

ULTRASONIC INSPECTION OF A GLUED LAMINATED TIMBER FABRICATED WITH DEFECTS

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ABSTRACT

The Federal Highway Administration (FHWA) set up a validation test to compare the effectiveness of various nondestructive inspection techniques for detecting artificial defects in glulam members. The validation test consisted of a glulam beam fabricated with artificial defects known to FHWA personnel but not originally known to the scientists performing the validation tests.

Ultrasonic inspection was effective for identifying voids within the glulam beam. The glulam was inspected across the width and through the depth. The inspections from each direction were combined to accurately detect and locate artificial voids in three dimensions. Wave travel time allowed identification of some of the voids, but signal amplitude parameters, such as RMS voltage and peak voltage, provided more precise location of the voids. The three-dimensional image provided valuable insight into the internal condition of the glulam. However, through-the-width inspection was able to locate voids in two dimensions along the length and depth of the glulam. For a field inspection, two-dimensional location of decay would provide sufficient information for judgments to be made on the future of the inspected specimen.

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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.

Ultrasonic testing is a proven and relatively simple method for nondestructively inspecting the interior condition of metals and composites (Bray and Stanley, 1997). An ultrasonic inspection technique was developed at Washington State University (WSU) for identifying decay in large timber structural elements. The Federal Highway Administration (FHWA) set up a validation test to compare the effectiveness of various nondestructive inspection techniques for detecting artificial defects in glulam members. The validation test consists of glulam beams fabricated with artificial defects known to FHWA personnel but not originally known to the scientists performing the validation tests.

Provided Glulam Beam

The FHWA provided one glulam beam to WSU for validation of an ultrasonic inspection technique. The $8\frac{3}{4}$ inch wide by $16\frac{1}{2}$ inch deep by 4 feet long glulam was composed of eleven $1\frac{1}{2}$ inch by $8\frac{3}{4}$ inch by 4 feet Douglas fir laminations. A photograph of the glulam member is shown in Figure 1. The glulam was manufactured with artificial defects, which are discussed later. The nature and location of the defects were not known prior to the ultrasonic inspection, but were made available to WSU after the inspection was complete.

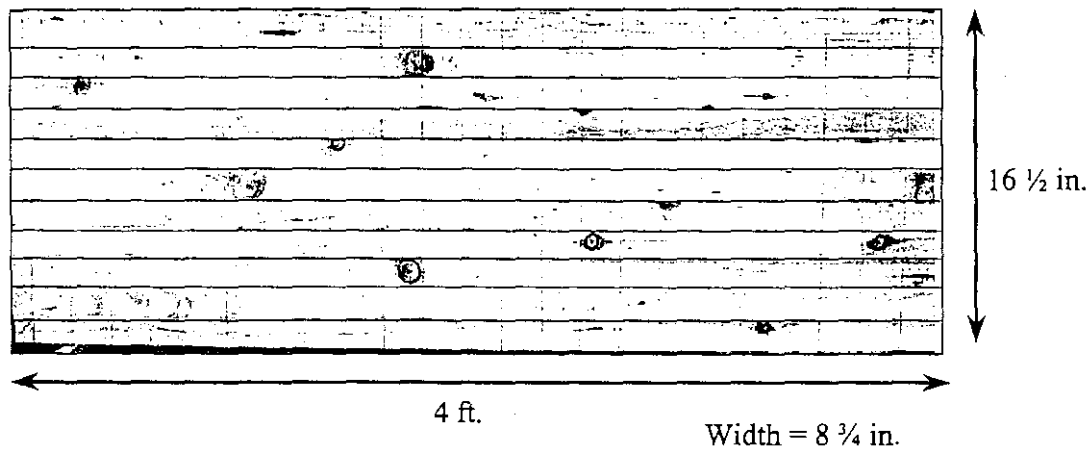


FIGURE 1 Glulam beam.

Inspection Methods

The glulam was inspected with ultrasonic waves propagated through both the width and depth of the member. All eleven laminations were inspected individually through the width, and the entire glulam was inspected at 92 locations through the depth. Ultrasonic inspections were performed every 2 inches along the length. Figure 2 shows the ultrasonic inspection locations on the top and side surfaces of the glulam member

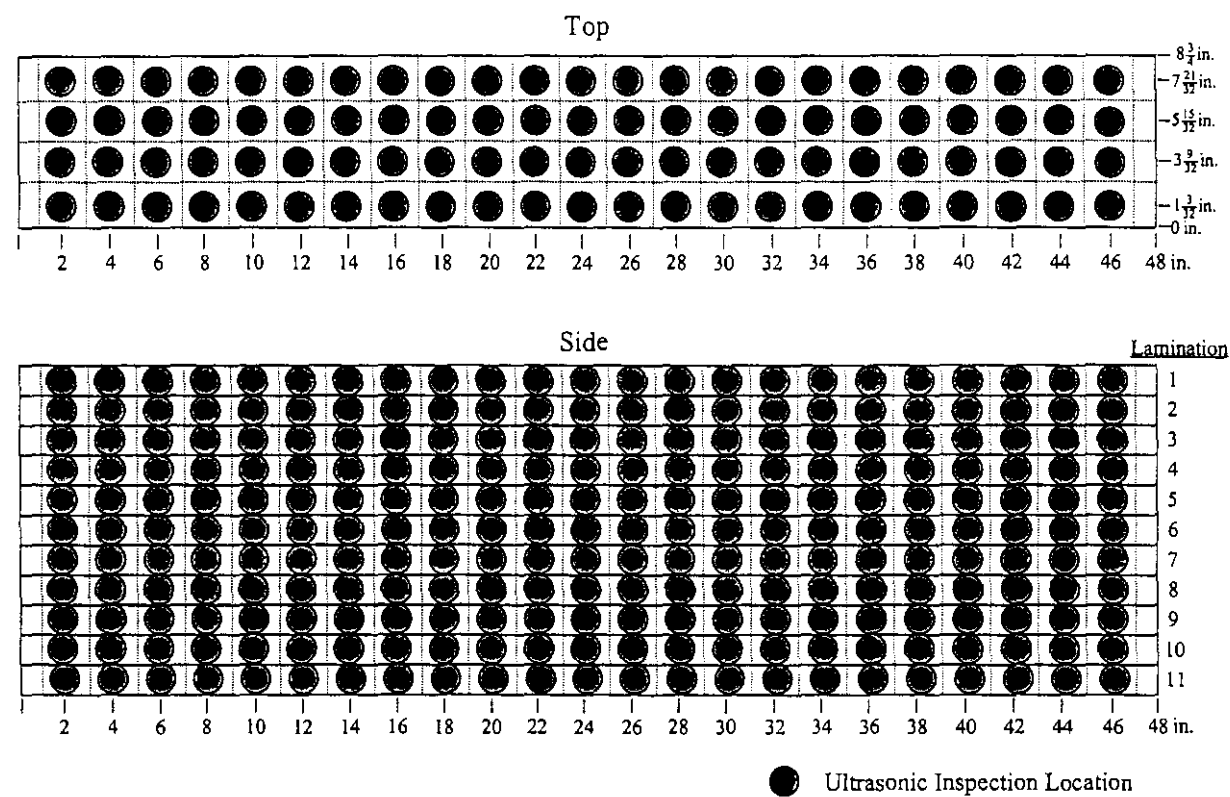


FIGURE 2 Ultrasonic inspection locations for glulam beam.

Through-transmission ultrasonic inspection was performed at each of the grid locations with commercial 1.5-inch diameter, 100 kHz broadband transducers powered by a high voltage pulser-receiver. The transducers were coupled to the glulam surface with the clamping system shown in Figure 3. The clamp had a fixed arm and a sliding arm that is controlled by a threaded rod. Scales positioned on the arms allowed the transducers to be aligned with each other. A pancake load cell was positioned behind the transducer attached to the fixed arm. Ultrasonic signal amplitude parameters are affected by coupling pressure. Coupling force was monitored via the inline load cell in order to provide consistent coupling pressure.

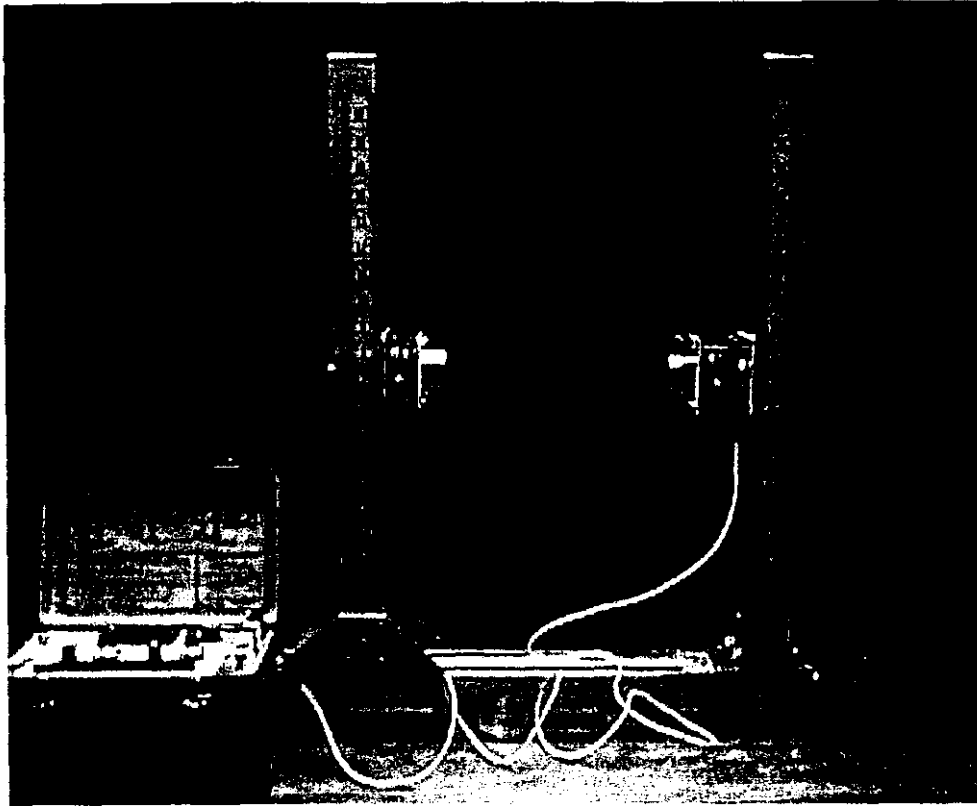


FIGURE 3 Coupling clamp with inline load cell.

Analysis

Three ultrasonic wave parameters were employed for locating voids in the glulam. Wave travel time and root mean square (RMS) voltage were used for locating voids across the width. Wave travel time and peak voltage were used for locating voids through the depth. Peak voltage and RMS voltage were both used to assess their effectiveness. Peak voltage measurements simply require the inspector to read the peak voltage from the ultrasonic signal's A-scan. RMS voltage measurements require further processing of the ultrasonic signal.

The velocity (V) of an ultrasonic wave in a material is proportional to the material density (ρ) and elastic modulus (E) as defined in Equation 1. Decay in wood decreases both the density and elastic modulus. However the elastic modulus is diminished much more rapidly than density. Consequently ultrasonic wave velocity in decayed wood will be slower than in sound wood. Wood containing early decay has diminished density and elastic modulus while maintaining the physical wood structure. Wood containing advanced decay may have voids due to complete degradation of internal wood structure. Regions of advanced decay are commonly accompanied by adjacent regions

of early decay. Artificial voids in the form of holes effectively emulate pockets of advanced decay with no adjacent regions of early or moderate decay.

$$\text{EQUATION 1} \quad V = \sqrt{\frac{E \cdot g}{\rho}} \quad g = \text{acceleration due to gravity}$$

Ultrasonic stress wave travel times alone may not adequately identify voids in the glulam since the wave may travel around a void in the sound wood. However, not all of the energy in the wave will travel around a void. Some of the energy will be reflected from the surface of a void or be attenuated by a soft material in a void and not arrive at the receiving transducer. Decayed wood will also attenuate the energy in an ultrasonic wave.

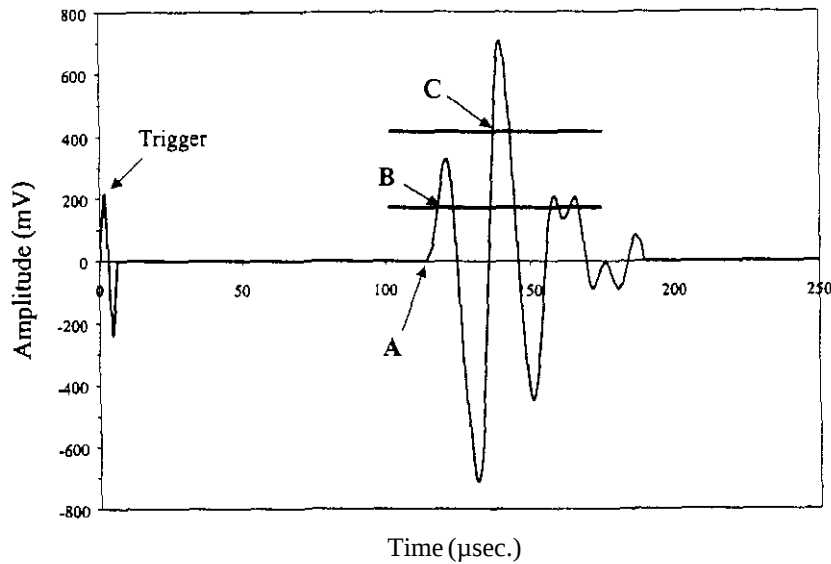
Relative comparisons of peak voltage or RMS voltage can be used to identify differences in received energy. Peak voltage is the maximum amplitude of the received wave. RVS voltage is calculated as the square root of the sum of the squares of the voltage for each data point divided by the number of data points and is presented in Equation 2. Ultrasonic signal amplitude parameters such as RMS voltage are very sensitive to transducer coupling pressure. The previously described coupling clamp provided consistent transducer coupling pressure.

$$\text{EQUATION 2} \quad \text{RMS Voltage} = \frac{\sqrt{\sum \text{Voltage}_i^2}}{n} \quad \text{Voltage} = \text{signal amplitude}$$

Artificial voids in the form of holes in wood may affect ultrasonic wave velocity in two ways. A vacant hole may reflect the some of the wave energy and force the remainder of the wave energy to travel around the hole resulting in a longer travel path. Therefore the received wave will contain less energy and have a slower apparent velocity due to the vacant hole. A hole filled with a material softer than wood has two potential effects on wave velocity. First, the wave may reflect at the surface of the filled hole just as it would for a vacant hole. Second, the wave may travel directly through the softer material. The wave's energy would attenuate in the softer material. The wave velocity would be slower through the softer material, thus increasing the time it takes for the wave to arrive at the receiving transducer.

Two other factors were taken into account when using ultrasonic wave velocity to inspect the glulam member. First, each lamination had different material properties and growth ring orientations affecting wave velocity. Therefore, relative comparisons of travel times within a lamination were used to identify probable void locations. However, the possibility of the ultrasonic wave travelling faster through the adjacent lamination(s) may provide a faster apparent wave velocity for the lamination under current inspection. Second, local material variations affect wave velocity. These variations include knots and the altered ring patterns around them. Knots have varying effects on wave propagation (McDonald, 1978). For this glulam inspection, knots were identified on the surface and their locations were accounted for during signal analysis.

Variances in ultrasonic wave travel times were expected to reveal the locations of the internal voids. Reported stress wave velocities for sound Douglas fir typically range from approximately 0.036 in./ μ sec to 0.066 in./ μ sec depending on growth ring orientation (Ross et. al., 1999). Based on this, stress wave travel time for the sound locations of the glulam should be expected to range from 132 μ sec to 243 μ sec through the 8 $\frac{3}{4}$ inch width and 250 μ sec to 458 μ sec through the 16 $\frac{1}{2}$ inch depth. However, ultrasonic wave travel times were less than these expected stress wave travel times. Ultrasonic wave travel times ranged from 85 μ sec to 126 μ sec through the width and 204 μ sec to 330 μ sec through the depth. The differences between the obtained ultrasonic wave travel times and the expected stress wave travel times are due to differences in equipment and potential differences between the wood samples. Figure 8.3.1 shows how the different equipment determine wave travel time. Ultrasonic wave travel time determined from a captured ultrasonic signal allows the travel time to be measured from the initial trigger to the exact time the signal is received, as shown by label A. Conventional stress wave timers rely upon the signal amplitude exceeding a certain threshold to stop the timer. The required amplitude arrives after the leading edge of the stress wave resulting in a longer reported wave travel time. The reported travel time is also dependent on the threshold of the gate. Two scenarios for determining stress wave travel time are depicted by labels B and C in Figure 4.



- A. Travel time determined by leading edge of signal
- B. Travel time determined by signal crossing lower threshold gate
- C. Travel time determined by signal crossing upper threshold gate

FIGURE 4 Example A-scan showing variation in wave travel time determination.

Locations containing voids were expected to be identified by longer ultrasonic wave travel times. Large voids could effectively block the signal completely or force a longer travel path resulting in no received signal or an extremely longer wave travel time, respectively. Smaller voids may force a longer travel path resulting in a longer wave travel time or not be seen at all depending on the positioning of the ultrasonic transducers and the wavelength of the ultrasonic wave in the material. Voids smaller than the wavelength may be missed by the ultrasonic wave. Ultrasonic wavelength is dependent on the frequency of the wave and the velocity of the wave in the material as shown in Equation 3. Based on the average travel time of 85 μsec , 8 $\frac{3}{4}$ inch travel path, and 100 kHz probes, the expected wavelength of the ultrasonic waves propagated through the glulam is 1.03 inches. Therefore, voids in the glulam smaller than 1 inch would be expected to be hidden to ultrasonic inspection.

$$\text{EQUATION 3} \quad \lambda = \frac{C}{f} \quad \lambda = \text{wavelength}, C = \text{wave velocity}, f = \text{frequency}$$

Through-the-Width Inspection*Wave Velocity Based Inspection*

Algorithms involving comparisons of ultrasonic wave travel times were used to identify possible and probable void locations within a lamination. Possible void locations were identified when the local wave travel time exceeded a threshold value. The wave travel time threshold value for identifying possible void locations was equal to the minimum travel time for the lamination plus ten microseconds. Ten microseconds were selected to approximate ten percent of the average wave travel time for all of the laminations. Probable void locations were identified by two methods. First, probable void locations were identified where the local wave travel time exceeded a threshold time equal to the minimum travel time for the lamination plus fifteen microseconds. Fifteen microseconds were selected to approximate fifteen percent of the average wave travel time for all of the laminations. Second, probable void locations were identified where the local wave travel time was at least five microseconds longer than at an adjacent inspection location. Five microseconds were used to approximate five percent of the average wave travel time for all of the laminations. Percentage changes in travel times were selected based on research involving matched control and decayed pairs of small clear Douglas fir specimens. These changes were found to be a reasonable identifier of early decay. Possible and probable void locations were identified when knots were and were not accounted for. When knots were accounted for, the inspection locations containing knots were not used in determining the minimum wave travel time for the lamination or in adjacent inspection location comparisons. Two plots were developed for each lamination: one not accounting for knots and one accounting for knots. A representative plot of relative wave travel time within each lamination is presented in Figure 5 for lamination three. The yellow area indicates the location and size of a knot visually identified on the surface of the glulam. The green lines represent the minimum wave travel time plus ten microseconds threshold used to identify possible void locations. The blue lines represent the minimum wave travel time plus fifteen microseconds threshold used to identify probable void locations. The red dashes represent probable void locations identified when the local wave travel time was at least five microseconds greater than at an adjacent inspection location.

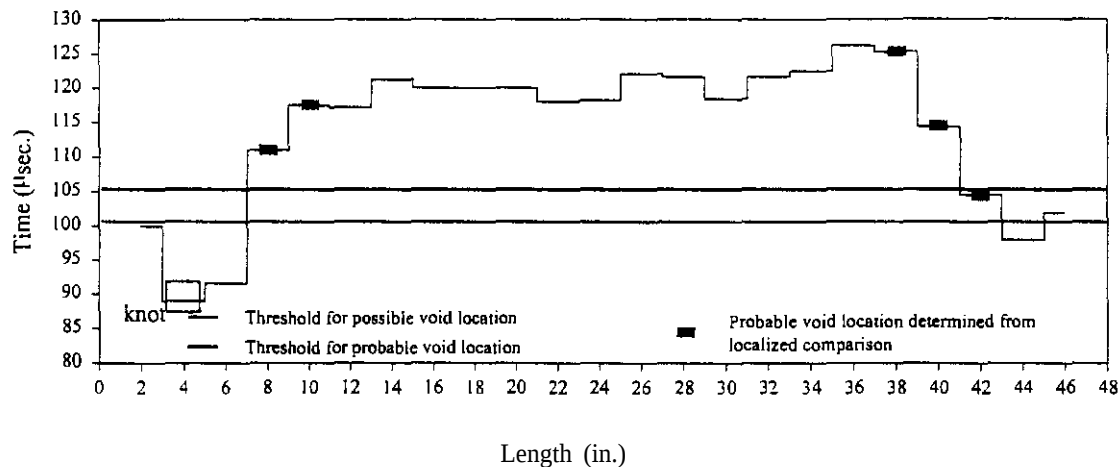


FIGURE 5 Ultrasonic wave travel time for lamination three accounting for knots.

Wave Amplitude Based Inspection

Algorithms involving comparisons of RMS voltages were used to identify possible and probable void locations within a lamination. Possible void locations were identified when the local RMS voltage dropped below a threshold value. The RMS voltage threshold value for identifying possible void locations was selected to equal fifty percent of the maximum RMS voltage for the lamination. Probable void locations were identified by two methods. First, probable void locations were identified where the local RMS voltage dropped below a threshold value equal to the twenty-five percent of the maximum RMS voltage for the lamination. Second, probable void locations were identified where the local RMS voltage was less than or equal to fifty percent of the RMS voltage at an adjacent inspection location. Percentage changes in signal amplitude were selected based on research involving matched control and decayed pairs of small clear Douglas fir specimens. These changes were found to be a reasonable identifier of early decay. Possible and probable void locations were identified when knots were and were not accounted for. When knots were accounted for, the inspection locations containing knots were excluded from RMS voltage comparisons for adjacent inspection locations.

Two plots were developed for each lamination: one not accounting for knots and one accounting for knots. A representative plot of relative RMS voltage within each lamination is presented in Figure 6 for lamination 3. The yellow area indicates the location and size of a knot visually identified on the surface of the glulam. The green lines represent the fifty percent of maximum RMS voltage threshold used to identify possible void locations. The blue lines represent the twenty-five percent of maximum RMS voltage threshold used to identify probable void locations.

The red dashes represent probable void locations identified when the local RMS voltage was at least fifty percent less than the RMS voltage at an adjacent inspection location.

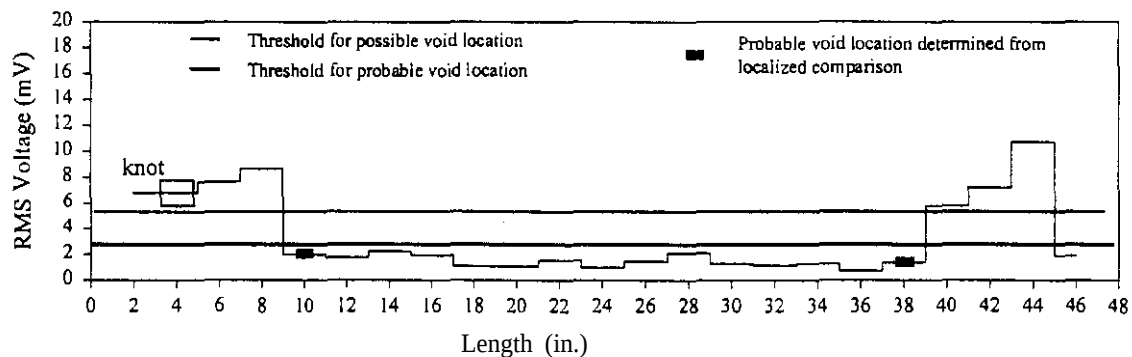


FIGURE 6 Ultrasonic wave RMS voltage for lamination three accounting for knots.

Velocity and Amplitude based Inspection

Analyses of across-the-width ultrasonic inspections for each lamination were combined to assess the condition of the glulam as a whole. Six different combinations were developed for identifying void locations within the glulam. Ultrasonic wave travel time and RMS voltage information for each lamination were assessed individually and then combined. These three different combinations were developed not accounting for knots and then again accounting for knots. The locations of predicted voids identified from combination of ultrasonic wave travel times and RMS voltages accounting for knots are presented in Figure 7. This figure is provided to represent the most robust inspection provided by the six combinations. The green areas represent possible void locations identified by the local ultrasonic parameter crossing the threshold value. Red areas represent probable void locations identified by either the local ultrasonic parameter crossing the threshold value or by comparing the local ultrasonic parameter with parameters of adjacent locations.

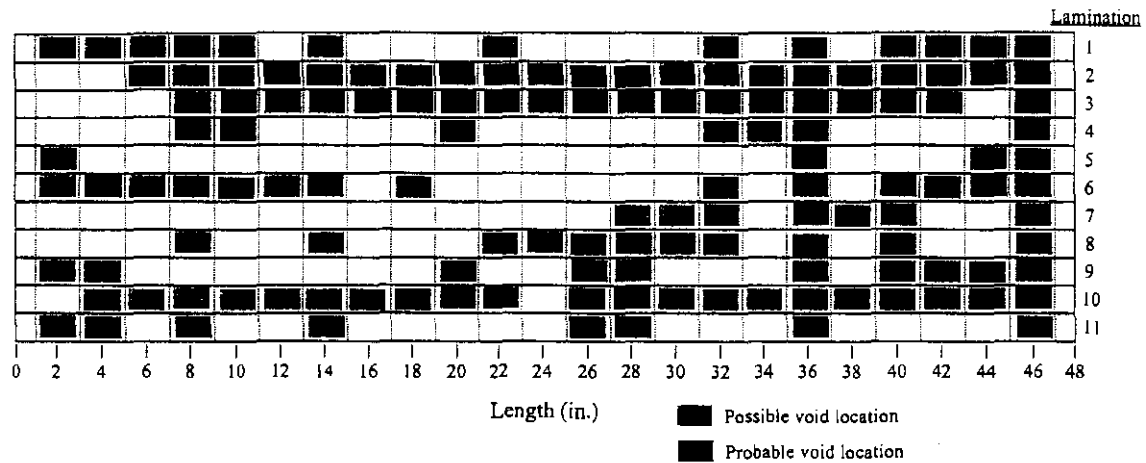


FIGURE 7 Locations of predicted voids identified from combination of ultrasonic wave travel times and RMS voltages accounting for knots.

Through-the-Depth Inspection

Interpretation of ultrasonic inspection data acquired through the depth of a glulam is more straightforward than interpreting the data acquired through the width since a wave travelling through the depth of the glulam is exposed to all laminations. Ultrasonic data obtained at one through-the-depth inspection location can be compared with ultrasonic data obtained from all other through-the-depth inspection locations. Travel time and peak voltage were used for analyzing ultrasonic waves passed through the depth of the glulam. Measurements of each parameter are graphically presented as a contour plot and a color gradient plot overlaid on a top view of the glulam beam. Through-the-depth travel times are illustrated in Figure 8. The graphs may be interpreted as follows. Larger contour values represent longer travel times. The areas with longer travel times represent locations where voids probably exist. This is also displayed in the color gradient plot. The blue area represents sound regions of the glulam. The teal area represents a predicted void that occupies a small portion of the depth. The green, yellow, orange, and red areas represent predicted voids that occupy a larger percentage of the depth.

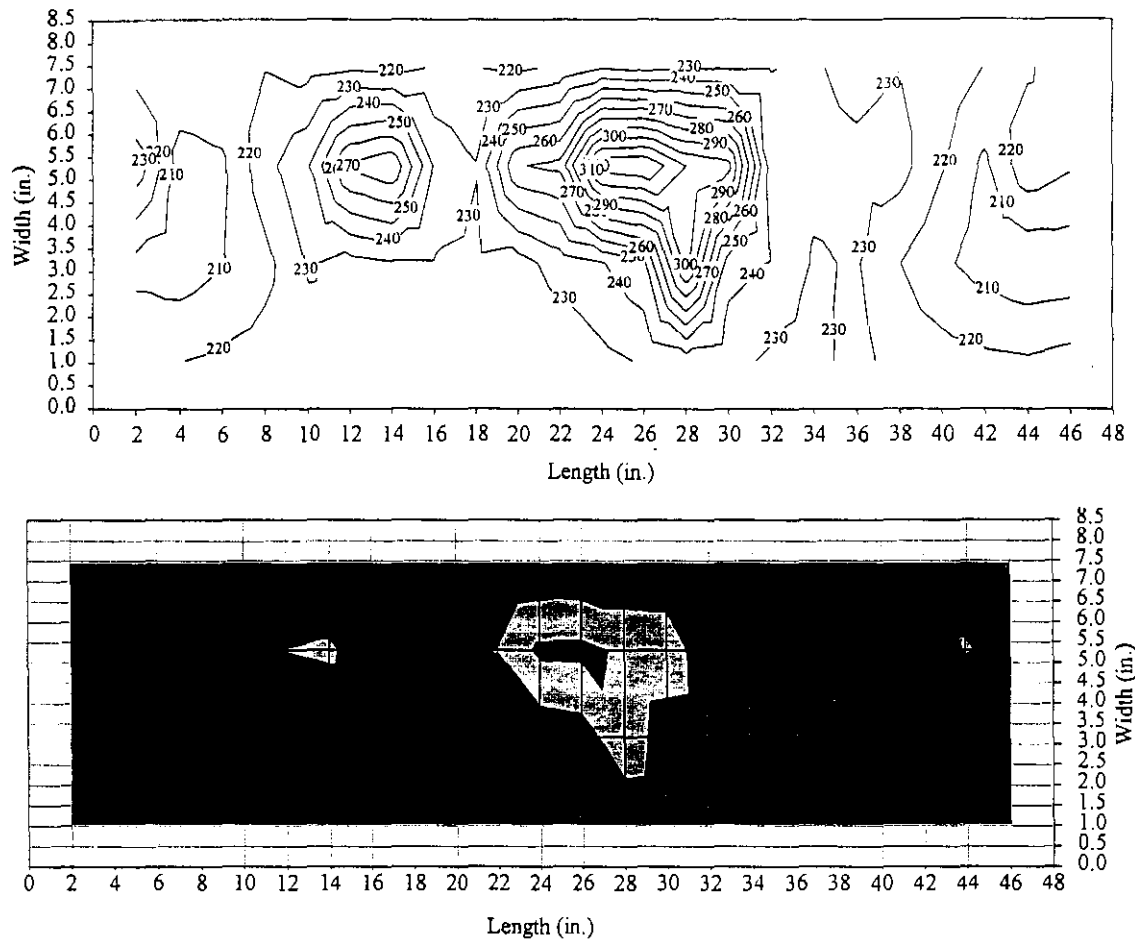


FIGURE 8 Ultrasonic wave travel time through-the-depth contour plot and gradient.

Peak voltages are plotted in Figure 9. These graphs are interpreted in the opposite manner of the travel time graphs. Travel time is expected to increase with the presence of voids. Peak voltage is expected to decrease in the presence of voids. In Figure 9 smaller contour values represent lower peak voltages. The areas with lower peak voltages represent locations where voids probably exist. This is also displayed in the color gradient plot of peak voltages. The blue, purple, green, and yellow areas represent sound regions of the glulam. The orange area represents a predicted void that occupies a relatively small portion of the depth. The red areas represent predicted voids that occupy a larger percentage of the depth.

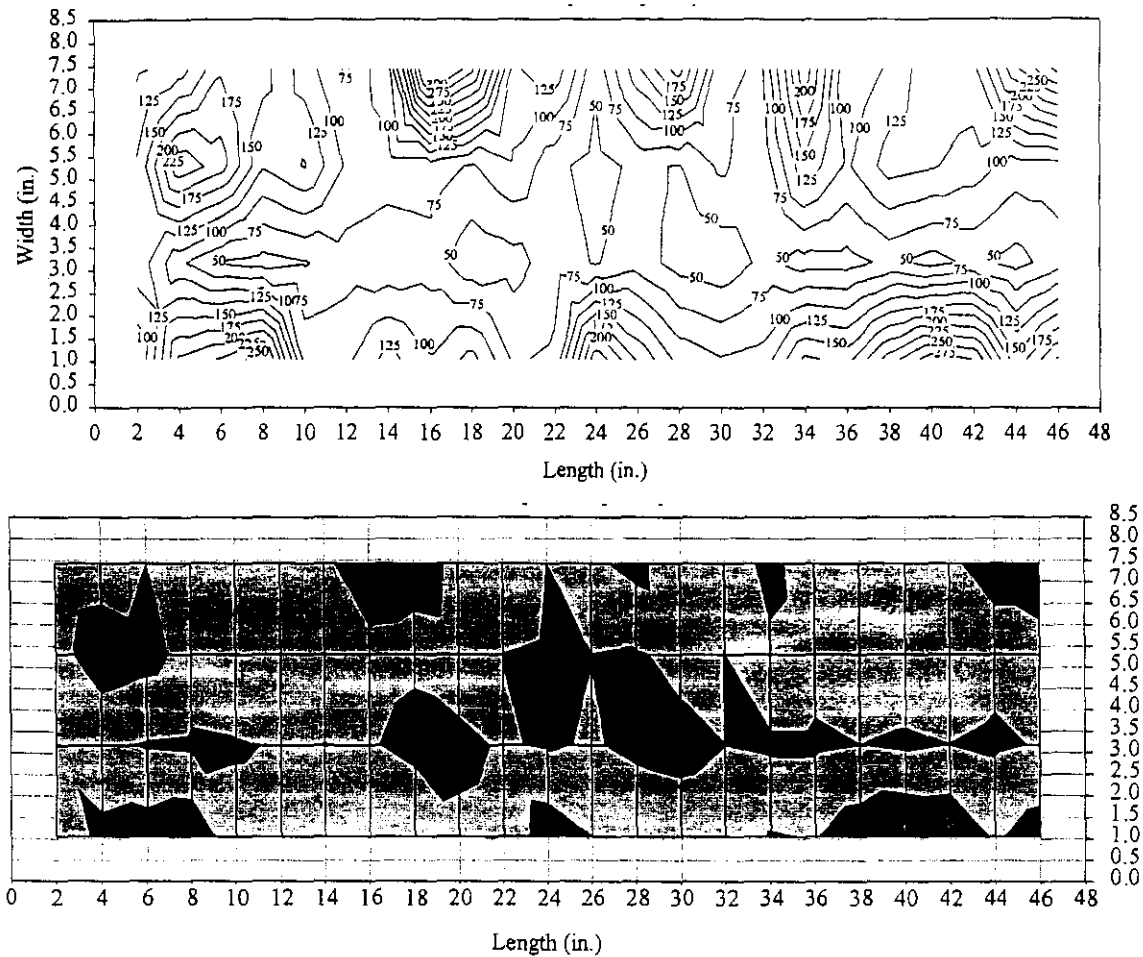


FIGURE 9 Ultrasonic wave peak voltage through-the-depth contour plot and gradient.

Combined Inspection

Through-the-width and through-the-depth ultrasonic inspections were combined to predict the three-dimensional locations of voids in the glulam beam. Predicted probable void locations identified during through-the-width inspection that corresponded with predicted voids identified during through-the-depth inspection were kept as predicted void locations. Predicted through-the-width void locations that did not correspond with through-the-depth void locations were discarded. Void locations predicted by both through-the-width and through-the-depth inspections were overlaid onto the side of the glulam beam, as shown in Figure 10.

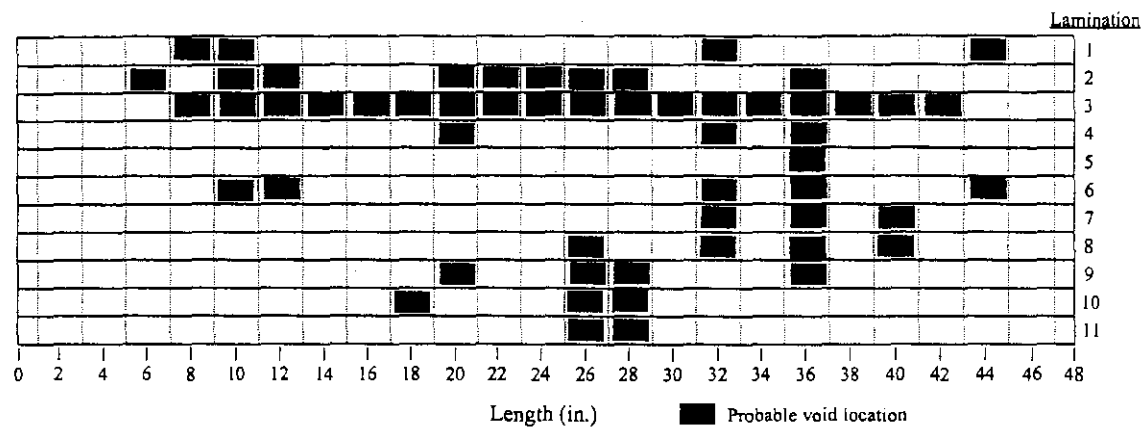
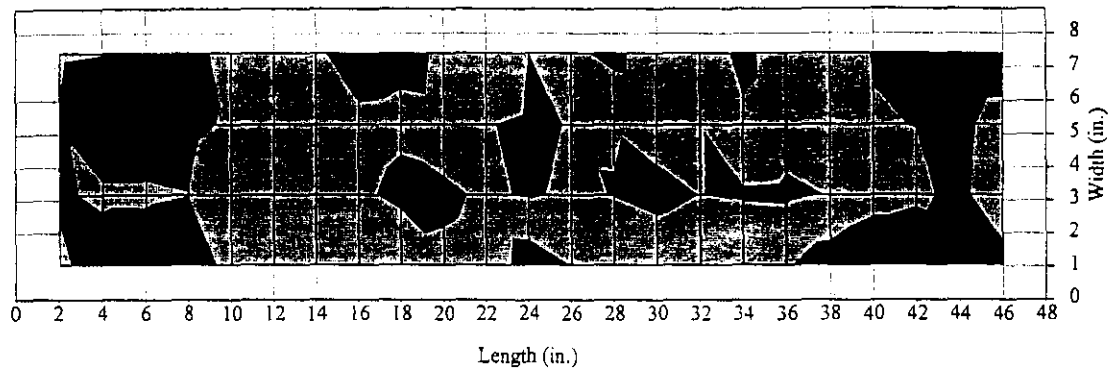
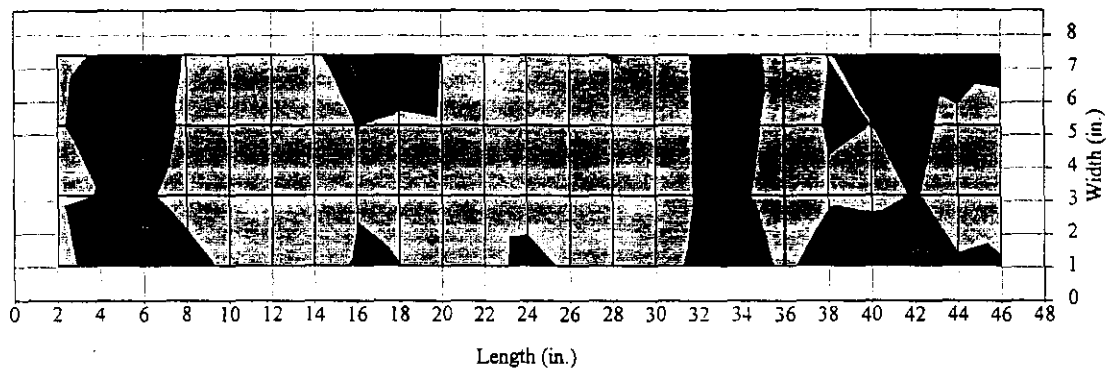


FIGURE 10 Void locations predicted by both through-the-width and through-the-depth inspections.

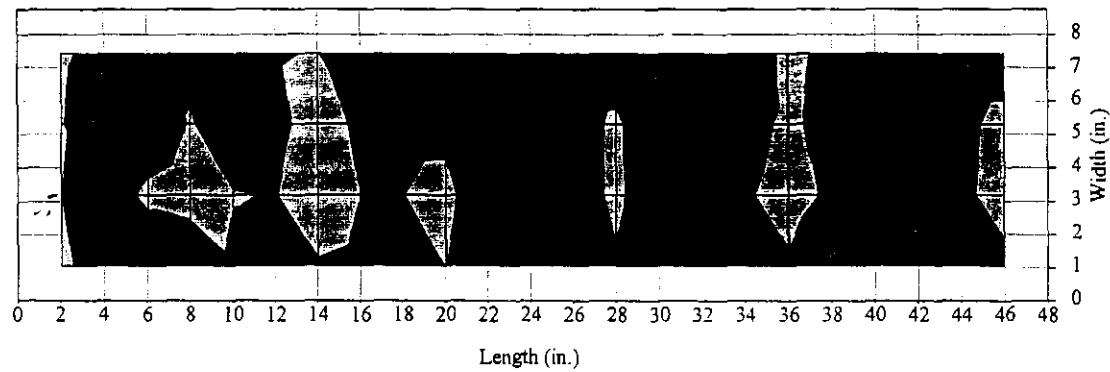
In order to predict the two-dimensional location of the voids within each lamination another combination was developed. Through-the-depth ultrasonic amplitude parameters were combined with through-the-width ultrasonic amplitude parameters for each laminate. This combination was achieved with a square root of the sum of the squares approach. The resulting combinations for laminates 3, 8, and 11 are presented in Figure 11 as representative analyses. Orange and red areas represent the two-dimensional locations for predicted voids within each laminate.



Laminate 3



Laminate 8



Laminate 11

FIGURE 11 Two-dimensional locations of predicted voids within individual laminates.

COMPARISON WITH SPECIFIED DEFECTS

After predicting the locations of defects in the glulam via ultrasonic inspection, the specified defect locations were revealed on diagrams provided by the FHWA. Figure 12 reveals the void locations within each laminate.

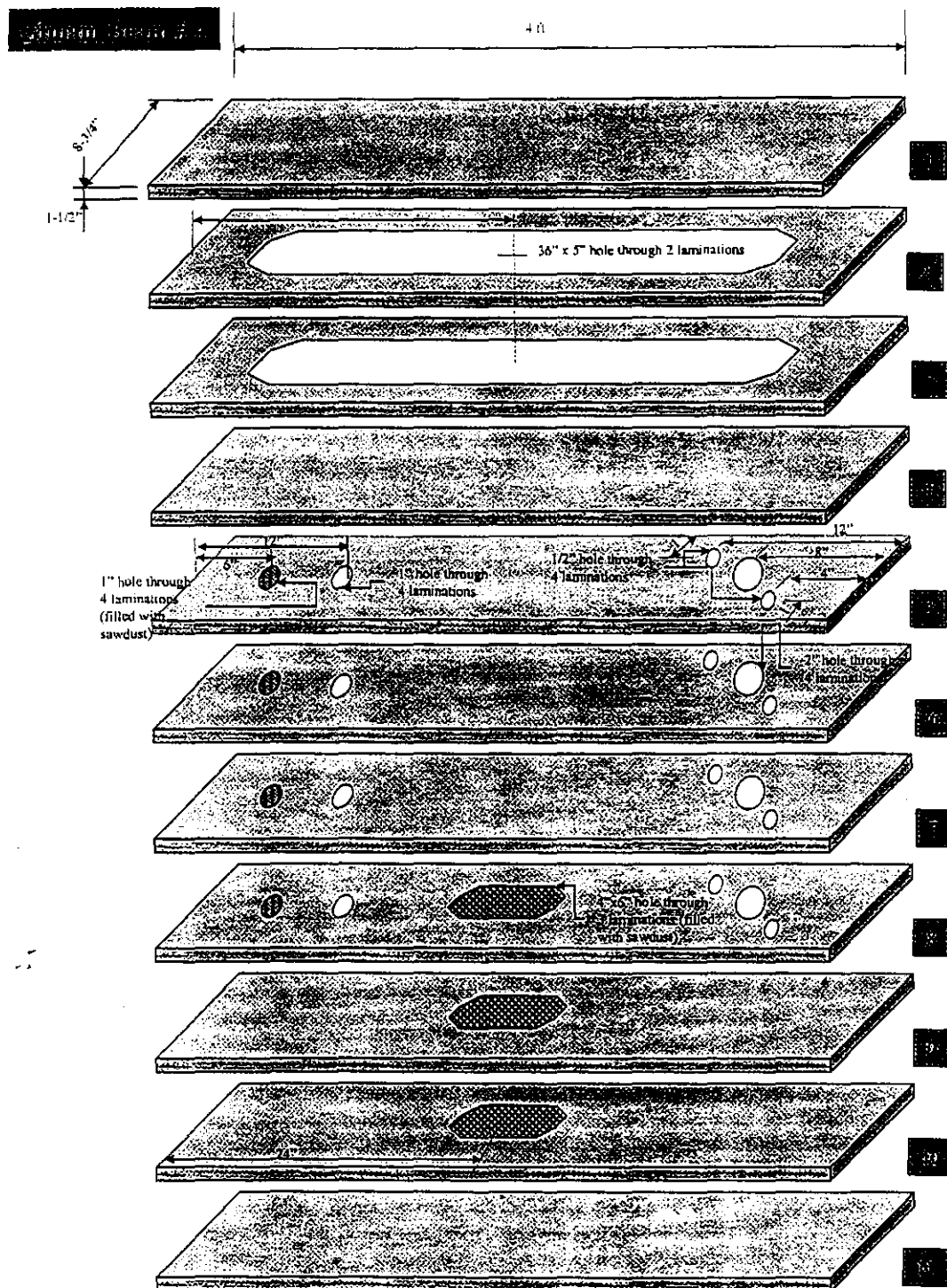


FIGURE 12 Glulam voids layout provided by FHWA.

A comparison between the predicted locations of voids within each laminate and the void locations provided by FHWA revealed the effectiveness of ultrasonic inspection for identifying the voids in the glulam beam. The comparison is presented in Table 1. The location of the center of each predicted hole was measured from the left end and front face of the glulam

TABLE 1 Comparison of predicted void locations with locations provided by FHWA

Lamination		Size of Hole L x W	Center of Hole Length	Width	Comparison Comment
1	Predicted	4" x 2"	8"	3"	false positive
		4" x 4"	44"	4"	false positive
	FHWA	None			
2	Predicted	4" x 2.5"	11.5"	3"	part of 36" x 5" hole
		6" x 4"	21"	4"	part of 36" x 5" hole
		2" x 2"	31"	3.25	part of 36" x 5" hole
		2" x 2"	36"	3.25	part of 36" x 5" hole
	FHWA	36" x 5"	24"	4.375"	
3	Predicted	30" x 5"	24"	4.375"	36" x 5" hole
	FHWA	36" x 5"	24"	4.375"	
4	Predicted	1" x 1"	10"	3"	false positive
		1" x 1"	20"	3"	false positive
		1" x 1"	36"	3"	false positive
	FHWA	None			
5	Predicted	1" x 1"	36"	3"	0.5" hole at 36"
	FHWA	1"	6"	4.375"	
		1"	12"	4.375"	
		0.5"	36"	7.75"	
		2"	40"	4.375"	
		0.5"	44"	1"	
6	Predicted	3" x 2.5"	13"	3.5"	1" hole filled with sawdust
		2" x 2"	18"	3.5"	false positive
		2" x 2"	36"	3.5"	0.5" hole at 36"
		4" x 4"	44"	4"	0.5" hole at 44"
	FHWA	1"	6"	4.375"	
		1"	12"	4.375"	
		0.5"	36"	7.75"	
		2"	40"	4.375"	
		0.5"	44"	1"	
7	Predicted	2" x 2"	13"	3.5"	1" hole filled with sawdust
		2" x 3"	18"	3.5"	false positive
		2" x 2"	27"	4"	false positive
		4" x 2"	36"	3.5"	0.5" hole at 36"
	FHWA	1"	6"	4.375"	
		1"	12"	4.375"	
		0.5"	36"	7.75"	
		2"	40"	4.375"	
8	Predicted	8" x 4"	26"	4.375"	6" x 4" hole at 24"
		2" x 2"	36"	3.5"	0.5" hole at 36"
	FHWA	1"	6"	4.375"	
		1"	12"	4.375"	
		6" x 4"	24"	4.375"	
		0.5"	36"	7.75"	
		2"	40"	4.375"	
		0.5"	44"	1"	
9	Predicted	2" x 4"	20"	3.25"	false positive
		4" x 4"	27"	4.375"	6" x 4" hole at 24"
	FHWA	6" x 4"	24"	4.375"	
10	Predicted	8" x 4"	24"	4"	6" x 4" hole at 24"
	FHWA	6" x 4"	24"	4.375"	
11	Predicted	None			
	FHWA	None			

Based solely on the comparisons presented in Table 1, ultrasonic testing provided a reasonable inspection of the internal condition of the glulam beam. Larger voids were positively identified and located. Some smaller voids were identified. Ultrasonic inspection also provided only a few false positives. The 36 inch by 5 inch holes in laminations two and three were located accurately when compared to the layout provided by the FHWA. The 4 inch by 6 inch holes in laminations nine, ten, and eleven were identified but ultrasonic inspection located them approximately two inches to the right of where they were positioned in the provided layout. The regions that contain the half inch to two inch diameter voids within laminations five through eight were identified. However, the sizes and locations do not quite match.

Voids smaller than one inch in diameter were not expected to be identified by the ultrasonic inspection based on the ultrasonic wavelength of approximately one inch. The one inch diameter hole filled with sawdust, located six inches from the left end, was not identified. The one inch diameter hole located twelve inches from the left end was identified as approximately a 2.5 inch by 2.5 inch hole in laminations six and seven. The half inch holes at the right end of the glulam beam were identified as 2 inch by 2 inch to 4 inch by 4 inch holes depending on the lamination.

The two inch diameter hole located eight inches from the right end of the glulam was not identified when through-the-depth and through-the-width signals were combined to predict the two-dimensional location of voids within each lamination. However, three voids were predicted at the right end of the glulam by through-the-width inspection. The ultrasonic inspection indicates that the half inch diameter holes are positioned at 32 inches and 40 inches from the left end of the glulam, and the two inch diameter hole is positioned 36 inches from the left end of the glulam.

CONCLUSIONS

Ultrasonic inspection was effective for identifying voids within the glulam beam. Wave travel time allowed identification of some of the voids, but signal amplitude parameters, RMS voltage and peak voltage, such as provided more precise location of the voids. Across-the-width ultrasonic inspection identified the 36 inch by 5 inch hole in laminations two and three, the 4 inch by 6 inch hole filled with sawdust in laminations 8, 9, and 10, and the regions of the glulam where the smaller holes existed. Ultrasonic inspection through the depth identified all of the voids in the glulam. Through-the-width and through-the-depth ultrasonic inspections provided two-dimensional

information on the internal condition of the glulam. Combining the two-dimensional information from both inspection directions provided three-dimensional information on the internal condition of the entire glulam. A three-dimensional image can provide valuable insight into the internal condition of a beam. However, transmitting and receiving ultrasonic waves propagated through the depth of a beam in a bridge may not be possible due to physical constraints. This difficulty forces us to look at the effectiveness of only using through-the-width inspections. Through-the-width inspections locate voids along the length and depth of a beam. Based on the results presented in Figures 5, 6, and 7 this information should be sufficient for determining the condition of the beam and whether the beam should be repaired or replaced.

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FIGURE 2 Glulam beam.

FIGURE 2 Ultrasonic inspection locations for glulam beam.

FIGURE 3 Coupling clamp with inline load cell.

EQUATION 1 $V = \sqrt{\frac{E \cdot g}{\rho}}$ $g = \text{acceleration due to gravity}$

EQUATION 2 $\text{RMS Voltage} = \frac{\sqrt{\sum \text{Voltage}_i^2}}{n}$ $\text{Voltage} = \text{signal amplitude}$

FIGURE 4 Example A-scan showing variation in wave travel time determination.

EQUATION 3 $\lambda = \frac{C}{f}$ $\lambda = \text{wavelength}, C = \text{wave velocity}, f = \text{frequency}$

FIGURE 5 Ultrasonic wave travel time for lamination three accounting for knots.

FIGURE 6 Ultrasonic wave RMS voltage for lamination three accounting for knots.

FIGURE 7 Locations of predicted voids identified from combination of ultrasonic wave travel times and RMS voltages accounting for knots.

FIGURE 8 Ultrasonic wave travel time through-the-depth contour plot and gradient.

FIGURE 9 Ultrasonic wave peak voltage through-the-depth contour plot and gradient.

FIGURE 10 Void locations predicted by both through-the-width and through-the-depth inspections.

FIGURE 11 Two-dimensional locations of predicted voids within individual laminates.

FIGURE 12 Glulam voids layout provided by FHWA.

TABLE 1 Comparison of predicted void locations with locations provided by FHWA

Wood Engineering and Drying Systems Design Criteria

FPL-4719

Problem 3 Develop and evaluate new nondestructive technologies for assigning engineering properties

FY 2001 Research Attainments

Publications

Emerson, Robert N.; Pollock, David G.; McLean, David I.; Fridley, Kenneth; Ross, Robert J.; Pellerin, Roy F. 2001. Ultrasonic inspection of a glued laminated timber fabricated with defects. In: Proceedings of the 90th annual meeting of the transportation research board: 2001 JANUARY 07-11:1-19.