Ultrasound Transmission Times in Biologically Deteriorated Wood

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Abstract
The use of a variety of stress wave transmission techniques for the in-service condition assessment of deteriorated wood is well documented. This paper summarizes results from an extensive study designed to examine the relationship between ultrasound transmission times and the deterioration of exposed wood. Two hundred seventy (270) southern pine lumber specimens were evaluated nondestructively using a through transmission ultrasound technique after field exposure for periods of up to fifty seven (57) months. Ultrasound transmission times increased with exposure time. Several statistical models of the relationship between transmission time and length of exposure were developed and are presented.

Keywords
Ultrasound, stress wave transmission, deterioration model, weathering, exposure

Introduction

Wood is used extensively for both interior and exterior applications in the construction of a variety of structures (residential, agricultural, commercial, government, religious). The deterioration of an in-service wood member may result from a variety of causes during the life of a structure. It is important, therefore, to periodically assess the condition of wood used in structures to determine the extent of deterioration so that degraded members may be replaced or repaired to avoid structural failure. An assessment is especially critical for building officials in municipalities affected by catastrophic events.

Assessment of the condition of wood in a building can be conducted for a variety of reasons. Code compliance, historic preservation, or alternative uses of a structure are frequently cited reasons for conducting a condition assessment. A structural condition assessment consists of the following: 1) a systematic collection and analysis of data pertaining to the physical and mechanical properties of materials in use; 2) evaluation of the data collected; and 3) providing recommendations, based on evaluation of the collected data, regarding portions of an existing structure that affect its current or proposed use. Such an assessment relies upon an in-depth inspection of the wood members in the structure. A wide variety of techniques are used to assess the condition of wood in structures. Visual assessment, probing, resistance drilling, and stress wave or ultra-sound-based techniques are all used either individually or in combination to evaluate the condition of in-service members (Ross and others 2006).

The use of a variety of stress wave transmission techniques for the in-service condition assessment of deteriorated wood is well documented, from the evaluation of historic artifacts (Dundar and Ross 2012) to timber bridges (Brashaw and others 2005a; Brashaw and others 2005b; Emerson and others 2002; Ross and others 1999), to historic structures and ships (Allison and others 2008; Clausen and others 2001; Ross and others 1998; Ross and Wang 2005; Wang and others 2008). Of particular note are the *Wood and Timber Condition Assessment Manual-Second Edition* (White and Ross 2014) and an extensive literature review on the use of ultrasound techniques for evaluating wood by Senalik and others (2014).

Pellerin and others (1985) were the first to report on a systematic examination of the effect of biological attack on the acoustic properties of clear wood. They used small, clear southern pine specimens in a laboratory study designed to examine the effect brown-rot decay fungi and termite attack have on acoustic velocity and static strength. Time-of-flight measurements, parallel to the fiber axis, were made using a pitch/catch system on specimens after various exposure times. They observed a considerable change in acoustic time-of-flight with exposure time. More importantly, they were able to conclude the following:

1. Changes in time-of-flight occurred well before measureable weight loss (density), and before strength loss, were observed.
2. Significant correlation was observed between residual strength and acoustic time-of-flight.
3. Because termite attack was preferential to the early wood sections of the specimens, time-of-flight measurements parallel to the fiber axis were not useful for monitoring changes in corresponding strength.

DeGroot and others (1994, 1995, 1998) reported on a follow-up study they performed to examine both energy storage and loss parameters for monitoring the deterioration of clear wood when exposed to natural populations of decay fungi and subterranean termites. They used a pulse echo test setup (Ross and others 1994) to measure speed of sound transmission and wave attenuation, parallel to the fiber axis, in small clear southern pine specimens in field exposure conditions and developed empirical models which used both parameters that were capable of predicting residual compressive strength with a high level of accuracy (Ross and others 1996, 1997). A similar relationship was reported by Ross and others (2001) for timbers removed from service.

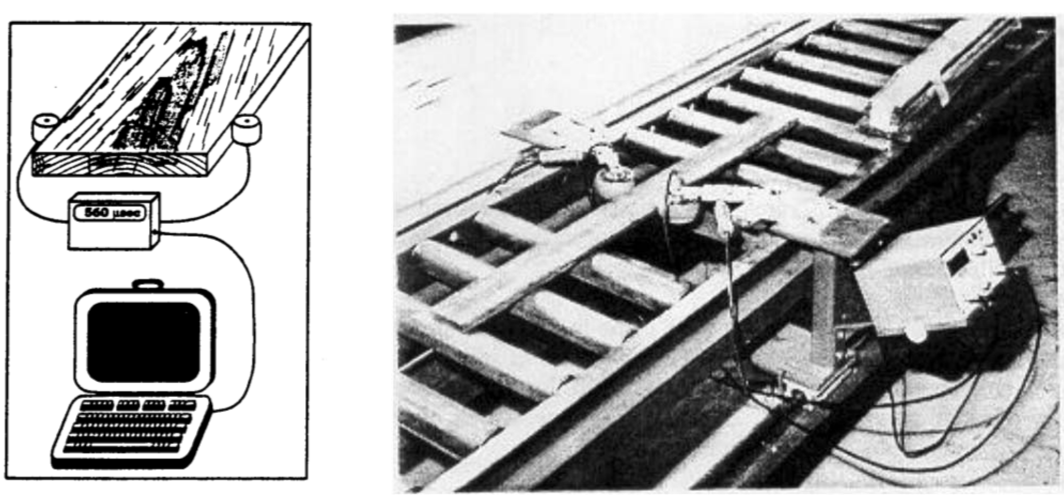
The objective of this research was to examine the relationship between ultrasound transmission and wood deterioration. This paper presents a mathematical relationship between the changes in transmission times along the length of the wood board specimens and the months of weathering exposure time.

Materials and Methods

Clear, southern pine lumber specimens, nominal 5.1 cm (2 in.) by 10.2 cm (4 in.) by 243.8 cm (96 in.) in length, were used in this study. All specimens were obtained from southern pine sapwood lumber, Class C or better, obtained from a mill in Georgia. The species of trees from which the wood was cut could not be identified but is assumed to be from a major southern pine species in the area. These species are longleaf pine (*Pinus palustris*), shortleaf pine, (*P. echinata*), loblolly pine (*P. taeda*), and slash pine (*P. elliottii*). Clear sapwood was used in this study to maximize the opportunity to establish relationships between ultrasound transmission and the deterioration of the wood. From a sample of 400 specimens, 270 were selected for inclusion in the study. After conditioning to approximately 10% moisture content, the modulus of elasticity (MOE) of each piece was nondestructively determined using stress wave techniques. The specimens were sorted into nine groups, 30 specimens per group, with each group having nearly identical MOE distributions (mean values and standard deviations).

One group of 30 specimens was randomly selected as the reference or control group. This group was retained in a controlled environment room until the conclusion of the field phase of the study. The remaining specimens were installed in a field plot on the Harrison Experimental Forest in April 1990. Note that the specimens were not in ground contact; they were placed horizontally on racks approximately 1 m above the ground. This forest is located in southern Mississippi, approximately 32 km from the Gulf of Mexico. Specimens were removed from the field after 2, 9, 14, 21, 26, 35, 45, and 57 months of exposure.

Upon removal from the field, each specimen was shipped to FPL and reconditioned in a controlled environment room. After conditioning, each specimen was tested nondestructively using the experimental setup shown in Figure 1. The setup consisted of two 84 kHz rolling transducers, coupled to an ultrasonic transmitting and receiving unit (Ross and DeGroot 1998). A stress wave was induced into the specimen through the width of the board by the transmitting transducer. The wave was then received by the opposing transducer. Stress wave transmission times were displayed by the unit and recorded on a personal computer. Transmission times were measured at increments along the length of the specimens at the locations illustrated in Figure 2. Note that measurements were made in 76 mm (3 in.) increments near the ends of the specimens and in 152 mm (6 in.) increments elsewhere along the length. Each specimen was tested several times; excellent agreement was observed between scans for individual specimens.



a. **b.**

Figure 1–Nondestructive experimental setup used to measure ultrasonic transmission times across the width of timber boards. **a.** experimental setup schematic, **b.** photograph of experimental setup

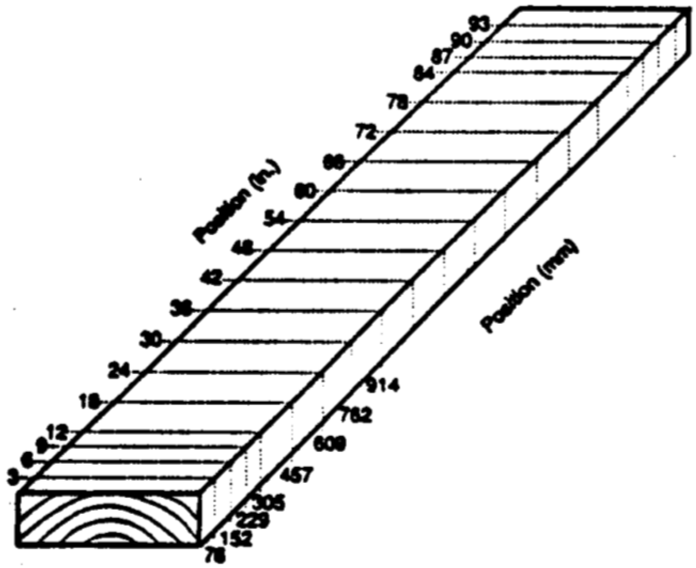


Figure 2–Transmission time measurement locations. Measurements were made in 76 mm (3 in.) increments near the ends of the specimens and in 152 mm (6 in.) increments elsewhere along the length.

Deterioration Model

Wood can be considered a cylindrically orthotropic, hygroscopic material. The three principle directions of wood are longitudinal, tangential, and radial. Wood draws water into itself from all directions; however, the rate at which it draws water longitudinally is much greater than the rate it draws water in either tangentially or radially. The presence of water is one of the four key ingredients for wood decay: wood, water, air, and acceptable temperatures. As a result of the higher rate of water absorption in the longitudinal direction, cut timber tends to decay more quickly at the ends that were cut normal to the longitudinal axis of the original tree.

It should be noted that the model presented was constructed using data collected from specimens including up to 45 months of exposure. The transit times recorded using specimens exposed for 57 months were several times higher than any other transit time and were excluded from the model.

At the time of the deterioration model construction, it was believed that the boards would have end regions of decay and then center portions that were largely sound. As a result, the transit times near the ends of the board should be high and transition to a lower value as the distance from the end increased. The form of equation chosen to model this behavior was a second order exponentially decaying function, shown in Equation (1).

$$T_s = (A_H - A_L)\exp\left[-\left(\frac{2l}{d_t}\right)^2\right] + A_L \qquad (1)$$

Where
T_s is the transit time in microseconds,
A_H is transit time near board end (NE),

A_L is the transit time along the center board (CB),
l is the distance to the nearest end of the board, and
d_t is the distance from the board end that the decay has intruded into the board.

Figure 3 shows predicted values versus the actual board transmission data. Near the end of the board, the transit time, T_s will have a high value of A_H. As the distance from the end of the board, l, increases, the transit time will decrease. At a distance, d_t, the transit time will be near to the low value, A_L. The transit time was recorded over several months at constant distances from the ends of the boards. The transit time at the same distance from both ends of the board were averaged to construct representative transit time transition curves for modelling. The high and low transit time values were extracted from the curves and each curve was fitted to a second order exponentially decaying function. Microsoft Excel Solver function was used to find a transition distance, d_t, that maximized the coefficient of determination, r^2, and minimized the root mean square error.

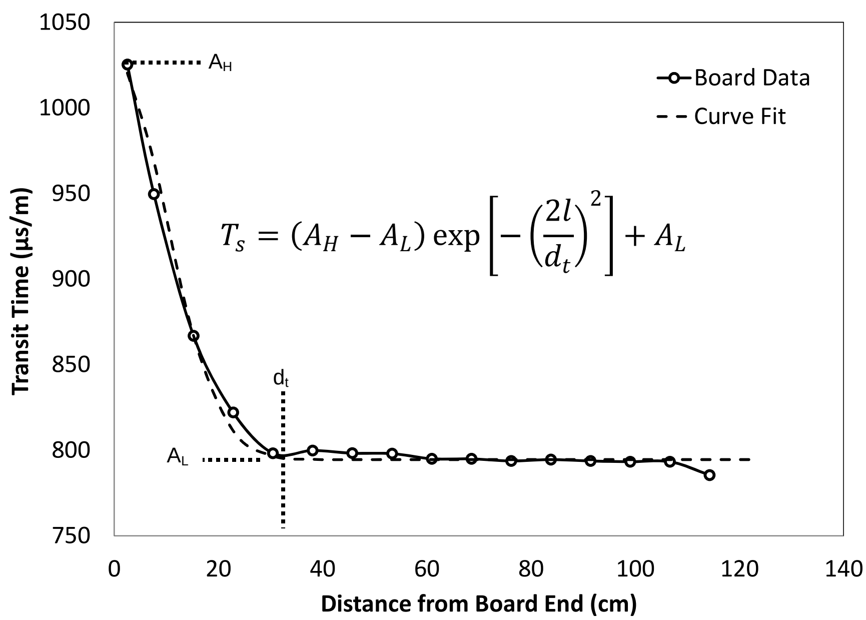


Figure 3–Average transit time as a function of distance from the end of the board for a specimen weathered for 21 months. Also shown is the curve fit of the data using a second order exponentially decaying function.

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The general form of the mathematical relationships relating high and the low transit values to months of weathering are presented in Equations (2a) and (3a), respectively. The terms Δ_H and Δ_L are adjustments applied to the trends based upon precipitation within three months prior to testing, and are discussed later in this report. Simple linear regression (LR) was used to determine the values of the coefficients. The LR coefficients for the high values were constrained such that the constant term matched the constant term of the low value coefficients; the underlying assumption is that without weathering (0 months of exposure), the high and low transit values should be equal. The equations with the numerical coefficients are given for high (r^2 = 0.9136) and low (r^2 = 0.8739) are given in Equations (2b) and (3b), respectively. The r^2 values presented above include no adjustments for precipitation (Δ_H, Δ_L = 0).

$$A_H = a_{H1}t + a_{H0} + \Delta_H \quad (2a)$$
$$A_H = 13.93t + 721.4 + \Delta_H \quad (2b)$$

$$A_L = a_{L1}t + a_{L0} + \Delta_L \quad (3a)$$
$$A_L = 4.497t + 721.4 + \Delta_L \quad (3b)$$

Where
t is the weathering time in months,
a_{H1} and a_{H0} are linear regression (LR) coefficients for the near board end (NE) 1st and 0th order terms,
Δ_H is the NE precipitation adjustment applied after the third month of weathering,
a_{L1} and a_{L0} are LR coefficients for the center board (CB) 1st and 0th order terms, and
Δ_L is the CB precipitation adjustment applied after the third month of weathering.

Simple linear regression (LR) was used to relate the natural logarithm of the transition distance (r^2 = 0.8531) to months of weathering. The general form of the equation is given in Equation (4a); the equation with numerical coefficients is given in Equation (4b). Precipitation occurring near the time of testing did not significantly influence the transition distance.

$$\ln d_t = a_{d1}t + a_{d0} \quad (4a)$$
$$\ln d_t = 0.036t + 2.494 \quad (4b)$$

Where a_{d1} and a_{d0} are LR coefficients for the transition distance 1st and 0th order terms.

The precipitation for the three months prior to specimen testing was found to influence the high and low transit values. Equations (5a) and (6a) are the general form of the relationships between the high and low adjustment values, respectively, and a weighted average precipitation for the three months prior to the removal of the specimen from the test environment. Equations (5b) and (6b) have the coefficient values shown. The method of determining the coefficient values is given below.

$$\Delta_H = a_{\Delta H1}p_w + a_{\Delta H0} \quad (5a)$$
$$\Delta_H = 10.25p_w - 171.7 \quad (5b)$$

$$\Delta_L = a_{\Delta L1}p_w + a_{\Delta L0} \quad (6a)$$
$$\Delta_L = 4.661p_w - 65.52 \quad (6b)$$

Where
p_w is the weighted average precipitation,
$a_{\Delta H1}$, $a_{\Delta H0}$ are 1st and 0th order term LR coefficients for the NE precipitation adjustment, and
$a_{\Delta L1}$, $a_{\Delta L0}$ are 1st and 0th order term LR coefficients for the CB precipitation adjustment.

Equation (7a) has the general form the weighted average precipitation for the three months prior to the removal of the specimens from the test environment. Microsoft Excel Solver was used to find three weighted averages that maximized the minimum of the coefficients of determination for Equations (5a) and (6a). Equation (7b) has the numerical values for the weighted coefficients. Table 1 shows the precipitation values, the weighted average precipitation, and the deviations of the transit time for the high and low values. The precipitation adjustment trends are shown in Figure 4; the r^2 values for both trends are 0.9156.

$$p_w = \frac{a_{r-2}p_{r-2} + a_{r-1}p_{r-1} + a_r p_r}{a_{r-2} + a_{r-1} + a_r} \quad (7a)$$

$$p_w = \frac{0.315p_{-2} + 1.125p_{-1} + 0.721p_0}{0.315 + 1.125 + 0.721} \quad (7b)$$

Where p_r, p_{r-1}, and p_{r-2} are the precipitation levels for the month of removal, one month prior to removal, and two months prior to removal, respectively. a_r, a_{r-1}, and a_{r-2} are the weight factors for the precipitation levels for the month of removal, one month prior to removal, and two months prior to removal, respectively.

Table 1–Adjustment for precipitation at the time of specimen collection

Exposure	Precip. (cm) Relative to Removal			Precip. (cm)	Deviation from Model	
(Months)	-2 Months	-1 Month	0 Months	Weighted	NE Val.	CB Val.
4	10.0	10.4	5.7	8.8	–92.99	–26.05
9	4.8	13.0	31.7	18.1	12.40	10.15
14	17.8	39.3	9.7	26.3	107.49	57.67
21	6.2	7.0	26.5	13.4	–3.98	13.27
26	6.1	3.3	24.1	10.7	–61.10	–23.95
33	42.3	13.1	17.9	19.0	–6.31	23.83
45	15.3	6.0	11.8	9.3	14.13	–27.49

NE and CB denote near board end and center board, respectively.

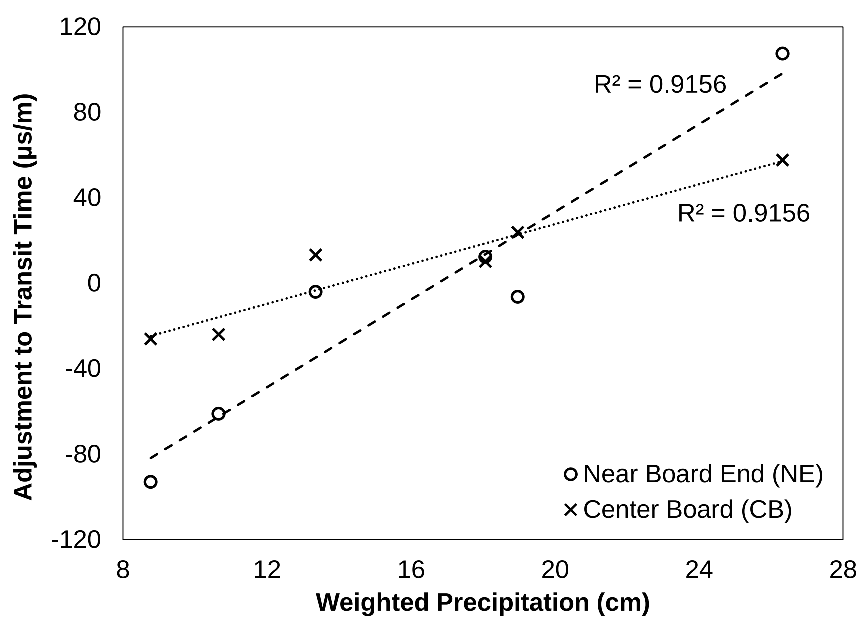

Figure 4–Precipitation adjustment to transit time.

Table 2 describes the variables and constants used in deterioration model.

Table 2–Symbols and coefficient descriptions

Symbol	Value	Description
T_s	Calculated	Transit time in microseconds
A_H	Calculated	Transit time near board end (NE)
A_L	Calculated	Transit time along the center board (CB)
l	Independent	Distance to the nearest end of the board
d_t	Calculated	Distance from board end where transit time transitions from NE to CB
t	Independent	Time of weathering in months
a_{H1}	13.93	Coef. 1st order term NE linear regression method (LRM)
a_{H0}	721.4	Coef. 0th order term NE LRM
Δ_H	Calculated	NE precip. adjustment applied after 3rd month of weathering
a_{L1}	4.497	Coef. 1st order term CB LRM
a_{L0}	721.4	Coef. 0th order term CB LRM
Δ_L	Calculated	CB precip. adjustment applied after 3rd month of weathering
a_{d1}	0.036	Coef. 1st order term transition distance LRM
a_{d0}	2.494	Coef. 0th order term transition distance LRM
p_w	Calculated	Weighted average precipitation
p_{r-2}	Independent	Precipitation two months prior to specimen removal
p_{r-1}	Independent	Precipitation one month prior to specimen removal
p_r	Independent	Precipitation the month of removal
a_{r-2}	0.315	Weight factor for precipitation two months prior to removal
a_{r-1}	1.125	Weight factor for precipitation one month prior to removal
a_r	0.721	Weight factor for precipitation the month of removal
$a_{\Delta H1}$	10.25	Coef. 1st order term NE precip. adjustment LRM
$a_{\Delta H0}$	–171.7	Coef. 0th order term NE precip. adjustment LRM
$a_{\Delta L1}$	4.661	Coef. 1st order term CB precip. adjustment LRM
$a_{\Delta L0}$	–65.52	Coef. 0th order term CB precip. adjustment LRM

Results and Discussion

The transit times predicted by the deterioration model are plotted alongside the transit times measured from the test specimens in Figures 5 through 12. The vertical dotted lines represent the transition distance from the end of the boards. At that point, it is predicted that the transit time will begin transitioning from the low value of the center of the board to the high value of the deteriorated ends of the board. The model developed here attempts to explain variation in transit times caused by wood decay, not variation in transit times inherent to the wood specimens. The model predicts a uniform transit time for the control specimen (0 months exposure); the underlying assumption is that the control boards have no variation in the transit times. In reality, the wood does have variation in transit times that are inherent to the wood boards themselves. The r^2 value is the percentage of the variation explained by the model. For the control specimens, any variation from the starting control transit time would therefore be unexplained by the model and be indicative of variation inherent to the wood, not variation caused by decay. As a result, the r^2 value for the control group is near zero. The low r^2 value for the control group does not mean the model poorly fits the data. The average percentage error between the control data and the predicted values is 0.24% indicating that the model closely matches the control data. With increased exposure, decay causes the transit times to increase; a larger percentage of the transit time variation is explained by the model, and the r^2 values increase.

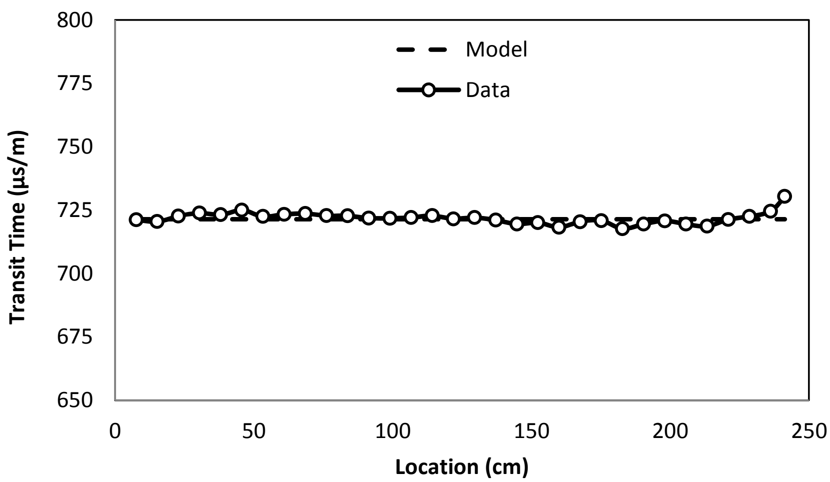

Figure 5–Transit time data and predicted transit time for 0 months (Control) of weathering. Average percentage error = 0.24%, r^2 = NA.

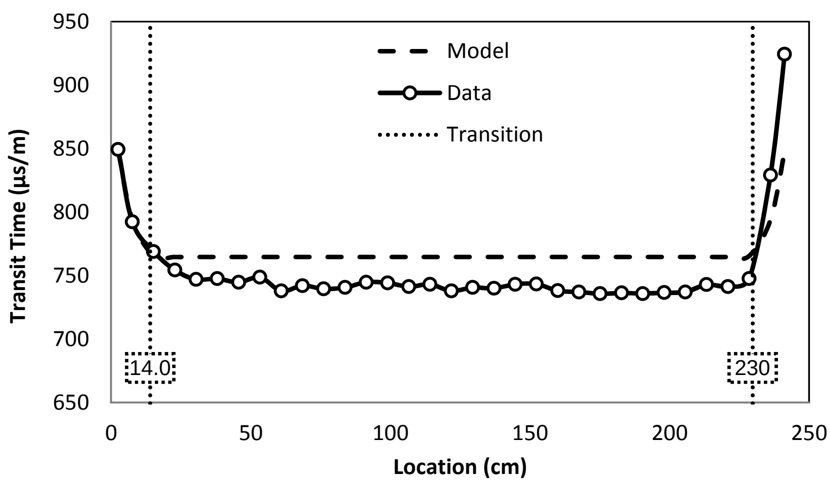

Figure 6–Transit time data and predicted transit time for 4 months of weathering. Average percentage error = 2.9%, r^2 = 0.8958.

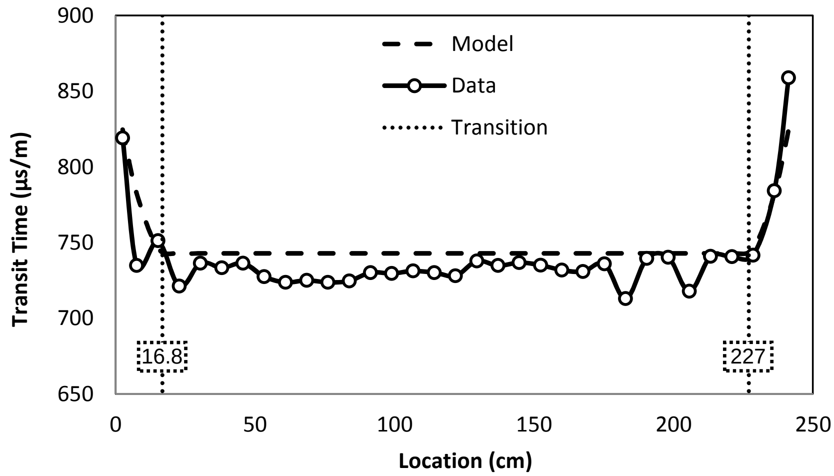

Figure 7–Transit time data and predicted transit time for 9 months of weathering. Average percentage error = 1.7%, r^2 = 0.8254.

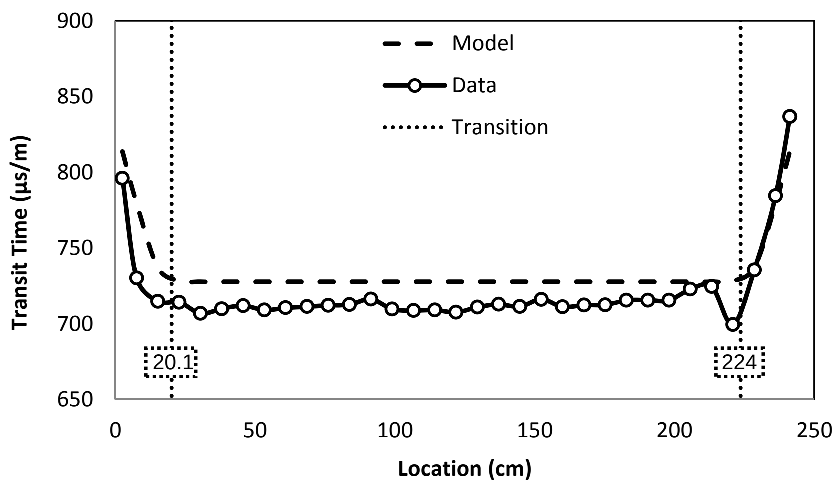

Figure 8–Transit time data and predicted transit time for 14 months of weathering. Average percentage error = 2.2%, r^2 = 0.8620.

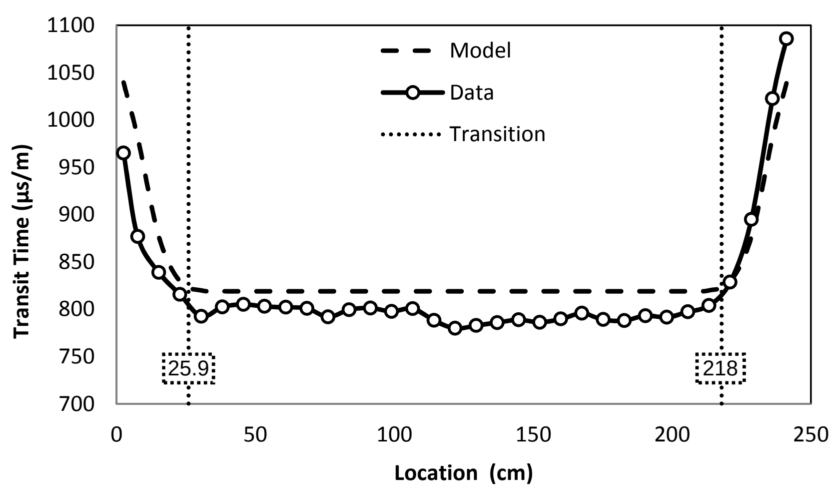

Figure 9–Transit time data and predicted transit time for 21 months of weathering. Average percentage error = 3.3%, r^2 = 0.8620.

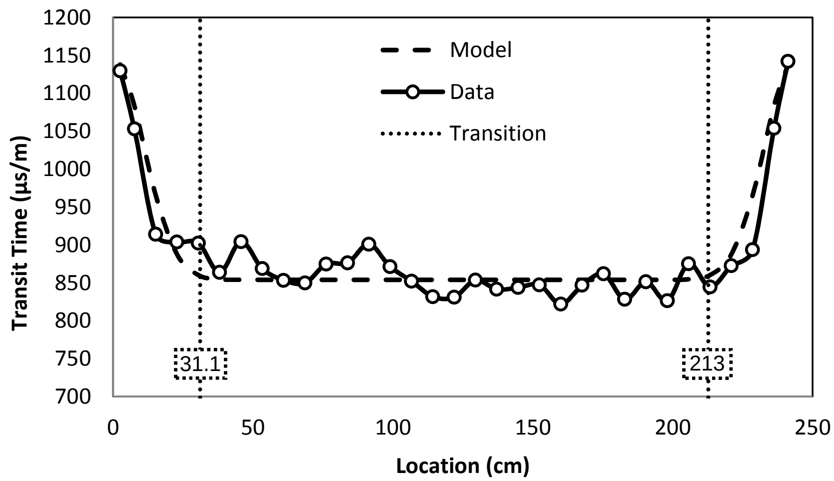

Figure 10–Transit time data and predicted transit time for 26 months of weathering. Average percentage error = 2.3%, r^2 = 0.9068.

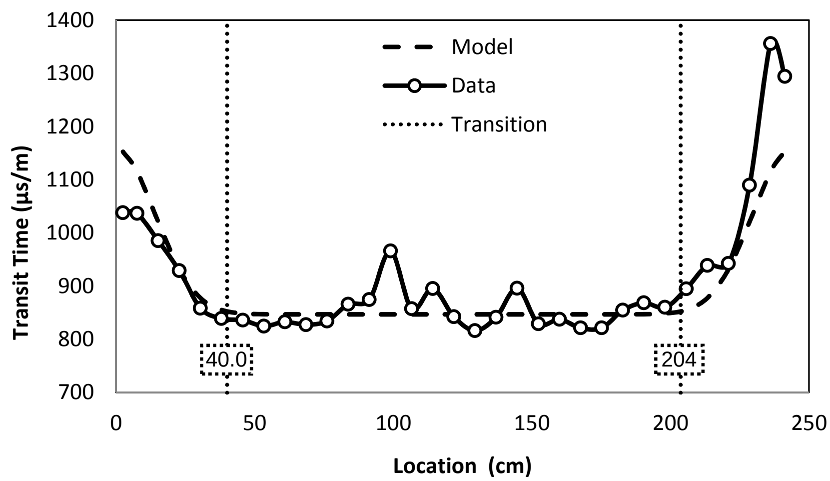

Figure 11–Transit time data and predicted transit time for 33 months of weathering. Average percentage error = 4.2%, r^2 = 0.7609.

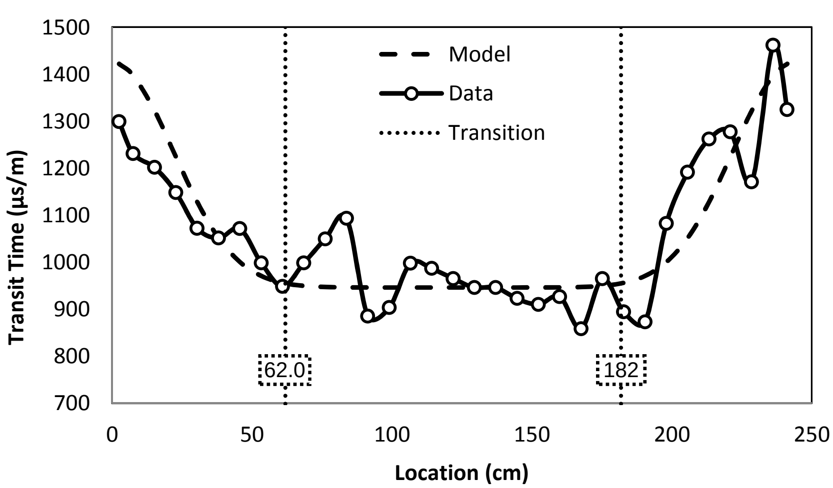

Figure 12–Transit time data and predicted transit time for 45 months of weathering. Average percentage error = 6.1%, r^2 = 0.7608.

Conclusions

The deterioration model presented in this report describes the change in ultrasonic wave transit times along the length of the wood specimens subjected to weathering of up to 45 months. The model was a second order exponentially decaying function. The transit times were found to be dependent upon of the months of weathering, the distance from the end of the boards, and the precipitation for the three months prior to testing. Precipitation for the three months prior to the removal of the specimens from the weathering environment was found to influence the transit times of the tested specimens despite the fact the specimens underwent conditioning prior to testing. Accounting for precipitation, the model was capable of estimating the transit times within the specimens to an average percentage error of 6.1% for 45 months of weathering. If precipitation was excluded from the analysis, the average percentage error exceeded 9% during the wettest months.

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