Stress Wave NDE 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 results of a study that investigated the use of longitudinal stress wave nondestructive evaluation (NDE) 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. Stress wave speed and damping characteristics of the specimens were determined after exposure. These nondestructive parameters were then incorporated into a multivariable regression model and used to predict the compressive strength of the specimens. Excellent agreement was found between predicted and actual compressive strength values.

Keywords: Nondestructive evaluation, decay, termites, degradation

Introduction

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 severely 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 stress wave speed and damping characteristics of the member in question. Considerable application of these techniques for large void detection in wood structural members has been reported (Ross and Pellerin 1988). 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 and others (1985). They focused on stress wave speed and found a useful correlative relationship with the compressive strength of wood attacked by brown-rot fungi. A relationship between longitudinal stress wave speed and compressive strength was not found in members attacked by termites.

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. The purpose of the research reported herein was to investigate use of stress wave speed and damping characteristics of wood, measured using longitudinal stress wave NDE techniques, to estimate the compressive strength of wood attacked by both fungi and termites.

Materials and Methods

Specimens, 1 by 1.5 by 20 in. (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 prior to field exposure. A total of 144 specimens were used in the study. These specimens were placed in six groups of 24, with each group having nearly equivalent stress wave speed values. One group was randomly chosen as a control and not subjected to field exposure. The remaining five groups were inserted in the ground on a field plot in southern Mississippi. Approximately half the length of each specimen was at or below groundline. This would expose specimens to both fungal and termite attack.

The five groups of specimens were removed from the field plot according to the following schedule. One group

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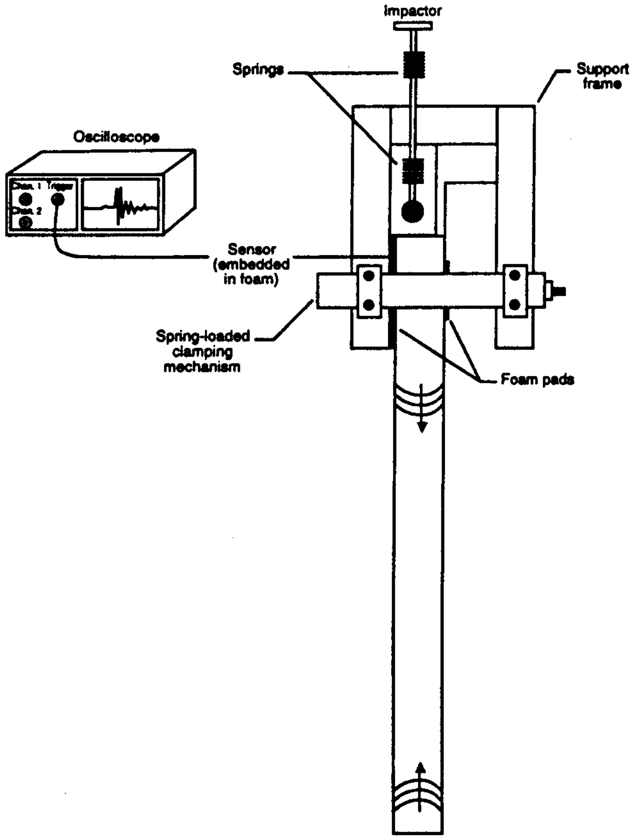

Figure 1—Experimental setup used to observe stress wave behavior in specimens.

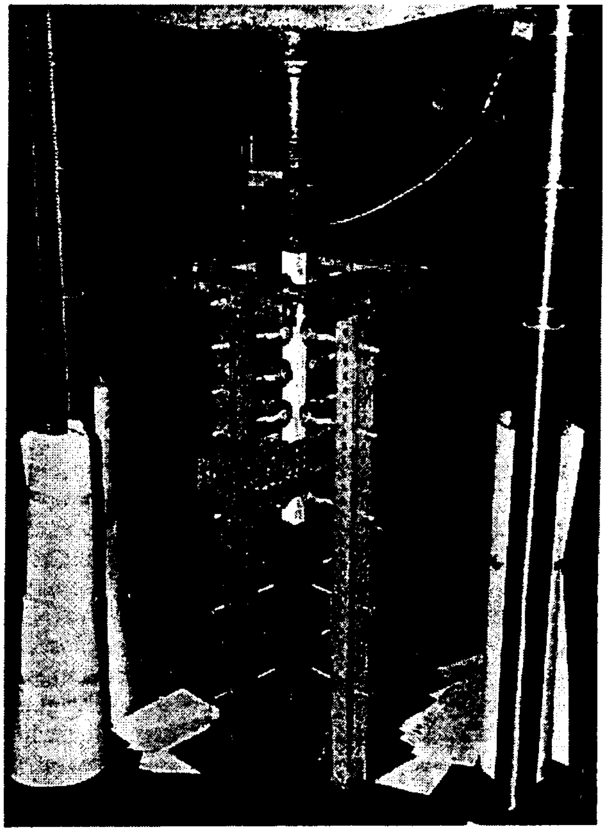

Figure 2—Static test setup used to obtain compressive strength of specimens.

of stakes was removed after each of the exposure periods of 2, 4, 6, 9, and 15 months. After equilibration to approximately 10 percent moisture content, stress wave speed and damping characteristics were determined for each specimen using the setup shown in Figure 1.

A detailed description of the setup and analysis procedures used are described by Ross and others (1994). The specimens were then tested to failure in compression (Fig. 2).

A multivariable linear regression analysis was then used to examine relationships between measured NDE parameters and compressive strength. The NDE parameters included stress wave speed and the decay rate of the wave as it traversed through the specimen. Previous work on nondegraded composites (Ross and Pellerin 1988) supported the multiplicative model.

$$M = b_0 N_i^{bi} \qquad (1)$$

where
M = Maximum compressive strength,
b_0 = Model parameters (i = 0,1,...,k), and
N_i = Measured nondestructive variables (i = 1, 2,. . .,k).

The nondestructive variables used were specimen weight stress wave speed, and decay rate of the wave.

The model can be transformed into a linear model using the following form:

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

Assuming an additive error in Equation (2), which corresponds to a multiplicative error in Equation (1), 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 (SAS Institute Inc. 1989). A similar model and analytical approach were previously used by Ross and Pellerin (1988) and Kaiserlik and Pellerin (1977).

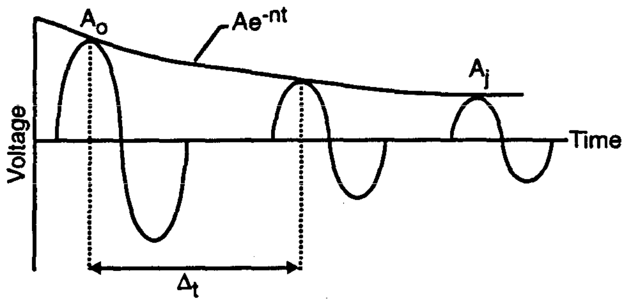

Figure 3—Theoretical wave behavior.

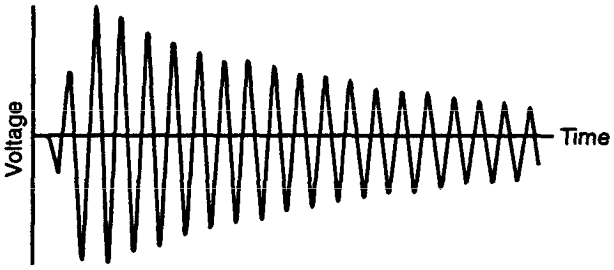

Figure 4—Typical wave behavior in control specimen.

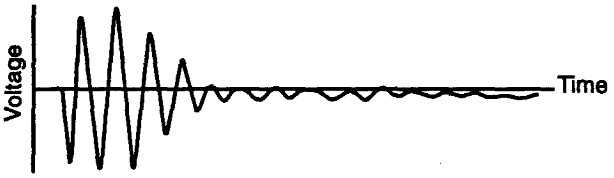

Figure 5—Typical wave behavior in a degraded specimen.

Results and Discussion

Qualitative Analysis

In using our experimental setup, elementary wave theory (Kolsky 1963) suggests that the waveforms should consist of a series of equally spaced sine-shaped pulses whose magnitude decreases exponentially with time (Fig. 3). 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:

$$C = \frac{2L}{\Delta t} \tag{3}$$

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

$$\delta = \frac{1}{j}\ln\frac{A_0}{A_j} \tag{4}$$

where
A_o and A_j are the amplitudes of two pulses *j* cycles apart.

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:

$$f(t) = Ae^{-nt} \tag{5}$$

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.

$$\ln f(t) = \ln A - nt \tag{6}$$

By comparing the natural log of the peak values of the waveform as the ordinate to the natural log of time on the abscissa, 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.

$$\delta = n\Delta t \tag{7}$$

An oscilloscope trace of a waveform obtained from monitoring stress wave behavior in the laboratory on a typical 1- by 1.5- by 20-in. (0.025- by 0.038- by 0.508-m) control specimen is shown in Figure 4. 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 5 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 4. A significant difference existed in the rate at which energy was lost as the wave traversed through the specimen.

Quantitative Analysis

To further highlight this phenomenon, examine the median values that were recorded between the control and degraded specimens in waveform and weight variables (Table 1). Degradation levels were based on visual characteristics. Note that the slowest wave (larger *t*) and rate of attenuation of the peak amplitudes were greater (larger *n*) for the degraded specimens than for the control group.

Table 1—Comparison of median values of the control and degraded specimens.

	Degradation level			
Nondestructive variable	Control	Trace	Moderate	Severe
Time between pulses (*t* sec)	0.000195	0.000196	0.000207	0.000223
Slope of line (*n*)	–397.04	–415.87	–456.83	–1219.94
Residual weight (g)	313	302	275	254

Table 2—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, decay rate of the wave, and stress wave speed, respectively.

Table 1 characterizes the progression and type of degradation observed over time. Obviously at time zero, there is no fungal or termite attack. The effects of termite or fungal attack alone on nondestructive measurements were addressed in a study by Pellerin and others (1985) and were not addressed in this study, because the pattern of degradation experienced did not allow it. A wide range of degradation levels were observed at 4 and 6 months, presumably increasing observed variability in compressive strength values at these times.

Table 2 reports the parameter estimates and standard errors from the fitting model (Eq. (2)) with end weight N_1, stress wave slope $N_2 = n$, 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, decay rate of the wave, and stress wave speed, respectively.

The estimates in Table 2 are based on a model that excluded one specimen evaluated at 15 months whose maximum crushing 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 maximum compressive strength can be explained. Figure 6 is a comparison of actual compressive strength values and those predicted from stress wave parameters. This comparison shows that the model tends to under predict 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

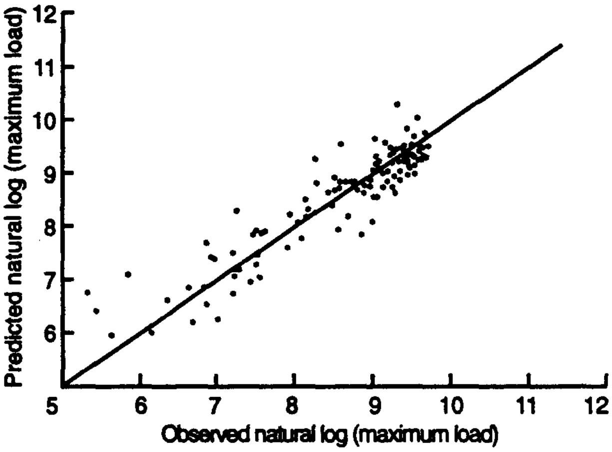

Figure 6—Comparison of actual compressive strength values and those predicted from stress wave parameters.

each degraded specimen. In fact, the same model tit to specimens with at least a trace of decay or termite attack mimics the observed model in Table 2, and a model of nondegraded specimens is somewhat different. This appears to be because slope 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.

This research, in combination with past studies, shows that the NDE instrument needs to be calibrated for the environment in which it is used. 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 decay and termite degradation independently.

Concluding Remarks

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

- Stress wave speed and damping 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 compressive strength of Southern Pine sapwood that has been attacked by decay fungi and termites.

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