NON-DESTRUCTIVE ASSESSMENT OF WOOD DECAY AND TERMITE ATTACK IN SOUTHERN PINE SAPWOOD

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Abstract

Field methods for evaluating wood decay and termite attack lack a means for quantitative measurement of weight loss or residual strength. Quantitative relationships between speed of impact-induced waves travelling parallel to the grain and residual compressive strength have been demonstrated in softwood attacked by brown-rot fungi, but such quantitative relationships have not been developed between wave speed and termite attack. We tested Southern Pine sapwood stakes that were vertically inserted half their length in soil in a Southern Pine forest in southern Mississippi. Results showed that measurement of both speed and attenuation of a reciprocating impact-induced wave will yield quantitative information on the extent of total biodegradation in Southern Pine sapwood that has been attacked by natural populations of termites and decay fungi.

Introduction

Static mechanical properties of undegraded (sound) wood can be determined using nondestructive evaluation (NDE) techniques that are based upon established mathematical relationships between stress (compression) wave parameters and static mechanical properties (Ross and Pellerin 1994). Heretofore, mathematical relationships between stress wave parameters and resultant properties of partially biodegraded wood, independent of the agent of degradation, had not been developed. Such relationships would be of fundamental value to ecological studies of natural recycling of lignocellulosic tissues, to applied field evaluations of durable wood products, and to engineering analysis of residual strength in critical components of structures being recycled or repaired.

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In natural environments, various groups of microflora and fauna may degrade wood by a diversity of biochemical and histological/anatomical modes of attack. Ideally, any NDE technique for monitoring residual strength or actual loss of material in biodegraded wood would be independent of the mechanisms of degradation and should not be unduly influenced by variations in wood moisture content.

The present authors have been exploring the potential of pulse echo techniques, which monitor both speed and attenuation of longitudinal stress waves, for this application. These parameters are controlled by the same mechanisms that determine the mechanical behaviour of a material (Jayne 1959, Kaiserlik and Pellerin 1977, O'Halloran 1969, Pellerin 1965).

In our research, several sizes of wood members are challenged with either natural or controlled populations of biodeteriogens. In this work small stakes of Southern Pine sapwood were exposed in ground contact and underwent progressive degradation by naturally occurring populations of microflora and subterranean termites. Emphasis is placed on explaining relationships between modes of attack and visual and NDE measurements. Another report describes the time-sequenced changes in properties of these stakes during field exposure (DeGroot *et al.* 1994).

Parallel-to-grain stress-wave velocity has been shown to decrease as wood moisture content increases (Burmester 1965, Gerhards 1975), but the relationship is curvilinear. The maximum wood moisture content at which wave speed is not significantly influenced by additional increments in wood moisture seems to be species dependent. The moisture content is about 30% for pine (Burmester 1965) and 70% for sweetgum (Gerhards 1975).

It has been postulated that changes in wood moisture content in utility poles would mask changes in acoustic velocity caused by the effects of wood decay (Dunlop 1981). However, DeGroot and colleagues (Pellerin *et al.* 1985) demonstrated a correlation between longitudinal wave speed and modulus of elasticity (MOE) in compression in 17 x 17 x 279 mm (0.75 x 0.75 x 11 in.) beams of Southern Pine sapwood degraded by the brown-rot fungus. *Gloeophyllum trabeum* (Pers. ex Fr.) Murr., under laboratory conditions. The authors were unable to demonstrate a relationship between longitudinal wave speed and attack by subterranean termites *(Reticulitermes* sp.). They presumed this was because the termites preferentially degraded the earlywood, leaving the latewood bands intact throughout the length of at least some portion of the beams. In a study of both softwood and hardwood mine timbers (Chudnoff et at. 1984), stress-wave velocity measurements were made parallel-to-the-grain on the timbers in the "as is" moisture content condition. At the time of testing, 95% of the mine timbers had less than 35% moisture content. Dynamic MOE parallel to the grain, as computed from the stress wave measurements, had good linear correlation with crushing strength. However, actual stress wave values were less well-correlated with crushing strengths.

Stress wave speed, in a transverse direction, has been shown to be sensitive to the presence of decay in large structural members (Hoyle and Rutherford 1987, Rutherford *et al*. 1987). In general, as decay progresses, wave speed decreases. The principle has also been applied to detecting decay in utility poles (Anon 1979). With poles, wave speed is generally monitored in a transverse direction. Ultrasonic pulse velocity measurements, taken in the transverse direction, also showed promise of detecting decay in beams of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], but measurements in the longitudinal direction were ineffective in delineating decay in the beams (Wilcox 1988).

Wave attenuation is also influenced by the presence of wood decay (Wang *et al.* 1980). Dunlop (198 1) recognised that measurements of the acoustic damping parameter showed promise of providing a technique suitable for testing utility poles. Dunlop (1983) subsequently postulated that degradation within a pole by rot or other agency would lead to increased damping of longitudinal acoustic waves. In field trials on *in-situ* poles designated for removal because of decay, results of acoustic tests that monitored damping compared favourably with gradings of decay damage in poles after dissection.

Wave attenuation is sensitive to the bonding characteristics of manufactured, wood-based composites and is a valuable NDE parameter that contributes significantly to the prediction of mechanical properties in those composites (Ross and Pellerin 1988). It is presumed that wave attenuation is controlled by internal friction mechanisms to which the natural bonding characteristics between constituents of undegraded wood contribute significantly.

[Subsequent to the submission of this paper the authors showed that both wave speed and attenuation can be used to predict the compressive strength of biologically degraded wood that was equilibrated to a constant moisture content. (Ross et al., 1997)]

Objective

Our experiment was initiated to determine if longitudinal pulse echo measurements could be used to detect biodegradation, monitor the amount of wood lost, and conversely, estimate and residual strength in small stakes of Southern Pine sapwood partially embedded in the ground, where stakes would be subject to combined attack by decay fungi and termites.

Materials and Methods

Exposure Tests

All stakes were cut from Southern Pine sapwood lumber, Class C or better. Lumber was 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)*. At our laboratory, lumber was cut into stakes 25 x 38mm (1 x 1.5 in.) in cross section and 0.5 m (20 in.) long. Clear sapwood was used in this study to maximize the opportunity to establish relationships between energy storage : dissipation properties of wood, and residual strength of wood undergoing decomposition by naturally occurring microbial complexes. The stakes were the same length, the same thickness, and 12.7mm (0.5 in.) less wide than the stakes used by the International Forestry Research Organization (IUFRO) for field evaluation of preservatives in ground contact.

Prior to field installation, all stakes were equilibrated until a constant weight was measured for each stake, in a controlled environment at which Southern Pine sapwood equilibrates to a moisture content of 10%. The MOE of each beam was then detemrined by stress wave analysis; beams were sorted into six groups with equivalent MOE (average and standard deviation) properties. Each group contained 24 stakes.

One group of 24 stakes was randomly selected as the reference or control group. This group was retained in the controlled environment room until the conclusion of the field phase of this study. Then, each beam in the reference group was remeasured using NDE technology and destructively tested in compression parallel to the grain.

The remaining stakes were installed in a field plot on the Harrison Experimental Forest in April 1990. This forest is located in southern Mississippi, approximately 32 km from the Gulf of Mexico. The actual plot was established in soils characterized as Poarch fine sandy loam (Smith 1975). Stakes were vertically inserted into the ground to a depth of 250 mm (10in.), according to a randomized block design. Spacing of stakes within the plot and plot maintenance procedures followed practices given in ASTM D1758 (ASTM 1989).

Stakes were evaluated at 2, 4, 6, 9, and 15 months after installation. At each inspection, one predefined group of 24 stakes was nondestructively tested and visually evaluated for degradation in the field. The stakes were then shipped to the Forest Products Laboratory (FPL) for reconditioning, weighing, additional nondestructive testing, and destructive testing in compression.

In the field, stakes were nondestructively evaluated in three positions: (1) original location with no movement; (2) elevated 25.4 mm (1 in.) from original set depth, but still within the ground; and (3) removed from the ground and resting upon a styrofoam pad.

At each measurement, a clamp that contained a spring-loaded impactor and a piezo film was affixed to one end of the stake (Figure 1).

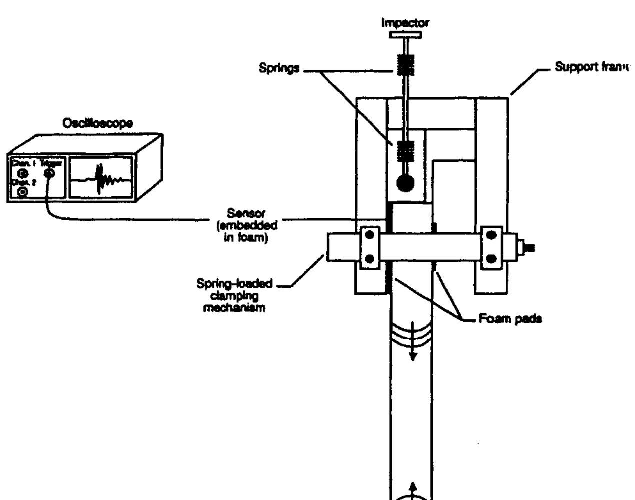

Figure 1. Equipment used to impart and receive pulse echo signal from stakes.

A single impact wave was induced in the stake. The repeated passage of that wave past the piezo film as the wave reciprocated from end to end was detected and recorded with a Nicolet 310 portable digital oscilloscope. In making these measurements, the energy of the impact (and thus the amplitude of the initial waves) had to be controlled to the extent that the vertex of each wave could be fully recorded. After nondestructive tests were completed, stakes were visually rated for decay and termite attack (Table 1). This rating scheme was patterned after procedures defined in D 1758 (ASTM 1989) but degradation was expressed as percentages of cross-section area that was attacked.

TABLE 1 : System for visually rating stakes for fungal decay and termite damage

Stake Condition	Rating	
	Fungal decay	Termite damage
No attack	1	A
Trace attack: up to 10% of cross section area affected	2	B
Moderate attack: 10 - 50% of cross-section area affected	3	C
Severe attack: Not easily broken but more than 50% of cross section area affected	4	D
Failure: easily broken in field at time of inspection	5	E

After field inspection, stakes were banded in plywood overwrap and shipped by surface freight to the FPL, Madison. The stakes were placed in a cold room (32°C (0°F)) for 1 week. The stakes were then equilibrated to a constant weight in a controlled environment room in which wood equilibrates at a moisture content of 10%. Pulse echo measurements were then taken of the re-equilibrated beams prior to destructively testing them in compression. Maximum load in compression, parallel to the grain, was determined in compression tests. Parallel-to-grain maximum crushing strength and modulus of rupture (MOR) in beams subjected to failure in bending were the best indicators of decay found by Scheffer's (1936) study of progressive effects of *Polyporus versicolor* L:Fr [now *Trametes versicolor* (L.:Fr) Pilat] on the physical properties of red gum sapwood.

Data Analysis

Wave speed, wave attenuation (slope), and the combined effect of wave speed and slope were evaluated as indicators of residual equilibration weight and compressive strength after exposure and as indicators of weight loss during exposure. The measurements were expressed as log decrement (Ross *et al.* 1994) in the pulse echo signals obtained from stakes in their original position as installed in the field.

The NDE parameters and visual ratings were compared with weight loss and residual strength properties only for stakes that could be tested in compression parallel to the grain following field exposure. During the latter phase of the study, some stakes degraded to the extent that they could not be withdrawn from the soil without separating into two parts. Those stakes were not further analyzed.

Linear regression analysis (SAS Institute 1989) was used to determine correlations between NDE parameters and resultant strength or weight and between NDE parameters and percentage of weight loss (percent weight loss). Difference between means in specific data sets were tested using the Tukey Multiple Range Test (SAS Institute 1989).

We recognize that degradation by termites and wood decay fungi may be simultaneous events and cannot be regarded as separate and independent phenomena within individual stakes. Nevertheless, patterns of visual ratings for each type of degradation were compared to gain additional insight into possible relationships between mode of attack and residual strength. Visual estimates of termite attack and decay at time of stake extraction from the soil were also evaluated as indicators of residual properties in the beams and as covariants of NDE parameters. In these comparisons, data are summarized using box plots (Velleman and Hoaglin 1981).

In these plots, the middle 50% of data, from the 25th to 75th percentiles, are defined by the lower and upper boundaries of the box. The median is depicted as a horizontal line within that box. The lowest and highest values are shown as dashed lines ('whiskers') below and above the boxes. However, extreme values, outside the box by more than 1.5 times the height of the box above the 75th or below the 25th percentile lines, are depicted as isolated lines.

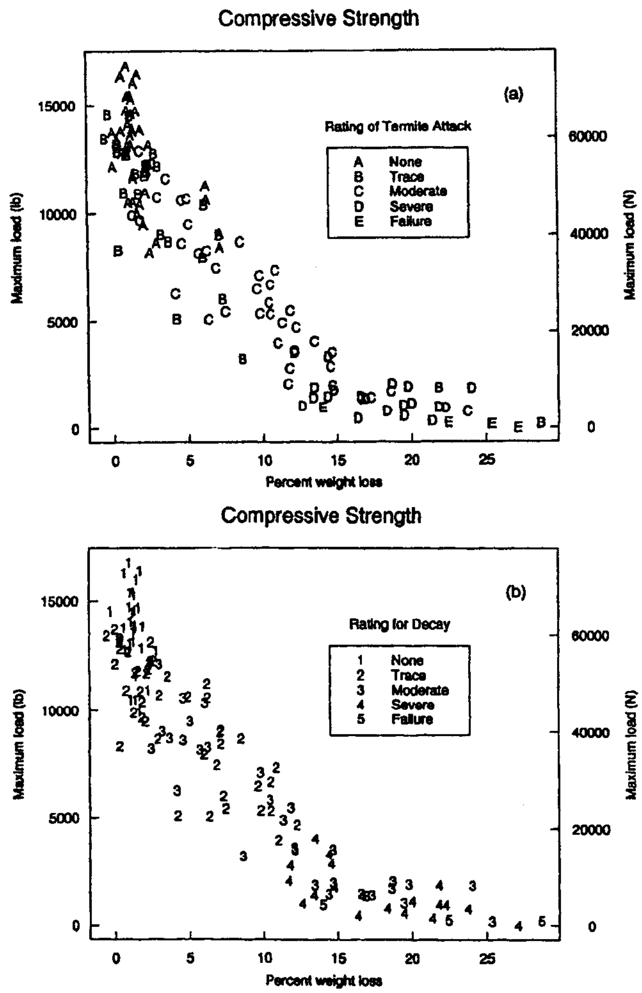

Figure 2. Comparison of maximum load in compression parallel to the grain and % weight loss in exposed stakes. Distribution of visual ratings for (a) termite attack and (b) decay is shown.

Results

Physical/Mechanical Properties

When comparing all exposed stakes as a group, the maximum compressive strength was not linearly related with the amount of wood lost as a result of degradation, whether that loss was expressed as a percentage of original weight (Figure 2) or in grams of wood tissue lost.

Pulse Echo Signals

The number of reciprocating waves that could be recorded when pulse echo measurements were made on the 50-mm (2 in.) stakes, either prior to their removal from the soil (Figure 3a) or after re-equilibration (Figure 3b), tended to decrease as the amount of biodeterioration increased. Higher

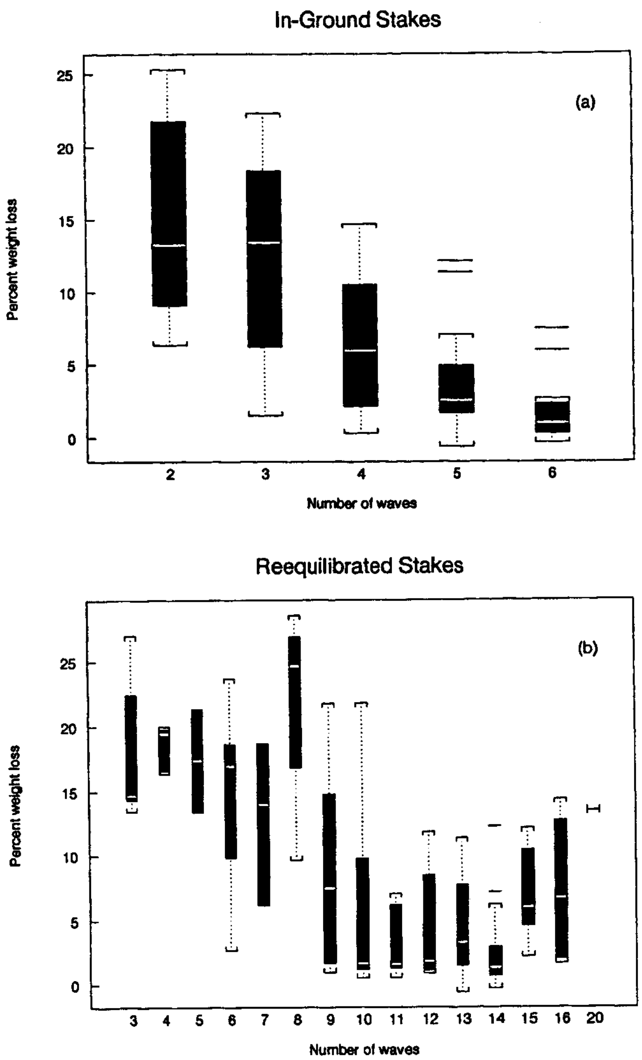

Figure 3. Number of reciprocating waves recorded for stakes with various amounts of degradation: (a) NDE measurements made in the field on stakes in original installation position, (b) NDE measurements made on stakes removed from the field and re-equilibrated at 10% moisture content.

percentages of weight loss were associated with a reduced number of pulses, but the reverse was not always true, particularly for stakes monitored while installed in the soil.

In the field, no echo could be obtained from stakes that were degraded to the extent that they would separate into two sections when extraction was attempted. The recording consisted of a single pulse. Stakes yielding signals with two waves had at least 5-percent weight loss (Figure 3a). Stakes yielding pulse echo signals with three to five waves had an array of weight losses, and stakes that had pulse echo signals with more than five waves generally had less that 5% weight loss.

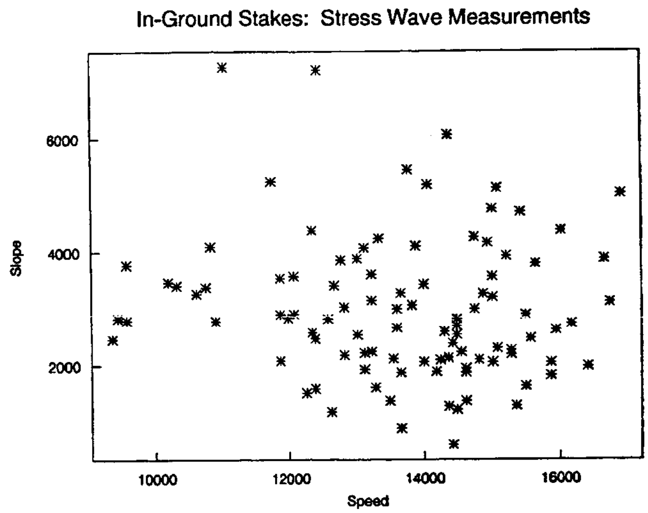

Figure 4. Comparison of slope and speed for all pulse echo signals obtained from stakes in the field after various exposure times in ground contact.

The number of waves recorded per stake after re-equilibration (Figure 3b) was more indicative of attack. Stakes with less than six recorded waves showed more than 10% weight loss. Signals with six to ten waves recorded were generally from stakes with more or less than 13% weight loss; stakes from which 11 or more stress waves could be recorded had less than 13% weight loss, with two exceptions: one stake each for 14.0 and 13.5% weight loss. In pulse echo signals obtained from the field, wave slope and wave speed were not correlated (Figure 4).

For stakes monitored while positioned in the ground. a progressive increase in attenuation of pulse echo signals was associated with increased decay as judged by visual estimates (Figure 5b). The relationship between wave attenuation (slope) and visual rating of termite attack (Figure 5a) was not as well-defined. The greatest variability among stakes occurred in the group with no evidence of termite attack. This suggests that some stakes were already attacked by decay fungi prior to onset of termite attack.

A significant increase in attenuation of pulse echo signals obtained from re-equilibrated stakes was associated with termite attack of more than 50% of the cross sectional area of the stake (Figure 6a). An increase in attenuation of pulse echo signals is also associated with decay present in more than 25% of the cross sectional area (Figure 6b), but the magnitude of change was not as great as that with termite ratings. This suggests that the damping component of this signal is more sensitive to late stage of termite attack than is wave speed. The

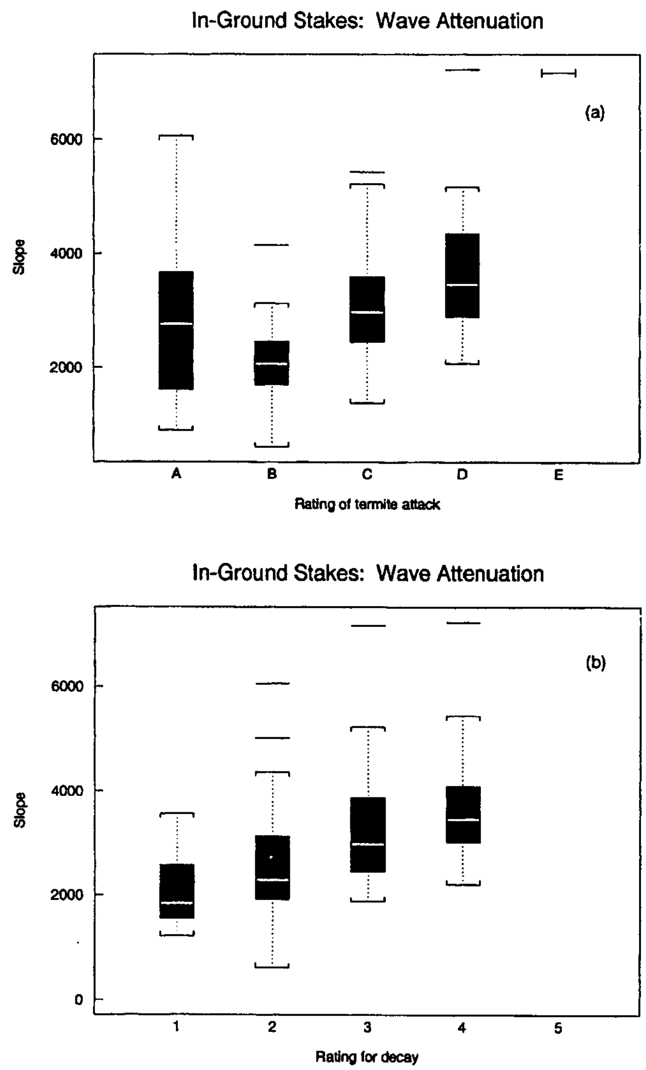

Figure 5. Wave attenuation (slope) in pulse echo signals obtained in the field on stakes prior to removal from ground. After extraction from the soil, stakes were rated for severity of (a) termite attack and (b) wood decay.

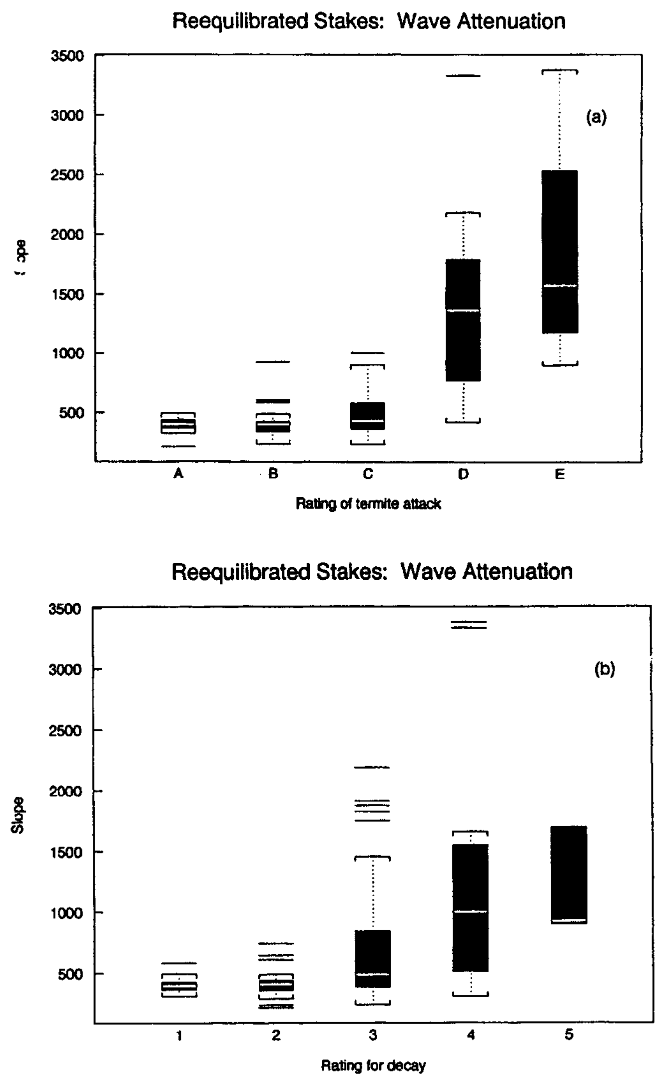

Figure 6. Wave attenuation (slope) in pulse echo signals obtained in stakes following removal from plot and re-equilibration. Stakes are grouped according to visual ratings of (a) termite attack of(b) wood decay.

confounding of fungal and termite attack prevents definitive conclusions; a future study will address this hypothesis.

In the pulse echo signals obtained from stakes that were monitored after each exposure in their original position in the ground (prior to partial or complete removal from original position), linear regression analysis using the log decrement could explain approximately 47% of the variation in % weight loss, approximately 30% of the variation in the final weight, and 43% of the variation in maximum load when tested in compression parallel to the grain (Table 2).

Wave speed was not a good indicator of the residual weight at time of observation (end weight) or the percentage of tissue that had been lost due to degradation during exposure. Wave attenuation (slope) was somewhat less variable in distribution when compared with end weight or % weight loss, but wave attenuation still did not account for much of the variation seen in those parameters. The log decrement of the signal was a better indicator of final weight and % weight loss resulting from degradation during exposure than was wave speed or slope.

Wave speed [microsecond/ft (microsecond/meter)] alone was somewhat correlated with maximum load in compression. Slightly more variation in maximum load during compression parallel to the grain could be explained by the log decrement as computed from the signal obtained in the field. during exposure than was

TABLE 2 : Results of statistical analysis

Wave parameter	Coefficient of determination (r^2)		
	Final weight	% weight loss	Maximum load
Time	0.14	0.30	0.38
Speed	0.13	0.28	0.37
Slope	0.22	0.31	0.27
Log decrement	0.30	0.47	0.43
Speed, slope	0.32	0.54	0.58

wave speed or slope. Wave speed [microsecond/ft (microsecond/meter)] alone was somewhat correlated with maximum load in compression. Slightly more variation in maximum load during compression parallel to the grain could be explained by the log decrement as computed from the signal obtained in the field.

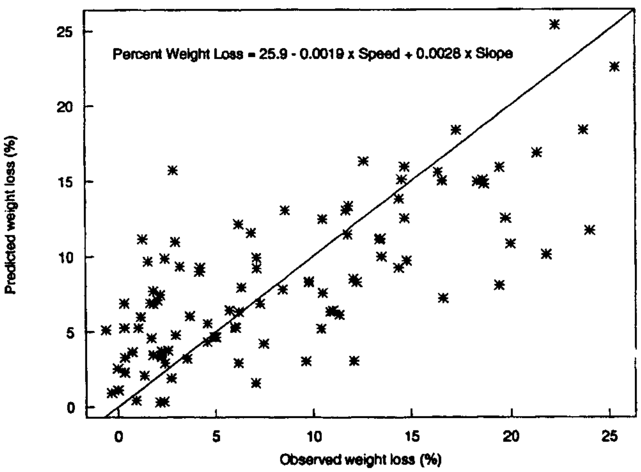

Figure 7. Comparison of actual and predicted % weight loss in stakes from pulse echo signals obtained in the field. Reference line illustrates ideal agreement between predicted and observed values

A better estimate of % weight loss (Figure 7) or maximum load in compression parallel to the grain (Figure 8) could be obtained from field data using a multiple regression developed from wave speed and slope:

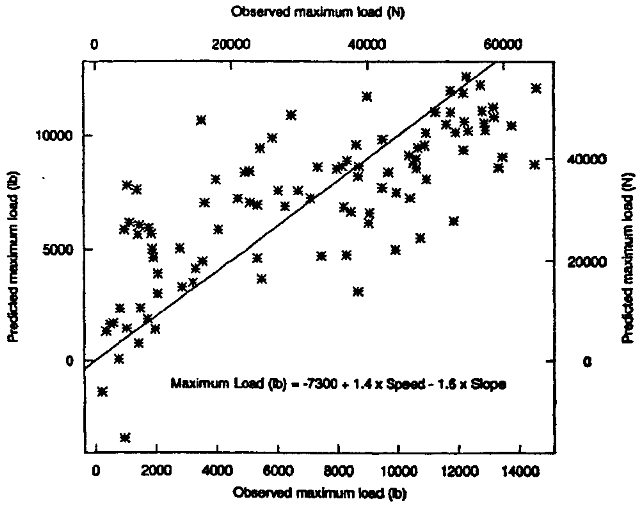

Figure 8. Comparison of actual and predicted compressive strength of stakes from pulse echo signals obtained in the field. Reference line illustrates ideal agreement between predicted and observed values.

PWL = 25.9 - 0.0019 x speed + 0.0028 x slope

where: PWL - Percent weight loss

MCS (lbf*) = -7300 + 1.4 x speed - 1.6 x slope

where: MCS - Maximun compressive strenght

* 1 lbf = 4.448222 N

Visual Evaluation

A significant difference in maximum load in compression was detected between populations of stakes showing no termite attack (rating of A) and those showing attack up to 10% of the cross-sectional area (rating of B) (Figure 9a) and between stakes with no evidence of decay (rating of 1) and those with decay in up to 10% of the cross-sectional area (rating of 2) (Figure 9b). There was no detectable difference in compressive strength for stakes in either of the last two visual rating categories for maximum decomposition. The range of compressive strength within the termite-attacked stakes was greater than that of their unattacked stakes.

A fairly linear relationship (Figure 10) may be developed between residual compressive strength and visual ratings if ratings from each stake are converted to a scheme that essentially expresses decomposition as a percentage of a maximum value. If visual ratings for both decay and termite attack are changed to an arithmetic scale ranging from 0 (total failure) to

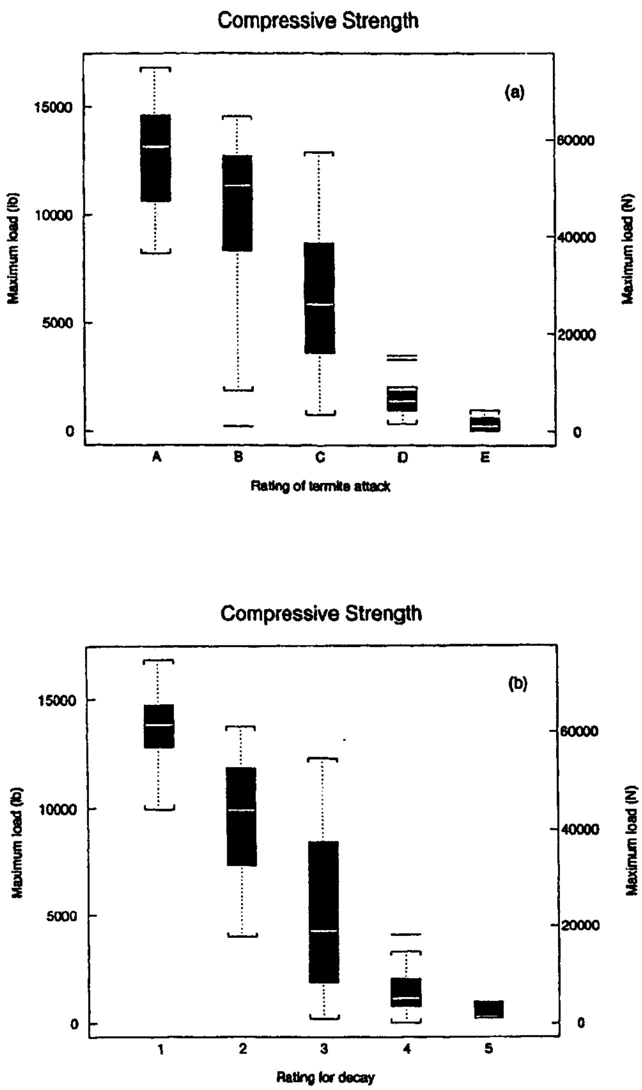

Figure 9. Compressive strength of stakes visually graded for (a) termite attack and (b) wood decay.

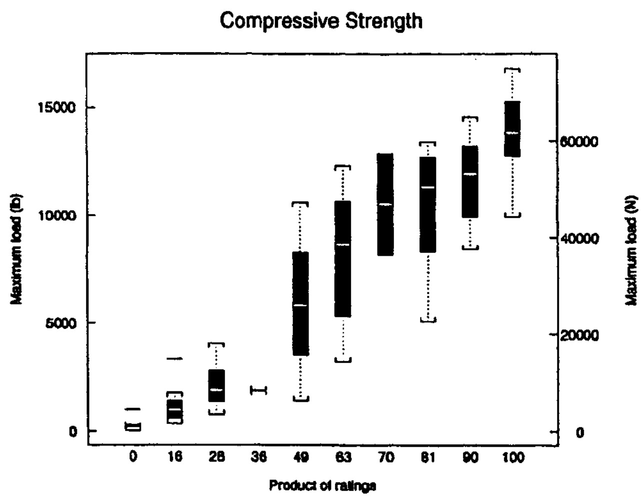

Figure 10. Compressive strength of stakes given a combined rating derived from products of visual ratings. Note: Few specimens survived to be visually rated, as indicated by height of box plot.

10 (no attack) and the respective converted values for both termite attack and decay in each stake are multiplied together, then divided by 10, the product of the converted ratings shows a fairly linear relationship with compressive strength at products greater than 4.9. There appears to be discontinuity below the 4.9 value, but the representation of stakes in that area was not sufficient to define the discontinuity.

Discussion

Physical/Mechanical Properties

The curvilinear relationship between weight loss and resultant compressive strength indicates that loss in compressive strength results from two different mechanisms.

The maximum load in compression is an indication of the weakest cross-sectional area of the column being compressed if that column does not flex. It may be inferred that the impact of decay fungi, particularly white-rot fungi, on the cross-sectional area of these beams would be more closely related to weight loss than would termite attack. Decay fungi would tend to progress through both earlywood and latewood tissues. Termites preferentially remove the earlywood tissue, thereby leaving isolated bands of the more dense latewood tissue. The isolated bands of latewood tissue would easily flex in compression. Thus, the rate of loss in compressive strength per unit loss of wood could be greater in termite-degraded wood than in wood decayed by white-rot fungi. These is some evidence to support this hypothesis in that most stakes with little compressive strength showed advanced attack by termites, that is, a rating of D or E, as visually determined in the field (Figure 2a). However, some stakes did not show advanced decay, that is, a rating of 4 or 5, as visually determined in the field (Figure 2b),

Pulse Echo Signals

In this experiment, the portion of each stake that was embedded in the soil and most subject to degradation was approximately half the volume of the total stake. Future evaluations of pulse echo analysis as a tool for nondestructive measurement of wood will have to account for proportionate differences in wood members that are degraded. It might be assumed that construction materials being considered for recycling would be mostly undegraded or only slightly degraded. In contrast, the major application in ecologically oriented field research would be in following degradation of wood members to completion.

The general decrease in number of waves detected as deterioration progressed reflected loss of signal energy through absorption or damping. We suggest that if pulse echo signal analysis is applied to future recycling or quality control programs where one objective is to separate degraded wood members from those with acceptable strength properties, inclusion of the count of reciprocating waves may proved to be a valuable component of the analysis. In future studies, we intend to explore the merits of wave counts as a component in the analysis of partially degraded wood members.

Several prominent outliers occur within the data set collected over time. The exact nature of these cannot be determined. It is possible that wounded tree roots, which are bonded by pitch exudates to some stakes, could alter the signal somewhat, but this has not been verified. Further explanation of these outliers will have to be explored as this research progresses to engineering applications.

Sensitivity

From an engineering perspective, definition of the initial changes in strength properties is important. From an ecological perspective, however, definition of the final stages of decomposition may be of prime importance. The earliest onset of attack, particularly termite attack, is detected by visual observation on stakes removed from the soil. Although relationships between resultant compressive strength and visual ratings could be developed for these stakes, a greater opportunity is to establish fundamental relationships between progressive levels of deterioration and pulse echo parameters than between advanced levels of degradation and visual relationships. Pulse echo measurements would have an obvious advantage in monitoring decomposition in wood members that cannot be visually inspected.

Conclusions

This study demonstrated that analyses of both wave speed and damping characteristics of pulse echo signals moving parallel to the grain have potential for nondestructive monitoring of wood biodegradation and nondestructive estimation of residual strength independent of cause of biodegradation. Pulse echo analysis, has utility beyond that of single parameter analysis of impact-induced waves and should be explored to further define its full potential as an engineering tool and as a tool with application in field research on degradation of wood materials.

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