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Identifying Bacterially Infected Oak by Stress Wave Nondestructive Evaluation

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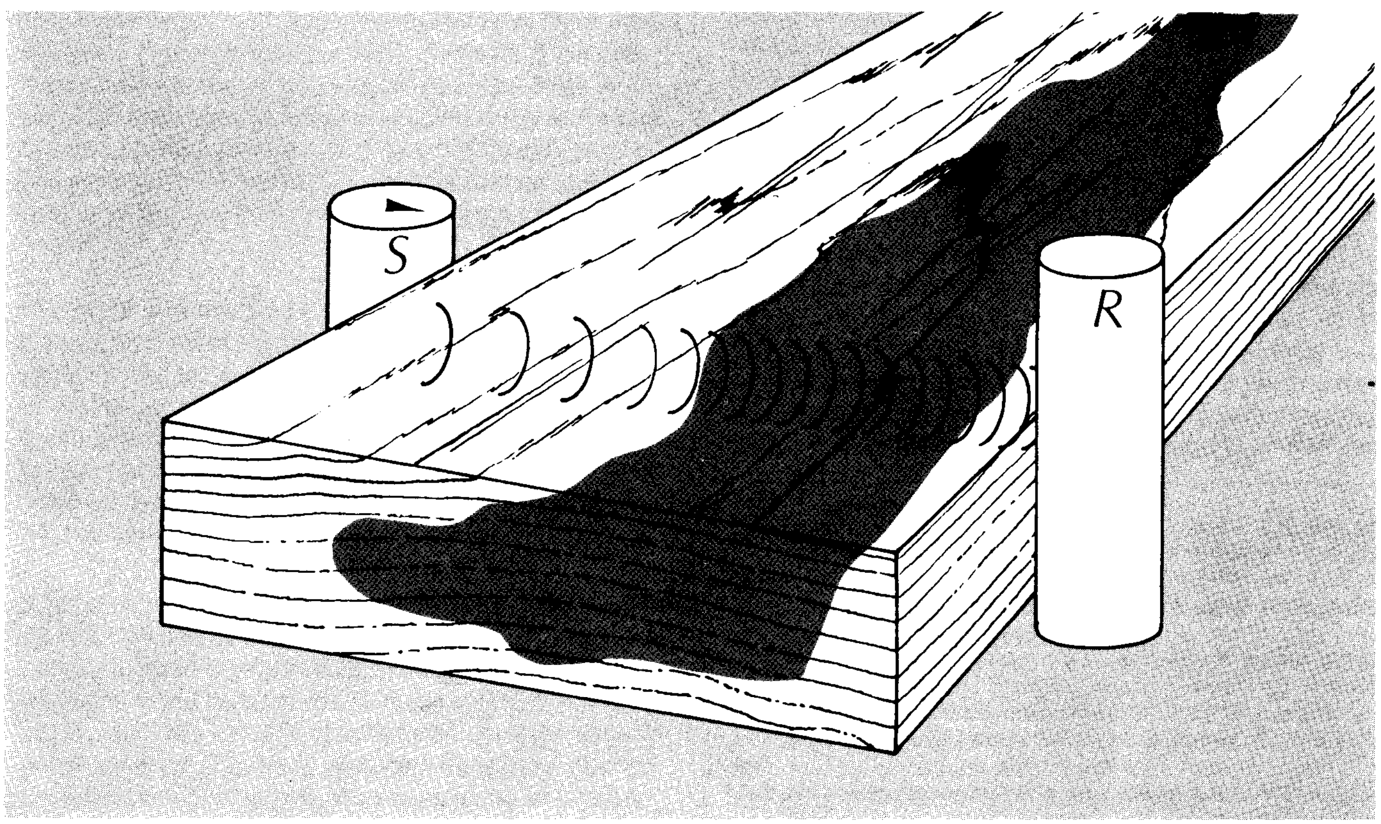

Abstract

Bacterially infected wood, called wetwood, is often not visually apparent in logs or green lumber. When kiln dried, lumber containing wetwood is prone to develop costly defects. The objective of this study was to determine the effectiveness of a stress wave nondestructive evaluation (NDE) technique to detect the presence of wetwood, thereby allowing separation of bacterially infected and noninfected lumber before kiln drying. On average, this NDE technique correctly identified 84 percent of bacterially infected red oak lumber. However, the technique was less effective on white oak, correctly identifying an average of 45 percent of the infected lumber. The difference in results between red and white oak needs to be further investigated. Because this NDE technique shows promise, especially for red oak, and because analysis is rapid, implementation of this technique into a sawmill operation needs to be examined.

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Introduction

Wetwood is an abnormal type of heartwood. Lumber containing wetwood is difficult to kiln dry without developing costly defects (Ward and Pong 1980). Wetwood develops from the infection of living trees by anaerobic bacteria, decreasing the mechanical properties of wood (Ward and Zeikus 1980). Consequently, oak lumber containing wetwood (also called bacterial oak) is more prone than normal (uninfected) oak lumber to develop honeycomb, ring shake, and deep surface checks when kiln dried under normal conditions (Ward and Groom 1983, Ward and Hart 1985).

It is difficult to recognize the presence of wetwood in lumber on the green chain during mill operation; therefore, the drying defects that develop in oak wetwood are unexpected (Ward and Groom 1983). These unexpected drying defects in oak can be costly to the hardwood lumber industry. It is not easy to differentiate between various causes for drying defects. However, the Hardwood Research Council estimates that as a result of wetwood-related drying defects in oak lumber, losses can total as much as 500×10^6 board feet (nominal 1.2×10^6 m^3) per year and cost as much as \$25 $\times 10^6$ per year (John A. Pitcher, personal communication).

Wetwood also limits the potential for lumber drying at accelerated schedules. Forest Products Laboratory (FPL) drying tests showed that accelerating kiln drying of red oak at elevated temperatures increases the incidence of honeycomb in normal lumber. However, losses from honeycomb in lumber containing wetwood were three times greater than were similar losses for normal lumber (Ward and Groom 1983).

A rapid, nondestructive evaluation (NDE) technique that can identify wetwood in oak lumber before drying could minimize these drying losses. If lumber containing wetwood could be detected and separated from normal wood, separate kiln drying schedules could be used to minimize drying defects. Wetwood in oak can now be detected with destructive, time-consuming laboratory tests, but a rapid, economical nondestructive test suitable for commercial operating conditions is needed (Ward and Hart 1985, Ward and Simpson 1987). Several techniques have been investigated. For example, Harris and Taras (1986) reported success using green density to isolate defect-prone oak lumber.

We investigated use of stress wave NDE techniques. Currently, these techniques are successfully used to evaluate the mechanical properties of a wide range of wood-based materials, and in the wood products industry, to grade veneer and evaluate wood structural components.

Background

Stress wave NDE techniques use low-stress motions to measure two fundamental material properties: energy storage and dissipation. Energy storage is manifested as the speed at which a wave travels in a material; the rate at which a wave attenuates is an indication of energy dissipation.

A commonly used technique that employs stress wave NDE technology utilizes simple time-of-transmission measurements to determine speed of sound. The technique uses a mechanically or ultrasonically induced impact to impart a wave into a specimen. Piezo-electric sensors are placed at two points on the specimen and used to sense passing of the wave. The time it takes for the wave to travel between sensors is measured and used to compute wave propagation speed.

Stress wave NDE methods are commonly used in industrial applications for testing the properties of both wood and nonwood products. With nonwood manufactured materials (i.e., metals, polymers, ceramics, composites, and concrete), much of the NDE research effort has been qualitative and directed toward detecting intrinsic material flaws that may occur in the manufacturing process. Nondestructive evaluation research and industrial applications with wood and wood-based products are concerned more with predicting the strength properties of wood than with detecting manufacturing flaws.

A review of stress wave NDE techniques and their application to wood-based materials was presented by Ross and Pellerin (1991). They noted several research studies that examined the effects that various types of biological degradation have on stress wave parameters. Results from these studies revealed that speed-of-sound transmission was sensitive to strength losses induced by fungal attack.

Stress wave NDE studies at FPL and Oregon State University evaluated the use of both impact stress wave and ultrasonic pulses to detect wetwood, sapwood, and normal heartwood in green hemlock and true fir samples and full-size dimension lumber (Ward and others 1985). Measurements made along the grain showed that impact stress wave and ultrasonic pulse measurements were effective in distinguishing heartwood boards with less than 100-percent moisture content from the heavier sapwood and wetwood boards with greater than 100-percent moisture content. No distinction could be made between wetwood and sapwood boards if their weights, or densities, were similar. Wetwood in aspen and white fir could be distinguished from sapwood by use of pulsed electric currents (Ward 1984) but this method was unsuccessful with red oak (Ward and Groom 1983).

Stress wave or other NDE tests that detect strength differences between wetwood and normal wood might be especially useful to detect wetwood containing *Clostridium.* This type of bacteria degrades pectin and the chemical bonds between wood cells (Schink and others 1981). An FPL drying study using elm reported that honeycomb and ring failure did not develop in wetwood boards that were not infected by clostridial bacteria (Boone and Ward 1977).

Mechanical tests with green wood of various species showed that wetwood can be weaker than normal wood when the results are corrected for differences in density (Haygreen and Wang 1966, Knutson 1968, MacKay 1975, Seliskar 1950, Wilcox 1968).

Because oak wetwood develops honeycomb and ring failure more readily than does normal wood during kiln drying, NDE tests to detect wetwood in oak should be designed to measure reductions in strength across the grain rather than along the grain. Honeycomb susceptibility suggests that bacterially infected oak has been weakened in strength perpendicular to the rays, and ring failure suggests a weakening at the interface of the earlywood with the latewood of the previous year.

Objectives and Scope

The objective of this study was to determine if measuring speed-of-sound transmission across the width of boards would be an effective technique to detect the presence of wetwood before kiln drying red and white oak lumber.

Experimental Procedures

Materials

Thirty-two red and white oak trees were selected from timber growing on different sites in Wisconsin, northeast Iowa, and southeast Minnesota: 18 northern red oak (*Quercus rubra* L.), 12 white oak (*Quercus alba* L.), and 2 black oak (*Quercus velutina* Lam.). During the selection process, trees and logs were screened for the presence and absence of bacterial infections. Increment cores and wood shavings were taken from the heartwood and examined for odor and color. Final tree selection was based on this inspection. Bacterially infected heartwood in red and black oaks usually had sour rancid odors, and infected white oaks had sour vinegar-type odors. Color differences between bacterially infected and normal (noninfected) oaks cannot always be noted, but sometimes infected heartwood will have a greenish cast that does not exist in normal heartwood. We used these identification techniques, because they served as a baseline in previous research. A minimum of two increment cores per tree were also aseptically removed from standing trees and later cultured for presence of bacteria in the heartwood.

Sample trees were felled and bucked into 9-ft- (2.7-m-) long logs and hauled to FPL. As shown in Figure 1, 6-in.- (140-mm-) long disks were cut from the ends of each 9-ft log leaving an 8-ft (2.4-m) log. Radial sections were cut from the log discs, wrapped in aluminum foil, and frozen. Wood specimens from the frozen sections were used later for more definitive microbial culture tests than could be made with the initial screening tests from the trees. The pattern of wetwood formation in the tree is usually pyramidal, resulting from bacterial infections that start in the roots and lower trunk and progress upwards. Therefore, the presence of bacterial infection in the disks allowed us to “map” the likely location of bacterial infection in the log (Figs. 1, 2) and make a preliminary estimate of the amount of bacterial infection from the original location of the board in the log. Figure 2 illustrates how various combinations of normal and bacterial heartwood result when boards are sawed from logs.

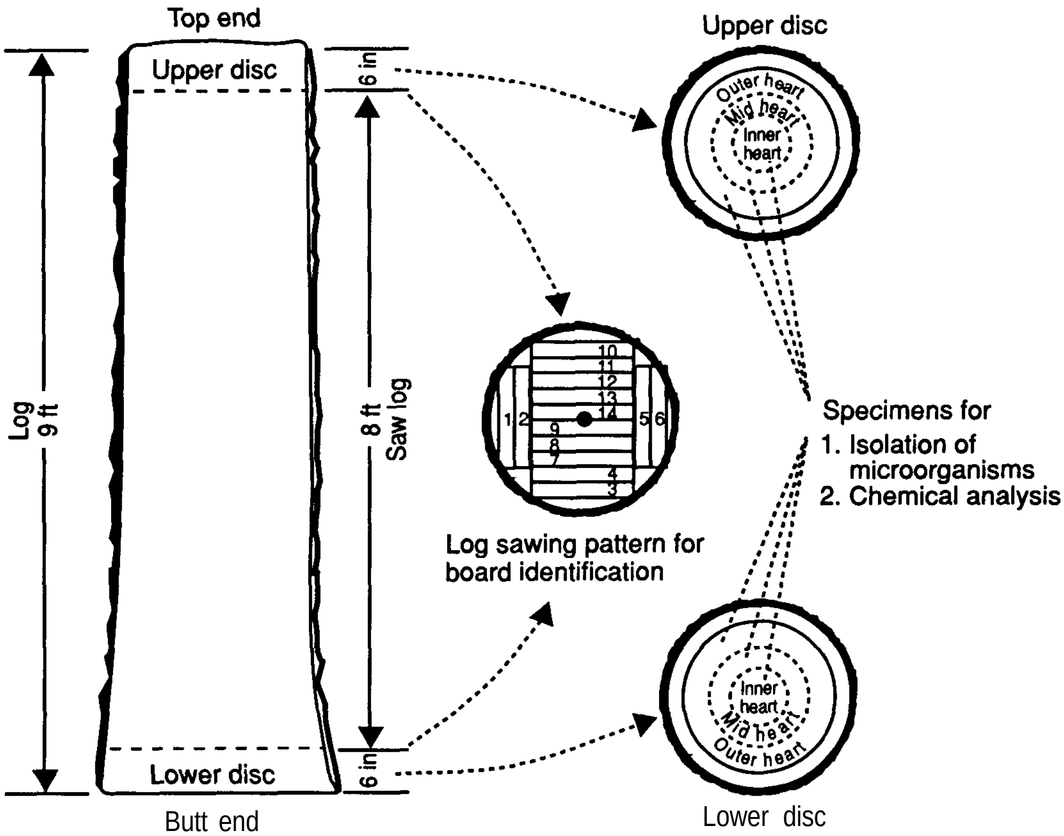

Figure l-Cutting diagram used to collect specimens from oak logs.

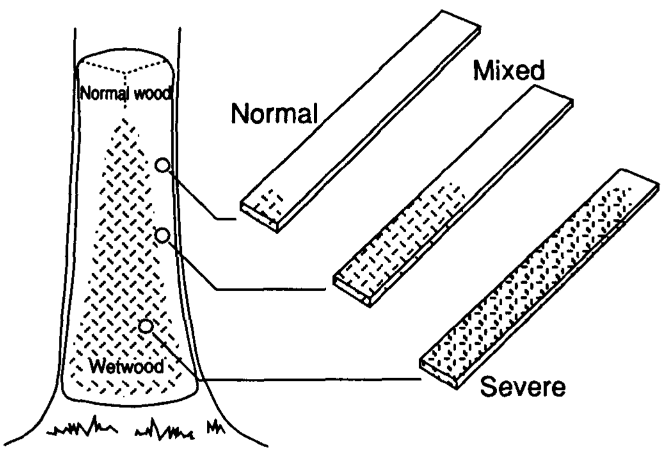

Figure 2—Example of bacterial infection pattern in a tree and the lumber obtained from it.

All 8-ft logs were sawed into 1-3/16-in.- (30-mm-) thick lumber, and FPL staff graded it according to the rules of the National Hardwood Lumber Association. Sample boards consisted of the following five lumber grades:

Firsts and Seconds (FAS), Selects (Sel), Number One Common (No. 1C), Number Two Common (No. 2C), and Number Three Common (No. 3C). The number and volume of sample boards according to species and grade are presented in Table 1. The red oak category included black oak and northern red oak boards.

Table 1—Oak boards used in NDE stress wave tests

Species	Grade	Number of boards	Volume (board feet)[a]
Red oak	FAS	59	297
	Selects	56	261
	No. 1 C	114	557
	No. 2 C	80	393
	No. 3 C	61	301
	All grades	370	1,809
White oak	FAS	30	149
	Selects	16	76
	No. 1 C	39	191
	No. 2 C	26	128
	No. 3 C	25	124
	All grades	136	668

[a]1 board foot = nominal 2.4 x $10^{-3} m^3$.

Table 2—Presence of bacterial infection by species and lumber grade[a]

Species	Grade	Total boards in grade (%)			Total volume in grade (%)		
		Normal	Mixed	Severe	Normal	Mixed	Severe
Red oak	FAS/Selects	63	13	24	62	12	26
	No. 1 C	55	11	34	55	11	34
	No. 2 C	36	20	44	35	20	45
	No. 3 C	25	21	54	23	22	55
	Ail grades	48	15	37	48	15	37
White oak	FAS/Selects	76	9	15	77	8	15
	No. 1 C	69	8	23	68	8	24
	No. 2 C	65	8	27	66	8	26
	No. 3 C	52	4	44	53	4	43
	All grades	68	7	25	68	7	25

[a]Normal boards have less than 30 percent infected heartwood; mixed boards have between 30 and 70 percent infected heartwood; severe boards have greater than 70 percent infected heartwood.

To confirm the preliminary estimates of the amount of wetwood per board, each board was examined for the presence and amount of normal heartwood and for bacterially infected heartwood. Sample boards were divided into three categories: normal, mixed bacterial, and severe bacterial. Normal boards contained less than 30 percent infected heartwood; mixed bacterial boards contained between 30 and 70 percent infected heartwood; and severe bacterial boards contained 70 percent or more infected heartwood. If there was uncertainty about the presence of infection, samples were removed for inspection by microscope and culturing.

The red oak category contained more boards with bacterially infected heartwood than did the white oak. Table 2 shows that the amount of bacterial heartwood increased with decreasing lumber grade. This occurs because clear boards in the higher lumber grades are generally sawn from the outer shell of the butt and upper log, and knotty boards in the lower grades are sawn from the interior where wetwood is more prevalent (Fig. 2).

Speed-of-Sound Transmission

We measured speed-of-sound transmission across the boards at 1-ft- (0.3-m-) intervals along the length of each green board. Stress waves were induced in the boards by impact, and the transit time measured with a commercial stress wave timing device (Fig. 3). The unit of measurement is microseconds. The effective zone of each stress wave measurement for all samples was 1-3/16-in. (30-mm) thickness and 6- to 9-in. (150- to 230-mm) width. For analysis, all measurements were expressed in microseconds across a 7.5-in. (190-mm) span of board width. Measurement accuracy was ±1 µs.

Results and Discussion

Measurement of stress wave transit time across the width of green boards ranged from 140 to more than 300 µs per 7.5-in. (190-mm) span. We found that transit times for bacterially infected heartwood of red and black oak lumber tended to be greater than 250 µs, while normal heartwood usually had times less than 250 µs. This corresponds with a stress wave speed of 2,500 ft/s (760 m/s). Differences in stress wave travel times between infected and normal wood were significantly greater than what would be expected from differences in ring orientation (McDonald 1978). However, this pattern was not as clear for white oak where stress wave transit times in infected wood were often less than 250 µs and similar to transit times for normal heartwood.

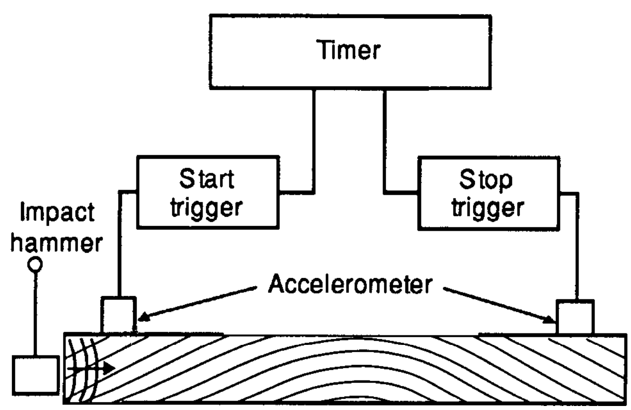

Figure 3—Technique used for measurement of speed-of-sound transmission.

Table 3—Accuracy of speed-of-sound measurements compared to previously used techniques when identifying normal and bacterially infected green lumber

				Bacterial boards[b]			
		Normal boards[a]		Mixed and severe		Severe	
Species	Grade	Total boards (number)	Correctly identified (%)	Total boards (number)	Correctly identified (%)	Total boards (number)	Correctly identified (%)
Red oak	FAS/Selects	72	100	43	72	28	82
	No. 1 C	62	98	52	83	39	92
	No. 2 C	27	93	51	90	35	100
	No. 3 C	14	93	46	89	33	97
	Ail grades	175	98	192	84	135	93
White oak	FAS/Selects	35	100	11	9	7	14
	No. 1 C	27	96	12	42	9	56
	No. 2 C	17	88	9	67	7	71
	No. 3 C	13	100	12	67	11	73
	All grades	92	97	44	45	34	56

[a]Normal boards have less than 30 percent infected heartwood.
[b]Mixed boards have between 30 and 70 percent infected heartwood; severe boards have greater than 70 percent infected heartwood.

We found that maximum transit time values for each green board usually provided a clearer distinction between boards in different wetwood categories than did the board average of the readings. Table 3 shows the relative success of wetwood identification using (1) maximum stress wave transit time values for each green board and (2) NDE classification categories greater and less than 250 µs per 7.5-in. (190-mm) width. For red oak, more than 93 percent of the normal boards and more than 82 percent of the severe bacterially infected boards were correctly identified. For white oak, more than 88 percent of the normal boards were correctly identified, but not more than 56 percent of the No. 1C severe bacterially infected boards. Successful identification of bacterially infected white oak in the No. 2C and No. 3C grades had an accuracy not greater than 71 percent. Mixed bacterially infected boards of both white and red oak were less easy to identify than were the normal boards and the severe bacterially infected boards.

Additional research is needed to explain the differences between stress wave transit times for bacterially infected heartwood of red and white oak. One explanation might be related to the differences in microbial populations between red and white oaks. Bacterial cultures from infected heartwood of red oak usually contained populations of anaerobic bacteria, such as *Clostridium* spp., *Fusobacterium* sp., *Lactobacillus acidophilus,* and *Peptostreptococcus anaerobius.* Cultures from white oak often contained unidentified microaerophilic actinomycetes. Actinomycetes are filamentous branching organisms that superficially resemble fungi but are related to true bacteria.

In the infected white oaks, the actinomycetes appeared to attack mainly extractives such as the tannins, while in the red oaks, the anaerobic bacteria appeared to attack the compound middle lamellae and the extractives. Bacterial disintegration of the middle lamella would cause a weakening of the bonds between wood cells and presumably have an effect on stress wave transit times. Anaerobic bacteria were also cultured from some infected white oaks, but usually from the inner core of the logs where the low-grade lumber was sawn.

Conclusions

Nondestructive evaluation (NDE) stress wave measurements identified bacterially infected heartwood in green, red oak lumber with an average accuracy of 84 percent. Of the severe bacterially infected red oak boards, 93 percent were identified. The average accuracy of NDE stress waves for identifying bacterial heartwood in green, white oak was much less than the accuracy for red oak (45 percent). Differences between the bacterial populations in red and white oak may be responsible for the dissimilarity of NDE stress wave measurements. Further evaluation of stress wave analysis with white oak and other species is needed. The practical effectiveness and how to integrate this technique into a sawmill operation also needs to be examined.

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