Measuring wood fungal decay by ultrasonic methods

by

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ABSTRACT

The objective of this study was to establish a relationship between wood weight loss caused by fungal decay and change of ultrasonic velocity so as to use the ultrasonic technique to detect or measure wood decay. Ponderosa pine sapwood specimens 1.9 cm by 1.9 cm by 1.9 cm in size were prepared to obtain near true transverse, radial, and tangential surfaces. After oven-drying, ultrasonic velocities in the longitudinal, radial, and tangential directions were measured for each specimen. Then, test specimens were exposed to a brown-rot fungus to obtain various degrees of decay. Ultrasonic velocities of each specimen were measured again after the fungal decay process.

In the range of 0% to 32% specimen weight loss, reduction in ultrasonic velocity was highly correlated to specimen weight loss. Correlations between ultrasonic velocity and specimen weight losses decreased with decreasing degrees of decay. In the range of 0% to 5% specimen weight loss, however, the correlation between ultrasonic velocity and specimen weight loss was significant at the 1% level. Therefore, the ultrasonic velocity technique can be used to detect incipient decay and to measure specimen weight loss caused by fungal decay with a reasonable accuracy.

CHAPTER 1. INTRODUCTION

Wood has been a preeminent construction material for its low cost and availability in various forms and sizes. In addition, wood is relatively strong for its light weight. Wood in service, however, is susceptible to deterioration caused by biological, chemical, and physical agents. Biological deterioration and fire are by far the major causes of wood deterioration, causing billions of dollars in property loss annually (AWPA 1989). In the event of biological agents, the interior of the wood material may be decayed while leaving no visible surface indication. As a result, weight loss and delimitation effects can go undetected by the naked eye, and consequently structure strength and stability could be adversely affected. Fortunately, nondestructive methods exist that allow the detection of deterioration and the evaluation of the remaining strength.

Early research with wood subjected to different levels of fungal decay frequently found in wood structures has been limited to studies that have employed only energy storage parameters. Pellerin et al. (1985) showed that stress wave speed could be successfully used to monitor the degradation of small clear-wood specimens exposed to brown-rot fungi. They showed a strong correlative relationship between stress wave speed and parallel to-grain compressive strength of decayed wood. Rutherford et al. (1987) and Rutherfrod (1987) showed similar results. They also revealed that modulus of elasticity (MOE) perpendicular to the grain, measured using the stress wave nondestructive-evaluation techniques, was significantly affected by degradation

caused by brown-rot decay and could be used to detect incipient decay. Chudnoff et al. (1984) reported similar results from experiments that utilized an ultrasonic measurement system for several hardwood and softwood species. These methods, however, frequently involved destructive testing of wood specimens. Control specimens, not exposed to decay, were often required to estimate a base strength for comparison. In other words, the amount of strength loss due to decay is obtained indirectly from the difference in strength between the decayed specimens and the controls. Because of the variability in wood, values of control specimens may differ significantly from the original strengths of decayed specimens. Hence, these estimates may be a source of experimental error. For this reason, these methods do not appear to be acceptable approaches for detection of wood decay. Nondestructive evaluation (NDE) methods, on the other hand, should result in improved reliability.

Ultrasonic methods are among the most extensively used nondestructive techniques for evaluating and detecting degradation of wood. The ultrasonic wave velocity method was reviewed by Kaiserlik (1978), who found it was the most extensively used nondestructive testing method for materials. Also, McDonald (1978) and Syzmani (1981) considered it to be the most promising internal defect detection method and the most advantageous system for detecting decay in wood. Elvery et al. (1970) found a high correlation between ultrasonic pulse velocity and mechanical strength of wood when density was accounted for in the relationship. Such techniques have been successfully used to detect advanced internal decay or defects in utility poles and marine pilings (Jensen 1965, Breeze et al. 1978, Dunlop 1981, 1983). However, many of these methods are of qualitative nature and can not be used to detect subtle changes

in the early stages of wood degradation. Wilcox (1988) reported that the ultrasonic pulse velocity method was capable of detecting the early stages of decay in laboratory controlled wood specimens, but the instrument used in the study did not allow accurate measurement of pulse velocity through thin specimens. Wang et al.(1980) proposed a method based on changes in natural frequency on the same specimens to indicate the amount of decay in wood by free transverse vibration method. They found that wood decay significantly affected the frequency of oscillation of small eastern pine sapwood specimens.

The objective of this research was to develop an ultrasonic method to measure wood weight loss caused by fungal decay. In this study, quantitative relationships between weight loss of fungal decay specimens and changes of ultrasonic pulse velocities in the three principal structural directions are investigated.

CHAPTER 2. LITERATURE REVIEW

Wood decay is caused primarily by fungi, which are filamentous eukaryotic cells, generally multicellular, heterotrophic, and with external digestion. There are numerous characteristics of damages to wood in use caused by fungi. Chief among these damages is decay which essentially is the result of enzymatic digestion of wood by fungi. The slow, progressive digestion of the wood by fungi causes a continuum of changes in its appearance and physical and chemical properties. Only a limited group of fungi possess the enzymatic capability of digesting wood. Different fungi attack the wood cell-wall constituents in different ways, and consequently result in several types of decay. Soft rots are caused by fungi that selectively attack the S_2 layer of the cell wall. High wood-moisture contents and soil exposures seem to favor soft rot development. Brown rots are caused by a group of fungi that attack primarily the carbohydrates in the cell wall, while white rots are caused by a group of fungi that attack both the carbohydrates and lignin in the cell wall. All types of decay, in the final stages, result in drastic reduction in strength and other properties or total destruction.

2.1. General Features of Wood Fungal Decay

Wood fungal decay is caused by the external fungal enzymatic digestion of the water-insiluble cellulose, hemicelluloses, and lignin of the cell wall. The digestion is carried out primarily by enzymatic hydrolysis and oxidation

(Kirk 1984), reducing the complex polymers to water-soluble units that can be absorbed as nutrients for fungi.

The decay process, under ideal conditions, is a linear continuum that begins with a few innocuous spores and ends when the wood is destroyed or mineralized. Points along the continuum have been selected arbitrarily to designate various stages in decay development (Figure 2-1), which can be related to various use properties. Decay begins when fungal spores germinate and the hyphae penetrate wood, initiate colonization, and release enzymes. At this early colonization phase, damage is limited, and because there are no visible evidences, it is termed the incipient or hidden stage of decay. As decay advances, slight changes in color, wood texture, and fiber brashness may appear, and these changes constitute the early stage when decay is detectable, but not obvious. As decay reaches the intermediate stage, obvious changes in wood color and texture are evident, but the gross structure still remains intact. At late stages, the wood structure is totally disrupted and the residual wood becomes a brownish amorphous, whitish punky, or fibrous material. Some white-rot fungi may completely degrade the wood, producing weight losses approaching 96% to 97%. Brown-rot fungi degrade only the carbohydrate portions of the wood cell wall causing as much as 60% to 70% weight loss (Zabel 1992).

Wood attacked by brown-rot fungi has been compared to acid hydrolysis, in which cellulose and hemicelluloses are the main wood constituents decomposed. The increase in solubility of decaying wood is a reflection of degradation of carbohydrates and lignin into water-soluble molecular

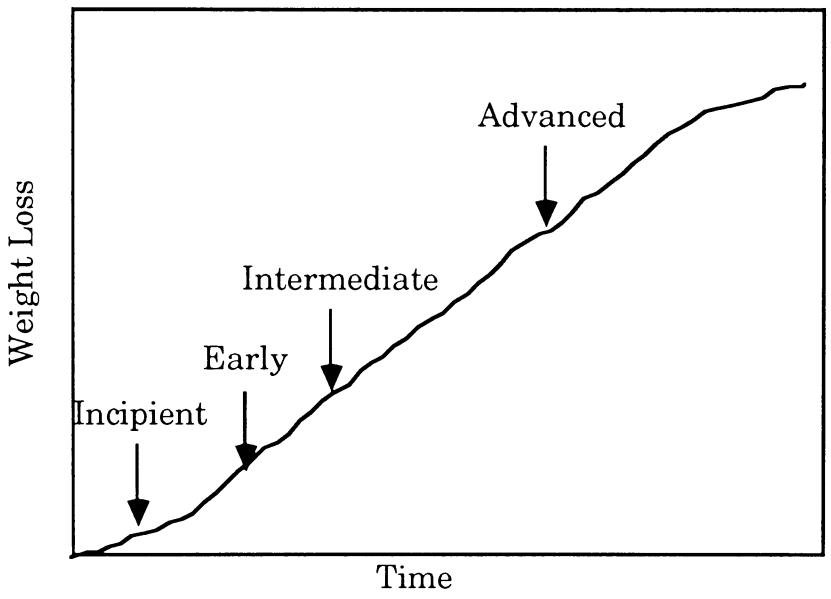

Figure 2-1. The continuum of the decay process under ideal decay conditions and its subdivision into several decay stages (Zabel 1992).

fragments. Solubility determinations also reveal minor changes in lignin caused by the brown-rot fungi (Zabel 1992).

Decay fungi secrete hydrolyzing and oxidizing exoenzymes which can diffuse through the film of moisture coating the cell lumens into the cell wall and depolymerize cell wall components (Kirk 1984). Those partially degraded, water-soluble products can then be assimilated by the fungus and metabolized by oxidative means.

2.2. Changes of Physical Properties of Wood Caused by Fungal Decay

2.2.1. Wood Weight Loss

As fungi grow through wood, they utilize various components of the cell wall, reducing overall wood weight. Mold and stain fungi utilize primarily accessible nutrients in storage tissues or extractives, causing relatively minor weight losses and minimal damages. Decay fungi, however, attack the more chemically complex components of the wood cell wall, eventually metabolizing them to carbon dioxide and water. Wood weight loss can approach 70% with brown-rot fungi, 96% to 97% for white-rot fungi, and 3% to 60% for soft-rot fungi. As shown in Figure 2-2, wood weight loss depends on types of fungi and wood species being attacked. Weight loss, which is generally expressed on an oven-dry basis (ODW), is the most commonly used measure of decay and is generally expressed as

$$\text{Weight loss (\%)} = [(\text{Original weight} - \text{Decayed weight}) / \text{Original weight}] \times 100\%$$

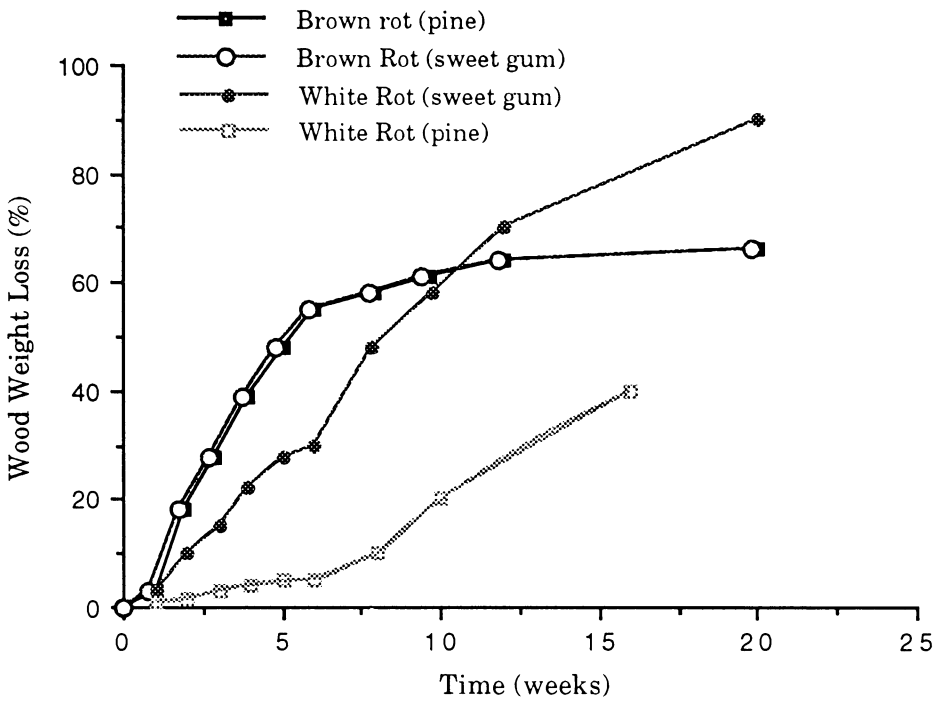

Figure 2-2. Relationships between time and weight loss as affected by type of decay and substrate (Zabel 1992)

2.2.2. Strength Properties

The effects of decay fungi on wood strength have been intensively studied. As fungi grow through the wood, they depolymerize wood components and remove mass, thereby reducing the mechanical properties of wood. Wood derives its strength from a combination of highly oriented cellulose microfibrils and encrusting hemicellulose and lignin. Depolymerization of cellulose in microfibrils causes sharp reductions in wood strength.

The extent of strength loss at a given degree of decay varies with the fungus, the wood species, and the strength property considered. Toughness and impact bending are the two strength properties most sensitive to fungal decay. For example, Richards (1954) found a loss in toughness of more than 50% in a softwood which sustained only a 1% weight loss caused by brown-rot and white-rot decay. Kennedy (1958) found, in tropical hardwoods, a 2% and a 4% weight loss caused by brown-rot decay that reduced modulus of rupture (MOR) by 32% and 49%, respectively. The corresponding reductions for white rot were 13% at 2% weight loss and 20% at 4% weight loss. Because of the importance of estimating loss of wood strength due to fungal decay, Wilcox (1978) compiled such data from the available literature in a convenient reference.

2.2.3. Acoustic Properties

Wood is an excellent transmitter of sound waves and also produces characteristic acoustic emissions as it is stressed mechanically. As wood is colonized by fungi and begins to decay, its ability to transmit or emit sound is

generally altered. The change in acoustic properties can be exploited to detect various stages of decay. As sound waves move through wood, they may pass around decay pockets and voids or they may be transmitted through decayed regions with altered properties. The time of flight (velocity) of a given pulse of sound across the cross section of a timber can be used to determine the internal condition of the wood. Because of the difficulty of measurement and the natural variability in the wood structure, velocity measurements appear to be the easiest method for detecting advanced decay (Zabel 1992).

A second approach to measure changes in acoustic properties is to analyze the characteristics of a sound wave after it has passed through the wood. As a sound wave moves through the wood, the characteristics of the wood (growth rings, knots, check, et.) modify the wave pattern. Therefore, the sound wave represents an acoustic fingerprint of the wood. Small changes in the structural integrity of the wood due to microbial activity should be discernible in the resulting fingerprint. At present, the wave-form analysis of wood is still relatively crude. Progress in other areas of material science, however, suggests that this technique has promise to nondestructively monitor changes in the wood over the course of decay (Pellerin et al. 1992; Ross and Pellerin 1990).

2.3. Nondestructive Testing of Wood Decay

Nondestructive testing of wood has been reviewed in a series of symposiums (Washington State University 1978). Numerous nondestructive testing (NDE) methods are available to detect wood defects. The technique used will depend upon the application and the situation. Ultrasonics is the most

widely used nondestructive method for the detection and evaluation of wood decay. Ultrasonic detection of decay and other wood defects has received much recent attention. The theory of ultrasonic testing in general has been reviewed by Krautkramer et al. (1977). After reviewing all NDE techniques for detecting defects in lumber, Szymani and McDonald (1981) considered ultrasonic methods to be the most promising and advantageous for detecting decay in wood. Such techniques have been successfully used to detect advanced internal decay or defects in utility poles and marine pilings (Jensen 1965, Agi 1978, Dunlop 1981 and 1983, Wilcox 1988).

The phenomenon of ultrasound is the same as that of normal audible sound. It occurs when mechanical vibrations in one region of a medium are transmitted to another region by the mechanical interaction of the atoms and molecules of the medium. Ultrasound is the term used to describe the sound having a pitch that is too high for human to hear. The lower limit of the ultrasonic spectrum is usually taken as about 20 KHz.

Ultrasonics can be described as the analysis of the reaction of mechanical sound waves with their surrounding environment. In the specific case of wood decay, an ultrasonic wave will behave differently when delimitation is encountered. By comparing ultrasonic waves from undecayed and decayed wood, an evaluation can be made as to the severity of wood decay.

2.3.1. Ultrasonic Wave Propagation in Wood

Acoustical wave propagation in anisotropic media such as wood, which exhibits a honeycomb structure, is a complex phenomenon, involving different wave modes. Propagation of sound waves in wood also is angular dependent

and may be subjected to dispersion effects. The propagation of acoustical waves in wood, however, depends primarily on the mechanical properties of the wood. The speed of sound in wood varies, depending on propagation direction and species of wood. For example, sound velocity in pine wood is 4,760 m/s in the direction parallel to grain and 932 m/s in the direction perpendicular to grain; and the corresponding values for oak wood is 4,304 m/s and 1,193 m/s, respectively (Kollmann and Cote 1968).

According to Kollmann and Cote (1968), the theoretical relationship between modulus of elasticity and speed of sound is as following:

$$V = \sqrt{\frac{E}{R_o}}$$

where

V = speed of sound (m/s or ft/s)

E = modulus of elasticity (N/mm^2, or psi)

Ro = oven-dry density (specific gravity)

Based on this relationship, modulus of elasticity can be estimated from measured V and R_o, in which the estimated modulus of elasticity (E_u) is called ultrasonic modulus of elasticity. Elvery and Nwokoye (1970) used Eu to predict, with good results, compression modulus of elasticity (r=0.96), static bending strength (r=0.916), and dynamic vibration modulus of elasticity (r=0.873) for individual laminae in glued laminated beams.

Like other materials, wood has an ability to absorb sound. As an acoustical wave travels through a medium, its amplitude and intensity are reduced as an exponential function of distance which is referred to as

attenuation. Attenuation of acoustical waves in wood depends on the properties of the cell wall constituent, cellulose microfibrils and binding lignin. Microfibrils exhibit crystalline elastic properties with low attenuation, whereas lignin is an amorphous material with considerable plasticity and greater attenuation. In addition, acoustical attenuation, like velocity, is related to the direction of propagation of sound waves. In the longitudinal direction, the principle propagation path is along the S_2 microfibrils. These microfibrils are highly crystalline and elastic, and act as a low damping medium. When sound waves are traveling in the transverse direction, however, they must cross through the more amorphous, inelastic lignin and are therefore subjected to greater damping. Dunlop (1968) reported that damping in the transverse direction may be three times greater than damping in the longitudinal direction.

In addition, as shown in the Figure 2-3, moisture reduces the speed of sound because with increasing moisture, modulus of elasticity decreases and density increases. Sound speed is also reduced with increasing temperature, because higher temperatures reduce density due to thermal expansion of wood (Tsoumis 1991).

2.3.2. Relationship Between Ultrasonic Velocity and Wood Decay

Significant strength loss may occur below 10 percent weight loss in decaying wood (Wilcox 1978). Current field diagnostic techniques, however, are not reliable to detect decay at weight loss lower than 10%. An effective technique to detect early stages of decay in the field, preferably a nondestructive one, is urgently needed.

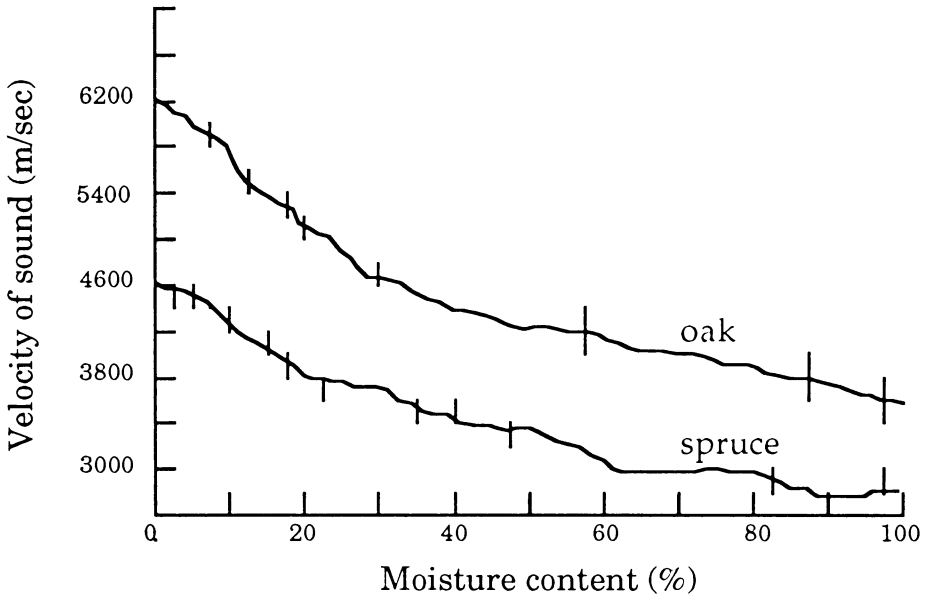

Figure 2-3. Relationship of sound velocity to moisture content (Tsoumis 1991).

Kasiserlik (1978) found that ultrasonic wave velocity methods were the most extensively used nondestructive testing methods for different materials. Ultrasonic pulse velocity has been used effectively by field inspectors to locate advanced decay. Wilcox (1988) showed that the ultrasonic pulse velocity technique was promising to detect early stages of decay. Elvery and Nwokoye (1970) found an empirical relationship between ultrasonic pulse velocity and mechanical strength of wood , with a very high correlation when density was accounted for in the relationship. Lee (1965) found that pulse velocity measurement related directly to the elastic properties of wood, and therefore the method was sensitive to detect any deviations in the grain direction which may not necessarily be visible on the surface. Agi (1983), Bucur (1983), and Ross and Pellerin (1988) all found that ultrasonic velocity was strongly correlated to MOE and density. Ultrasonic velocity also is affected by the presence of internal voids and checks, grain irregularities, and other defects because sound waves travel faster through sound wood (Pellerin et al. 1985).

Wood that has been attacked by fungus is characterized by a reduction of most of its mechanical properties. The effects of decay can range from minimal decomposition of the binding lignin, to complete disintegration of the cell wall structure. The degradation of wood would be expected to produce changes in the acoustic propagation characteristics.

Decomposition or scission of cellulose chains will result in a reduction in the elastic modulus of microfibrils and hence a reduction in the acoustic velocity along the grain of the wood. This reduction in acoustic velocity due to fungal degeneration of cellulose, however, may be influenced by the variations in velocity that is normally observed between micropores in microfibrils due to

variation of the S2 microfibrillar orientation and the moisture content. In decayed wood, the longitudinal acoustic waves have to travel through severed ends of cellulose chains, leading to a significant reduction of sound velocity and an increase in the acoustic damping or attenuation. In the transverse direction, or across the grain, acoustic velocity and damping may also be changed by the effects of degradation cellulose and lignin. Therefore, fungal decay of wood and rot will lead to changes in the acoustic properties (Dunlop 1981). In examining used timber, Wilcox (1988) found that the greatest reduction in ultrasonic pulse velocity occurred in the area of the interior advanced decay, with a gradual increase occurring in wood that visually appeared not to be decayed, and therefore ultrasonic pulse velocity measurements were able to accurately locate the relatively abrupt boundary of decay. He also showed a relatively strong relationship between weight loss and ultrasonic pulse velocity.

The technique of ultrasonic wave velocity measurement is shown in Figure 2-4, where a sound wave is induced at one end of the wood and a second transducer picks up the signal at the other end. The technique is used to measure transit time and calculate an average wave velocity over a predetermined distance. Ultrasonic pulse velocity measurement has a considerable advantage because the shape and size of the material under evaluation does not appear to present any serious restrictions. In addition, due to the ease of measurement and availability of instrumentation, the ultrasonic pulse velocity technique has been applied to detect defects in wood.

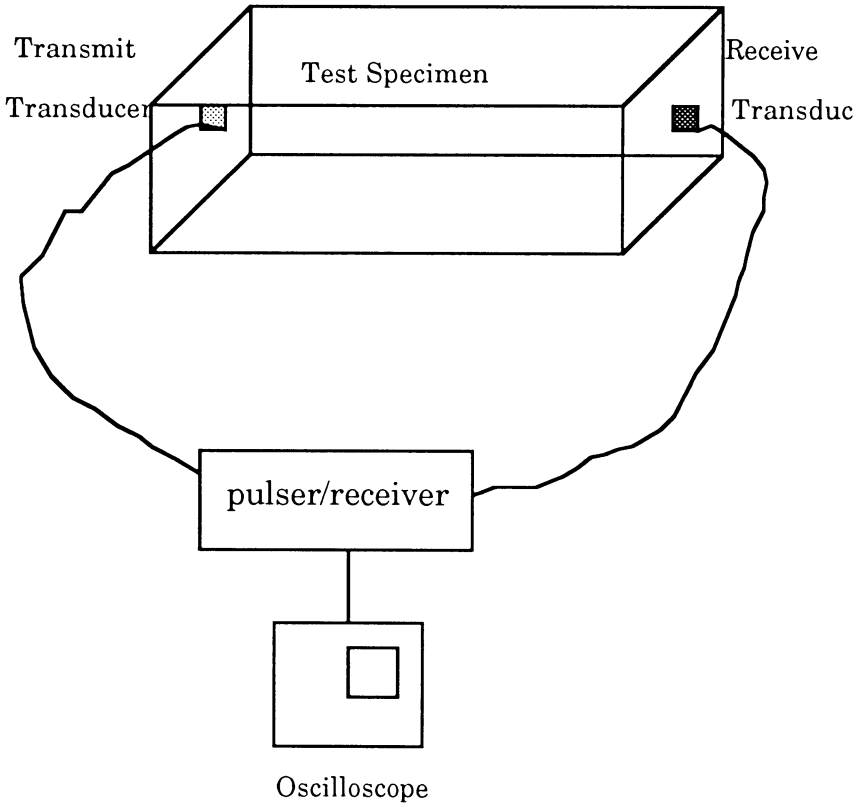

Figure 2-4. Ultrasonic wave velocity measurement.

CHAPTER 3. MATERIALS AND METHODS

3.1. Methodology and Experimental Design

Because wood is a biological material, it is extremely variable in its properties including acoustic properties. Therefore, it is very difficult, if not impossible, to establish a quantitative relationship between wood fungal decay and ultrasonic velocity in wood without knowing the wood's original ultrasonic velocity before it is decayed. In this experiment, 270 pieces of wood specimens were prepared and the ultrasonic velocity in the longitudinal, radial, and tangential directions were measured for each specimen. Then, all these wood specimens were subjected to different degrees of fungal decay, and changes in ultrasonic velocity due to known stages of decay was determined for each individual specimen. The quantitative relationship between fungal decay and ultrasonic velocity was then established by statistical analyses.

3.2. Wood Specimen Preparation

Ponderosa pine (Pinus ponderosa Laws.) sapwood was chosen for this study. This species was chosen for two reasons. Firstly, ponderosa pine wood normally does not possess grain irregularities such as spiral grain and cross grain which might influence ultrasonic measurements. Secondly, ponderosa pine sapwood is relatively non-decay resistant, and therefore is relatively easy to control desired degree of brown-rot decay of wood specimens.

Several 2" by 10" by 12' ponderosa pine boards containing mostly sapwood were purchased from a local lumber store. Clear sapwood cubes, 1.9 cm by 1.9

cm by 1.9 cm, were cut in such a manner to obtain near true transverse, radial, and tangential surfaces. Smooth radial and tangential surfaces were obtained by a planer, and smooth transverse surfaces were obtained by cross-cutting by using a table saw with a sharp saw blade. Transverse surfaces so obtained were smooth enough that further sanding was not necessary. A total of 270 ponderosa pine sapwood cubes having a fairly uniform growth rate were selected for this study.

3.3. Initial Ultrasonic Measurements

Ponderosa pine cubes were dried in an oven at 100°C overnight, followed by determination of oven-dried weight to the nearest 0.001 gram and dimensions in the longitudinal, radial, and tangential directions to the nearest 0.0254 mm. Specimens were temporarily stored over silicone gel in a desiccator before ultrasonic measurements.

Through-transmission ultrasound velocity measurement in the longitudinal, radial, and tangential directions of ponderosa specimens was done as illustrated in Figure 2-4. The ultrasonic measuring system consisted of a ultrasonic pulser/receiver (Panametric Model 5052PR), a digital oscilloscope (Tektronix Model 2252), and a pair of piezoelectric transducers (Ultran KD75-0.5 MHz). The 0.5 MHz Ultran transducers have a thin elastomer film on the contact surface to provide a good contact during measurements, allowing the elimination of the use of a liquid contact medium. To avoid possible errors due to variation in contact pressure during measurements, a spring clamp which provides a constant contact pressure in each measurement was used for all measurements. In addition, a printer was

added to the system to record wave forms and different measurements when necessary.

The two transducers were placed on opposite sides of a specimen. Ultrasonic waves from the transmit transducer were projected into the test specimen, and a short train of damped ultrasonic waves were received by the other transducer. Waveforms were displayed on the digital oscilloscope, and the time of flight measured in micro seconds (μs) was measured and recorded (Figure 3.1). The ultrasonic velocity through the specimen was calculated as follows:

$$V = \frac{L}{T}$$

Where

V = ultrasonic velocity through the specimen in a particular structural direction

L = length ultrasound traveled

T = transit time of ultrasonic wave

The ultrasonic transit time was not corrected for the transit time through the thin elastomer films on transducers because this value is a constant in each measurement due to the use of the spring-clamping device.

3.4. Brown-rot Decay of Wood Specimens

A standard soilblock method (ASTM D-1413) was used to prepare wood specimens with different degree of brown-rot decay. In this process, 8-ounce French square bottles half filled with Iowa topsoil (approximately 80% in

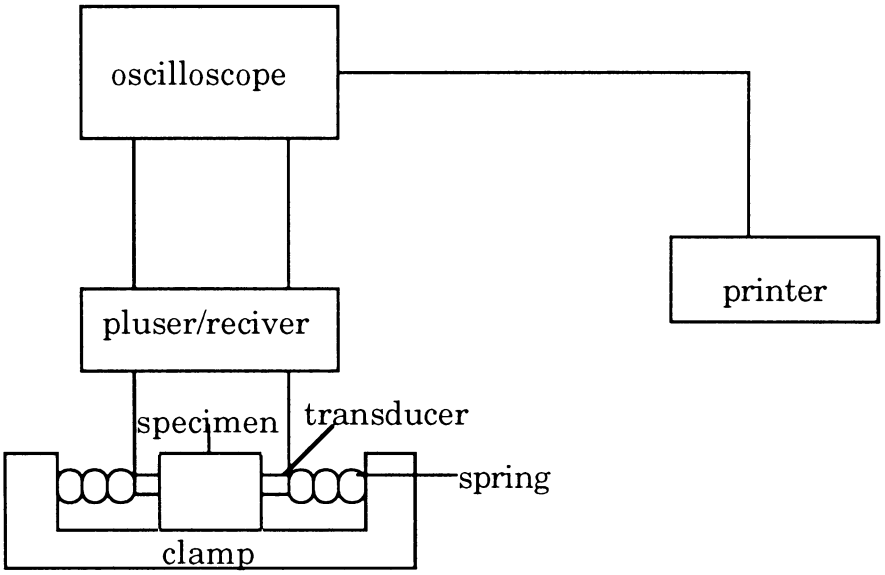

Figure 3-1. Schematics of ultrasonic pulse velocity measurement

moisture content) and with a ponderosa pine sapwood feeder black on top of soil in each bottle were sterilized in an autoclave at a pressure of 15 psi for 25 minutes. Then, the wood feeder blocks were inoculated with brown-rot fungus *Gloeophyllum trabeum*. When the feeder blocks were covered with fungal mycelium in about 2 weeks, 2 sterilized ponderosa pine cubes were placed on top of the feeder block in each bottle. These soilblock cultures were incubated in a chamber with a 80% relative humidity at 27°C. Forty wood specimens in twenty soilblock cultures were incubated for 1, 2, 3, 4, 6, and 8 weeks. In addition 60 more specimens were exposed to the fungus for 10 days to prepared specimens with 5% to 15 % weight loss range. Thirty wood specimens were used as a control group without subjecting them to fungal decay. At the end of each incubation period, wood cubes were remove from bottles, cleaned of fungal mycelium, air-dried for 2 days, and oven-dried at 100°C overnight. Decayed oven-dried weight, and longitudinal, radial, and tangential dimensions were immediately measured. Weight loss of each wood specimen as a result of brown-rot decay was expressed in percentage and calculated as follows:

$$dW \text{ (weight loss)} = \frac{W_1 - W_2}{W_1} \times 100\%$$

Where

W_1 = original oven-dried weight

W_2 = decayed oven-dried weight

3.5. Ultrasonic Measurement of Decayed Specimens

Speed of ultrasound transmission through the three principal structural directions of decayed wood specimens was measured in the same manner as before they were subjected to decay, and the corresponding velocities were calculated by dividing the speed by the decayed dimension. Changes in ultrasonic velocity were expressed in percentages and calculated as follows:

$$dV \text{ (change in velocity)} = \frac{V_1 - V_2}{V_1} \times 100\%$$

where

V_1 = ultrasonic velocity before fungal decay

V_2 = ultrasound velocity after fungal decay

3.6. Data Analysis

To test the sensitivity of the ultrasonic method to measure extent of fungal decay of wood specimens, changes in ultrasonic velocity due to fungal decay were analyzed in the specimen weight loss ranges of 0% to 5%, 0% to 10%, 0% to 15%, 0% to 20%, 0% to 25%, and 0% to 35%. Within each of these weight loss ranges, a simple correlation between percent weight loss and percent ultrasound velocity change was analyzed for each of the three principal structural directions. All statistical analyses were performed by using a personal computer with a Microsoft Excel Analysis Toolpak software.

CHAPTER 4. RESULTS AND DISCUSSION

4.1. Ultrasonic Measurement

In this study, a through-transmission technique was used to measure ultrasonic velocities in the three principal structural directions of wood specimens before and after they were subjected to fungal decay. Two transducers driven by a voltage pulse from an ultrasonic pulser/receiver were placed on opposite sides of the specimen. Ultrasonic waves were projected from the transmit transducer into the tested specimen. A short train of damped ultrasonic waves were propagated in the specimen and received by the opposite transducer. Ultrasonic waves transmitted through test specimens were displayed on the digital oscilloscope and the transit times were measured on the oscilloscope. Figure 4-1 shows typical ultrasonic waveforms transmitted through the longitudinal, radial, and tangential directions of an undecayed ponderosa pine tested specimen. Figure 4-2 shows the method of determining the ultrasound transit time through a test specimen. The ultrasonic velocity through a test specimen was calculated as follows, based on the specimen dimension in a particular structural direction and the corresponding transit time measured on the oscilloscope:

$$V = \frac{L}{T}$$

Where

L = distance ultrasonic wave traveled

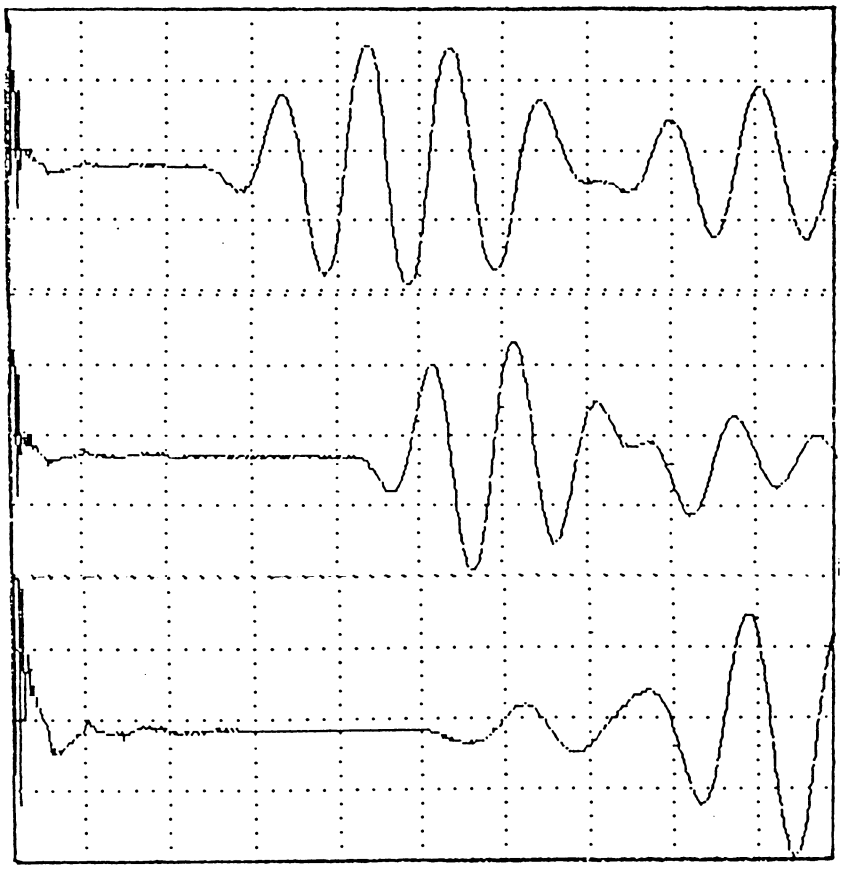

Figure 4-1. Ultrasonic waveforms in the longitudinal (top), radial (middle), and tangential (bottom) directions of ponderosa specimens

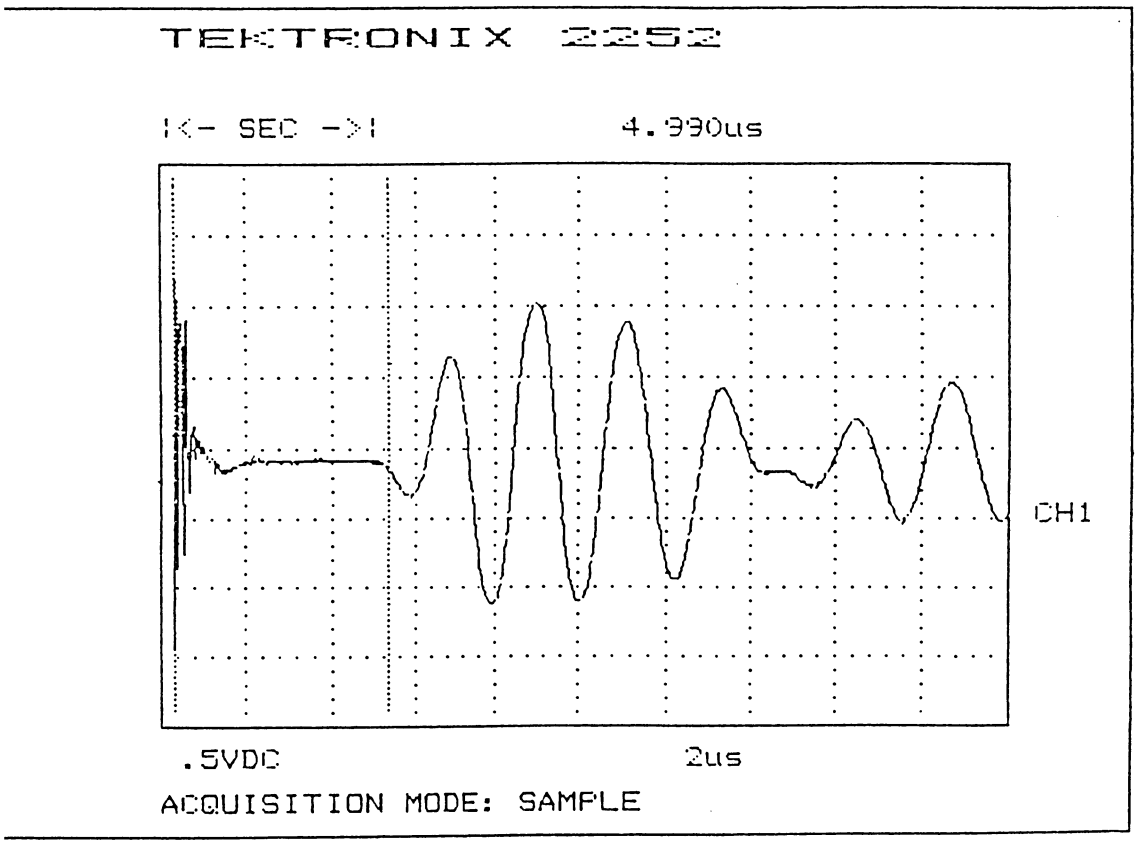

Figure 4-2. Determination of ultrasonic transit time

T = transit time of ultrasonic wave

V = ultrasonic velocity of specimen

On the average, the ultrasonic velocities in the longitudinal (V_L), radial (V_R), and tangential (V_T) direction of undecayed ponderosa pine specimens had ratios of $V_L : V_R : V_T = 1 : 0.557 : 0.459$. Therefore, the average longitudinal velocity was about 1.8 times greater than the average radial velocity, and the average radial velocity was 1.2 times greater than the average tangential velocity. Longitudinal and transverse sound velocities differ because their respective moduli of elasticity are different. In the longitudinal direction, the principal sound wave propagation path is along the S_2 microfibrils which run helically in the cell wall with a small angle to the longitudinal axis. The S_2 microfibrils are low sound-damping media because they are highly crystalline and have high values of modulus of elasticity. When sound waves travel in the transverse direction, they must cross through micro-voids between microfibrils and through the amorphous and inelastic lignin, and therefore are subjected to a greater damping. The radial sound velocity is faster than the tangential velocity because of ray cells which have their long axis along the radial direction and because of the more regular alignment of tracheids in the radial direction. Species with more ray volume have greater radial sound velocity than those species with less ray volume. Ray tissues, however, reduce sound velocity in the longitudinal direction. For example, fir has about 5% and oak more than 20% ray volume (Paushin and C. De Zeeuw 1970), and the longitudinal sound velocity of fir is about 10% faster than that of oak (Kollmann and Cote 1968).

4.2. Fungal Decay of Wood

After the initial ultrasonic velocity measurement of each test specimen, 240 of them were exposed to the brown-rot fungus *Gloeophyllum trabeum* for various durations to obtain a wide range of amount of decay. At the end of fungal exposure, specimens were taken out of decay bottles and air-dried for 2 days before oven drying to avoid any drying defects such as checks and collapse. Eighty three specimens, including 30 controlled specimens, sustained below 5% weight loss, 43 specimens had weight loss between 5% and 10%, 71 specimens between 10% and 15%, 59 specimens between 15% and 20%, and 14 specimens had weight losses greater than 20%. Distribution of percentage weight loss of all specimens after exposing to the brown-rot fungus is shown in Figure 4-3.

Due to the nature of the soilblock method, the process of fungal decay started from the bottom of each test specimen and progressed slowly upward. On the average, it took about three weeks of incubation for fungal mycelium to cover the entire test specimen. Specimens exposed to the fungus for one week normally had less than 2.0% weight loss, and few specimens exposed to the fungus for 4 weeks sustained more than 30% weight loss. Specimens with more than 35% weight losses were excluded from these study because these specimens were severely deformed after drying, making ultrasonic measurements very difficult.

Physical appearances of decayed specimens varied with degree of decay. Specimens with less than 5% weight loss did not have noticeable physical changes. Specimens with 5% to 10% weight loss, however, showed some discoloration and shrinkage where the fungus had grown. Beyond 10% weight

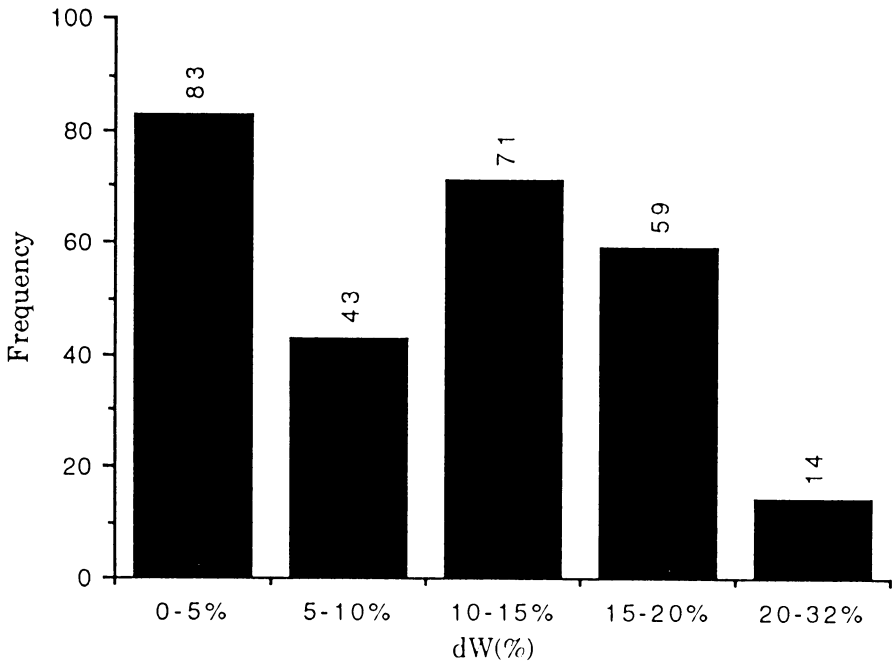

Figure 4-3. Weight loss distribution of all test specimne

losses, specimen surfaces became spongy and developed checks upon drying. All decayed specimens, especially those had more than 5% weight loss showed evident shrinkage upon drying. Just as expected, specimens with low percentages of weight loss did not show excessive longitudinal shrinkage. Specimens with more than 20% weight losses showed cross-grain checks on specimen surfaces, an indication of longitudinal shrinkage. Radial shrinkage of decayed specimens usually did not produce severe checks. Tangential shrinkage often resulted in large checks or fissures along the rays seen on the transverse surfaces. Most of these fissures along the rays ran a certain depth along the grain which would cause a great effect on ultrasonic measurements. In few cases, deformation of specimens due to shrinkage brought about some difficulties in the ultrasonic velocity measurements. In this situation, it was necessary to sand the specimens surfaces to improve the ultrasonic measurements.

4.3. Effect of Fungal Decay on Sound Velocity

An initial analysis of the effect of fungal decay on sound velocity for all specimens is shown in Figure 4-4. Between the weight loss range of 0% to 32%, correlation coefficients (r^2) were 0.762, 0.849, and 0.711 respectively for ultrasonic velocity reduction in the longitudinal (dV_L), radial (dV_R), and tangential (dV_T) direction. A multiple regression analysis taking account of sound velocity reduction in all three structural directions showed a relationship as follows:

$$dW = 0.463(dV_L) + 0.715(dV_R) + 0.131(dV_T) + .0693$$

With this relationship, percent weight loss (dW) of a decayed specimen can be

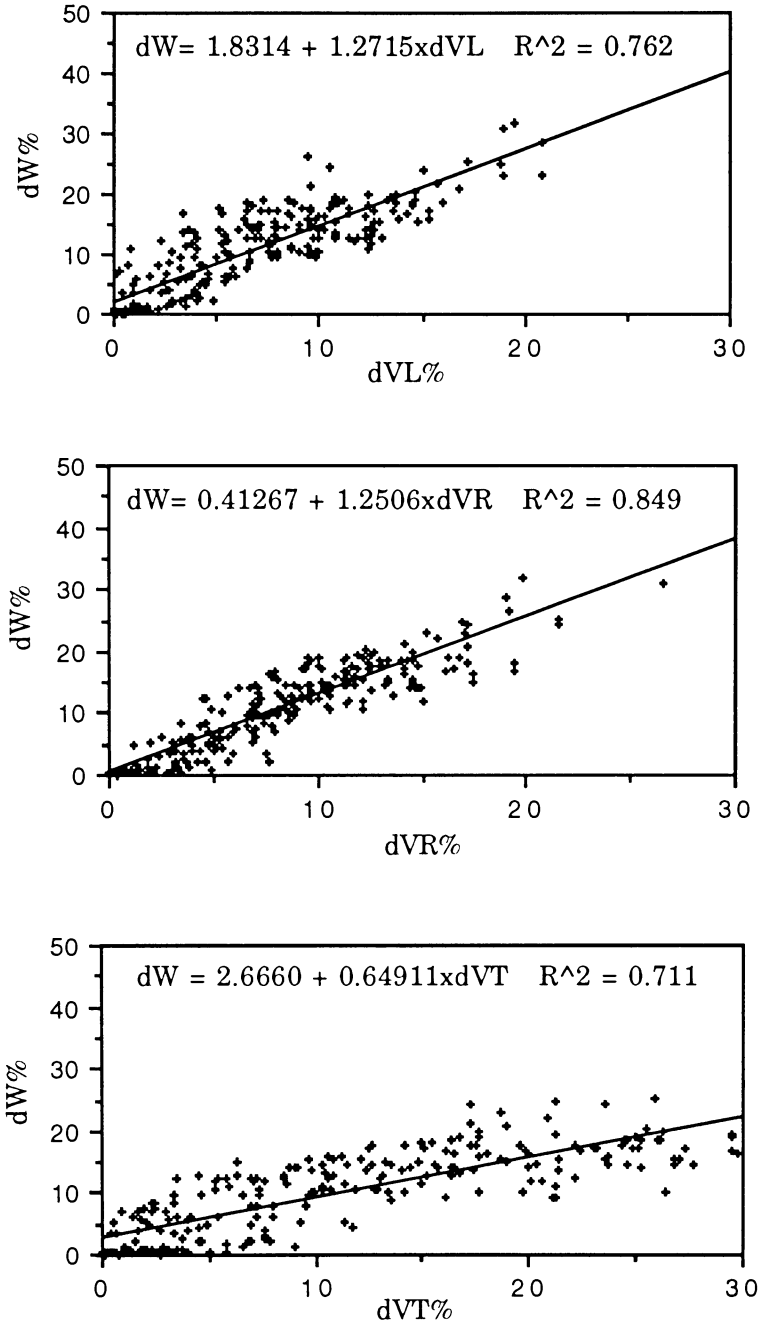

Figure 4-4. Relationship between percent wegiht loss (dW%) and ultrasonic velocity for specimens having percent weight losses 0%-32%. dVL%=percent reduction in longitudinal velocity; dVR%=percent reduction in radial velocity; dVT%=percent reduction in tangential velocity.

calculated for any percent weight loss within the range from 0% to 32% from ultrasonic measurements. Values of calculated or predicted dW and those of measured dW had a very high correlation coefficient (r^2) of 0.907 (Figure 4-5). Unfortunately, this relationship has little practical applications because of the inaccessibility problem in nondestructive tests where ultrasonic velocity in the three principal structural directions may not be all obtained.

To further examine the effectiveness of using ultrasonic velocity measurements to predict weight loss due to fungal decay, the effect of specimen weight loss on sound velocity reduction was analyzed for different specimen weight loss ranges, 0% to 5%, 0% to 10%, 0% to 15%, and 0% to 20%. Relationships between dW and dV for all weight loss ranges are shown in Table 4-1 and Figures 4-6 to 4-9, and these relationships are all significant at the 1% level. Correlation coefficients between specimen weight loss and sound velocity reduction increased with increasing ranges of specimen weight loss. Therefore, the result indicates that the higher the specimen weight loss the more effective is the ultrasonic velocity measurement to predict specimen weight loss. Results also show that the radial ultrasonic pulse velocity was more sensitive to weight loss than the longitudinal ultrasonic pulse velocity, and that the tangential ultrasonic pulse velocity had the least sensitivity to weight loss.

The most significant result of this study is that ultrasonic velocity measurements can be used to detect incipient decay. For specimens with 0% to 5% weight loss, percent weight loss and percent longitudinal ultrasonic velocity reduction had a correlation coefficient (r^2) of 0.450 which is significant at the 1% level. The regression equation (Figure 4-6) shows that for each

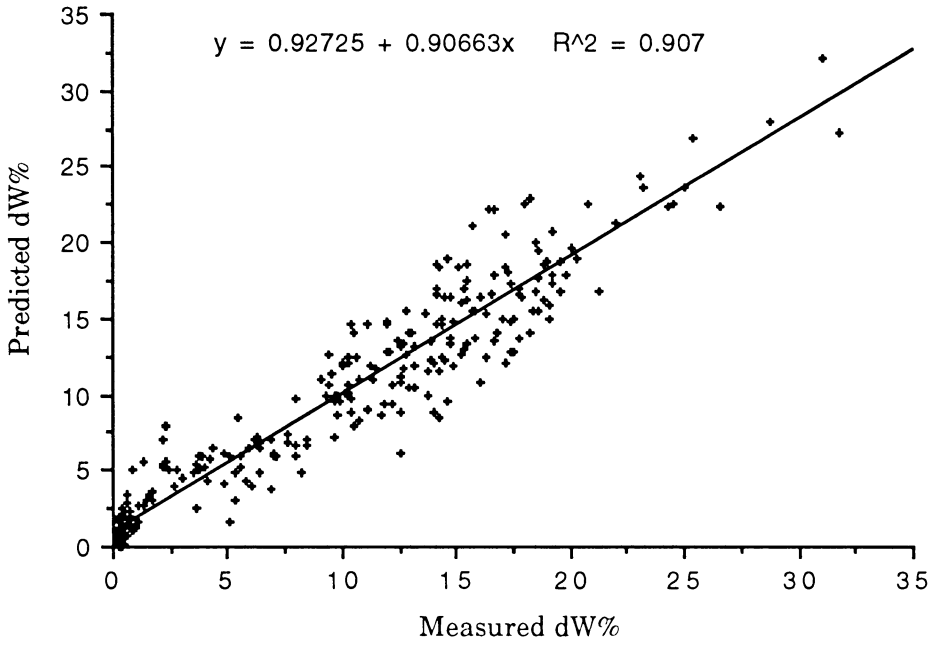

Figure 4-5. Relationship between predicated precent weight loss and measured precent weight loss for specimens weight loss ranging from 0%-32%.

Table 4-1. Correlation Coefficients (r^2) between ultrasonic velocity and different degrees of fungal decay of wood

Correlation Coefficients (r^2)* in different ranges of specimen weight loss r^2					
Velocities	0-5%	0-10%	0-15%	0-20%	0-32%
dVL	.45	.61	.68	.72	.76
dVR	.63	.76	.80	.81	.85
dVT	.28	.32	.56	.68	.71

* All correlation coefficients are significant at the 1% level

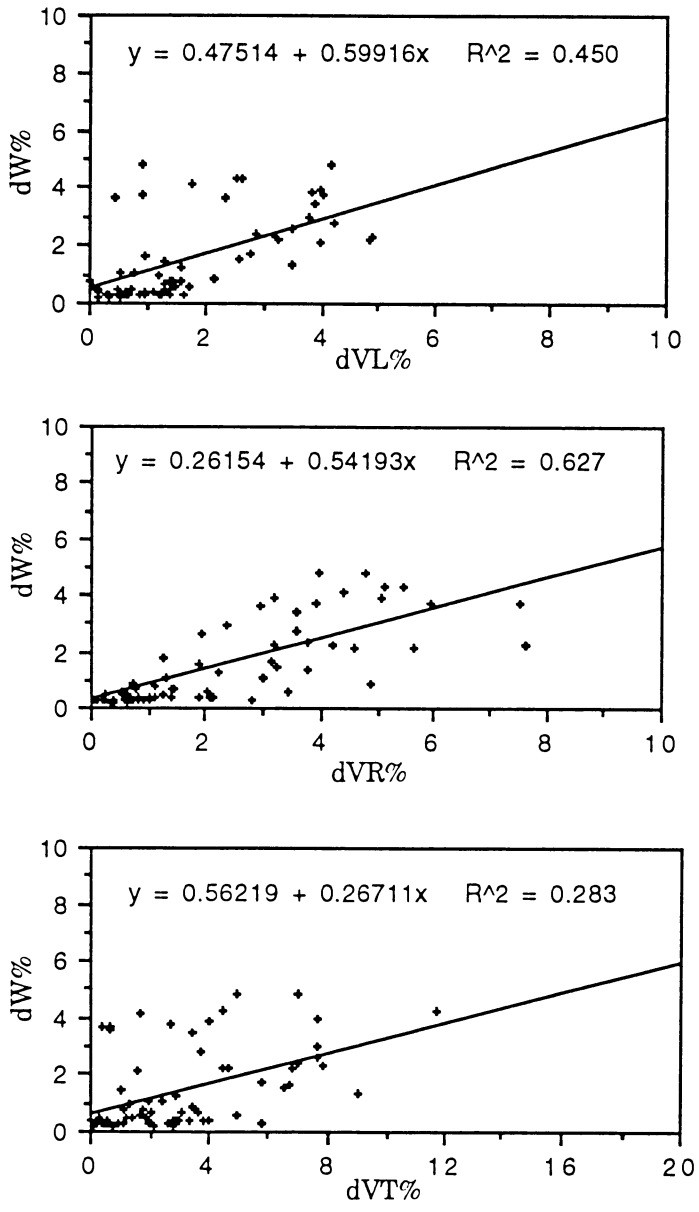

Figure 4-6. Relationship between percent weight loss (dW%) and ultrasonic velocity for specimens having percent weight losses 0%-5%. dVL%=percent reduction in longitudinal velocity; dVR%=percent reduction in radial velocity; dVT%=percent reduction in tangential velocity.

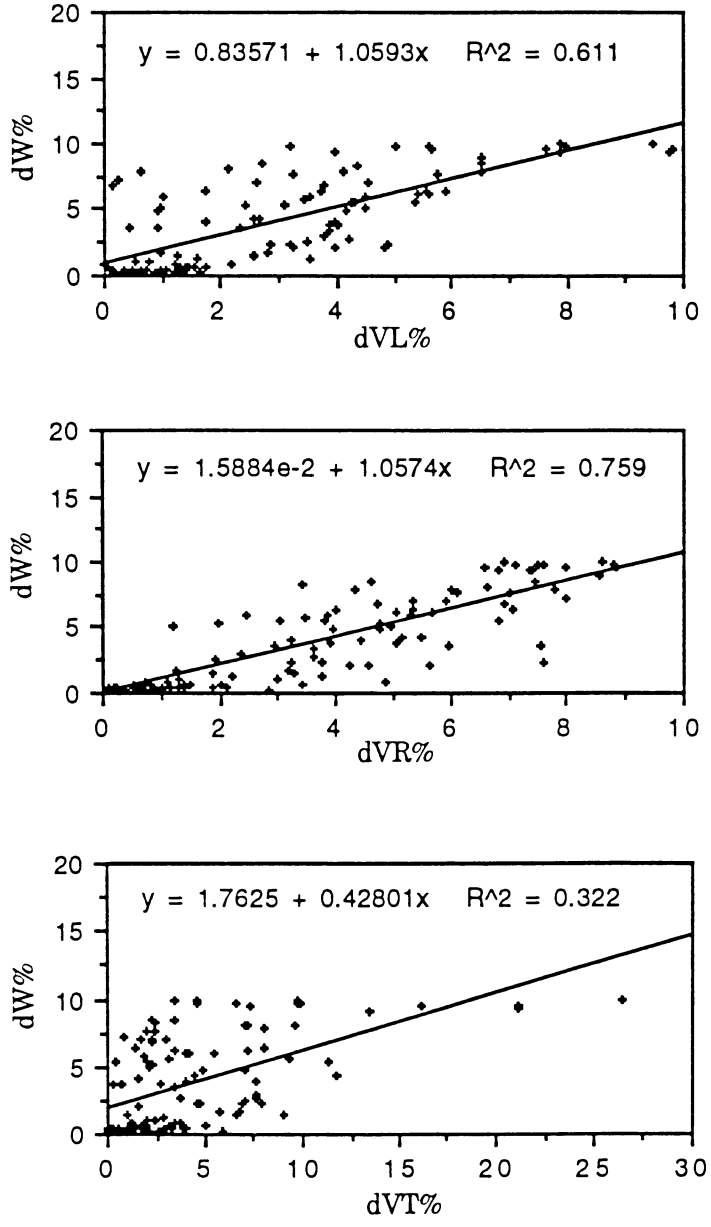

Figure 4-7. Relationship between percent weight loss (dW%) and ultrasonic velocity for specimens having percent weight losses 0%-10%. dVL%=percent reduction in longitudinal velocity; dVR%=percent reduction in radial velocity; dVT%=percent reduction in tangential velocity.

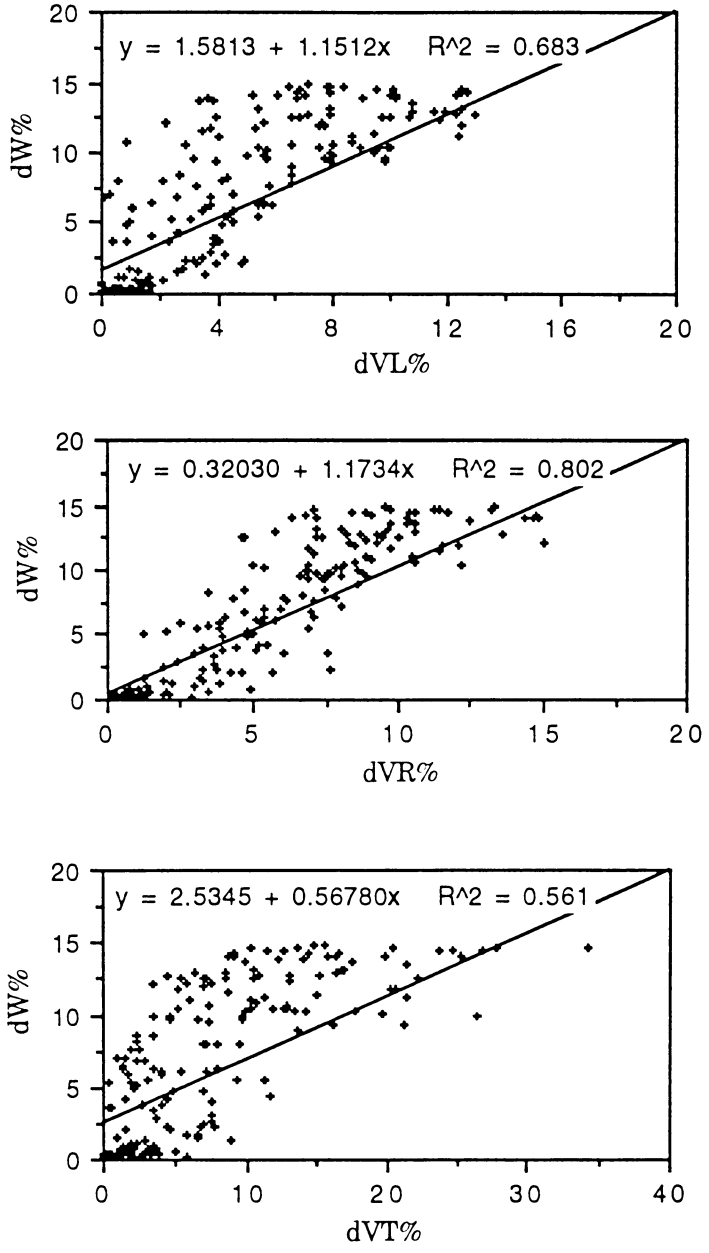

Figure 4-8. Relationship between percent weight losses (dW%) and ultrasonic velocity for specimens having percent weight losses 0%-15%. dVL%=percent reduction in longitudinal velocity; dVR%=percent reduction in radial velocity; dVT%=percent reduction in tangential velocity.

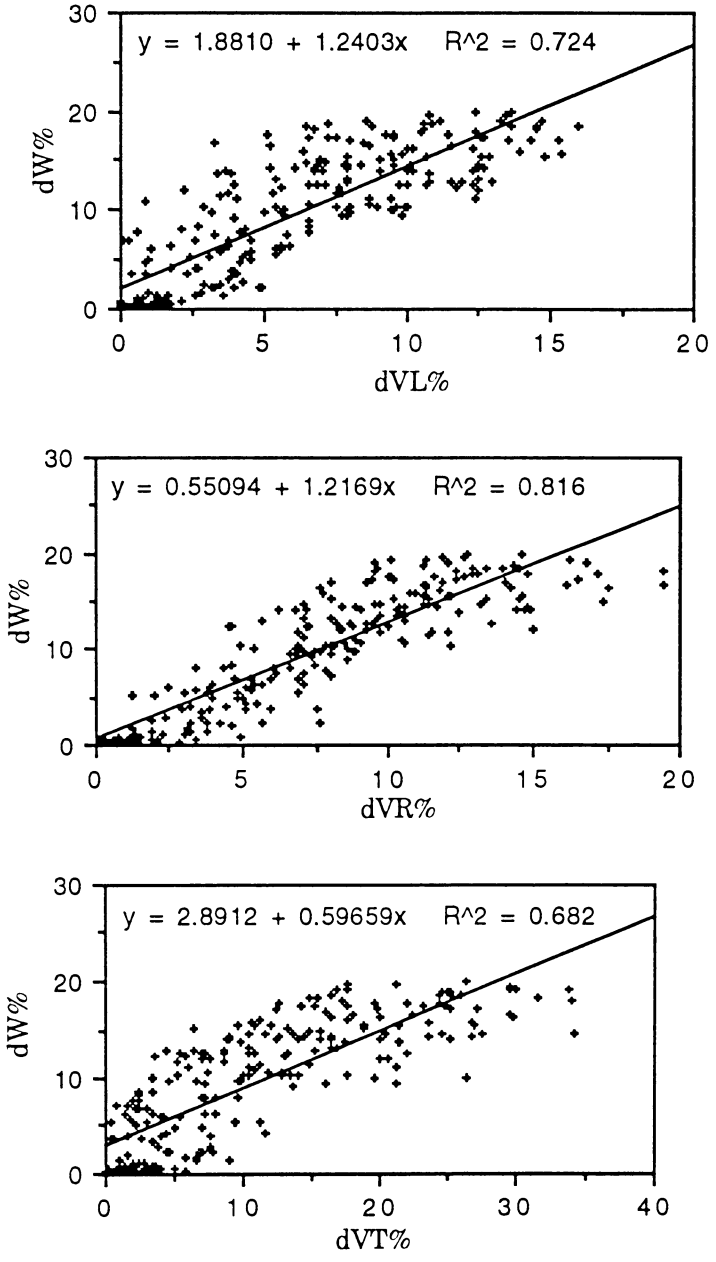

Figure 4-9. Relationship between percent weight loss (dW%) and ultrasonic velocity for specimens having percent weight losses 0%-20%. dVL%=percent reduction in longitudinal velocity; dVR%=percent reduction in radial velocity; dVT%=percent reduction in tangential velocity.

percent of specimen weight loss, the longitudinal sound velocity was reduced by 0.60%. The radial ultrasonic velocity is even more sensitive to detect early stages of decay. In the same percent weight loss range, the correlation coefficient between dW and dVR was 0.627, and the regression equation shows that the radial ultrasonic velocity was reduced by 0.54% for each percent of specimen weight loss. Although dW and dVT had a relatively low correlation coefficient ($r^2 = 0.283$), the correlation also is significant at the 1% level. Sensitivity of using ultrasonic velocity method to detect fungal decay increased considerably when specimens had more than 5% weight loss.

During the initial infestation in wood, fungi depend almost entirely on stored substances such as starch grains and other carbohydrates in rays to sustain their growth. Upon the establishment of infestation, fungi begin to release enzymes to digest cell wall components for their proliferation. Because fungi establish their infestation in rays, it is most likely that they would digest the ray cell wall first. Kuo et al. (1988) found that the brown-rot fungus *Gloeophyllum trabeum* severely destroyed cottonwood ray cell walls in the early stages of decay while fiber tracheids nearby showed very little deterioration. Because rays significantly contribute to sound transmission in the radial direction, early destruction of ray cell walls in the early stages of decay is likely to be responsible for reducing radial sound velocity. Therefore, early destruction of ray cell walls is a logical explanation for the greater sensitivity of radial ultrasonic velocity to specimen weight loss.

It is not clear why tangential sound velocity is considerably less sensitive to measure decay than longitudinal and radial sound velocity. In this study, it was found that longitudinal and radial ultrasonic velocities of undecayed test

specimens did not vary much, but tangential ultrasonic velocities had a wide range of variation. This wide range of tangential ultrasonic velocity is certainly due to internal characteristics of specimens not identified in this study. One of the possibilities is radial fissures formed during oven-drying. The radial fissure is a common drying defect for some low-density species, in which wood tissue is separated along the ray due to tangential shrinkage. Radial fissures usually occur in the earlywood and are confined within a growth ring. Radial fissures would affect sound velocity in the tangential direction more than in the longitudinal and radial directions because tangential propagation of sound waves forms a right angle with the separation plane. In this study, test specimens with low percentages of weight loss probably did not have a uniform occurrence of radial fissures, and therefore suffered a great variation in tangential ultrasonic velocity measurements. At later stages of decay, the occurrence of radial fissures became more uniform because of increasing amount of specimen weight loss.

CHAPTER 5. CONCLUSIONS

Results indicate that there is a positive correlation between ultrasonic velocity reduction and specimen weight loss due to fungal decay. The correlation increased with increasing range of specimens weight loss. For the range of 0% to 0 32% specimen weight loss, correlation coefficients (r^2) greater than 0.700 were found between specimen weight loss and reduction in ultrasonic velocities in different structural directions. A multiple regression equation was obtained to describe the relationship between specimen weight loss and ultrasonic velocities in all three principal structural directions. The measured weight loss values and predicted weight loss values calculated from the multiple regression equation showed a very strong correlation ($r^2 = 0.907$). This relationship, however, probably has little practical implication because it would probably be very difficult to measure sound velocity in all structural directions in the field.

Results also indicate that the ultrasonic velocity technique can be used to detect incipient decay with a reasonable accuracy. In 83 specimens with 0% to 5% weight losses, correlation coefficients (r^2) between specimen weight loss and reduction in longitudinal, radial, and tangential ultrasonic velocity were 0.450, 0.627, and 0.283, respectively. All these correlation coefficients are significant at the 1% level.

The radial ultrasonic velocity had a higher sensitivity to specimen weight loss caused by fungal decay than the longitudinal and tangential ultrasonic

velocities because ray cell walls are usually deteriorated at the early stages of decay. The tangential ultrasonic velocity had the least sensitivity to specimen weight loss, especially when specimens had low percentage of weight losses, probably because of occurrence of nonuniform specimen defects not related to fungal decay.

This study has shown that specimen weight loss caused by fungal decay can be measured by ultrasonic velocity through the specimen. However, physical properties of wood , including acoustical properties, vary widely between species of wood and between pieces of wood from the same tree. Therefore, for field applications of this technique, it is necessary to establish a base ultrasonic velocity measurement at any particular location in the wood member as a reference for the subsequent and periodical ultrasonic velocity measurements.

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