b_0 (\mathrm{SG})^{b_1} (\mathrm{ATT})^{b_2} \left(C^2\right)^{b_3} \tag{1}$$

where

P is the strength parameter (either MOR or ultimate tensile stress (UTS)),

SG is specific gravity,

ATT is logarithmic decrement,

C is wave speed, and

b_i are empirical model parameters (i = 0,1, 2, 3).

Table 3—Stress wave transmission times and compressive properties for eastern white pine specimens removed from blacksmith shop trusses

Specimen no.	Stress wave transmission time[a] (μs)	Compressive stress at proportional limit[a] (lb/in^2)	Maximum compressive stress[a] (lb/in^2)	Visual assessment of specimen condition
1	213	202	562	Sound
2	212	188	533	Sound
3	208	221	543	Sound
4	250	140	465	Sound
5	525	67	170	Center severely deteriorated
6	1,260	—	—	Severely deteriorated[b]
7	2,207	—	—	Severely deteriorated[b]
8	3,680	—	—	Severely deteriorated[b]

[a]Perpendicular to grain. 1 lb/in^2 = 6.89 kPa.
[b]Specimens fell apart during preparation for static testing.

The model can be transformed into a linear model by taking the natural logarithm yielding as shown in the following equation (The empirical model parameters for UTS and MOR are given in Table 4):

$$\ln(P) = \ln(b_0) + b_1 \ln(\mathrm{SG}) + b_2 \ln(\mathrm{ATT}) + b_3 \ln(C^2) \quad (2)$$

where

P is the strength parameter (either MOR or UTS),

SG is specific gravity,

ATT is logarithmic decrement,

C is wave speed, and

b_i are empirical model parameters (i = 0,1, 2, 3).

Assuming an additive error, which corresponds to a multiplicative error in Equation (2), a multiple linear regression analysis can then be used to evaluate the appropriateness of the model form. Based on the estimated coefficients and measured NDE parameters, predicted values for compressive strength were compared with observed values through residual analysis to evaluate the usefulness of the model. A similar model and analytical approach were previously used by Ross and Pellerin (1988) and Kaiserlik and Pellerin (1977).

Applications

Stress wave techniques were used to evaluate the wood members of a barn, constructed in 1925 for the College of Agriculture, Washington State University, Pullman, Washington, USA (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 wave propagation parallel to the grain was measured on 50% 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.

Stewart and others (1986) used stress wave techniques to evaluate the wood members of several water cooling towers. Approximately 7,700 4-ft- (1.2-m-) long nominal 2- by 4-in. (standard 38- by 89-mm) redwood columns were evaluated.

Table 4—Results of linear regression relating strength to multiparameter regression model[a]

Strength parameter	$\ln(b_0)$	b_1	b_2	b_3	R[b]	S_{yx}[c]
UTS[d]	–5.822	1.461	–0.312	0.812	0.95	0.140
MOR[e]	–3.642	1.780	–0.518	0.769	0.97	0.130

[a]From Ross and Pellerin (1988).
[b]R, correlation coefficient.
[c]S_{yx}, standard error estimate.
[d]UTS, ultimate tensile strength.
[e]MOR, modulus of rupture.

With 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 been needlessly replaced.

The Trestle was constructed between July 1976 and February 1979 and is one of the largest known glued-laminated structures in the world. It is located at Kirkland Air Force Base, New Mexico, USA. The Trestle was built as a test stand for aircraft that weigh up to 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. 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 The Trestle. One evaluation method relied on speed-of-sound transmission measurements. 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% of the structural members) were evaluated. They concluded that the structural framework of The Trestle had not measurably degraded but the exposed deck system was significantly degraded.

Stress wave techniques have been used to increase lumber yield. Stress waves were used to identify bacterially infected logs, called wetwood, in red and white oak by Ross and others (1992). Lumber containing wetwood developed costly defects during the drying process. To increase yield, it was desirable to remove lumber containing wetwood prior to drying. Stress wave ToF identified 84% of red oak containing wetwood and 45% of white oak containing wetwood. Xu and others (2018) used a combination of high-resolution laser scanning and wavelet analysis of acoustic impact signals to increase lumber yields from logs. By examining features of the acoustic impact signal such as time centroid, damping ratio, and combined time- and frequency-domain parameters, log cutting decisions were improved, which increased the grade of the lumber cut from the logs.

The effect and spread of decay through wood has been estimated using stress wave techniques. Ross and others (1996b) used longitudinal stress waves to assess the strength of wood members exposed to biological attacks. Specimens of clear Southern Pine were degraded by fungi and termites in outdoor conditions in southern Mississippi. A multivariable model of compressive strength was developed from the specimens after exposure using the parameters of stress wave speed and signal damping. The model explained 85% of the observed variability in compressive strength. Senalik and others (2015) revisited the results and found ToF could be used to estimate the spread rate of the decay with respect to months of exposure. A model was produced estimating severity of decay and depth of penetration based on the data collected nearly two decades earlier.

Wooden bridge components have been the subject of several studies. Pellerin and others (1996), Emerson and others (2002), and Ross and others (2001) examined the relationship between stress wave speed (measured perpendicular to the grain) and the residual compressive strength of a small sample of timbers removed from service. The 12- by 12-in. (0.31- by 0.31-m) Douglas-fir timbers were obtained from several timber bridges in eastern Oregon, USA, that were scheduled for demolition. All the timbers had been treated with creosote prior to their installation. Acoustic wave transmission times were measured on each timber specimen using a pitch and catch technique. The specimens were then taken to the laboratory and tested in compression, parallel to the grain, to failure. Results obtained are summarized in Table 5. The maximum load obtained from the tests was inversely related to acoustic transmission times. The mode of failure of one specimen, as demonstrated in Figure 5, is also interesting. The interior of the specimen, which consisted of untreated wood, was severely deteriorated. The compression load applied was, therefore, carried entirely by its outer shell. The shell simply buckled outward under the compressive load. Emerson and others (2002) examined the large, creosote-treated bridge timbers using ToF and frequency content of waves through the members. The sensitivity of ToF measurements to wood rot made them excellent indicators of interior decay. Advanced decay was easily identified. Contour plots of the ToF showed the effect of creosote treating on the technique. Amplitude measurements were highly sensitive to the coupling of the transducer to the member.

Table 5—Stress wave transmission times and failure loads for Douglas-fir specimens removed from timber bridges

Specimen no.	Stress wave transmission time[a] (μs)	Load at failure[b] ($\times 10^3$ lb)
1	1,657	178
2	1,806	179
3	4,787	38
4	1,918	119
5	2,425	132
6	1,679	172

[a]Perpendicular to grain.
[b]Compression parallel to grain. 1 lbf = 4.448 N.

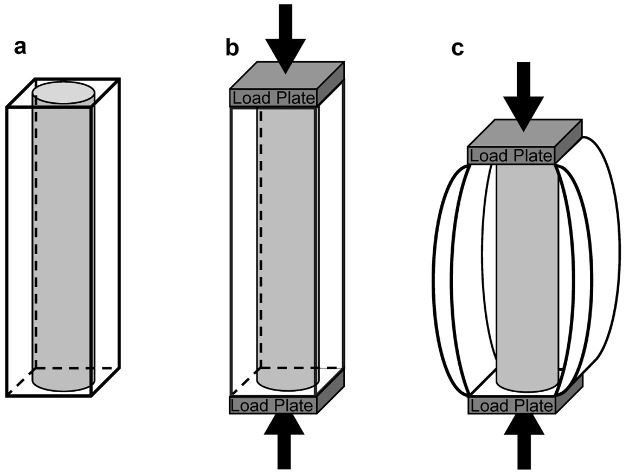

Figure 5. Collapse of a timber column with interior rot under compression: (a) square cross section of the column with decayed interior; (b) compressive force applied through metal load plates that covered the entire end of the column; and (c) interior provided no resistance to compression so the outer "shell" split along the corners and buckled.

Applications for Historical Objects and Structures

Condition assessment of historical objects and structures is an ideal application for stress wave inspection technique because it does not alter the current state of the artifact. Witherall and others (1992) used stress wave techniques in the assessment of the USS Constitution, which is the oldest commissioned ship in the U.S. Navy. The USS Constitution was launched in 1797. Through active duty during wartime and longevity of service, it earned its place as an irreplaceable part of U.S. history. During maintenance performed in the late 1980s and early 1990s, stress wave techniques were used to identify rot at the water level. The use of stress wave helped to minimize the wood replaced, which is important because each timber is considered historic.

Wang and others (2002) used stress wave techniques to assess the old growth timbers used in the original construction of the Quincy Mine Blacksmith Shop in Keweenaw National Historical Park in Calumet, Michigan, USA. The mining camp was established in 1840, and the buildings were constructed of old growth eastern white pine. During the 2002 testing, stress wave inspection revealed that although some surface decay was present, a substantial amount of good wood remained in the timbers, allowing them to be salvaged for renovation.

Ross and Dundar (2012) used stress wave techniques to inspect a 2,500-yr-old mummy coffin. Deterioration was found near the rear of the coffin. With this knowledge, a specialized display case was designed that allowed the coffin to be seen but did not risk further damage to it.

Two historic viewing towers, the Eagle Tower in Peninsula State Park in Wisconsin and a sister tower in Potawatomi State Park in Wisconsin, were examined by Ross and others (2017, 2018). In both instances, stress wave ToF was used as one of several nondestructive testing techniques to assess the condition of the towers. Despite the historic nature of the towers, the results of the inspections showed that they were severely compromised structurally. These inspections led to the disassembly and replacement of the Eagle Tower. For public safety, the Potawatomi State Park tower was closed. Senalik and others (2017) examined the phase and frequency content of the stress wave signals. The scope was limited to a pilot study, but the phase and frequency appeared to be more sensitive to the presence of decay than ToF alone. Although both ToF and phase and frequency methods could differentiate between severely rotten and sound wood, the phase and frequency method could detect changes to the wood around bolt holes that were not identified using ToF.

Concluding Comments

Assessing biologically deteriorated wood using acoustic techniques is a proven inspection strategy. There are several aspects of the inspection process that must be understood: taking acoustic measurements, analyzing the collected data, correlating them to mass loss and reduced material properties, and estimating residual member strength. This report provides a single reference starting point for those beginning to delve into this area of study. While by no means comprehensive, it should illuminate important aspects of the acoustic inspection process and provide references for further study.

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