THE RELATIONSHIP BETWEEN STRESS WAVE TRANSMISSION CHARACTERISTICS AND THE COMPRESSIVE STRENGTH OF BIOLOGICALLY DEGRADED WOOD

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ABSTRACT

Wood in service can be attacked by a variety of biological organisms. Such organisms feed on the constituents of wood, thereby reducing its ability to carry load and serve in an engineering capacity. This paper presents the results of a study that investigated the use of longitudinal stress wave nondestructive evaluation to assess the strength of wood members exposed to biological attack. Clear southern pine specimens were exposed to attack by wood-destroying decay fungi and termites under field conditions in southern Mississippi. The speed of stress wave transmission and attenuation characteristics of the specimens were determined using longitudinal stress wave techniques after exposure. These nondestructive parameters were then incorporated into a multivariable regression model and used to predict the parallel-to-grain compressive strength of the specimens. Excellent agreement was found between predicted and actual compressive strength values.

The degradation of a wood load-bearing (in-service) member may be caused by any one of several organisms that derive their nourishment or shelter from the wood substrate in which they live. Therefore, it is important to periodically examine wood structural components to determine the extent of degradation so that degraded members may be replaced or reinforced to avoid structural failure.

Longitudinal stress wave nondestructive evaluation (NDE) techniques show significant promise for use in such examinations. These techniques use low stress oscillations to measure both speed of stress wave transmission and attenuation characteristics of the member in question. Application of these techniques for large void detection in wood structural members has been reported (9). However, little has been reported on the use of these techniques to estimate the strength of biologically degraded wood.

The most systematic investigation on the use of these techniques to estimate the residual strength of wood was completed by Pellerin et al. (6). They focused on speed of stress wave transmission and found a useful correlative relationship with the parallel-to-grain compressive strength of wood attacked by brown-rot fungi. A relationship between the longitudinal speed of stress wave transmission and compressive strength was not found in members attacked by termites. They attack earlywood and leave latewood, which is still able to transmit the longitudinal stress wave.

Because wood used in structures can be exposed to a variety of biological agents, it would be useful to have an NDE technique that predicts strength independent of the degradation agent, i.e., independent of the mode of attack. The purpose of the research reported herein was to investigate use of speed of stress wave transmission and attenuation characteristics of wood, measured using longitudinal stress wave NDE techniques, to estimate the parallel-to-grain compressive strength of wood attacked by both fungi and termites.

MATERIALS AND METHODS

Specimens, 1 by 1.5 by 20 inches (0.025 by 0.038 by 0.508 m) long, were prepared from southern pine sapwood lumber. All specimens were free from growth defects, such as knots, to minimize variability. All specimens were equilibrated to approximately 10 percent moisture content (MC) prior to field exposure. A total of 144 specimens were used in the study. These specimens were placed in 6 groups of 24, with the average speed of stress wave transmission for each group being nearly equivalent. One group was randomly chosen as a control and not subjected to field exposure. The

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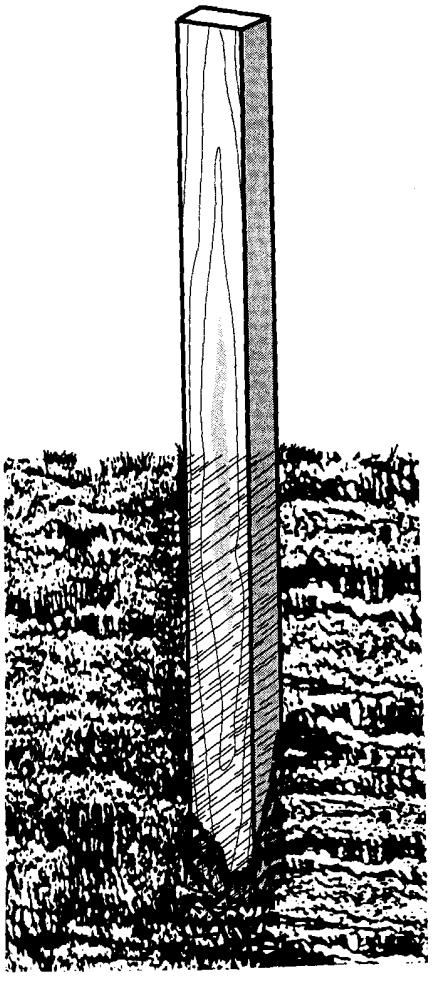

Figure 1. — Sketch of specimen inserted in ground.

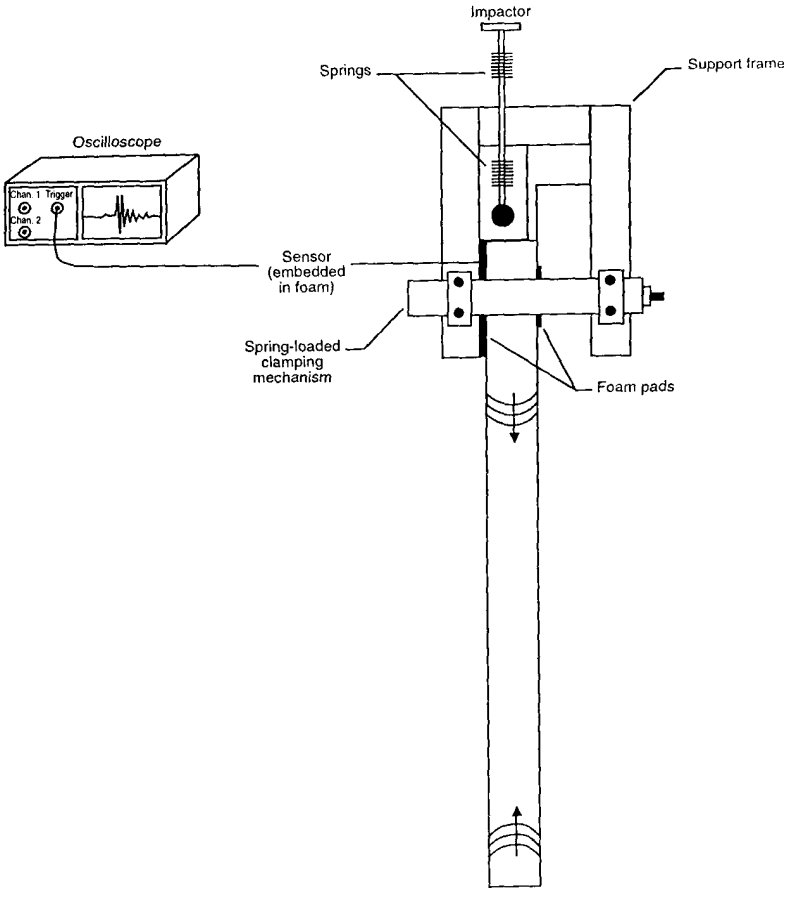

Figure 2. — Experimental setup used to observe stress wave behavior in specimens.

remaining five groups were inserted in the ground **(Fig. 1)** on a field plot in southern Mississippi. Approximately half the length of each specimen was at or below groundline, exposing specimens to both fungal and termite attack.

Stakes were evaluated at 2,4,6,9, and 15 months after installation. At each inspection, 1 predefine group of 24 stakes was nondestructively tested and visually evaluated for degradation in the field (2,3). Upon withdrawal from the soil, stakes were visually rated for the percentages of cross-sectional area that appeared most degraded as a result of either termite attack or wood decay. This rating scheme was patterned after procedures defined in ASTM D1758 (1), but with a more quantitative definition of degrees of attack. The product of these two ratings was linearly related with residual compression parallel to grain strength (2). The stakes were then shipped to the USDA Forest Service, Forest Products Laboratory (FPL), in Madison, Wis., for destructive testing.

After equilibration to approximately 10 percent MC, the speed of stress wave transmission and attenuation characteristics were determined for each specimen using the setup shown in **Figure 2.** A detailed description of the setup and analysis procedures used are described by Ross et al. (7). A stress wave was induced in each specimen by a spring-loaded impactor. Corresponding wave behavior in each specimen was monitored using a piezofilm sensor coupled to a digital storage oscilloscope. The specimens were then tested to failure in compression **(Fig. 3).** Failure was defined as a significant, irreversible decrease in load during test. Visual characteristics of the failed specimens ranged from failures on 45-degree planes for the control specimens to buckling of latewood regions in specimens severely degraded by termites.

A multivariable linear regression analysis was used to examine the relationships between measured NDE parameters and compressive strength. The NDE parameters included the speed of stress wave transmission and the attenuation of the wave as it traversed through the specimen. Previous work on nondegraded composites (8) supported the following multiplicative model:

$$M = b_0 N_{ibi} \qquad [1]$$

where:

M = maximum compressive strength
b_i = model parameters $(i = 0,1,...,k)$
N_i = measured nondestructive variables $(i = 1,2,...,k)$

The nondestructive variables used were specimen weight, stress wave transmission, and attenuation of the wave.

The model can be transformed into a linear model by taking the natural logarithm yielding:

$$\ln (M) = \ln (b_0) + b_i \ln (N_i) \qquad [2]$$

Assuming an additive error in Equation **[2],** which corresponds to a multiplicative error in Equation **[1],** a multiple linear regression analysis can then be used to evaluate the appropriateness of the model form. Based on the estimated coefficients and measured NDE parameters, predicted values for compressive strength were compared to observed values through residual analysis to evaluate the usefulness of the model (10). A similar model and analytical approach were previously used by Ross and Pellerin (8) and Kaiserlik and Pellerin (4).

RESULTS AND DISCUSSION

QUALITATIVE ANALYSIS

Elementary wave theory (5) suggests that the waveforms should consist of a series of equally spaced sinusoidally shaped pulses whose magnitude decreases exponentially with time **(Fig. 4).** The speed *(C)* at which a wave moves through a specimen can be determined by coupling measurements of the time *(t)* between pulses and the length *(L)* of the specimen using the following:

$$C = \frac{2L}{\Delta t} \qquad [3]$$

Wave attenuation can be measured as the rate of decay or logarithmic decrement of the amplitude of pulses using:

$$\delta = \frac{1}{j} \ln \frac{A_0}{A_j} \qquad [4]$$

where A_0 and A_j are the amplitudes of two pulses *j* cycles apart, and in represents the natural logarithm.

This analysis method is an estimate that can be improved by using additional pulses to give an average result. Using the time value between several pulses and dividing by the number of cycles gives an accurate *C* value. In addition, using a high value of *j* in Equation **[4]** gives an accurate value.

If values of the peak amplitudes are collected, a curve can be fit to the set, giving an equation of the form:

$$f(t) = Ae^{-nt} \qquad [5]$$

Equation **[5]** describes the outer envelope of the original pulse signal and is a decreasing exponential function. By taking the natural log of both sides of Equation **[5],** a linear equation results, where *n* is slope of the line.

$$\ln f(t) = \ln A - nt \qquad [6]$$

By comparing the natural log of the peak values of the waveform as the ordinate to the natural log of time on the absissa, a linear relationship can be observed. The slope of the line will determine the constant *n.* The slope *n* of this line is proportional to δ.

$$\delta = n \Delta t \qquad [7]$$

An oscilloscope trace of a waveform obtained from monitoring stress wave

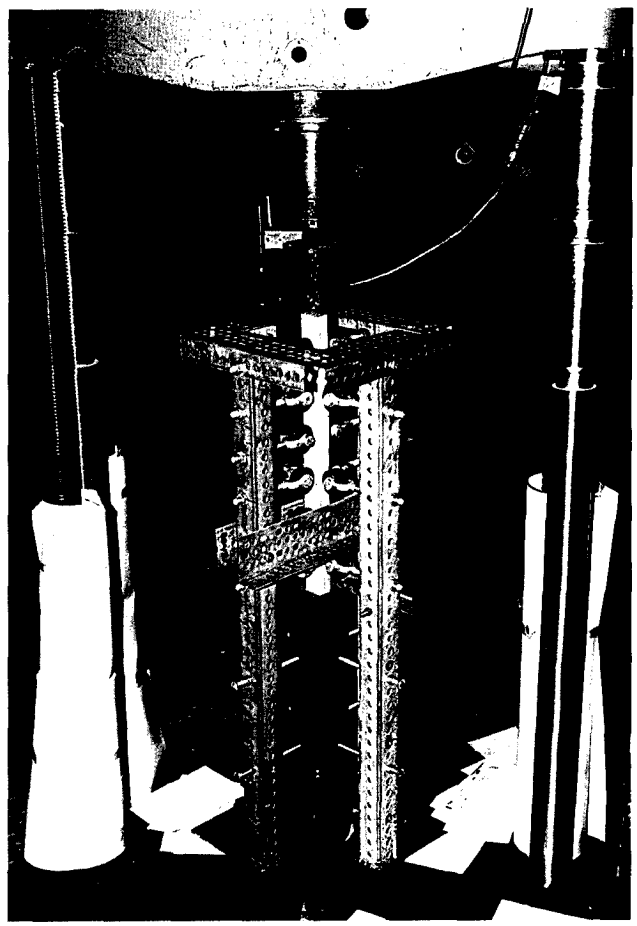

Figure 3. — Static test setup used to obtain compressive strength of specimens.

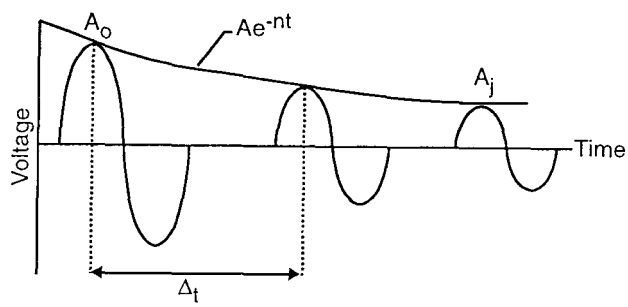

Figure 4. — Theoretical wave behavior.

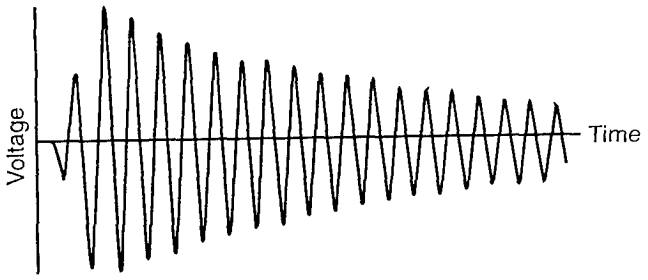

Figure 5. — Typical wave behavior in control specimen.

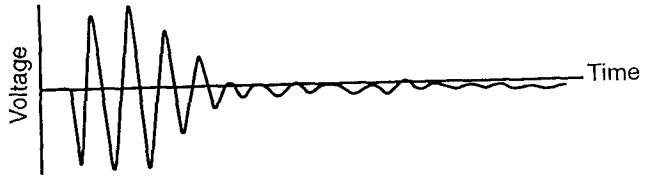

Figure 6. — Typical wave behavior in a degraded specimen.

*TABLE 1. — Parameter estimates and standard errors from fitting model (**Eq. 2**) with end weight N_1, stress wave slope $N_2 = n$, and stress wave speed $N_3 = C$ as independent variables.*

	Parameter[a]			
	b_0	b_1	b_2	b_3
Parameter estimate	-31.598	4.168	-0.939	2.322
Standard error	3.831	0.432	0.088	0.306

[a] Parameter b_0 is a regression constant and parameters b_1 through b_3 correspond to specimen weight, attenuation rate of the wave, and speed of stress wave transmission, respectively.

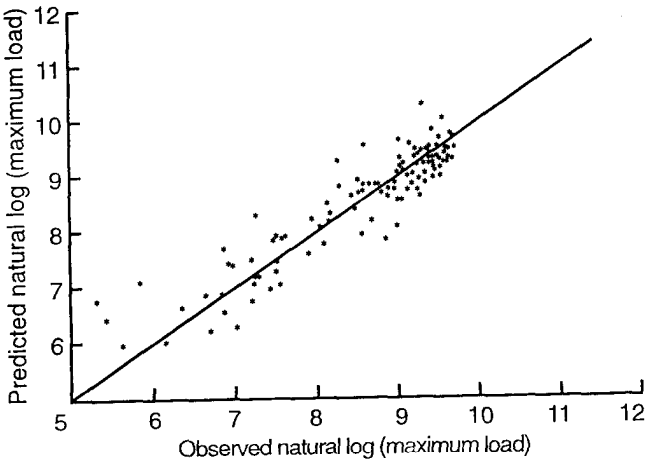

Figure 7. — Comparison of actual compressive strength values and those predicted from stress wave parameters.

behavior in the laboratory on a typical 1- by 1.5- by 20-inch (0.025- by 0.038- by 0.508-m) control specimen is shown in **Figure 5.** Note that the waveform consists of a series of equally spaced sine-shaped pulses whose magnitude decreases with time, as predicted by elementary wave theory.

To illustrate some basic differences in stress wave NDE parameters between a nondegraded specimen and one that has been exposed to natural biodegradation, **Figure 6** shows an oscilloscope trace of a waveform taken in the laboratory from a specimen that was in the field 6 months. Note the difference in shape of the curve relative to that from a control specimen shown in **Figure 5.** A significant difference existed in the rate at which energy was lost as the wave traversed through the specimen.

QUANTITATIVE ANALYSIS

Table 1 reports the parameter estimates and standard errors from the fitting model (Eq. **[2])** with end weight N_1, stress wave attenuation $N_2 = n$, and a stress wave speed $N_3 = C$ as independent variables. Parameter b_0 is a regression constant and parameters b_1 through b_3 correspond to specimen weight, attenuation of the wave, and speed of stress wave transmission, respectively.

The estimates in **Table 1** are based on a model that excluded one specimen evaluated at 15 months whose parallel-to-grain compressive strength was reduced beyond accurate measurement. The inclusion of the specimen alters the slope parameter estimate sufficiently to declare the specimen overly influential. With such a model, 85 percent of the variability observed in parallel-to-grain compressive strength can be explained. **Figure 7** is a comparison of actual compressive strength values and those predicted from stress wave parameters. This comparison shows that the model tends to underpredict strength at the higher values. Otherwise, the model appears satisfactory, especially given the complicated nature of fungi or termite attack occurring on only half of each degraded specimen. In fact, the same model fit to specimens with at least a trace of fungal or termite attack mimics the observed model in **Table 1,** while a model of nondegraded specimens is somewhat different. This appears to be because attenuation is not a factor for predicting compressive strength of nondegraded

specimens. These results are reaffirmed with marking of the residuals as to the degree of fungi or termite attack observed.

Until better models can be theoretically justified, the transformed multiplicative model is the most meaningful. In addition, it may be useful to examine the most effective model for fungal attack and termite degradation independently.

Conclusions

Based on the results of this study, we conclude the following:

- Speed of stress wave transmission and attenuation characteristics of clear southern pine sapwood are sensitive to the presence of degradation caused by fungi and termites.
- These two nondestructive evaluation parameters can be used to predict the parallel-to-grain compressive strength of southern pine sapwood that has been attacked by fungi and termites.

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