ULTRASONIC INSPECTION OF LARGE BRIDGE TIMBERS

ROBERT EMERSON*
DAVID POLLOCK*
DAVID MCLEAN
KEN FRIDLEY*
ROY PELLERIN*
ROBERT ROSS*

ABSTRACT

Timber bridges are susceptible to attack from wood decay fungi. Significant losses in wood material properties are associated with increasing decay. Therefore, timber bridges must be monitored for decay in order to maintain structural safety. Historically, decay has been identifiable in large timber structural elements only after significant losses in structural performance have occurred. Recent developments in nondestructive evaluation techniques have focused on identifying decay before large strength losses occur. For this study, an ultrasonic inspection technique was developed for identifying incipient decay in large bridge timbers. Two large bridge timbers were nondestructively evaluated via ultrasonic inspection. Relative ultrasonic wave velocity measurements were used to identify locations of moderate to advanced decay. The timbers were then dissected and the predicted internal condition compared favorably to the actual internal condition. Specimens suspected of containing incipient decay were removed from one of the bridge timbers and subjected to further ultrasonic testing followed by physical testing. The objective was to develop an ultrasonic inspection technique that can be used to identify the presence of decay before significant losses in physical properties occur. The developed technique involved transmitting ultrasonic waves through the specimen and measuring characteristics of the received signal. The characteristics of the received signal were then correlated with the physical properties of the specimen. Two main signal parameters can be used to identify decay. Wave velocity can be used to identify the presence of moderate to advanced decay but cannot be used to identify incipient decay. Relative ultrasonic wave attenuation can be used to identify incipient through advanced decay. The ability to identify incipient decay will allow for corrective action to take place before structural safety is compromised and before expensive structural repairs are required.

Timber transportation structures are generally exposed to varying and frequently harsh conditions. Over time, this exposure can lead to deterioration resulting from decay, insect attack, weathering, and mechanical damage. In turn, this deterioration may lead to a loss of structural integrity that is detrimental to the structure and its users. Nondestructive evaluation (NDE) can be used to monitor a bridge's condition and maintain structural safety.

WOOD DECAY

Given appropriate environmental conditions, wood decay fungi can cause significant damage to wood structures, including utility poles, buildings, bridges, and piles. Decay is both a physical condition and a chemical process where the wood is externally digested by enzymes and oxidants released by fungi. Decay progresses through four stages as fungi penetrate, colonize, and degrade the wood substrate. These four stages are termed incipient, early, moderate, and

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The authors are, respectively, Assistant Professor, Oklahoma State Univ., School of Civil and Environmental Engineering, 207 Engineering South, Stillwater, OK 74078-5033; Assistant Professor, Professor, Professor, and Professor Emeritus, Washington State Univ., Dept. of Civil and Environmental Engineering, Spokane St., Sloan Hall, Room 101, Pullman, WA 99164-2910; and Project Leader, USDA Forest Serv., Forest Prod. Lab., Madison, WI. This paper was received for publication in September 2000. Reprint No. 9185.

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TABLE 1. —Effects of early decay, as measured by weight loss, on wood mechanical properties (Wilcox[2]).

	Weight loss		
	2%	6%	10%
Physical parameter	Losses in physical parameter		
	- - - - - - - - (%) - - - - - - - -		
Toughness and impact bending strength	50	- -	15
Static bending (MOE)	4	66	- -
Static bending (MOR)	13 to 50	61	70
Compression perpendicular to the grain	18 to 24	48	66
Compression parallel to the grain	10	25	45
Tension parallel to the grain	23 to 40	60	- -
Shear parallel to the grain	2	- -	20

advanced. Fungi penetrate and colonize the wood during the incipient decay stage. Decay enzymes are also released from the fungi but damage is limited and cannot be seen visually. During the early stage of decay, the enzymes and oxidants released by the fungi begin to degrade the tracheid cell walls, and the wood begins to change in color, texture, and fiber brashness. The moderate stage of decay is signified by obvious color and texture changes but the gross wood structure remains intact. Wood becomes completely degraded in the advanced stage of decay. The remaining wood structure is completely fragmented and often consists of only a powdery wood residue. By the advanced stage of decay, brown rot and soft rot completely degrade the carbohydrates in the tracheid cell wall, which make up to 70 percent of the wood structure. However, white rot attacks all of the tracheid cell wall components and degrades up to 97 percent of the wood structure by the advanced stage of decay.

EFFECTS OF DECAY ON WOOD STRENGTH AND PHYSICAL PROPERTIES

Decay as measured by weight loss has significant effects on structural performance. Incipient decay, unidentifiable by weight loss, can diminish structural properties by more than 10 percent. The later stages of decay are typically classified by the amount of weight loss. Wood that contains early decay, identified by up to 10 percent weight loss, may have its mechanical properties reduced by up to 80 percent.[1] Wilcox reviewed literature on the effects of early decay on wood strength.[2] Through his review he found that early decay, as measured by weight loss, significantly affects the structural properties of wood. The results of his review are found in **Table 1.**

Decay fungi attack the strength-providing components of the wood structure. During the early stages of the fungal decay process, wood experiences significant losses in mechanical properties. Wood essentially loses all of its mechanical strength between the moderate and advanced stages of decay. In order to diminish the possibility of catastrophic failures, decay needs to be detected before these drastic losses in mechanical properties occur.

NONDESTRUCTIVE EVALUATION OF LARGE BRIDGE TIMBERS

Comprehensive *in-situ* assessment of timber bridges requires nondestructive evaluation of the individual structural elements. Ultrasonic inspection techniques were used to identify and locate decay in two creosote-treated Douglas-fir timbers. A system was developed for coupling the ultrasonic transducers to rough-sawn timbers. Then, ultrasonic waves were transmitted and collected over a grid of inspection points on each timber specimen to identify decay locations and categorize the extent of decay. Predictions based on ultrasonic inspection were made regarding the internal condition of the timbers. Then the timbers were dissected and the actual internal condition was visually compared to the predicted condition. Advanced and moderate decay were easily identified and mapped by incorporating time of flight data into contour and color gradient plots. These contour plots also show the effects of creosote treatment on ultrasonic wave velocity. Ultrasonic and physical tests were performed on small specimens removed from the timber beam. The test materials were removed from an area suspected to contain incipient and early decay.

LARGE TIMBERS

Two large, rough-sawn, creosote-treated Douglas-fir timbers were obtained from a stockpile of used timbers that had been salvaged from retired/replaced railroad bridges near Pullman, Washington. The first timber, a railroad bridge pile cap, was selected as a relatively sound creosote-treated timber based on visual inspection. The dimensions of the pile cap were 8-1/4 inches wide, 10 inches deep, and 120 inches long. Spike holes were present in this timber. The spike holes were initially considered locations for potential decay. The pile cap was subjected to ultrasonic inspection transverse to the grain. Then it was dissected to assess the actual internal condition. The second timber, an obviously decayed railroad bridge beam, was subjected to ultrasonic inspection transverse to the grain. The dimensions of the decayed beam were 8 inches wide, 14 inches deep, and 120 inches long. Extensive decay was present at one end, as shown in **Figure 1.** After ultrasonic inspection, the decayed beam was dissected to assess the actual internal condition. Smaller specimens were then removed from the wood adjacent to the decayed area for further study. These small specimens were individually subjected to ultrasonic inspection followed by compression perpendicular-to-the-grain testing in accordance with ASTM D 143.[3] Compression perpendicular-to-the-grain tests were employed for two reasons. First, timber bridge flexural elements commonly fail at the supports due to compression perpendicular to the grain failure of decayed wood. Second, limited data exist on the effects of decay on perpendicular-to-the-grain strength.

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[1] Forest Products Laboratory. 1987. Wood Handbook: Wood as an Engineering Material. Agri. Handb. 72. USDA Forest Serv., Washington, DC. pp. 4-2 to 4-44.

[2] Wilcox, W.W. 1978. Review of literature on the effects of early stages of decay on wood strength. Wood and Fiber 9(4):252-257.

[3] American Society for Testing and Materials. 1998. Annual Book of ASTM Standards. Vol. 04.10, Wood. ASTM D 143-94. ASTM, West Conshohocken, PA. pp. 22-52.

Figure 2. — Ultrasonic transducers and coupling materials.

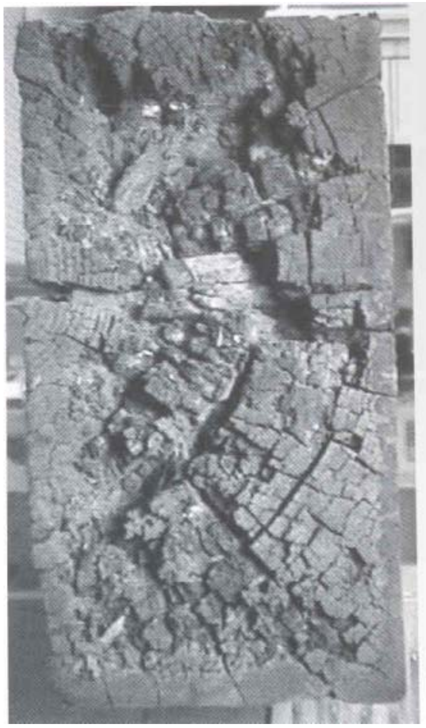


Figure 1 .— Beam with extensive decay at end.

INSPECTION OF ROUGH-SAWN CREOSOTE-TREATED DOUGLAS-FIR TIMBERS

Ultrasonic inspection of rough-sawn timbers for condition assessment requires special consideration of ultrasonic transducer characteristics, the coupling system between the transducers and the timber, and the analysis techniques used to interpret the acquired signals.

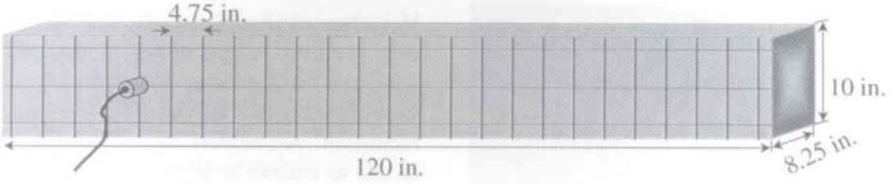
Ultrasonic equipment. — High-frequency ultrasonic waves attenuate rapidly in wood. Therefore, large timbers require the use of transducers in the lower ultrasonic frequency range. Panametrics 50 kHz (nominal frequency) narrowband ultrasonic transducers were used for this study. The transducers had a peak frequency of 40 kHz with a half bandwidth of approximately ± 9 kHz. These transducers were paired with a Panametrics model 5058PR ultrasonic pulser/receiver to transmit and receive ultrasonic signals. This particular pulser/receiver is a laboratory model capable of powering the transducers with up to 900 volts.

Coupling. —Transmission and reception of ultrasonic waves require coupling the transducers to the material under inspection. The amount of energy transferred into a material is proportional to the coupling force applied to the transducers. Coupling to smooth surfaces is relatively easy, requiring only a small amount of liquid couplant and slight finger pressure. Coupling the transducers to the rough-sawn timbers posed a few problems and was a trial and error process. Excessive amounts of liquid or gel couplant were required to effectively transmit an ultrasonic wave. The timber also absorbed the gel. Fortunately, a dry, flexible membrane couplant was found that transmitted the wave effectively. The dry couplant membrane was a thin elastomeric disk that provided adequate coupling by fitting to the contour of the rough surface of the timbers. For convenience, a thin layer of silicone gel couplant was used to adhere the dry couplant membrane to the ultrasonic transducer. The transducers and coupling materials are shown in **Figure 2.**

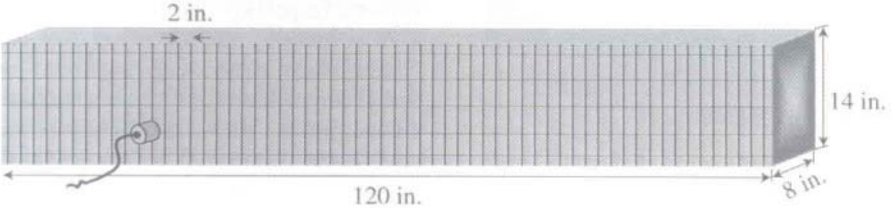
In order to provide sufficient coupling force and hands-free operation, a basic clamping jig was developed for inspection of the timber transverse to the grain. The clamping jig was composed of transducer holders, a threaded rod with washers and nuts, a clamping device, and rubber straps to keep the transducers in the holders.

Transverse ultrasonic inspection. — Transverse ultrasonic inspection involved propagating longitudinal ultrasonic waves through the width of the specimen, primarily radial to the grain, over a grid of inspection points. For the pile cap, three transverse measurements were taken along the depth at 25 locations along the length. The measurements were taken at mid-depth and at 1 - 1/2 inches from the top and bottom at 4-3/4-inch intervals along the length. For the decayed beam, 5 transverse measurements were taken along the depth at 60 locations along the length. The measurements were taken at the center and at 1-1/2 inches and 4-1/4 inches from the top and bottom at 2-inch intervals along the length. The fine grid was chosen for the 8- by 14-inch beam in order to provide a more precise assessment of wood quality in the region containing incipient decay. Graphical representations of the transverse measurement locations for each member are depicted in **Figure 3.**

Ultrasonic wave acquisition and analysis. — The ultrasonic waves were analyzed immediately after capture with a GageScope digital oscilloscope. The acquired ultrasonic waveform was analyzed to determine the wave travel times through the specimen to within 0.5 µsec. Travel time was measured as the time between the front of the trigger pulse and the start of the received ultrasonic



a) Pile cap



b) Decayed beam

Figure 3. — Inspection grids for the pile cap and decayed beam for transverse inspection.

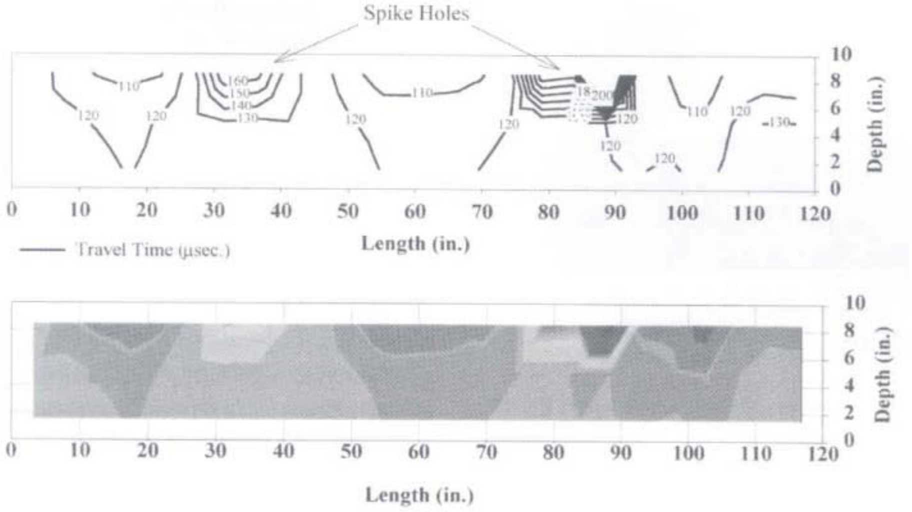


Figure 4. — Contour and color gradient plots of wave travel time through the pile cap.

signal. Relative travel time values were used to identify decay since stress waves travel slower through decayed wood than through sound wood.

Results of pile cap inspection

Ultrasonic wave travel times transverse to the grain of the timber pile cap were incorporated into contour and color gradient plots along the pile cap profile using SigmaPlot software. These plots are depicted in **Figure 4** and convey the following information. The pile cap appears to be sound, except in the immediate vicinity of the spike holes and at the ends of the timber. Longer travel times adjacent to the spike hole locations suggest potential early decay. Slightly longer travel times are present at both ends of the pile cap. These longer times were suspected to be due to heavy creosote treatment at the ends since the presence of creosote decreases wave velocity.[4]

Pile cap dissection. — After local transverse ultrasonic inspection, the pile cap was cut into *25* segments along the length. The center of each segment corresponded with an ultrasonic inspection location. Visual inspection of the *25* segments revealed the following information about the internal condition of the timber. The creosote treatment fully penetrated approximately 10 inches into the ends of the timber, as shown in **Figure 5a.** The creosote treatment penetrated approximately 3/4 inch into the surface of the timber elsewhere, as shown in **Figure 5b.** The creosote treatment accumulated into the material around the spike holes as shown in **Figure 5c.** The creosote accumulation into the material surrounding the spike holes prevented advanced decay. Visual inspection of test specimens removed from the pile cap segments revealed that the timber was sound except in the immediate vicinity of the spike holes where early to moderate decay was present.

Results of decayed beam inspection

Ultrasonic wave travel times transverse to the grain of the decayed beam were incorporated into contour and color gradient plots along the beam profile for three inspection grids using SigmaPlot software. The original inspection grid contained 300 points. These original points were positioned at five locations along the depth and spaced at 2-inch intervals along the length, providing a fine inspection grid. Contour and color gradient plots of wave travel time for the fine inspection grid are presented in **Figure 6.** Contour and color gradient plots were also developed for medium and coarse inspection grids. The medium inspection grid contained 150 points. These points were positioned at five locations along the depth and spaced at 4 inches along the length. Contour and color gradient plots of wave travel time for the medium inspection grid are presented in **Figure 7.** The coarse inspection grid contained 90 points. These points were positioned at three locations along the depth and spaced at 4 inches along the length. Contour and color gradient plots of wave travel time for the medium inspection grid are presented in **Figure 8.**

The three inspection grids provided similar information on the internal condition of the beam. The fine and medium inspection grids predict severe decay in the lower third of the left end of the beam and extending approximately

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[4] Ross, R.J., R.F. Pellerin, N. Volny, W.W. Salsig, and R.H. Falk. 1999. Inspection of timber bridges using stress wave timing nondestructive evaluation tools, A guide for use and interpretation. Tech. Rept. FPL-GTR-114. USDA Forest Serv., Forest Prod. Lab., Madison, WI. 15 pp.

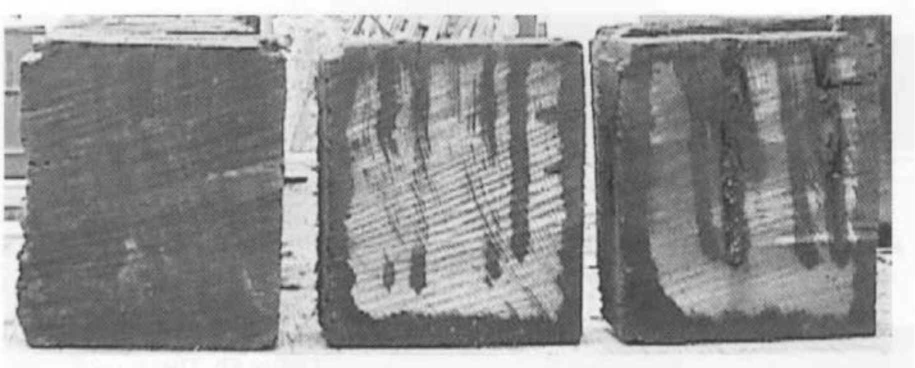

Figure 5. — Internal condition of Douglas-fir pile cap segments.

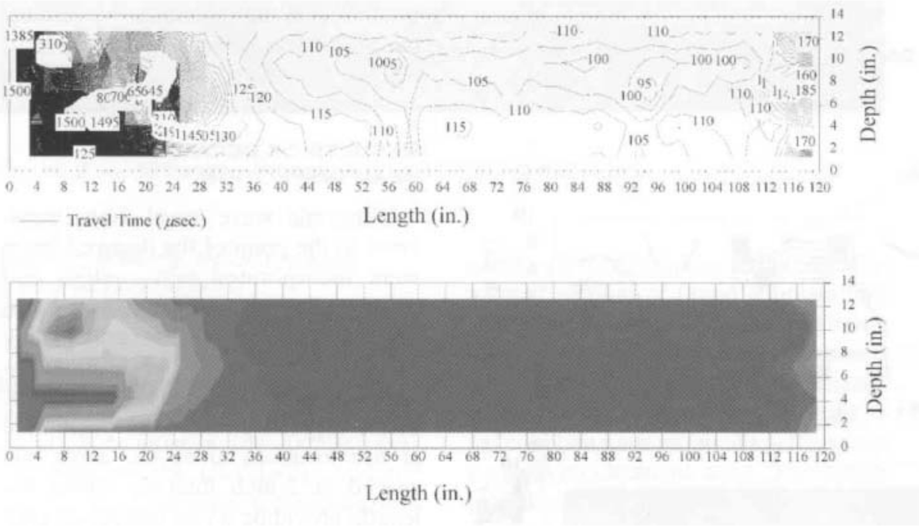

Figure 6. — Contour and color gradient plots of wave travel time through the decayed beam for the fine inspection grid.

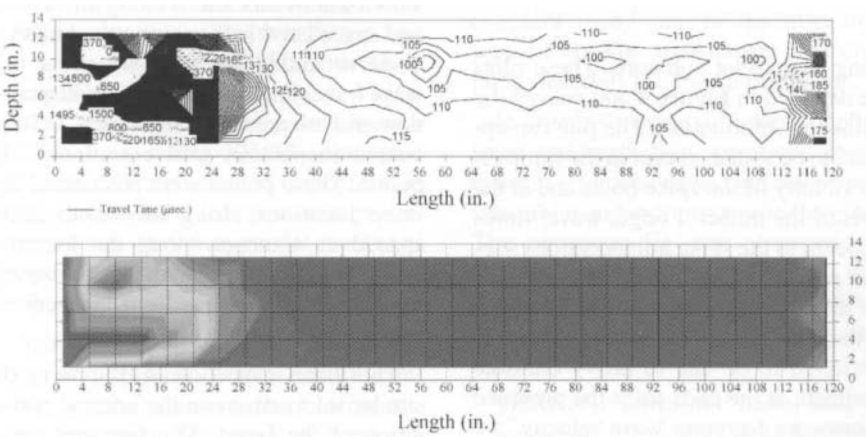

Figure 7. — Contour and color gradient plots of wave travel time through the decayed beam for the medium inspection grid.

16 inches into the beam. The coarse grid only predicts severe decay at the end. All three grids predict locations of advanced and moderate decay in the same locations. Advanced decay was predicted to extend at least 15 inches into the left end of the beam. Moderate decay was predicted to extend up to 30 inches into the left end of the beam. Ultrasonic inspection detected knots at 55 and 94 inches from the left end of the beam. These knots were confirmed by visual inspection of the beam's surface. Longer travel times were present at the end of the beam with full penetration creosote treatment.

Decayed beam dissection. — After ultrasonic inspection, the beam was dissected in order to compare the predicted condition with the actual internal condition of the beam. The beam was sawn through the depth at the middle of the 8-inch thickness. The internal condition of the decayed length of the beam is presented in **Figure 9,** with the condition predicted from ultrasonic inspection. The predicted locations of moderate through severe internal decay match nearly perfectly based on visual comparison. Incipient and early decay are very hard to identify visually. However, the good correlation between the predicted and actual visually identifiable decay locations provide reasonable evidence that the locations of early and incipient decay can be identified as well.

SPECIMEN TESTING OF THE DECAY TRANSITION ZONE

Gradually decreasing ultrasonic wave travel times suggest that the level of decay diminishes along the length of the beam. The region between advanced decay and sound wood was labeled the transition zone. This transition zone was the region between 24 and 44 inches from the decayed end of the beam.

Compression perpendicular-to-the-grain test samples were removed from the beam starting at 30 inches from the decayed end. Eight sets of four 2- by 2- by 6-inch modified ASTM D 143 test specimens were removed. **Figure 10** shows half of the specimens in their relative locations. This figure is also the key for specimen location. Each set of four specimens was considered a matched set along the length. It was predicted that the B and C specimens removed at 30 inches from the decayed end contained early or incipient decay and the rest of the material samples were composed of sound wood.

Each of the specimens was subjected to ultrasonic inspection and compression perpendicular-to-the-grain tests in the tangential direction following ASTM D 143. Ultrasonic inspection of the specimens was performed with 100-kHz broadband transducers. The broadband transducers were used instead of the 40 kHz-narrowband transducers to allow for a larger range of frequency content. It was expected that decayed wood would filter out higher frequencies and a larger frequency range would allow for larger frequency shifts to be observed. The ultrasonic signals were analyzed for velocity, peak voltage, and root mean squared (RMS) voltage in the time domain and peak frequency in the frequency domain.

Elastic modulus and stress at the proportional limit were determined from each load-displacement curve. The results from the ultrasonic and compression tests are presented in **Table 2.** The locations that were expected to contain early or incipient decay are highlighted in the table. The effects of decay were determined by comparing values at these locations with their matched sets. This was achieved by calculating the value at the expected decay location as a percentage change from the average of the values at the other three matched locations. This procedure is shown in Equation [**1**] for RMS voltage for the specimen set Left B. Left refers to which half of the dissected beam the ASTM specimen was removed from. The letter B refers to the location of specimen with respect to beam depth.

Table 3 contains the percentage changes for the specimens expected to contain early or incipient decay. The extent of decay in each specimen was estimated by comparing changes in mechanical properties between the specimens and sound wood with values found in the literature.' Based on the combination of percentage changes in elastic modulus and stress at the proportional limit, the specimens from locations Left C 30 and Right C 30 were concluded to contain incipient decay. The specimen from location Right B 30 contained early decay. The specimen from location Left B 30 contained moderate decay. It also experienced the largest changes in ultrasonic parameters.

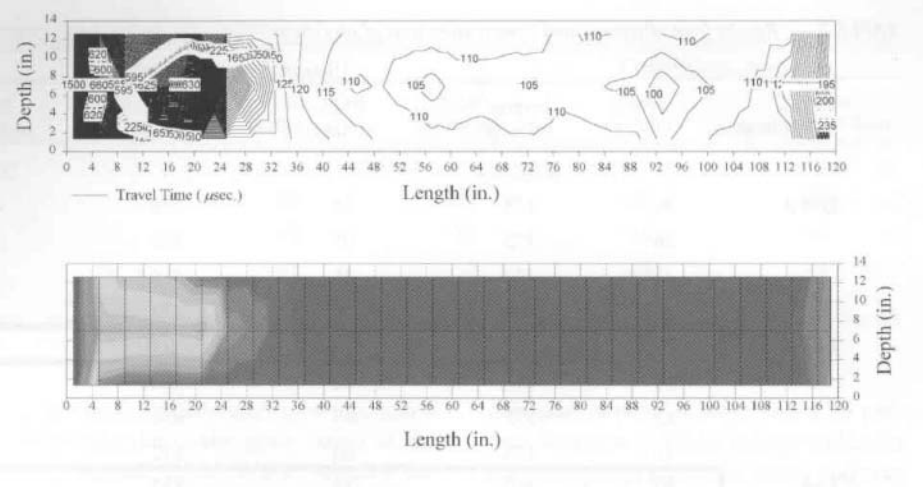

Figure 8. — Contour and color gradient plots of wave travel time through the decayed beam for the coarse inspection grid.

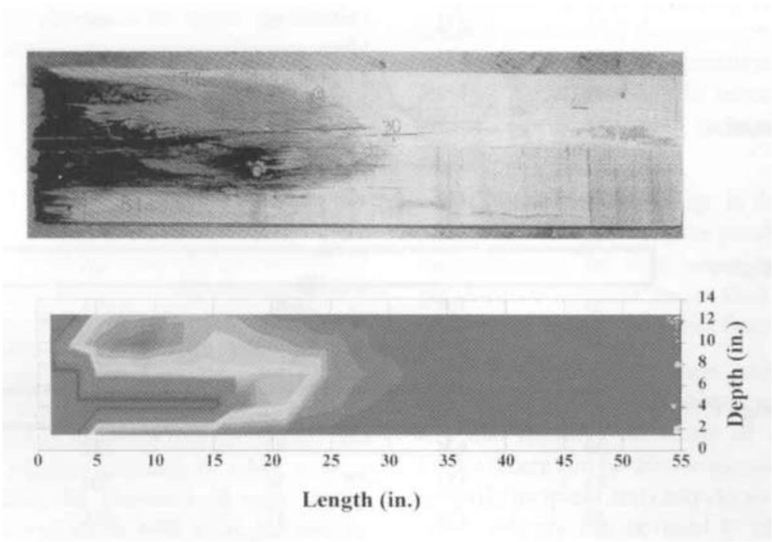

Figure 9. — Actual and predicted locations of decay.

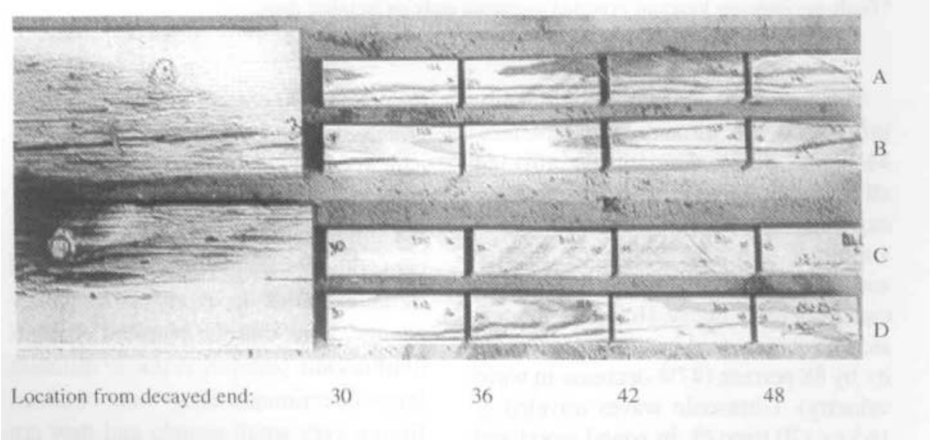

Figure 10. — Incipient decay and sound wood specimens removed from decayed beam.

TABLE 2. — Results from ultrasonic and compression tests of specimens.[a]

		Ultrasonic parameters				Compression parameters	
Location		Inverse velocity	RMS voltage	Peak voltage	Peak frequency	Elastic modulus	Stress at proportional limit
		(µsec./ft.)	- - - - - - - - - - - (mV) - - - - - - - - - - -		(kHz)	- - - - - - - - - - - (psi) - - - - - - - - - - -	
Left A	30	I73	55	536	46	74,335	1,329
	36	172	95	840	53	70,555	1,175
	42	170	55	520	36	69,007	1,294
	48	173	38	472	52	76,285	1,319
Left B	30	332	5	24	26	24,049	565
	36	176	72	856	47	64,957	974
	42	177	89	856	45	62,636	944
	48	176	60	672	44	64,754	847
Left C	30	180	35	312	38	56,189	92I
	36	181	41	456	45	66,276	1,009
	42	176	81	816	44	66,580	1,172
	48	I80	46	520	48	66,916	1,154
Left D	30	278	30	264	41	91,708	1,404
	36	171	52	464	42	91,400	1,421
	42	171	78	672	46	98,063	1,420
	48	168	36	344	39	96,955	1,305
Right A	30	165	99	880	45	99,462	1,427
	36	165	93	872	46	95,053	1,383
	42	164	93	864	48	97,726	1,422
	48	164	105	880	49	103,411	1,274
Right B	30	171	9	80	22	66,329	1,290
	36	168	87	864	47	87,385	1,222
	42	169	94	864	45	92,800	1,266
	48	171	79	816	46	94,426	1,326
Right C	30	183	12	64	23	69,954	1,207
	36	174	43	352	39	90,176	1,218
	42	I77	38	320	36	82,848	1,350
	48	174	41	384	40	86,488	1,387
Right D	30	171	51	568	48	79,464	1,348
	36	171	40	400	41	85,072	1,390
	42	166	46	416	46	90,849	1,433
	48	169	26	280	49	88,902	1,238

[a] Outlining indicates locations expected to contain early on incipient decay.

The presence of decay significantly influenced the ultrasonic parameters. Moderate decay dramatically affected all of the parameters, while incipient decay only significantly affected signal amplitude and peak frequency. Inverse wave velocity was affected little by incipient or early decay. However, moderate decay increased inverse wave velocity by 88 percent (47% decrease in wave velocity). Ultrasonic waves traveled at 165 to 170 µsec./ft. in sound wood and greater than 300 µsec./ft. in moderately decayed wood. Amplitude parameters dropped by 90 percent in early and moderately decayed wood and up to 70 percent in wood containing incipient decay. Peak frequency was affected the least, but still experienced losses up to 51 percent, although there was not a clear trend in the extent of decay versus frequency change. Note that the reported changes in ultrasonic parameters due to different levels of estimated decay were obtained from a very small sample and they are solely intended to convey the potential of the parameters.

SUMMARY AND CONCLUSIONS

Two large timbers were inspected with ultrasonic waves. Transverse ultrasonic inspection provided accurate localized information on the internal condition of both large rough-sawn creosote-treated timbers. Wave travel time was used to identify and locate zones of moderate to severe decay.

The effects of incipient and early decay on ultrasonic wave velocity, amplitude, and frequency content were studied by testing specimens removed from the area in the beam suspected to con-

TABLE 3. — Percentage changes in ultrasonic parameters and compression behavior.

		Ultrasonic parameters				Compression parameters	
Location		Inverse velocity	RMS voltage	Peak voltage	Peak frequency	Elastic modulus	Stress at proportional limit
		(% change)					
Left B	30	88	-93	-97	-43	-62	-39
Left C	30	1	-40	-48	-17	-16	-17
Right B	30	1	-90	-91	-52	-28	1
Right C	30	5	-70	-82	-40	-19	-8

tain early and incipient decay. These specimens were subjected to ultrasonic inspection and compression perpendicular-to-the-grain tests. Wave velocity was found to be primarily sensitive to moderate or greater decay. Peak voltage and RMS voltage were found to be sensitive to all levels of decay. Peak frequency was found to be sensitive to the presence of decay but without any discernible trends associated with the level of estimated decay present.

The following conclusions can be made based on the ultrasonic inspection of the large timbers and ultrasonic inspection and compression perpendicular-to-grain testing of the small number of specimens removed from the extensively decayed beam.

1. Wave velocity is a good ultrasonic parameter for identifying and quantifying moderate through severe decay but a poor indicator of incipient or early decay. A 50 percent decrease in wave velocity may indicate the presence of moderate decay and corresponds with a 60 percent decrease in elastic modulus and a 40 percent decrease in compression perpendicular-to-the-grain stress at the proportional limit. Wave velocity decreased by less than 5 percent due to the presence of incipient and early decay based on changes in material compression properties.

2. Ultrasonic peak voltage and RMS voltage appear to be better parameters for identifying and quantifying early levels of decay. However, at moderate to severe levels of decay, relative changes in amplitude parameters become negligible. Decreases in peak voltage of approximately 40 to 80 percent and decreases in RMS voltage of approximately 40 to 70 percent indicate the presence of incipient decay and correspond with a 15 to 20 percent decrease in elastic modulus and a 10 to 15 percent decrease in compression perpendicular-to-the-grain stress at the proportional limit. A 90 percent decrease in peak voltage and a 90 percent decrease in RMS voltage indicates the presence of early decay and corresponds with a 30 percent decrease in elastic modulus. A 95 percent decrease in peak voltage and a 95 percent decrease in RMS voltage indicates the presence of moderate decay and corresponds with a 60 percent decrease in elastic modulus and a 40 percent decrease in compression perpendicular-to-the-grain stress at the proportional limit.

3. Ultrasonic peak frequency is a reasonable indicator of the presence of decay, but is unreliable for quantifying the level of decay. A 20 to 50 percent decrease in peak frequency indicated the presence of decay.

4. Ultrasonic peak voltage is the best parameter for identifying the presence of incipient decay. It is more sensitive to the presence of incipient decay than ultrasonic wave velocity and peak frequency.

5. Ultrasonic peak voltage and wave velocity should be used together to identify and quantify all levels of decay. Peak voltage can be used to identify and quantify incipient and early decay while wave velocity can be used to identify and quantify moderate to severe decay.