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Ultrasonic-Based Nondestructive Evaluation Methods for Wood

A Primer and Historical Review

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Abstract

The authors conducted a review of ultrasonic testing and evaluation of wood and wood products, starting with a description of basic ultrasonic inspection setups and commonly used equations. The literature review primarily covered wood research presented between 1965 and 2013 in the Proceedings of the Nondestructive Testing of Wood Symposiums. A table that lists the wood species used in the reviewed studies is included.

Keywords: Ultrasound, acoustic, nondestructive evaluation, wood, literature review

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Contents

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A Primer and Historical Review

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Introduction

With the recent compilation of 50 years of the NDT International Nondestructive Testing and Evaluation of Wood Symposium Series, now is a good time to examine how the nondestructive testing of wood in all of its forms has changed over the last half century. The purpose of this paper is twofold: to provide a basic primer to nondestructive testing using ultrasonic inspection and to provide a literature review of the use of ultrasonic techniques in the inspection, characterization, classification, and evaluation of wood and wood products as presented in 50 years of the NDT Wood Symposium series. This paper does not present a detailed explanation of wave theory, a robust description of wave propagation through heterogeneous anisotropic mediums, such as wood, or derivations of fundamental equations. For a more rigorous explanation of ultrasonic wave motion through wood and foundational equations upon which the motion is based, the reader is directed to Bucur (2003, 2006, 2011a).

Background

When preparing an ultrasonic test of a specimen, several factors must be considered. Among these are source, power, frequency, receiver, and coupling. These factors must be determined holistically for any inspection as the choice of any one affects the others. For example, a particularly large specimen might require high power for the signal to be observable. Generally the size at which internal defects are discernable is related to the frequency used to inspect the specimen; higher frequencies can detect smaller defects. The source selected must be capable of generating the necessary signal power at the desired frequency. The source may also act as the receiver, such as in a pulse-echo test setup. If the receiver is non-contact, such as a microphone or non-contact transducer, then no coupling is needed. If contact is necessary, then a coupling agent must be chosen that is adequate for the test and will not corrupt the condition of the specimen.

Sources generate stress waves that are used to inspect the specimen. A source may be anything capable of generating detectable stress waves. In a nondestructive test, the chosen source must be able to generate the desired signal without altering the condition of the specimen post-test. Two common external sources are mechanical impacts and piezoelectric transducers. The source may originate from within the specimen itself. Some internal phenomena are capable of generating a detectable emission. Microfractures, check formation, water movement, and pit aspiration are just a few internal phenomena in wood that may be detectable by external receivers. This type of inspection is known as acoustic emission.

Ultrasonic waves have frequencies of 20 kHz and higher. The resolution of any ultrasonic scan is dependent upon the frequency. As frequency increases, wavelength decreases. The smallest discernable feature during an ultrasonic scan is about one half the wavelength. Signal attenuation in wood increases as frequency increases; the phenomenon becomes more evident at higher frequencies. As attenuation increases, the energy loss of the wave as it transverses the wood cross section becomes large. Balance must be struck between obtaining the best resolution possible while maintaining an observable level of signal energy. Today, ultrasonic inspection equipment exists with sufficient power for inspection of standing trees and poles, but this has not always been the case. Historically, because of power limitations of the inspection equipment, ultrasonic waves have more commonly been used for inspection of members with smaller cross sections such as rectangular members and engineered wood products. Standing trees and poles were more often inspected with higher power acoustic techniques using mechanical impacts as the signal source. Ultrasonic waves for testing are commonly produced by piezoelectric transducers that convert voltage to mechanical motion. Inspectors can purchase ultrasonic transducers with center frequencies between 20 kHz and up to the megahertz range.

Transducers may or may not require contact with the wood specimen. If contact is necessary, a coupling agent, known as couplant, is normally required. The couplant aids the transmission of the transducer pulses into the test specimen. The couplant used is chosen based upon inspection or test application. Common couplants include water, grease, glycerin gels, petroleum jelly, starch glucose, cellophane sheets, and silicone rubber, just to name a few. Care must be used when selecting a couplant, as they may be capable of corrupting the condition of the specimen (Bucur 2006). Pressure between transducers and the specimen must also be considered. In general, as the pressure between the source and specimen increases, the power transmission increases; however, there is a point of diminishing returns above which additional applied pressure yields little additional transmitted energy. Non-contact transducers use the medium surrounding the test specimen as the coupling agent. Air-coupled transducers, as the name implies, use surrounding air as the coupling agent. Immersion tests submerge transducers and specimen in a liquid that acts as the coupling agent.

Stress Waves in Wood

Wood in its natural form is often assumed to be a cylindrically orthotropic material with three principle directions: longitudinal along the tree length, radial from the exterior to the tree center, and tangential around the tree center circumferentially. Orthotropic materials have nine independent elastic constants: three Young's moduli, three shear moduli, and three Poisson's ratios (Hearmon 1961). For wood, an assumption of six independent Poisson's ratios rather than three has been found to more accurately represent wood structure (Bucur 2006).

Within an infinite solid medium are two types of waves, longitudinal and shear. Longitudinal waves have particle motion normal to the wave front and parallel to the direction of wave propagation. Shear waves have particle motion parallel to the wave front and normal to the direction of wave propagation. In an orthotropic material, each principle direction will have an associated longitudinal wave velocity and two shear wave velocities. The relationship between stress-wave velocity and material stiffness has been established through the equations of motion, Hooke's law, and Christoffel stiffness tensors (Hearmon 1961; Graff 1975; Bucur 2006). Derivation of the relationship can be found in many texts, including the two references provided and will not be repeated here. For a longitudinal stress waves traveling along a principle axes, the relationship can be expressed as

$$C_D = \rho V_L^2 \tag{1}$$

where
C_D is dynamic stiffness,
ρ density, and
V_L velocity of the longitudinal wave.

Similar relationships can be developed for shear waves (Bucur 2006). Stress-wave velocity, therefore, yields information about elastic constants of the material. In many analyses, velocity or the squared value of velocity is correlated to modulus of elasticity. Whereas modulus of elasticity and stiffness are related, it is important to remember that values are not interchangeable and that stiffness is influenced by the Poisson's ratio of the material. The description above characterizes bulk wave behavior. Wave velocity is affected by dimensions of the specimen. Wave motion through plates and rods require special consideration beyond the simple analysis given here and can be found in Hearmon (1961), Graff (1975), and Bucur (2006).

Energy storage and dissipation properties of wood and engineered wood products are controlled by the same mechanisms that dictate many of their physical and mechanical properties. For example, consider how the microscopic structure of clear wood affects its energy storage, loss properties, and mechanical behavior. Clear wood is a composite material composed of long microfibrils of cellulose and hemicellulose cemented together with lignin. At the microscopic level, energy storage properties are controlled by orientation of the microfibrils and their structural composition, factors that contribute to stiffness and strength. Energy storage properties are observable as frequency of oscillation in vibration or speed of sound transmission. Conversely, energy dissipation properties are controlled by internal friction characteristics, to which bonding behavior within and between microfibrils contribute significantly. Rate of decay of free vibration or wave attenuation are frequently used to observe energy dissipation properties of wood-based materials (Pellerin and Ross 2002).

Wave velocity and attenuation are directly related to material properties. As a result, they are often used for defect detection. Fungal decay, cracks, and voids are defects that can degrade the structure of wood, lessening its strength and toughness. Fungal-infected wood decreases wave velocity and increases signal attenuation. Waves traveling from a source to a receiver will have to travel around cracks and void lengthening their travel distances. Greater travel distances increase both travel time and signal attenuation. Sensitivity to internal defects makes wave velocity and attenuation useful and commonplace parameters when assessing wood. However, there are a myriad of parameters that researchers have used for condition assessment. The list of parameters includes but is not limited to spectral content, rise time, pulse count above a threshold, signal length, root mean square of signal energy, time centroid, frequency centroid, decay rate, peak amplitude, and peak frequency. Inspectors and researchers may use one or dozens within a single assessment and often create new parameters to correlate to particular phenomenon.

Table 1 contains several common analysis techniques that are applied to ultrasonic measurements and recorded signals obtained during testing. Descriptions of techniques and the mathematical expression for each are also given. The literature review that follows this section contains several examples where these and other analysis techniques are applied. The study ends with Table 2, which is a list of the tree species examined by studies in the literature review and associated bibliographic references.

Table 1—Data analysis techniques

Ultrasonic parameter	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.	$\mathrm{TOF} = \frac{t_2 - t_1}{l}$ where t_2 is arrival time, t_1 initiation time, and l 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.	$\mathrm{PL} = K\Delta t \int v(t)^2 \mathrm{d}t$ where K is a constant, Δt time required for received wave energy integral from 10% to 90% of its final value, v signal voltage as a function of time, and t time.
Insertion loss (IL)	Ratio of energy received, after transmission through material, to energy input.	$\mathrm{IL} = 10 \log \left(G \frac{E_\mathrm{r}}{E_\mathrm{t}} \right)$ where E_r is received energy, E_t transmitted energy, and G receiver gain.
Elastic constants determination	Relate longitudinal and shear wave velocities to Poisson's ratio and dynamic modulus of elasticity.	$C_\mathrm{D} = \rho V_\mathrm{L}^2 \quad G_\mathrm{D} = \rho V_\tau^2$ where μ is Poisson's ratio, V_L longitudinal wave velocity, V_τ shear wave velocity, ρ density, C_D dynamic stiffness, and G_D dynamic shear elastic modulus.

Ultrasonic Inspection Methods

Several types of ultrasonic inspection can be used. Presented here are summaries of basic one or two sensor methods. Many other methods use multiple sensors; for instance, in linear arrays (Bray and Stanley 1997) or oriented around the specimen at multiple locations (Divos and Divos 2005). Single sensor methods are often referred to as pulse-echo methods. Two sensor methods are often referred to as through transmission methods. The stress waves from the source may be either longitudinal or shear waves depending upon the source selected. The source may be oriented such that the pulse incident to the specimen surface is either normal or angled. Below are brief descriptions of pulse-echo, through-transmission, and angled beam techniques. For greater detail regarding ultrasonic inspection techniques, the reader is directed to Bray and Stanley (1997), Bucur (2002, 2006), and Divos and Divos (2005).

Pulse Echo Test Method

Figure 1 illustrates a typical normal oriented pulse echo test configuration. A pulse on one side of the specimen induces stress waves that travel through the cross section, as shown in Figure 1a. As previously mentioned, stress waves may be either longitudinal or shear waves depending upon the source selected. A common pulse source is a piezoelectric transducer with a center frequency and power selected by the user. The pulse is initiated from the same transducer used to sense returning waves. As shown in Figure 1c, waves created by the pulse strike the opposite side of the specimen and are reflected, or "echoed," back toward the transmitting sensor; hence the term pulse echo. Characteristics of waveforms observed are highly dependent upon the type of sensor used. Various types of sensors, including those that measure particle displacement, particle velocity, and particle acceleration can be used with this type of setup.

Defects such as splits and voids can also be detected in this manner. Incident waves are reflected from these defects as shown in Figure 1b. If reflected waves are reflected back to the transmitting/receiving sensor as shown in 1d, then the depth of the defect can be calculated using the known speed of the traveling wave. Orientation of the defect with respect to the direction of wave travel can greatly affect how well it is discerned. A wood split oriented perpendicular to the

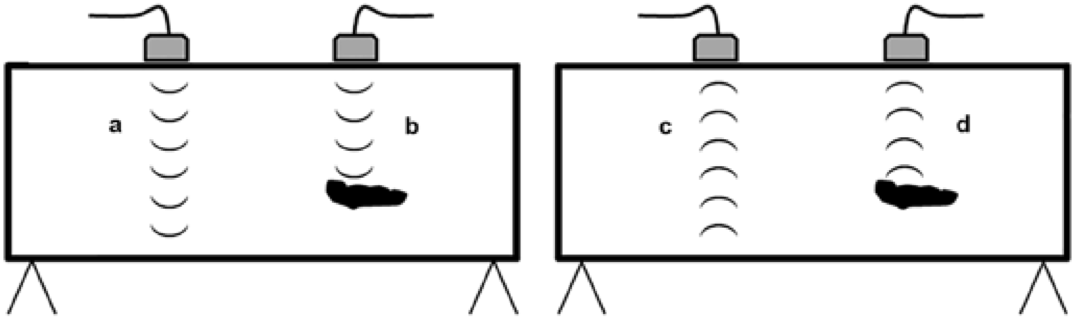

Figure 1. Typical pulse-echo test configuration using (a) clear path from transducer to opposite specimen edge, (b) defect is in the wave path, (c) wave reflects off opposite specimen edge and returns to the sensor, (d) wave reflects off the defect and returns to sensor.

wave travel path will reflect more wave energy than a split oriented parallel to the wave path. In a worst case inspection scenario, it is possible for a narrow split parallel to the wave path to be completely unobserved because of low defect reflectivity. A wave could travel on either side of a narrow split, reflect from the far edge of the specimen, and return to the transmitting/receiving sensor. In this case, the inspector may believe the specimen is completely free of defects. A more common case is a defect that is oriented at an angle to the wave path other than perpendicular (90°) or parallel (0°). In this case, some portion of the wave energy may be reflected away from the transmitting/receiving sensor. The inspector may be able to determine presence of the defect by a drop in magnitude in the received signal or a lack of an echo from the far edge of the specimen (Bray and Stanley 1997), or both.

Pulse echo method is convenient as only one side of the specimen needs be accessible for inspection. Also, if the wave speed through the specimen is known, depth of defects and thickness of specimen can be estimated from the travel time of the wave. Pulse echo does have some drawbacks. The pulse source must impart sufficient energy into the specimen such that an observable reflected signal is measureable. Wood is highly attenuating, and the traveling wave will need to be of sufficient magnitude to lose energy during two trips across the cross section and still be measureable at the end. If the transmitting and receiving transducer is one in the same, then ring down time must be considered. After the transducer pulses, the mechanical element requires a finite period of time to come to rest. This time is known as the ring down time. If the specimen is thin, the traveling wave can reflect from the far side of the specimen and return to the sensor before the mechanical element in the sensor has come to rest. In this case, the reflected signal will be contaminated by element motion still present from the initial pulse.

Through Transmission Test Method

Figure 2 illustrates a typical normal oriented through transmission test configuration. Like the pulse echo method, the signal source initiates a pulse that travels through the cross section of the specimen. As previously mentioned, stress waves may be either longitudinal or shear waves depending upon the source selected. Unlike the pulse echo method, a second separate sensor receives the signal and the source and receiving sensor are not co-located. For simplicity in this description, the source is a transducer of the same type as the receiving transducer; however, many different types of signal sources may be used. In Figure 2a, the source is on one side of the specimen and the receiver is directly across the specimen on the opposite side. This configuration is commonly known as through transmission. Because the waves need only travel across the specimen once, the power for the source signal can be lower than in pulse echo. This method reduces the probability of ring-down contamination as the receiving sensor was not in a state of motion prior to arrival of the wave. In Figure 2b, presence of a defect blocks the wave from the receiver. The defect may also redirect the wave energy around the defect that increases travel time between the source and receiver. Defects are detected by a loss of signal or an increase in time of flight; however, the depth of the defect is not known. One practical consideration of through transmission methods is that operating two sensors increases testing complexity and can increase complexity of analysis of results.

Angled Beam Methods

Figure 3 shows an alternative through transmission configuration. The transmitting source is tilted off normal to the specimen edge to direct the wave path at an angle to the cross section. Pulse-echo test configurations may also have an off-normal pulse direction. The incident wave reflects off of observable boundaries such as the opposite edge of the specimen or defects, and travels back towards the edge from which the wave originated. The reflecting wave arrives at a location away from the source and is observed with a second sensor. This method is capable of detecting defects that are oriented normal to the edges of the specimen. This method can require more power than the through transmission method, as the wave travel distances are often greater.

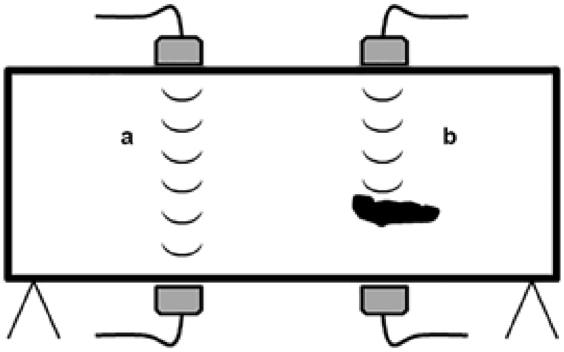

Figure 2. Typical through transmission test configuration: (a) clear specimen, (b) defect blocking the wave from the receiver.

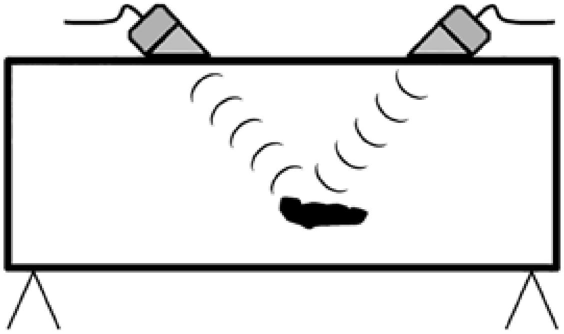

Figure 3. Angled through transmission test configuration.

A surface inspection can be performed by angling the source sensor to initiate a surface wave. This type of inspection is used to assess surface quality. The wave travels along the specimen surface and reflects off of near surface defects or sharp corners. Presence of surface waves in subsurface inspections has potential to cause spurious signals to be observed.

Literature Review

This literature review is divided into two subject areas: testing and analysis and inspection and assessment. Testing and analysis describes studies in which the process of testing using ultrasonic stress waves was the focus. Inspection and assessment describes studies that focus upon inspection of wood members or structures, determining their strength, and defect detection.

Testing and Analysis

There are several considerations when testing using ultrasonics. Beyond source, power, frequency, receiver, and coupling, other concerns include testing methodology, moisture content (MC), specimen geometry, and post-test analysis. The purpose of testing is also relevant; evaluating elastic properties of wood can involve testing protocols that are very different than those needed for inspection and assessment. This section describes how researchers have dealt with many of these issues.

The subsections address testing considerations, acoustic emission/acousto-ultasonics, MC, and determination of elastic constants of wood. The first subsection addresses testing considerations and focuses upon testing methodologies and post-test analyses. Moisture content of wood has great potential to change wood properties and affect ultrasonic results. Ultrasonic techniques are powerful tools when determining elastic constants of any material, including anisotropic materials such as wood. Acoustic emission is a testing method that uses stress waves emitted from the examined specimen. Acousto-ultrasonics assumes a source other than the specimen itself, but uses many of the same post-test analysis techniques.

Testing Considerations

Reliable and repeatable test results are only achieved when testing parameters are well suited for the testing conditions and specimen. Sensor placement, sensor coupling, resolution, specimen shape, and wood anisotropy are a few of the issues that must at be considered. Several researchers have examined the effect these conditions have upon the test results.

Anthony and Phillips (1991) refined the use of acousto-ultrasonic technique to evaluate fingerjoint strength through an examination of the test configuration. Advantages and disadvantages of various sensor locations were assessed. Broadband and narrowband excitation signals were compared. High frequencies of the broadband excitation were greatly attenuated. Narrowband excitation focused the signal energy in a narrow range, maximized the potential of high frequency signals to propagate through the wood. Several transducer types were studied with a variety of coupling agents. At the time of the study in 1991, Anthony and Phillips concluded that the ideal dry couplant for a manufacturing environment was compliant with respect to wood, had low creep properties, did not attenuate stress waves, and bonded easily to transducers. No such material was available at that time.

Hamstad and others (1993) explored farfield wideband acoustic wave behavior in wood rods and plates. Orientation of the waveform source and use of narrow band measurement systems were found to significantly affect the measured waveform. Potential to measure frequency dependence of material attenuation with a single waveband experiment was examined.

Relationship between wavelength and resolution and difficulties in visualizing data from acoustic microscopy were discussed in Bucur (1996).

Feeny and others (1996) examined how the frequency domain was affected by changes in wave speed through different types of wood within a tree. Speed through juvenile earlywood, juvenile latewood, adult earlywood, and adult latewood were measured. The goal of the research was to determine whether periodicity of wood caused stop bands within the frequency spectrum. Evidence of stop bands was found in Scots pine (*P. sylvestris* L.) but not spruce; however, wood variability and mode conversion made measurements difficult.

Berndt and others (2000) explored movement of wave energy through wood and noted that anisotropy had significant interaction with wave pulses. The experimental setup was constructed to primarily examine bulk waves. Phase shift was investigated as a tool to determine arrival time when high frequencies with attenuation are used. Mode conversion led to inaccuracies in energy measurements. The results strongly suggest that single path measurements were not advisable.

Bucur (2002) described three algorithms used for ultrasonic tomographic imaging: transform, iterative, and direct inversion.

Andrews (2002) examined the differences in measured wave velocity depending upon the method used and sensor location. Wave velocity of radiata pine (*Pinus radiata*) logs was measured end to end and incrementally along the length along the edge of the log. Wave speed measurements taken incrementally along the length of the log were highest, followed by time of flight end to end of the log, then followed by resonance methods. Time of flight was found to differ by as much as 6% depending upon source and receiver location. Resonance methods were not affected by sensor location on opposite sides of the log. Differences between wave velocity measured using resonance methods and end to end time of flight were expected to decrease with increasing length to diameter ratio.

Berdnt (2002) noted a stiffness gradient across tree trunks in specimens of white fir. Mature wood had a greater stiffness than juvenile wood.

He and others (2005) applied a series of filters to acoustic emission to increase the signal to noise ratio. Five different filters were applied to measurements collected from through transmission ultrasonic tests. Filters used included averaging, symmetrical moving average, two infinite impulse responses, and a filter created through fuzzy logic, which was the subject of the study.

In a 2005 study, Berndt and others developed phase slope methods to increase accuracy of time of flight measurements. The threshold method of measuring time of flight was affected by low amplitude or high attenuation. The phase slope method was effective at measuring thin wood samples. The phase slope method was also effective at separating multiple pulses within a single pulse.

Tjondro and Soryoatmono (2007) explored how specimen geometry affected elastic constant measurements. The assumption that MOE was the same as stiffness yielded an error of 6% in the longitudinal direction and up to 24% in the radial and tangential directions. Higher length to diameter ratios yielded higher estimates for longitudinal velocity. A square cross section for the specimen was found to yield the best results.

The effect of coupling media upon wave attenuation for longitudinal and transverse transducers was explored by Trinca and others (2009). A 100-kHz transducer was coupled to nine different species of Brazilian woods using six different coupling agents. Attenuation for each coupling was measured. To obtain consistent measurements, it was necessary to apply pressure to transducers.

Agrawal and Choudhari (2011) estimated the strength of wood using 22 measured NDE parameters. Signals collected using a through transmission test setup were subjected to FFT and the power spectral density was obtained. The model, known as IDSAM, was reported to yield strength estimates, which correlated to actual strength at a level higher than most other contemporary and previous studies.

Acoustic Emission/Acousto-Ultrasonics

In acoustic emission (AE), stress waves caused by a source within a structure are monitored. Internal sources of stress waves include, but are not limited to, microfractures, check formation, water movement, and pit aspiration. Several parameters are extracted from recorded waves, and the extracted parameters are then correlated to different phenomenon or properties inherent to the structure. Any number of parameters can be examined, including but not limited to, time of flight, peak voltage, time to peak voltage, stress-wave factor, root mean square voltage, number of threshold crosses, signal length, time centroid, frequency centroid, attenuation, etc. Acousto-ultrasonics (AU) uses many of the same post-test analysis techniques; however, the source is user-dictated such as a transducer.

The fundamentals of AE and AU were described in Beall (1987a). AE was not repeatable; AU was repeatable. AU relied on averaging several signals to minimize variability, and narrow band filters were used to improve signal-to-noise ratio. Attenuation of signals traveling through wood increased as frequency increased. Issues of coupling to wood-based material such as porosity and surface roughness were discussed. Pressure and couplant together minimized signal loss. A limited glossary of terms was included (Beall 1987a). In a follow-up paper, the future uses of AE/AU were discussed. Potential areas of use were laboratory testing, field testing, proof testing, online sensing, sensing adhesive integrity, sensing creep, fracture analysis, and drying defects (Beall 1987b).

Sandoz and others (2000) used AU variables in conjunction with stress-wave information to increase the reliability of strength grading. Parameters examinded included stress-wave factor, maximum peak, energy, and attenuation after first peak. MOE of glued-laminated beams was highly correlated to ultrasonic wave speed, whereas local defects had a significant effect upon MOR.

Kánnár (2000) examined the influence of moisture and temperature upon the Kaiser effect in Scots pine. The Kaiser effect is a phenomenon in which acoustic emissions are absent in a material for a load at or beneath previous loading levels. The Kaiser effect was observed in short-term experiments; however, the effect diminished as time elapsed. The Kaiser effect was observed 95% of the time if a second load was applied immediately, 60% if applied within 15 days, and 25% after two months.

Ballarin and others (2002) explored parameters that could be correlated to the physio-mechanical properties of clear wood. Douglas-fir, redwood, and spruce–pine–fir specimens were used. Time domain parameters exhibited more differences than frequency domain parameters.

In a follow-up study, Seeling (2002) examined additional parameters. The parameters included time of flight, maximum and minimum voltage, time to voltage maximum and minimum, root mean square voltage, total power, time and frequency centroid, stress-wave factor, and maximum frequency for the first quarter of the wave. Most of the AU parameters examined showed weak correlation to wood characteristics.

Moisture Content and Drying

Wood physical and mechanical properties are affected by MC of wood. Modulus of elasticity, wave speed, attenuation, and creep characteristic are just a few of the properties of wood affected by MC. Wave behavior through medium is dictated by properties of material. As properties change, wave propagation alters. Several researchers have explored how wave propagation changes as a function of MC with the goal of assessing and monitoring wood MC level.

Quarles and Zhou (1987) monitored the development of defects during drying using AE. The rate of acoustic emission events was correlated to drying conditions of California black oak (*Quercus kelloggii*) In addition, defects created during drying were related to the AE signals.

Groom (1991) examined the integrity of the truss-plate joint during moisture cycling using acousto-ultrasonics (AU). Signal energy was strongly correlated to the number of teeth of the plate and quality of the coupling between the teeth and the wood but was poorly correlated to the total coupling surface area. Presence of high frequencies in signals passing across the truss plate to the wood was indicative of sound joints. Weakened joints exhibited stronger low-frequency components.

Kawamoto (1993) used several AE parameters to predict the location of check formation during drying of Japanese red pine (*Pinus densiflora*). Low frequencies were associated with check growth. The number of checks in the location of the transducer was correlated to the AE count rate. Radial attenuation was an indicator of large check formation during drying. In a follow-up study, Kawamoto (1996) concluded that using only AE parameters for the detection of checking was imprecise.

Booker and others (1996) examined radiata pine (*P. radiata*) for variation in both sound velocity and dynamic MOE in three principle directions with changing MC. Velocity increased linearly as the MC decreased from fiber saturation point (FSP) to oven dry. The dynamic MOE had the lowest value at FSP, increasing both above and below. Below FSP, approximately 60% of the variation in MOE was attributed to wood shrinkage.

Schafer and others (1998) identified wetwood and honeycombing defects using TOF measurements. They concluded that wetwood increased viscoelastic damping in the wood and that honeycombing caused scattering of waves. Despite having different mechanisms, both types of defects decreased signal amplitude across the wood.

Booker and others (2000a) examined the timeframe of internal check development of radiata pine using AE. Internal checking occurred within the first 6 hours of drying. The maximum rate of checking occurred between 1.6 and 2 hours after drying began. This timeframe corresponded to within a half hour of the kiln reaching operating temperature. The number of AE events did not correlate to the number of internal checks.

Soma and others (2000) examined the effects of frozen moisture upon wave velocity in frozen cubes of Japanese cedar (Cryptomeria japonica). Wave velocity through the cubes was recorded in all three principle directions: longitudinal, radial, and tangential. Wave velocity through the frozen cube increased. The increase was most noticeable in the longitudinal, radial, and tangential directions for MC above 200%, 150%, and 150%, respectively.

Kang and Booker (2002) examined moisture gradient within radiata pine during kiln drying. The boards were weighed and the wave velocity was measured during the kiln-drying process. The velocity appeared to be both a function of MC and moisture gradient.

Miettinen and others (2005) made electrical and ultrasonic measurements of pine specimens. Measurements were correlated to MC, density, growth ring angle, hardness, and strength. A multivariable model accounted for a greater amount of the variability of parametric estimators such as density and MC.

A 2005 study by Rosner and Wimmer used acoustic emissions to monitor spruce trees during drying. The trees were debarked and dried. Mature trees were more susceptible to dehydration than juvenile wood. Juvenile wood had more AE events because of a higher number of tracheids per volume. High energy AE events were measured at the start of the drying process and were caused by the shrinking process.

Gonçalves and Costa (2005) performed a combined examination of ultrasonic wave velocity and stiffness on several Brazilian tree species. Stiffness terms decreased with increasing MC up to the FSP. Above the FSP, stiffness would sometimes increase with increasing MC. Stiffness values were partially corrected by accounting for mobility of free water in the wood. The MC had a greater effect upon wave velocity in the longitudinal direction than in the radial or tangential directions. Correlations were positive, but key supporting figures were absent.

In a later study (Rosner 2011), explored reversible and irreversible effects of drying upon spruce were explored using acoustic emission. Specimens were dried and then rewetted in successive cycles. During the first drying, the highest peak amplitudes were associated with moderate moisture loss. After rewetting, the highest peak amplitudes occurred near the end of the drying cycle. Wood that had never been dried had a higher rate of AE events below 175 kHz. Earlywood appeared more sensitive to irreversible changes during drying than latewood.

In a 2011 study, van der Beek and Tiitta (2011) monitored the drying process of spruce using AE. One goal of the research was to discriminate between AE events caused by crack formation and propagation and those caused by water movement. The cool down and moisture conditioning phases of drying were most critical in crack formation.

Gao and others (2011) examined the combined effects of temperature and MC on specimens of red pine. Specimens were conditioned to four different MC levels: green, 24%, 12%, and 0%. Wave velocity and energy loss through the specimens was measured over a range of temperatures from –45 °C to 35 °C. The MC had a significant effect upon the relationship between velocity and temperature. When green wood was well above freezing, temperature had little effect upon wave velocity. When green wood was near freezing, energy loss and wave velocity changed abruptly because of the phase change of water held in the cell lumens. As MC decreased, change near freezing became less pronounced.

In subsequent research from many of the same authors, the combined effects of temperature and MC upon modulus of elasticity was examined. Dynamic and static bending tests were performed upon specimens of red pine. Similar to velocity and energy loss, green wood had abrupt changes in MOE near freezing. As MC decreased, the change near freezing became less pronounced (Gao and others 2013).

In a similar study conducted by Llana and others (2013), the combined effects of temperature and MC upon MOE and ultrasonic velocity were examined on Scots pine. Between 10% and 18% MC, the effects of MC were close to linear. Trends above and below 0 °C were different from each other.

Dunbar and others (2013) used ultrasound to predict dimensional stability of sweet chestnut (*Castanea sativa*) and sessile oak (*Quercus petraea*). Wood samples were below the FSP. Wave velocity in the woods decreased as MC increased. Specific gravity alone was a poor predictor of wood shrinkage; ultrasonic velocity alone was a good predictor. The combination of both parameters produced the best predictor, explaining 72% and 77% of shrinkage in oak and chestnut, respectively.

Determination of Wood Elastic Constants and Properties

Ultrasound has been used in a variety of ways to quantify elastic constants of wood. The relationship between stress-wave velocity, density, and stiffness make it a powerful experimental tool.

An early property assessment study used vibrations and high frequency waves to explore the theoretical relationship between wave velocity, density, and stiffness (Hearmon 1965).

Bucur (1978) correlated changes in velocity to stress levels in wood. Stress was normalized by the rupture stress. Normalized values were between zero and one. Four stress levels were identified and correlated to physical phenomenon: 0.2, 0.2 to 0.7, 0.7 to 0.9, and 0.9 and above. In the first zone, velocity values increased. In the second zone, velocity was close to constant. The third and fourth were both characterized by a decreasing slope, but the slopes are different from each other.

Ross and Pellerin (1988) reported on use of acoustic techniques for assessing mechanical properties of a wide range of wood composite materials. They obtained excellent correlative relationships between acoustic parameters and mechanical properties.

Bucur (1996) discussed methods by which three different wave techniques were used to obtain material constants. Vibratory, acoustic, and ultrasound techniques were described, and an explanation of the theoretical foundation of the relating wave velocity and elastic constants was given.

The complex modulus of anisotropic materials, such as wood, was derived by Navi (1996). Navi noted that the inhomogeneity and viscosity of wood causes both dispersion and attenuation in waves traveling through the material. A dispersion relationship was developed by measuring the phase velocity by frequency. Attenuation was measured by frequency as well. Together, these properties were used to develop the complex modulus for anisotropic materials.

de Oliveira and others (2002) measured static and dynamic MOE of loblolly pine. Like many similar tests, dynamic MOE was approximately 20% higher than the static, and good correlation existed between the two MOE values.

Bucur and Berndt (2002) calculated nine elastic constants of an orthotropic material, which wood is often considered to be, using wave velocity and energy flux deviation. Six of the nine constants were calculated using longitudinal and shear wave velocity measurements. The six terms were along the diagonal of the stiffness matrix; the three remaining terms were off of the diagonal. Accuracy of the calculated value of three off-diagonal terms was greatly increased if considerations were made for energy flux.

Karlinasari and others (2009) calculated the MOE of two tropical species, mangium (*Acacia mangium*) and jackfruit (*Artocarpus heterophyllus*) using three different methods: dynamic method using ultrasonic velocity, static bending, and a mechanical grader. Each MOE was correlated to MOR. The best correlation existed between static MOE and MOR, with dynamic MOE second best; however, overall, the correlation between dynamic MOE and MOR was low.

Baradit and Niemz (2011) investigated mechanical properties of four Chilean species of wood using ultrasonic measurements. Longitudinal and transverse waves were used to determine MOE in three primary directions as well as the three shear moduli. Four hardwoods species: tepa, olivillo, laurel, and lenga, and two softwood species, alerce and manio, were tested. Hardwoods tested were found to have higher anisotropy than softwoods.

Grimberg and others (2011) determined the elastic tensors of wood plates using the phase velocity of lamb waves. Both symmetric and antisymmetric modes were employed in the calculation process. Good agreement was found between calculated values and the destructive tests. Wood plates were made of sycamore, alder, cherry, beech, and pine. Air-coupled transducers were employed to determine several elastic constants.

Wood specimens of three distinct shapes were tested ultrasonically by Gonçalves and others (2011) to obtain elastic constant data. The shapes were a 26-sided polyhedron, a multifaceted disk, and cubic prisms. Three species were tested: eucalipto, garapeira, and cupiúba. Cubic prisms were cut at specific angles to the wood grain. The prisms produced the best correlation to elastic constant values obtained from static test; however, prism specimens themselves were used for static tests after ultrasonic testing was concluded. The multifaceted disc and the polyhedron exhibited the second and third highest correlation to the static tests, respectively. Poisson's ratios proved harder to correlate with static results with some matching across all shapes and some diverging for all shapes.

In two related studies, Inés and others (2011) and Palacios and others (2011) used 30 wood species to develop correlations between MOE static bending, MOE from resonant frequency, MOE from ultrasound velocity, MOR, and specimen density. The high number of species represented made this study unique. Specimens were grouped according to density. Strong agreement existed between the MOE from ultrasonic velocity and MOR.

In a follow-up study to Gonçalves and others (2011), Vázquez and others (2013) extracted samples from 13 specimens of *Castanea sativa* and shaped them into 26-faced polyhedrons. Ultrasonic time of flight measurements for longitudinal and shear waves were used to estimate elastic constants of the polyhedron. Prisms were extracted from the specimens and used in compression tests to obtain the same elastic constants. No significant difference was found between the elastic constant values obtained using the two methods.

The acoustoelasticity of three wood species, *Eucalyptus citriodora*, *E. grandis*, and *E. pellita*, was explored by Bertoldo and others (2013). Specimens were subjected to bending tests and strain was measured using extensometers. Wave speeds longitudinal and transverse to the wood grain were measured. Longitudinal wave velocity tended to decrease as strain increased regardless of whether the strain was compressive or tensile in nature. Longitudinal wave speed was more affected by presence of strain than transverse traveling waves. Waves traveling in the radial or tangential direction during the bending test exhibited differing behaviors depending upon whether the specimen was a hardwood or softwood. Velocity increased with increasing strain for hardwoods and decreased for increasing strain for softwoods.

Inspection and Assessment

The purpose of ultrasonic inspections is to assess the condition of a member or structure. The condition assessment allows the inspector to decide whether or not the current condition is sufficient for the member or structure to perform its function safely and reliably. Internal defects can have a significant and deleterious effect on member strength. Therefore, a reliable assessment can be made if the inspection process can detect defects. The studies in this section focus upon defect detection and strength assessment using ultrasonic inspection. The literature review begins with studies involving inspection of wood in its least refined state, standing trees. Subsequent sections will focus upon inspection methods on increasingly processed wood products: round members, sawn lumber, and engineered wood products. Inspection of structures and artifacts follows.

Standing Trees

Modern ultrasonic equipment is capable of generating sufficient signal energy to perform inspection and assessment of standing trees and poles, and its use in that area has noticeably increased in the last decade. Historically, ultrasonic inspection of standing trees was not as common as acoustic stress-wave inspection. Acoustic stress waves were more commonly used to inspect standing trees and round members such as logs, poles, and piles. Acoustic stress waves have frequencies below 20 kHz and are often caused by an external impact. Impacts from hammers, pendulums, and BBs have greater signal energy than that produced using piezoelectric transducers. Also, low frequencies attenuate more slowly than high frequencies and can therefore travel farther in wood. As a result, signals from impacts had a greater probability of being sensed across the diameter of full-sized trees. Acoustic stress-wave inspection is not covered in this paper. With technological improvements, use of ultrasonic inspection of standing trees is becoming more widespread.

Huang (2000) used ultrasonic wave propagation through the outer wood of standing trees to predict lumber stiffness of loblolly pine. Wave velocity measurements were taken radially at 50 and 150 cm above the ground on standing trees. Speeds were correlated to modulus of elasticity (MOE) in an effort to determine the quality of stands of trees prior to harvesting. Huang (2000) found that trees with large percentages of corewood had higher radial wave velocity.

In a 2009 study, Najafi and others inspected a group of 112 Iranian birch trees for internal decay. Wave velocity was measured parallel and perpendicular to the slope of the grain. Trees were felled and cross sections were compared to inspection results. The study found that of the trees containing defect, 95% were detectable. When defects did occur in birch trees, they were usually around the pith. Because of the mountainous nature of the region in which the study took place, many trees contained reaction wood, causing eccentricities in the cross sections. Eccentricities could cause velocity measurements taken perpendicular to the grain to miss the decayed pith regions.

Pedroso and others (2011) measured the longitudinal ultrasonic velocity of a group of 210 Brazilian trees including the species *Eucalyptus grandis*, *Pinus elliottii*, and *Toona ciliata*. The measurements were taken vertically along the trunk above and below breast height. The trees were felled, cut into logs, and ultrasonic velocity through the logs was measured. Whereas it was possible to correlate velocity values between logs and trees, a nonlinear relationship existed because of differences in the manner in which waves traveled through each.

In a 2011 study, Brancheriau and others (2011) constructed an automatic ultrasonic inspection system mounted on a track around a standing tree. Initially, a 300-kHz transducer was used as a source, but attenuation through the tree was too great. An 80-kHz transducer was then used. Resolution provided by the lower frequency transducer was 17.7 mm longitudinally and 36.4 mm lateral to the tree. Radial wave velocity measurements were used to construct a tomographic view of an eastern cottonwood (*Populus deltoides*).

The effect of pruning upon a variety of loblolly pine was examined in eastern Argentina. Fassola and others (2011) found that trees without pruning had higher wave speeds. The trend continued when trees were cut into logs.

Several tree species in Bogor City, Indonesia, were examined (Karlinasari and others 2011). The focus of the study was evaluating trees in an urban environment. Tree species included *Swietenia* sp., *Pterocarpus indicus*, *Bauhinia purpurea*, *Mimusops elengi*, and *Agathis alba*. Trees were selected for radial ultrasonic testing based upon visual inspection. Sound, decayed, and questionable trees were selected. The velocity values were compared with results of the visual inspections, and a tree soundness criterion was developed based upon ultrasonic velocity. Trees with velocities above 1600 m/s were assumed to be good; decayed trees had velocities less than 500 m/s.

Song and others (2011) correlated radial ultrasonic and acoustic stress-wave velocities for the tree species *Populus simonii*, *Ulmus pumila*, *Salix matsudana* Koidz, and *Fraxinus mandshurica*. Good agreement was found between the two measurement methods in standing trees, although ultrasonic velocities were higher than acoustic velocities.

In a 2011 study by Yoza and Mallque, tangential and radial measurements were taken on *Cedrelinga cateniformis* Ducke. Elastic constants were determined using two ultrasonic frequencies, 23 kHz and 45 kHz.

Karlinasari and others (2013) used ultrasound inspection to determine if a commercially important fungus, known as agarwood, was present in standing *Aquilaria microcarpa* trees. Karlinasari and others (2013) found that radial ultrasound velocities less than 1000 m/s were indicative of agarwood.

Ultrasonic cross-sectional tomographs formed from radial and tangential wave velocity measurements were found in a 2013 study by Lino and others to be sensitive to the degree of irregularity (non-round) trees. Wave paths in irregularly shaped trees were complex and difficult to determine. Exterior digital tomographic profiles of the trees were obtained using triangulated laser measurements. The digital profiles were used to supplement ultrasonic measurements to make a more accurate ultrasonic tomograph.

Round Members

Round members include logs, poles, and piles. In round members, the orthotropic structure of the original tree remains largely intact. Historically, acoustic stress-wave inspection was generally favored over ultrasonic inspection for round members. The size of round members was such that the greater power and lower attenuation of acoustic stress-wave inspection yielded more easily observed signals. An example of the differences between acoustic stress-wave and ultrasonic inspection can be found in Booker and others (2000b). In that study, radiata pine logs were examined with several ultrasonic and acoustic measuring devices. This study found that ultrasonic devices were unsuitable because of the low power of their signals. The final evaluations were made with the acoustic devices only. Modern ultrasonic equipment produces greater signal power than those of past devices. Advancements in technology have overcome previous limitations, and use of ultrasonic techniques in inspection and assessment of round members, like standing trees, has increased in the last decade.

Strength and Grading

Log grading and strength characterization are important to the commercial value of logs. The ability to grade wood while it is still a standing tree or a log aids in obtaining the highest quality yields from each piece of wood and minimizes waste. Several papers have been written about log grading and characterization. Sandoz (1996) developed a transducer that was driven through the bark to the wood, eliminating the need for a couplant. Longitudinal wave speeds of logs were used for log grading and estimating performance of lumber made from the logs.

In a 1996 study, Curtu and others evaluated Romanian beech trees at three different levels: bottom, middle, and top. This study found variations in the wave speeds depending upon stress in the wood. Wave speeds decreased from base to canopy. In addition, the wave speed of logs cut from the trees was different than the wave speed of lumber cut from the logs.

Hauffe and Mahler (2000) compared the capability of two inspection methods for estimating log strength. They used x-ray inspection and ultrasound to evaluate 225 spruce logs. Ultrasound was found to be superior to x-rays in log strength estimation.

In a 2005 study, Yin and others estimated MOE of Chinese fir logs using ultrasound, stress wave, and vibration methods. Correlations were drawn between static MOE and modulus of rupture (MOR). The MOE based upon vibration methods had the best correlation. Between the top and bottom of the trees, the variation of MOE was significant, whereas the variation of MOR was insignificant.

In a related study, Gonçalves and others (2009) evaluated *Eucaliptus citriodora* poles using both ultrasonic and static tests. The static tests were carried out in accordance with ASTM D1036/1999 and NBR 6231/1980 specifications. The research goal was to evaluate the variability between new poles and suppliers and establish a nondestructive method of grading. The researchers found that ultrasound assessment allowed poles to be sorted by strength and suppliers to be sorted by quality.

Turpening (2011) constructed high frequency ultrasonic tomographs using densely spaced transducers positioned around a log. The images produced showed a high correlation with sandalwood oil, an important commercial derivative of sandalwood trees.

In 2013, Freitas and others evaluated deteriorated Brazilian utility poles for reuse in other capacities after they were removed from use. *Eucalyptus citriodora* and *E. saligna* poles were inspected using ultrasound. The research showed ultrasonic inspection can be used to determine which poles can be reused and which ones must be discarded.

Defect Detection

Abbott and Elcock (1987) inspected poles in Europe using a 40-kHz transducer. Signal attenuation was examined as an indicator of internal rot. The proposed procedure required multiple tests around the circumference of the pole.

A more recent study by Han and Birkeland (1991) used three ultrasonic techniques to evaluate logs: pulse echo, through-transmission, and grain sounding trace. Correlations were drawn between test results, and an attempt was made to use artificial intelligence to improve automated defect detection.

Lemaster and others (1993) examined the sensitivity of acousto-ultrasonic parameters in detecting holes in Douglas-fir utility poles. Three pole conditions were studied: lightly checked, heavily checked, and creosote treated. Several parameters were pulled from the signal data to evaluate sensitivity. Parameters that showed sensitivity to the presence of holes included transit time, centroid time, centroid frequency, and velocity. The technique detected holes 50 mm or larger in a 300-mm diameter pole.

A group of six sensors was employed by Dill-Langer and others (2002) along with acoustic emission techniques to identify and locate defects within a European spruce (*Picea abies*) wooden pole. Approximately 90% of the source locations were identified to an accuracy of ±7% of the transverse dimension and ±4.4% of the longitudinal dimension. Although failure locations were identified, the method did not permit prediction of failure location.

Divos and Divos (2005) explored the resolution of acoustic tomography to determine the dimension of the smallest detectable defect. Artificial defects were created within discs of larch. Defect sizes ranged from 10 mm to 100 mm. The number of sensors used to construct a tomograph of the cross section was varied from 6 to 30. The 10-mm defect was not detected using 30 sensors; a 25-mm defect was detected. In another study of detecting voids in cross sections, holes of different shapes, circular versus slots, were manually created in large wood discs. Wave velocity decreased linearly with the size of the hole, but slots had a greater adverse effect.

In the Najafi and others (2007) study on beech trees, the location of the hole had no influence on the wave velocity. The potential to detect the presence of tension wood using ultrasonic inspection was confirmed.

Yang and others (2007) measured the radial and longitudinal wave velocities in Eucalyptus globulus discs. Longitudinal velocity was found to be higher in areas of tension wood, but radial velocity was lower.

A portable ultrasonic CT device was developed by Kim and others (2007) to detect decay in wood poles. The devices created tomographs that were capable of detecting decay regions with less than 10% mass loss and less than 30% loss in strength.

Gonçalves and others (2011) examined the presence of artificial holes in wood cross sections composed of Pequía (*Aspidosperma desmanthum*). Tomographic images were created, but the image shapes of the holes were distorted.

In another void analysis, Wang and others (2013) constructed wave time of flight isolines along the surface of a Korean birch (*Betula costata*) log. Cavities of varying diameters were created within the log. The study examined how waves traveled through the cross section. The accuracy of the simulated reconstructions was able to identify the smallest defect, 40 mm, with an 83% accuracy. The accuracy improved as the hole size increased.

Oh and others (2013) used signal attenuation to detect small holes in round red pine members. The holes were used to simulate insect damage to the poles. A through transmission setup was used to collect data with varying levels of contact pressure on the transducers. A spectral analysis was carried out on the data. The results indicate that spectral analysis had great potential in locating insect damage.

Sawn Lumber

Sawn lumber has been cut from trees into rectangular cross sections. The dimensions of the cross section are typically smaller than those of round members and standing trees. The sawn lumber review is broken into two subsections, strength and grading and defect detection.

Strength and Grading

Like log grading, grading sawn lumber is important for its commercial value. Ultrasonic inspection has been used in a variety of applications to grade sawn lumber. Joint assessment has been included in this section as it directly relates to strength of the final member. In an effort to improve grading beyond what could be assessed visually, Sandoz (1991) measured ultrasonic wave velocity in spruce and fir beams. The ultrasonic longitudinal wave speed was correlated to the values of MOR and MOE. Moisture content and temperature were taken into account in the calculations.

Anthony and Phillips (1993) conducted a study in which the original finger joint paper was expanded with an examination of the sensors and the sensor coupling to the board. The signal from air-coupled transducers was found to lack the power necessary for use in tests. The signal from wheel sensors varied as the wheel turned, causing unacceptable inconsistencies. Coupling materials were limited to those that could be used in a manufacturing environment. Silicone rubber sheets and moldable urethane were examined and their relative advantages and disadvantages were discussed. Sensor placement was moved from the narrow edge of the boards to the wide face.

In a 2000 study of timbers, Duju and others applied six methods of measuring MOE to five different timber species of Malaysian wood: *Parashorea macrophlla*, *Gonystylus bancanus*, *Shorea albida*, *Dipterocarpus rigidus*, and *Cotylelobium burcki*. One MOE measurement method relied upon ultrasonic wave velocity. Good correlation was found between the calculated MOE and the values of MOR.

Another study (Diebold and others 2000) examined several methods of grading for hardwood and softwood. Softwoods examined included spruce, pine, larch, and Douglas-fir. Hardwoods included oak and beech. Testing methods included bending tests, x-ray, transverse vibration, and ultrasonic inspection. Of the methods used, ultrasonic inspection had the lowest correlation to bending strength.

In a similar study, visual grading and MOE estimated from the ultrasonic wave velocity were correlated to the bending strength. Kuklik and Kuklikova (2000) found that in the majority of cases, knottiness of the board was the decisive visual grading criteria.

Sasaki and Hasegawa (2000) examined changes in shear velocity with applied stress in Japanese magnolia (*Magnolia obovata* Thunb.). Compressive loading caused a reduction in shear velocity; tensile loads caused increases. The changes in shear velocity were less than 1%.

Gonçalves and Bartholomeu (2002) examined MOR and MOE for boards harvested at different heights within a Cupiúba (*Goupia glabra*) tree. MOR and MOE were highest in boards harvested near the base of the tree. The MOR and MOE were found to be weakly correlated; however, the MOE was found to be capable of reliably evaluating rigidity properties.

In 2002, Machado created a profile of bending strength using boards of maritime pine. Ultrasonic signals were applied to the boards perpendicular to the grain. Acousto-ultrasonic parameters were extracted from the signals and used to estimate modulus of elasticity through correlated relationships established by the author in a previous work. Bending tests were then performed along the length of the same boards. The results of the bending tests were correlated to modulus of elasticity values estimated using the acousto-ultrasonic parameters. The results showed that a lengthwise bending strength profile could be created using acousto-ultrasonic parameters.

While using timber grading, Sandoz and Benoit (2002) developed a relationship between the pair of parameters wave speed and transmitted energy and the properties of MOE and MOR. Empirical equations expressing the relationships were given. Energy damping of the wave was found to be directly dependent upon local singularities such as knots, decay, and grain angle.

Plinke (2005) proposed a finger joint inspection method in which high powered ultrasonic waves would generate friction at the joint and could be observed using infrared cameras. The method would be effective at defect detection, but not strength estimation.

Terezo and others (2005) tested two different species of Brazilian woods, Peroba (*Aspidosperma pirycollum*) and Angelim (*Hymenolobium petraeum*), using two commercially available ultrasonic tools to obtain estimates of the wave velocity. The correlation between MOE and wave velocity was lower than for most similar studies. Conversely, the correlation between wave velocity and MOR was higher than most similar studies.

Bartholomeu and Gonçalves (2007) examined the correlation between ultrasonic wave speed and MOE obtained from static bending. The six species were *Eucalyptus citriodora*, *E. grandis*, *E. saligna*, Cupiuba (*Goupia glabra*), Angelim araroba (*Votaireopsis araroba*), and *Pinus elliottii*. High correlation was found.

Iñiguez and others (2007) related changes in ultrasonic wave velocity to specimen length. The studies were conducted on Scots pine. For each meter of wood traveled, the wave velocity decreased approximately 83 m/s. The test was conducted to propose velocity adjustments during timber assessment.

Karlinasari and others (2007) examined the correlation between the dynamic modulus determined from ultrasound and the static modulus for Jeunjing (*Paraserianthes falcataria*).

Mechanical properties of three European species, radiata pine (*P. radiata* D. Don.), Scots pine (*P. sylvestris* L.), and Laricio pine (*P. nigra* Am. Ssp. salzmannii), were evaluated by Iñiguez and others (2009) using ultrasonic wave velocity perpendicular and parallel to the grain of the wood. Empirical relationships were constructed relating the wave speed to MOE and MOR; however, correlation values were low for ultrasonic values.

Yin and others (2009) investigated the feasibility of using ultrasonic wave velocities to estimate compressive and tensile strength of structural lumber composed of Larch (*Larix gmelini*). The author determines that lumber strength can be estimated from ultrasonic wave velocity, but correlation between the values is low.

Massak and others (2009) examined the influence of tree age on wave velocity and MOE. Beams were cut from *P. elliottii* trees of various ages ranging from 8 to 23 years. Both longitudinal velocity and MOE increased with age up to approximately 20 years. There were two groups of variation based upon age, 13 years and below, and 15 years and above. Rigidity properties would increase with age, but eventually become constant.

In a 2011 study, Pires and others estimated the MOE of eight Brazilian species using stress wave, transverse vibration, and ultrasound and then correlated to MOE determined from static bending tests. The species were *Pouteria guianensis*, *P. pachycharpa*, *Holopyxidium jarana*, *Vatairea sericea*, *Chrysophyllum venezuelanense*, *Astronium lecontei*, *Endopleura uchi,* and *Lecythis Pisonis*. Ultrasound and stress-wave inspection were similarly correlated with respect to MOE. None of the testing methods correlated to density.

Rohanová and others (2011) studied Slovakian spruce (*Picea abies*) and found that ultrasonic-based strength estimates for this species were higher than those estimated using the European standard EN 408.

Iñiguez-Gonzalez and others (2013) presented preliminary work for use of nondestructive techniques to evaluate properties of sawn lumber. The goal was to establish common procedures to be used. The species examined included several Spanish species: Scots pine, laricio pine, radiata pine, maritime pine (*Pinus pinaster* Ait.) and sweet chestnut (*Castanea sativa* Mill.).

A 2013 study by Ferreira and others investigated the adequacy of Brazilian standards for grading wood using ultrasonic inspection by testing the predicted compressive and tensile stiffness and loading on *Eucalyptus grandis* boards. The results largely supported the standards on compressive loading and stiffness. The study raised concerns about tensile loading and stiffness as outlined by the standard.

Hermoso and others (2013) examined a combined visual grading and ultrasonic grading technique using 116 Scots pine boards. Boards were accepted or rejected using three methods, visual grading, ultrasonic grading, and a combined method. Boards accepted using ultrasonic inspection had a higher modulus of elasticity and higher modulus of rupture than the rejected boards. The boards accepted using visual grading had higher MOE than the rejected boards, but the rejected boards had a higher modulus of rupture. Also, the mean MOE of the visually graded boards was higher than that of the ultrasonically graded boards. The combined visual–ultrasonic grading increased the MOE of the accepted boards over the ultrasonic method alone by 0.5%. and decreased the modulus of rupture by 1.3%.

Another study (van Dijk and others 2013) examined the degree of mode conversion of ultrasonic waves traveling through wood. A 7-m beam composed of Cabreúva (*Myrocarpus frondosus*) was used as the medium to observe traveling waves. Three frequencies were used for the tests: 25 kHz, 45 kHz, and 80 kHz. The receiving transducer was placed every 100 mm along the length of beam with its face parallel to the longitudinal axis. Two source transducer orientations were explored, direct, with the transducer directing wave energy along the longitudinal axis, and indirect, with the transducer directing wave energy perpendicular to the longitudinal axis. When the measurements were taken at a distance greater than five wavelengths, the velocities from both types of measurements were equivalent for all transducers. The degree of dispersion increased as the transducer frequency increased.

Defect Detection

In one early paper (Lee 1965), the possibility of using ultrasonic inspection as a safety measure was explored. Differences in wave speeds as a function of the wave angle to the grain orientation were examined. The possibility of detecting delamination as a function of amplitude and wave velocity was discussed. Energy reflection based upon the size of the reflecting defect was calculated.

An early paper in ultrasonic inspection (McDonald 1978) put a board in a fluid tank. McDonald sent signals through the specimen and recorded the time of flight (TOF). A good correlation between the TOF and defect location was observed. Also, a strong relationship between grain direction and the velocity of sound was noted.

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. They used small, clear Southern Pine specimens in a laboratory study designed to examine the effect of brown-rot decay fungi and termite attack on acoustic velocity and static strength. Time-of-flight measurements, parallel to the fiber axis, were made using a through transmission system on specimens after various exposure times. The researchers observed a considerable change in acoustic time of flight with exposure time. More importantly, they were able to make several conclusions. Changes in time of flight occurred well before measureable loss of either weight loss (density) or strength was observed. A significant correlation was observed between residual strength and acoustic time of flight. Time of flight measurements parallel to the fiber axis were not useful for monitoring changes in corresponding strength for termite attack because of their preferential consumption of the early wood sections of the specimens.

Hamm and Lam (1987) used transit times of waves traveling longitudinally as a metric for locating compression wood in western hemlock. Moisture content, grain angle, thickness, knots, and wane complicated the transit time measurement. Transit time uniformity along the board was used to eliminate the effects of knots and wanes. Moisture content and thickness did not completely mask the presence of compression wood. Grain angle was a factor that still affected compression wood identification.

In a 1987 study, Patton-Mallory and others used acousto-ultrasonics to determine the presence of brown rot in Southern Pine. Coupling the sensors to the wood proved difficult. Hot melt adhesives produced the most repeatable results. Time centroid and peak time were the most repeatable waveform parameters.

Hamm and Lum (1991) explored the feasibility of using ultrasound as an online tool to identify compression wood. A slope of grain indicator was also investigated using western hemlock, but its accuracy was insufficient for compression wood identification.

DeGroot and others (1994, 1995, 1998) reported both energy storage and loss parameters for monitoring the deterioration of clear wood when exposed to natural populations of decay fungi and subterranean termites.

Ross and others (1994) used a pulse echo test setup to measure speed of sound transmission and wave attenuation, parallel to the fiber axis, in small clear Southern Pine specimens in field exposure conditions.

In studies in 1996 and 1997, Ross and others also developed empirical models that used both parameters capable of predicting residual compressive strength with a high level of accuracy.

Ross and DeGroot (1998) reported on a test setup they developed to monitor deterioration in full-size lumber specimens that were exposed, above ground, to naturally occurring decay fungi. The setup was based on a through transmission concept, with rolling ultrasonic transducers used to transmit and receive the pulse, perpendicular to the fiber axis. Time of flight was measured with a commercially available timing unit. The specimens used in this study were completely free of natural defects. Consequently, changes in acoustic parameters after exposure were solely attributed to deterioration resulting from decay fungi.

Niemz and Kucera (1998) examined the ability of ultrasound to detect defects using small holes drilled into Norway spruce specimens. Holes were varied in both size and orientation. Small defects were difficult to discern because of wood variability. The influence frequency upon of wave speed was also studied. This study modeled velocity of waves traveling at angles across the wood grain using the Hankison equation.

Dolwin and others (2000) used both stress-wave and ultrasonic inspection to detect decay in cross sections of English oak (*Quercus robur* L.) and European beech (*Fagus sylvatica* L.). Cubes of wood were inoculated with white-rot, brown-rot, or soft-rot. The wave speeds were measured using ultrasonic and acoustic stress waves. The slowing effect that rot had upon waves was more noticeable in acoustic waves than in ultrasonic waves.

Brashaw and others (2000) used ultrasound conjunction with gas chromatography mass spectroscopy to identify wetwood in red oak lumber. The study also identified a relationship between the level of wetwood and energy-based ultrasound parameters.

Ross and others (2001) examined the relationship between time of flight (TOF) measurements made perpendicular to the fiber axis of large timbers that had been in service and their residual strength in compression (both parallel and perpendicular to fiber axis). Noting that the sample size they used was very small, they observed a strong relationship between TOF and compression strength.

Kabir and Araman (2002) examined several parameters derived from ultrasonic signals recorded during inspection of wooden pallets. Signal amplitude was decreased in the presence of defects. The severity and types of the defects correlated to the degree of dispersion of the power spectrum. Energy loss parameters were more sensitive to defects than time of flight measurements.

Schubert and others (2005) used resonant ultrasonic spectroscopy to determine the shear modulus of decayed and sound specimens of Norway spruce. The specimens were excited using ultrasonic transducers and displacement at the faces were measured using laser interferometers. The natural frequencies of the specimens were determined from the displacement response measurements. The reduction in shear modulus was six to ten times larger than the density loss from fungal decay. The shear velocity and damping were calculated at different stages of fungal rot.

Hasenstab and others (2005) used echo technique to detect local defects. Measurements were taken transverse and parallel to the grain. The echo technique only required access to one side of the inspected specimen.

The sensitivity of different MOE calculation methods to the presence of holes in a beam was explored in 2005 by Castellanos and others. Several 50-mm holes were drilled in beams of *Cryptomeria japonica* (Japanese Sugi). The MOE of the boards were then determined using four different methods. The four MOE calculation methods, ordered by increased sensitivity, were static bending, ultrasonic, acoustic stress wave, and longitudinal vibration.

Schubert and others (2006) used modal analysis and ultrasonic inspection to determine the change in shear modulus of Norway spruce upon exposure to white-rot fungus (*Heterobasidion annosium* and *Ganoderma lipsiense*). During the 12 weeks of exposure, *H. annosium* induced a 10% and *G. lipsiense* a 50% reduction in shear modulus.

Lin and others (2007) examined the degradation of railroad ties that had been taken out of service after 20 years. The goal of this research was to evaluate the possibility of reusing ties in the same or other applications. Hence, the ties were tested as is and after being cut down to lumber of two smaller sizes. The sound velocity was found to have the best correlation to the residual strength of the ties with it decreasing as the samples tested ranged from small lumber piece to larger lumber to tie. The dynamic modulus of elasticity was found to have a weaker correlation with residual strength and the values generally higher.

Hyvärinen (2007) used air-coupled transducers to detect defects in Scots pine. Knots, cracks, and heartwood were identified. The signal attenuation was capable of detecting heartwood while the board was moving between 1 and 3 m/s, opening the possibility of online grading. Air transducer sorting comported with visual sorting for 90% of the boards.

Tomographic views of timber members were constructed by Riggio and Piazza (2011) using ultrasonic transducers. Heterogeneities that affect wood strength were mapped using ultrasound and were then related to external features using digital photogrammetry. Drilling resistance tests were also used to corroborate results.

Examining the effect of fungal decay on Norway spruce, Reinprecht and Hibky (2011) demonstrated that sound velocity and dynamic modulus were suitable for revealing which fungal agent was responsible for the decay with known decreases in wood density. Yet, the study could not tell the difference between various strains of brown-rot fungus.

Ritschel and others (2013) studied damage mechanisms within failing spruce specimens in virtually real time using a combination of acoustic emission and synchrotron radiation x-ray tomographic microscopy (SRXTM). Acoustic emission enabled sub-millisecond resolution when determining damage initiation. The SRXTM produced high-resolution visualizations of the inner wood cellular structure in three dimensions. The visualizations allowed observation of changes in the microscopic wood structure in both time and space that led to ultimate failure.

White and others (2013) reviewed the ability of several nondestructive techniques to assess wood damaged by heat and fire. The study found that changes in time delay and wave velocity for charred yellow poplar specimens was minor, but the area under the power spectral density plot changed significantly. Several other non-ultrasonic NDE techniques were also discussed but were not included in this review.

Engineered Wood Products

Engineered wood products cover a variety of material including oriented strandboard (OSB), fiberboard, particleboard, plywood, glued-laminated (glulam) beams, and veneers.

Strength and Grading

An early review of ultrasonic evaluation of wood composites was given in Szabo (1978). This reference covered many aspects of ultrasonic inspection including anisotropy, coupling issues, wave types, attenuation, basic ultrasonic testing setups, transducer descriptions, and the advantages and disadvantages of higher frequency usage. The concepts presented were fundamental when ultrasound was used in inspection applications.

In a 1978 study, Kunesh found visual grading of parallel laminated veneer (PLV) made from Douglas-fir to be unsatisfactory with grading for strength. Ultrasonic inspection was capable of grading the material at a rate such that it could be used on a production line. A similar study was conducted using laminated veneer lumber with similar results and conclusions (Sharp 1985).

Petit and others (1991) examined the changes in ultrasonic behavior through laboratory aged structural flakeboard. The boards were tested before an aging process was applied. Ultrasonic wave velocity decreased as the angle diverged from parallel with the length of the boards. The aging processes were hygrothermal treatments and were performed in accordance with French standards NF 51-262 and NF 51-263. Ultrasonic wave velocity, modulus of elasticity, and modulus of rupture decreased after the aging process was applied. High correlation between wave velocity and MOE both prior to and after the aging process supported the hypothesis that the relationship could be used to develop nondestructive evaluation techniques. The correlation between wave velocity and modulus of rupture was not as high as wave velocity and MOE, but the potential to use the relationship in an evaluation technique still existed.

Lemaster and Beall (1993) examined surface roughness of medium density fiberboard (MDF) using acoustic emission. Wave guides of various shapes were moved across surfaces of MDF that were previously sanded using various sized grit sandpaper. The motion and the waveguides caused measurable acoustic emission events. The technique was capable of detecting groves and snaking.

A 1996 study by Kruse and others used contact and non-contact methods to measure wave speed through MDF and particleboard. Surface sanding affected the ultrasonic waves, so the two groups were tested separately. Unsanded boards had lower velocities. Non-contact methods were better correlated than contact methods for both internal bond of sanded boards and also swelling of unsanded boards. Wave velocity was measured through both MDF and particleboards with thicknesses of 34 mm or less without problems caused by signal attenuation.

Beall and Chen (1998) used ultrasonic waves and acousto-ultrasonic techniques to monitor particleboard curing. Wave guides allowed signals to be taken from the boards during pressing, but without interfering with the process. Strength development, board thickness, resin content, and press temperature correlated to the root mean square (RMS) of the collected signals.

In 1998, Tucker and others evaluated several ultrasonic frequencies for monitoring wood plastic composites. The study determined wave speed and attenuation from ultrasonic signals. Strong correlation existed between wave speed and MOE. Good correlation existed between MOE and MOR. High frequencies were significantly attenuated over short distances.

The relationship between wave velocity through wood-based composite materials and several different parameters was explored by Bekhta and others (2000). Particleboard, OSB, and MDF were studied. Parameters examined included relative humidity, temperature, direction of measurements, and frequency. Empirical equations relating modulus of rupture, resonance frequency, wave velocity, MOE calculated from resonance frequency, MOE calculated from wave velocity, and MOE measured from static bending tests as well as the associated correlation values for each relationship were given.

Vun and others (2000) used contact and non-contact sensors to inspect OSB. Wave velocities were higher when contact sensors, rather than non-contact, were used. Internal voids were found to reduce MOE and dimensional stability. Wave velocity and attenuation were fitted to a third order polynomial to density. The percentage of board resin affected the velocity trends.

Kruse (2000) explored use of various NDT technologies for process control of panel production. A good reference on several NDT technologies and their individual uses in panel production was provided. Ultrasonic velocity was useful in determining panel thickness, MOE, and internal bond for particleboard and MDF. The use of ultrasound to evaluate internal bond was thought to potentially reduce production cost between 2% and 8%.

Vun and others (2002) characterized the horizontal density of OSB using several parameters including ultrasonic velocity. Other parameters examined were attenuation and RMS. A polynomial and a power model were constructed. The power model provided a higher correlation with the measured density values.

A 2002 study by Moore and Bier found that veneer grading using both ultrasonic velocity and density produced lower variable grades than using ultrasonic velocity alone. Much of the discussion focused upon methods of adjusting calculations for veneers with higher MC so grading could be ultimately performed on green wood veneer.

Tucker and others (2002) evaluated the elastic properties of natural fiber composite panels using antisymmetric plate waves excited by an ultrasonic tone burst. Flexural and transverse shear rigidity values were obtained from dispersion curves using fundamental plate wave propagation theory. Good agreement existed between the shear modulus calculated from transverse through-thickness tests and the plate wave tests. The effects of panel othrotropy on the shear modulus and rigidity calculations were discussed. The method was determined to be feasible and accurate for panels less than 6.4 mm thick.

Najafi and Ebrahimi (2005) tested three different methods for predicting the longitudinal velocity in particleboard and fiberboard. Longitudinal wave velocity was found to change within particle and fiber boards because of constituent material aligning with manufacturing machinery during production. Hankinson and Jacoby equations were used to model the change in longitudinal velocity. Cubic and quadratic equations, using angle as the independent variable, were also examined. All three methods were effective at modeling the velocity changes to manufacturing angle.

Defect Detection

The success of ultrasonic inspection to detect voids led to a discussion of the feasibility of online production inspection of plywood and composite boards. Baker and Carlson (1978) found use of non-contact sensors as part of quality control had great potential to benefit both manufacturers and customers.

Beall and Biernacki (1991) evaluated Douglas-fir glulam beams using acousto-ultrasonic techniques. To minimize variation in reference tests conducted on control zones, the time to peak amplitude was used as a parameter. The acousto-ultrasonic techniques were not directly sensitive to bond strength, but were sensitive to the presence of certain defects.

Illman and others (2002) were the first to examine use of acoustic parameters for monitoring the deterioration of a commonly used wood structural composite, oriented strandboard (OSB). In a closely controlled laboratory experiment, they obtained similar results to those observed for clear wood. In a follow-up analysis of the data, Ross and others (2003) were successful at developing strong correlative models between acoustic parameters and the residual strength of deteriorated OSB.

Dill-Langer and others (2005) evaluated defects in adhesive boding between laminates of glulam beams using several ultrasonic parameters. Defects included lack of adhesive, adhesive curing prior to bonding, and epoxy block gluing. The parameters examined were time of flight (TOF), peak to peak amplitude, and amplitude of initial peak. The amplitude of the initial peak was found to be useful when detecting glue line defects. Both TOF and peak to peak amplitude showed large fluctuations and limited contrast. Three coupling conditions were also explored: dry, paste, and elastomer. Dry coupling produced the worst test results with low signal to noise ratio; paste coupling provided the best. Elastomer coupling had a higher signal to noise ratio than dry but did not alter the condition of the beam as did paste.

In 2009, Bobadilla and others artificially aged particle- and fiberboards and then tested using several inspection methods including ultrasound. Strong correlation was found between ultrasonic wave velocity and changes in mechanical properties of the boards subjected to aging. The independent variables were used to estimate the natural logarithm of density rather than density itself, which might have contributed to the strength of the correlation.

Sanabria and others (2009) identified delamination defects between two solid spruce boards bonded together with polyurethane adhesive by using ultrasonic inspection. The boards were 5-mm thick. The boards were bonded with adhesive, but portions of the bonding surfaces were left free of adhesive. Air-coupled transducers were used to perform through transmission measurements. The signal loss due to lack of glue bonding far exceeded the loss from normal wood heterogeneity spruce.

Divos and others (2009) measured the depth of cracks within glulam beams using ultrasonic techniques. Transducers were places on either side of the crack within 20 to 50 mm. The crack depth was estimated based upon TOF measurements and was accurate to within 10% of the true crack depth. Initial tests were carried out to estimate shear strength between lamina. Estimations of residual stresses within glulam beams were caused by the manufacturing process and changes to the climate condition.

In a follow-up to the study conducted by Bobadilla and others (2009), the researchers artificially aged OSB panels and then tested the panels using several inspection methods including ultrasound. Strong correlation was found between ultrasonic wave velocity and changes in mechanical properties of the OSB panels. During the inspection, the transducers were inclined 45° to the plane of the panel surface. The feasibility of using the technique in the field was demonstrated.

In 2011b, Bucur performed a dual high and low frequency inspection on wood based composites. A dual high and low frequency inspection was carried out on wood based composites. Local defects were detected using high frequency ultrasonic techniques. Global damage detection was based upon low frequency vibrations. A finite element model of the analyzed structure was used to estimate modal shapes, frequencies, and damping.

Sanabria and others (2011) examined the structural integrity of multilayered glued-laminated beams using air coupled transducers. Bonding defect between lamina were identified for specimens 520 mm (20.5 in.), demonstrating for the first time the feasibility of using air coupled transducers on lamina of such thickness.

Acoustic Emission

Acoustic emission is not strictly an ultrasonic method. The frequencies excited during an acoustic emission event can be within the acoustic or ultrasonic ranges, or both. The studies presented here involve researchers that have applied acoustic emission techniques within the ultrasonic range of frequencies to engineered wood products. Beall (1989) presented a literature review covering work in the area of acoustic emissions prior to 1989.

Sato and Fushitani (1991) used acoustic emission to detect poor bonding in plywood. A three-point bending test allowed both MOE and acoustic emissions to be monitored in a single test. The number of AE events was found to be a better indicator of MOR than the number of knots. Regions of poor bonding were characterized by an increased number of acoustic emission events.

Lemaster (1993) conducted a study in which the individual particles and flakes used to make engineered wood panels were characterized using acoustic emissions. Particles and flakes were dropped onto a plate and the waveform was recorded. Waveforms were analyzed in both the time and frequency domain. Size classes were best defined by the number of threshold crossings. Frequency centroid was used to describe the category of particles and flakes.

A two part study was conducted by Adams and Morris in 1996. In the first part, Adams and Morris (1996) used acoustic emission in conjunction with fracture pullout to observe how changes in MC affected the fracture of OSB and MDF. Adams and Morris (1996) used acoustic emission in conjunction with fracture pullout to observe how changes in MC affected the fracture of OSB and MDF. A beam specimen was notched and then loaded in three-point bending. The notch on the beam was in line with the center load and opened towards the opposite side. As the test continued, the specimen fractured and the acoustic emission events were counted. The speed of the tests strongly influenced the results. In the second portion of the study, Morris and Adams (1996) correlated acoustic emissions to crack propagation. OSB and MDF were again the materials examined. Acoustic emissions were used to identify different stages of fracture during a three point bending test. The specimens were notched boards as described above. Crack formation initiated with high numbers of acoustic emission events; crack propagation had fewer events than formation. High MC lowered the number of events making it difficult to identify phases for crack formation and propagation.

Beall (1996) explored duration of load behavior of OSB by loading specimens to 40%, 65%, and 80% of ultimate load and monitoring acoustic emission events. The number of events increased at a rate similar to the rate of specimen deformation until a constant load point was reached; at which point, the number of events decreased exponentially.

The difficulty of typical ultrasonic techniques to detect tensile damage in wood led to an investigation into identification through acoustic emissions. Pierre (2000) found that acoustic emissions showed promise as a tool to monitor tensile damage.

Vun and Beall (2002) demonstrated that acoustic emission was an effective tool in monitoring creep of OSB. The cumulative number of acoustic emission events correlated strongly to specimen deflection. The test also showed a potential future use of acoustic emission to evaluate fracture mechanisms and locating the source location.

Locations of fractures within specimens of OSB, plywood, and MDF were later located by Niemz and others (2007) using acoustic emissions. Four sensors were placed around the specimen. The difference in arrival time of the events allowed the fracture location to be estimated parallel to the panel. Perpendicular location was not possible as perpendicular wave speed was only a third of the wave speed parallel to the panel.

Ritschel and others (2011) performed tensile tests on LVL and monitored plywood samples using acoustic emission and digital image correlation. The rate and intensity of acoustic emission events changed with different strain behavior of the specimen, indicating that acoustic emissions were suitable for analyzing micro-mechanisms of damage growth.

El-Hajjar and Qamhia (2013) used acoustic waveforms produced by acoustic emissions during tensile testing of triaxially braided regenerated cellulose composites to identify failure modes. The study confirmed that acoustic emissions could be monitored to identify onset of internal damage.

Buildings and Structures

Many different ultrasonic inspection tools are commercially available. Ultrasonic inspection technology is well established, relatively low cost, and can be ruggedized for use outside ideal laboratory conditions. These features make ultrasound an attractive tool for use in situ. Palaia-Perez (1993) examined the time and frequency domain of ultrasonic signals through beams. Identifying conclusive patterns from the time domain signal was difficult; frequency domain signals provided useful information. Amplitude of the highest frequency decreases with the size of interior voids.

Baldassino (1996) used several nondestructive techniques in conjunction with each other including hardness testing, steel pin penetration, drilling resistance, and ultrasonic inspection. Beams were removed from the structure and tested. Baldassino determined that multiple techniques were necessary to assess the material behavior.

Anthony and others (1998) inspected timber piles from the Queens Boulevard Bridge in Queens, New York, using radial ultrasonic inspection and micro-drilling techniques. Ultrasound was used to determine areas that needed to be inspected using a resistograph. The study was part of a comprehensive inspection using innovative techniques.

Transducer coupling was a focus when Emerson and others (1998) inspected creosote-coated timbers. TOF and frequency were collected in a grid along each timber. Advanced decay was easily identified using TOF. Spectral analysis and peak frequency showed potential in identifying incipient decay. A dry flexible membrane was used as a couplant. Greater consistency of coupling force was needed.

During shear wall testing, Beall and others (2005) found that few acoustic emission events occurred up to 40% of the maximum load. The absence of AE events indicates the deformation was reversible. AE events were more likely to be observed in the frame than the panel.

A description of an ultrasonic through transmission setup for clear wood timbers was provided in Agrawal and Choudhari (2009).

Karlinasari and Bahtiar (2011) examined the differences between boards end-jointed using finger joints and those using scarf joints. The process of end-jointing did not significantly change ultrasonic wave velocity and dynamic MOE from those of the constituent boards. The correlations between dynamic MOE from ultrasound and static MOE or MOR were higher in finger-jointed boards than scarf-jointed.

Teder and others (2011) examined the effect of sensor spacing on structural timber assessment. The study determined that decreasing the sensor spacing caused the inspection results to yield more localized value. A sensor distance of 600 mm was found to be the best arrangement for determining physical and mechanical properties using either longitudinal or indirect measurements. This finding matched the literature reviewed upon the subject. A brief description of ultrasonic inspection was also provided.

Teder and Wang (2013) used several nondestructive techniques to examine 75-year old glulam arches extracted from a building during deconstruction. The arches were tested using stress-wave timing, ultrasonic wave propagation, resistance microdrilling, and visual inspection along cutting planes. This study found that wave propagation was a good indicator of moderate to large delaminations and internal decay.

Historical Structures and Artifacts

There are many historical structures and artifacts of cultural significance. The alteration of these structures and objects would be considered at best, undesirable and, at worst, a loss for a society or the world. Nondestructive testing is especially well suited for inspecting these places and things as the ending condition is unchanged, insuring their preservation for future generations.

Ceccotti and Togni (1996) used several nondestructive techniques to evaluate beams from a fifteenth century Florentine building under restoration. Techniques used included visual inspection, stress wave, free vibration, hardness testing, and ultrasound. Wave inspection was poor at detecting ring shakes, localized decay, and variations in MC. A multiparameter inspection had the best correlation with strength.

The copper pins and the wood surrounding the pins from the USS Constitution were tested by Ross and others (1998) for signs of deterioration using ultrasound.

Kandemir-Yucel and others (2005) examined timbers from the Aslanhane Mosque in Ankara, Turkey, using thermographic and ultrasonic inspection. Ultrasound measurements were taken perpendicular to grain of pillars to evaluate their soundness. Infrared was used in conjunction with ultrasound to determine the effects of MC.

Lee and others (2009) evaluated an ancient Korean wood building, Daeseongjeon in Yeosan, Hyanggyo, using wave TOF measurements. Ultrasonic tomographic cross sections of supporting pillars were created. Coupling the sensors to the pillars was major difficulty during the inspection process due to poor surface conditions.

In 2009, Arriaga and others proposed a methodology of testing ancient Spanish timbers composed of Scots pine and Laricio pine. Twenty-five timber pieces were extracted from an eighteenth century building and tested in the proposed method and mechanical testing. The correlation between the proposed method and mechanical testing was low for MOE and poor for MOR.

Ross and Dundar (2012) inspected a 2,500-year-old Egyptian wooden inner coffin of Meretites using ultrasound. The bottom portion of the coffin was found to have deterioration.

In 2011, Lee and others presented a portable device capable of inspecting rafters from an ancient Korean wooden building. Conventional TOF was ineffective for rafter inspection. Several ultrasonic parameters were examined including TOF, amplitude, energy, pulse length, and RMS voltage. A poor correlation relationship was developed to estimate deterioration depth using the TOF and pulse length parameters.

Beikircher and others (2013) tested timber strength in buildings constructed over a wide range of dates 1250 AD to 2011 AD using both nondestructive and destructive methods. The nondestructive methods included visual inspection, electrical resistance, and ultrasound; the destructive methods were drill resistance and fractometer. The goal was to compare aged wood with virgin wood. Temperature, MC, and natural variability of wood caused results to lack precision. Indirect ultrasound measurements were not reliable when estimating strength of the wood.

Noya (2013) examined two Scots pine structural members of the seventeenth century roof of the library of the College of San Pablo in Granada, Spain, using ultrasound, MC measurements, and fungal cultures. Ultrasound measurements were taken perpendicular to the grain of the timbers. Data from the inspection led to the conclusion that high decay was present.

Concluding Remarks

Ultrasonic inspection of wood has evolved over a half a century of research and development. In this report, a comprehensive literature review of the use of ultrasound in wood inspection was presented and information regarding basic ultrasonic inspection techniques and analyses were described. Table 2 at the end of this report contains a list of over one hundred species of wood that have been inspected using ultrasound.

Strength grading, determination of elastic constants, and evaluation of MC effects are a few of the fields to which ultrasonic inspection have been successfully applied. The most widespread application of ultrasonic inspection with wood is arguably defect detection. There is an ongoing need to detect and assess defects within standing trees, poles,

Table 2—List of tree species studies and associated bibliographic reference

Tree species	Reference
Agathis alba	(Karlinasari and others 2011)
Alan batu (*Shorea albida*)	(Duju and others 2000)
Alder	(Grimberg and others 2011)
Alerce (*Fitzroya cupressoides*)	(Baradit and Niemz 2011)
Angelim (*Hymenolobium petraeum*)	(Terezo and others 2005)
Angelim araroba (*Votaireopsis araroba*)	(Bartholomeu and Gonçalves 2007)
Annona duckei	(Inés and others 2011)
Apeiba membranaceae	(Inés and others 2011)
Apuleia leiocarpa	(Trinca and others 2009) (Inés and others 2011)
Aquilaria microcarpa	(Karlinasari 2013)
Aspidosperma polyneuro	(Trinca and others 2009)
Aspidosperma rigidum	(Inés and others 2011)
Aspidosperma schultesii	(Inés and others 2011)
Astronium lecontei	(Pires and others 2011)
Balfourodendron riedelianum	(Trinca and others 2009)
Bauhinia purpurea	(Karlinasari and others 2011)
Beech	(Diebold and others 2000) (Grimberg and others 2011)
Betula costata	(Wang and others 2013)
Bilat (*Parashorea macrophlla*)	(Duju and others 2000)
Black oak (*Quercus kelloggii*)	(Quarles and Zhou 1987)
Brosimum potabile	(Inés and others 2011)
Cabreúva (*Myrocarpus frondosus*)	(van Dijk and others 2013)
Caesalpinia echinata	(Trinca and others 2009)
Caryocar glabrum	(Inés and others 2011)
Cavanillesia umbellate	(Inés and others 2011)
Cedrelinga cateniformis	(Inés and others 2011)
Cedrelinga Cateniformis Ducke	(Yoza and Mallque 2011)
Cherry	(Grimberg and others 2011)
Cherry (*Prunus sar gentii Rehd. subsp. jamasakura Ohwi*)	(Kawamoto 1996)
Chinese fir (*Cunninghamia lanceolata (lamb.) Hook*)	(Yin and others 2005)
Chrysophyllum prieurii	(Inés and others 2011)
Chrysophyllum venezuelanense	(Pires and others 2011)
Clarisia racemosa	(Inés and others 2011)
Croton matourensis	(Inés and others 2011)
Cupiúba (*Goupia glabra*)	(Gonçalves and Bartholomeu 2002) (Gonçalves and Costa 2005) (Bartholomeu and Gonçalves 2007)
Cupiúba (*Goupia glabra*)	(Gonçalves and others 2011)
Dacroides nitens	(Inés and others 2011)
Diplotropis purpurea	(Inés and others 2011)
Dipteryx micrantha	(Inés and others 2011)
Dipteryx odorata	(Trinca and others 2009)
Douglas-fir (*Pseudotsuga menziesiii*)	(Kunesh 1978) (Lemaster and others 1993) (Anthony and Phillips 1991) (Beall and Biernacki 1991) (Anthony and Phillips 1993) (Diebold and others 2000) (Ballarin and others 2002) (Seeling 2002)
Eastern cottonwood (*Populus deltoids*)	(Brancheriau and others 2011)
Endopleura uchi	(Pires and others 2011)
English oak (*Quercus robur L.)*	(Dolwin and others 2000)
Eucalipto (*Eucalyptus saligna*)	(Gonçalves and others 2011)
Eucalyptus citriodora	(Bartholomeu and Gonçalves 2007) (Gonçalves and others 2009) (Bertoldo and others 2013)

Table 2—List of tree species studies and associated bibliographic reference

Tree species	Reference
	(Freitas and others 2013)
Eucalyptus globulus	(Yang and others 2007)
Eucalyptus grandis	(Bartholomeu and Gonçalves 2007)
	(Pedroso and others 2011, 2013)
	(Ferreira and others 2013)
Eucalyptus pellita	(Bertoldo and others 2013)
Eucalyptus saligna	(Bartholomeu and Gonçalves 2007)
	(Freitas and others 2013)
European beech (*Fagus sylvatica*)	(Dolwin and others 2000)
Ficus Americana	(Inés and others 2011)
Fraxinus mandshurica	(Song and others 2011)
Gallesia integrifólia	(Trinca and others 2009)
Garapeira (*Apulleia leiocarpa*)	(Gonçalves and others 2011)
Guarea kuntiana	(Inés and others 2011)
Holopyxidium jarana	(Pires and others 2011)
Imbuia (*Ocotea porosa*)	(Gonçalves and Costa 2005)
Jacaranda copaia	(Inés and others 2011)
Jackfruit (*Artocarpus heterophyllus Lamk*.)	(Karlinasari and others 2009)
Japanese cedar (*Cryptomeria Japonica D.Don*)	(Soma and others 2000)
Japanese magnolia (*Magnolia obovata Thunb*.)	(Sasaki and Hasegawa 2000)
Japanese Sugi (*Cryptomeria japonica*)	(Castellanos and others 2005)
Jeunjing (*Paraserianthes falcataria*)	(Karlinasari and others 2007)
Keruing utap (*Dipterocarpus rigidus*)	(Duju and others 2000)
Kruing (*Dipterocarpus spp*.)	(Tjondro and Soryoatmono 2007)
Larch	(Diebold and others 2000)
Larch (*Larix gmelini*)	(Yin and others 2009)
Laricio pine (*Pinus nigra Arn. Ssp. salzmannii*)	(Arriaga and others 2009)
	(Iñiguez and others 2009)
	(Iñiguez-Gonzalez and others 2013)
Laurel (*Laurelia sempervirens*)	(Baradit and Niemz 2011)
Lecythis pisonis	(Pires and others 2011)
Lenga (*Nothofagus pumilio*)	(Baradit and Niemz 2011)
Licania elata	(Inés and others 2011)
Loblolly pine	(Huang 2000)
Loblolly pine (*Pinus taeda*)	(Oliveira and others 2002)
	(Fassola and others 2011)
Madrone (*Arbutus menziesii*).	(Hamstad and others 1993)
Mangium (*Acacia mangium Willd.)*	(Karlinasari and others 2009)
Manio (*Podocarpus nubigena*)	(Baradit and Niemz 2011)
Maple (*Acer spp*.)	(Hamstad and others 1993)
Maritime pine (*Pinus pinaster Ait.*)	(Machado 2002)
	(Iñiguez-Gonzalez and others 2013)
Matisia bracteolosa	(Inés and others 2011)
Meranti (*Shorea spp*)	(Karlinasari and Bahtiar 2011)
Mezilaurus	(Trinca and others 2009)
Mimusops elengi	(Karlinasari and others 2011)
Myroxylon Balsamum	(Trinca and others 2009)
Naucleopsis glabra	(Inés and others 2011)
Nectandra	(Trinca and others 2009)
Oak	(Ross and others 1998)
	(Diebold and others 2000)
Ocotea fragantisima	(Inés and others 2011)
Olivillo (*Aextoxicon punctatum*)	(Baradit and Niemz 2011)
Oriental beech (*Fagus orientalis*)	(Najafi and others 2007, 2009)
P. pachycharpa	(Pires and others 2011)
Pequía (*Aspidosperma desmanthum*)	(Gonçalves and others 2011)
Peroba (*Aspidosperma pirycollum*)	(Terezo and others 2005)
Pine	(Diebold and others 2000)
	(Miettienen and others 2005)
	(Grimberg and others 2011)
Pinho do Parana (*Araucaria angustifolia*)	(Gonçalves and Costa 2005)

Table 2—List of tree species studies and associated bibliographic reference

Tree species	Reference
Populus simonii	(Song and others 2011)
Pouteria guianensis	(Pires and others 2011)
Pterocarpus indicus	(Karlinasari and others 2011)
Radiata pine (*Pinus radiata D. Don.*)	(Booker and others 1996, 2000)
	(Andrews 2002)
	(Moore and Bier 2002)
	(Kang and Booker 2002)
	(Iñiguez and others 2009)
	(Iñiguez-Gonzalez and others 2013)
Ramin (*Gonystylus bancanus*)	(Duju and others 2000)
Red oak	(Schafer and others 1998); (Brashaw and others 2000)
Red pine (*Pinus densiflora*)	(Kawamoto 1993,1996)
	(Kim and others 2007);(Oh and others 2013)
Red pine (*Pinus resinosa*)	(Gao and others 2011, 2013)
Redwood (*Sequoia sempervirens*)	(Hamstad and others 1993)
	(Ballarin and others 2002)
	(Seeling and others 2002)
Resak durian (*Cotylelobium burcki*)	(Duju and others 2000)
Romanian beech	(Curtu and others 1996)
Salix matsudana Koidz	(Song and others 2011)
Sandalwood (*Santalum album*)	(Turpening 2011)
Schefflera morototoni (*Sacha cetico*)	(Inés and others 2011)
Scots pine (*Pinus sylvestris L.*)	(Abbott and Elcock 1987)
	(Feeney and others 1996)
	(Kánnár 2000)
	(Iñiguez and others 2007)
	(Hyvärinen 2007)
	(Arriaga and others 2009)
	(Iñiguez and others 2009)
	(Hermoso and others 2013)
	(Iñiguez-Gonzalez and others 2013)
	(Llana and others 2013)
	(Noya 2013)
Sessile oak (*Quercus petrea*)	(Dundar and others 2013)
Silver fir (*Abies alba Mill.*)	(Ceccotti and Tongi 1996)
Simarouba amara	(Inés and others 2011)
Slash pine (*Pinus elliottii*)	(Bartholomeu and Gonçalves 2007)
	(Massak and others 2009)
	(Pedroso and others 2011)
Southern pine	(Patton-Mallory and others 1987)
Spruce	(Sandoz 1991)
	(Feeney and others 1996)
	(Diebold and others 2000)
	(Hauffe and Mahler 2000)
	(Kuklík and Kuklíkova 2000)
	(Pierre 2000)
Spruce (*Picea abies*)	(Niemz and Kucera 1998)
	(Dill-Langer et al 2002)
	(Seeling and others 2002)
	(Rosner and Wimmer 2005)
	(Schubert and others 2005)
	(Sanabria and others 2009)
	(Rohanová and others 2011)
	(Rosner 2011)
	(Sanabria and others 2011)
	(van der Beek and Tiitta 2011)
Sterculia frondosa	(Inés and others 2011)
Sweet chestnut (*Castanea sativa* Mill.)	(Dundar and others 2013)
	(Iñiguez-Gonzalez and others 2013)

Table 2—List of tree species studies and associated bibliographic reference

Tree species	Reference
	(Vásquez and others 2013)
Swietenia sp.	(Karlinasari and others 2011)
Sycamore	(Grimberg and others 2011)
Sycamore fig (*Ficus sycomorus*)	(Dundar and Ross 2011)
Tabebuia serratifolia	(Inés and others 2011)
Tepa (*Laureliopsis philipiana*)	(Baradit and Niemz 2011)
Tetragastris panamensis	(Inés and others 2011)
Toona ciliata	(Pedroso and others 2011)
Ulmus pumila	(Song and others 2011)
Unonopsis floribunda	(Inés and others 2011)
Vatairea sericea	(Pires and others 2011)
Vochysia lomatifolia	(Inés and others 2011)
Western hemlock	(Hamm and Lam 1987, 1991)
White fir (*Abies concolor*)	(Berdnt 2002)
Xylopia nitida	(Inés and others 2011)
Yellow pine	(Groom 1991)

lumber, structures, and engineered wood products. Increased sensitivity and more accurate approximations of remaining wood strength aid inspectors in the evaluating the utility and safety of wood structures. Wood is already the most common building material in the world, but with the increased reliability that comes with advanced ultrasonic inspection techniques, its use can only grow.

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