Pacific Timber Engineering Conference
Gold Coast Austraila
July 11 - July 15, 1994.

EVALUATION OF TIMBER BRIDGES USING STRESS WAVE TECHNOLOGY

R. Pellerin, * Washington State University, U.S.A., R. Ross, R. Falk, * USDA Forest Service,
N. Volny, * Volny Engineering Inc, U.S.A.

SUMMARY

The focus of this research was to develop stress wave NDE techniques for determination of the in-place properties and strength of timber bridge components. Current inspection procedures for timber bridges is often an art involving visual assessments of the degree of decay and mechanical damage and of the extent to which the deterioration has penetrated into hidden regions of the structure. NDE techniques utilizing stress waves has successfully been used to improve the assessment of the integrity of wood structures.

The research results show improved stress wave velocity methods that more accurately quantify the residual strength of wood members and the timber bridges themselves. These improved methods have been applied to wood bridges and piles that had been targeted for replacement. Stress wave evaluations were performed on the bridges in-place, followed by destructive testing of elements of the bridges and piles after demolition to verify the NDE conclusions. While the application of the stress wave methods in this study is for softwood timber bridges, the methods are applicable to all timber bridges. The ultimate goal of the research is to develop a comprehensive handbook for bridge inspectors which provides guidelines on the use, application and interpretation of stress wave methodology for locating and defining areas of deterioration in timber bridges. This presentation discusses the theory of stress wave technology, user guidelines for equipment use, interpretive procedures, and procedural guidelines for assigning design values to in-place bridge components and for assessing in-place capacity.

INTRODUCTION

It has been estimated by the Federal Highway Administration for the United States that as much as 41% of the nation's bridges are either structurally deficient or in need of repair (Tarricone, 1990). There have been several recent instances of catastrophic collapse and loss of life attributable to deterioration in bridges (Scalzi, 1990). Repair, retrofit, rehabilitation or replacement of severely deteriorated elements of the infrastructure is essential to preserve public safety. A key element in implementing these efforts to improve the infrastructure is the ability to accurately evaluate the material properties, degree of deterioration, and remaining life of structuralsystems.

Current methods of assessing the safety of structures typically rely heavily on visual inspection processes. Based largely on experience and judgment, an engineer will subjectively determine the degree of deterioration and remaining life of a structure. Destructive testing of samples taken from the structure (e.g. coring) will sometimes also be performed to assist in this assessment. Nondestructive evaluation (NDE) methods would clearly assist in evaluating the deterioration and integrity of structures. While many NDE techniques are available for metals, very few methods are available for application to the non-metal materials typically present in structures, such as wood, and concrete. Further, the few NDE methods that are used for structures are typically used on a comparative basis and the results are often unreliable. It is essential that quantitative NDE methods capable of being performed in the field on a routine inspection basis be developed to accurately assess the safety of structures.

The focus of this research is to develop NDE techniques for determination of the in-place properties and strength of wood in a bridge, both above and below ground. Current inspection procedures for timber structures is often an art involving visual assessments of the degree of decay and mechanical damage and of the extent to which the deterioration has penetrated into hidden regions of the structure. NDE techniques utilizing monitoring of stress waves has successfully been used to improve the assessment of the integrity of wood structures. This approach has been employed to inspect wood buildings (Hoyle and Pellerin, 1978), wood piers (Ross and Pellerin, 1991), and the world's largest laminated beam structure - TRESTLE (Brown, 1985; Neal, 1985).

This research quantitatively relates stress wave parameters. such as wave velocity and attenuation, to the residual strength of wood bridge members. The stress wave NDE method has been applied to wood bridges and piles that have been targeted for replacement. The nondestructive evaluations are performed on the bridges in-place, followed by destructive testing of elements of the bridges and piles after demolition to verify the NDE conclusions. While the application of the NDE methods in this study is for bridges, the methods will be generally applicable to wood structures. The ultimate goal of the research is to develop practical techniques for the quantitative NDE of wood structures and to develop a comprehensive handbook for bridge inspectors that provides guidelines on the use, application and interpretation of stress wave methodology for locating and defining areas of deterioration in timber bridges. Particular attention will be given to presenting the theory of stress wave technology describing the necessary instrumentation, defining practical procedures, and preparing interpretation guidelines for the quantitative NDE of timber bridges by inspection personnel.

BACKGROUND

NDE techniques for wood differ greatly from those for homogeneous, isotropic materials such as metals, plastics, and ceramics. In such materials, whose mechanical properties are known and tightly controlled by manufacturing processes, NDE techniques are used only to detect the presence of discontinuities, voids or inclusions. However, in wood, these irregularities occur naturally and are further induced by degradative agents in the environment. Therefore, NDE techniques for wood are used to measure how environmentally induced irregularities interact in a wood member to determine its mechanical properties.

Wood structures are always subject to degradation of their structural integrity due to decay. Periodic inspection of wood structures is necessary to insure continued performance. A method that has successfully been used for the NDE of wood structures is the inducement of a stress wave in a wood member and measurement of wave attenuation characteristics and the time required for the stress wave to propagate through the member. If decay is present in the member, the attenuation and propagation time of the stress wave passing through the member is increased. The increase in propagation time, in extensively decayed wood, may be as great as 10 times the propagation time for solid wood. Several techniques that utilize stress wave propagation have been developed for the in-place NDE of wood structures (Ross and Pellerin, 1991).

As an introduction to the stress wave method, a schematic of the stress wave concept for detecting decay within a rectangular wood member is shown in Figure 1. First, a stress wave is induced by striking the specimen with an impact device that is instrumented with an accelerometer that in turn emits a start signal to a timer. A second accelerometer, which is coupled to the specimen, then responds to the leading edge of the propagating stress wave and sends a step signal to the timer. Thus, the elapsed time for the stress wave to propagate between the accelerometers is displayed on the timer.

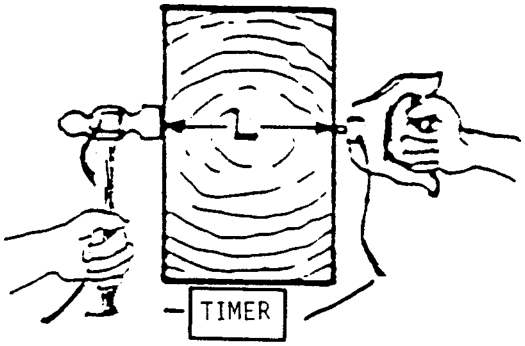

Figure 1. Schematic of stress wave timer.

The use of stress wave velocity equipment to detect rot, other defects and their extent in timber bridges and other structures is practical. It is limited only by access to the structures under consideration. It is especially useful on thick timbers or glulams 200 mm or wider where hammer sounding is not effective.

The timer measures the stress wave transit time through the materials in microseconds (millionths of a second). The soundness of the material is inversely proportional to the stress wave's transit time through it. The transit time is read directly on the instrument. The stress wave velocity and transit time are related to the timber as follows:

$$V = \sqrt{\frac{Eg}{P}} \quad \text{meters/sec} \qquad (1)$$

$$T = \frac{L}{V} \quad \text{microseconds}$$

Where
V = velocity-meters/sec
T = wave transit time - millionths of a second
L = path length - meters
E = dynamic modulus of elasticity - Kgf/m^2
p = density of material - Kg/m^3
g = accel of gravity = 9.81 $meter/sec^2$

Researchers have determined that the wave velocities in sound timber vary with the wood's grain orientation. The slowest transverse to grain velocity is found at a 45 degree orientation to the annual rings. The fastest is about 15% higher in a path that is radial. Tangential wave velocities are expected to be about halfway between those noted previously (Figures 2 and 3).

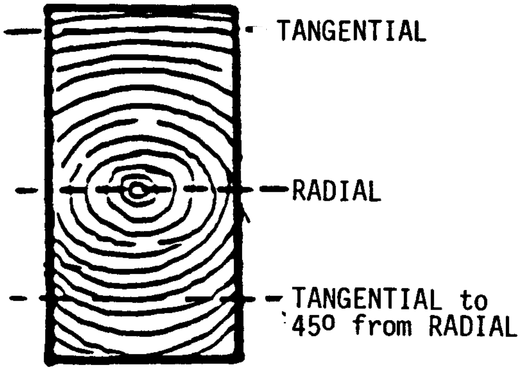

Figure 2. Transverse stress wave paths.

Even though the stress wave velocity can vary with moisture content, temperature and extent of pressure treatment, those variances can be discounted in field use as they are minor compared with variances due to unsound conditions of the timber.

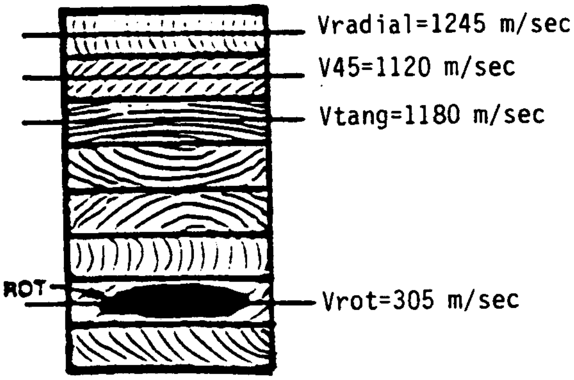

Figure 3. Transverse stress wave velocities in a glulam beam.

For evaluation of bridge piling both above and below ground level, longitudinal stress waves are proposed. Elementary wave theory (Kolsky, 1963) indicates that stress waves in a long, slender homogenous member, induced by impact using a setup such as that shown in Figure 4, will result in wave forms

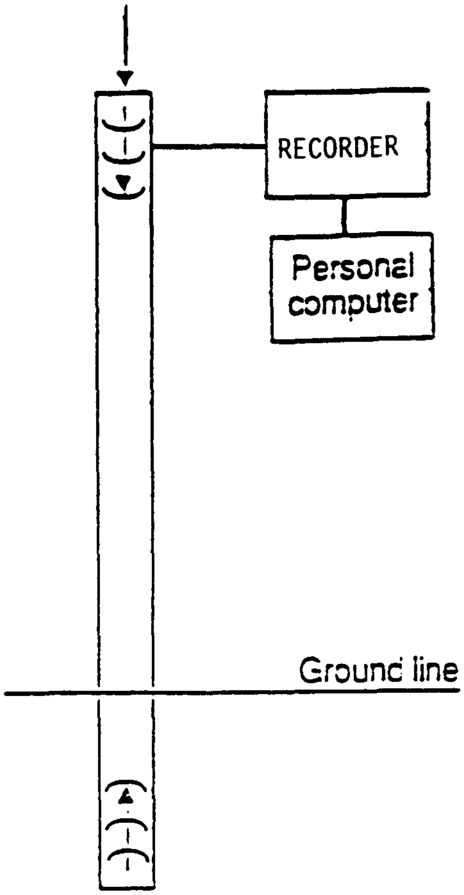

Figure 4. Longitudinal stress wave set-up for piling.

that consist of a series of equally spaced sine-shaped pulses whose magnitude decreases exponentially with time (Figure 5). The velocity (V) at which the wave moves through a material can be determined by coupling measurements of the time between pulses (T) and the length of the specimen (L) using equations 1.

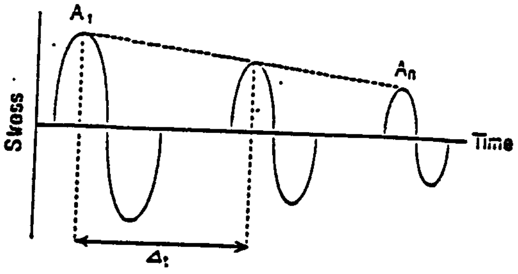

Figure 5. Longitudinal stress wave attenuation.

The modulus of elasticity of the material (MOE) can be computed using V and the mass density of the material (ρ) by:

$$\mathrm{MOE} = V\rho \qquad (2)$$

Wave attenuation can be measured as the rate of decay, or logarithmic decrement (δ), of the amplitude of the pulses using the following formula:

$$\delta = \frac{1}{n}\ln\frac{A_o}{A_n} \qquad (3)$$

where A_o and A_n are the amplitude of two pulses, n cycles apart. Wave attenuation calculated using this formula is highly dependent on the characteristics of the excitation system used (Ross and Pellerin, 1991). Thus, results reported by various researchers often cannot be directly compared.

Since wood is neither homogeneous nor isotropic, the usefulness of the previously described one-dimensional wave theory for wood could be considered dubious. However, several researchers have examined actual wave forms resulting from propagating waves in wood and have found that one-dimensional wave theory is adequate for describing wave behavior in wood. Bertholf (1965) verified predicted stress wave behavior with actual strain wave measurements and also verified the dependence of propagation velocity on the MOE of clear wood. Ross (1985) examined wave behavior in both clear wood and wood-based composites and observed excellent agreement with one-dimensionaltheory.

Considerable research activity has focused on development of techniques to measure stress wave attenuation in wood products (Ross and Pellerin, 1991). The interest in attenuation is because stress wave speed alone is not sufficient to detect different wood degradation with equal sensitivity, as demonstrated by Pellerin et al. (1986). In clear wood degraded under controlled laboratory conditions, stress wave speed parallel to the wood grain was affected by brown rot decay, but 'not by subterranean termites which attacked only a specific portion of the wood (i.e., the early wood) in the test beams.

There is extensive literature on the use of stress wave velocity and attenuation for the measuring of elastic properties of wood. This is documented in the reviews by Kaiserlik (1978b) and Ross and Pellerin (1991). A main conclusion reached as a result of this extensive research is that the extent of wood decay correlates to the modulus of elasticity. Numerous applications of stress wave NDE methods for the in-place NDE of wood structures are summarized by Ross and Pellerin (1991), including applications to wood buildings, stadiums, piers, bridges, utility poles, and cooling towers.

Simple mechanical NDE techniques have also been used for the in-place inspection of wood members in structures (Ross and Pellerin, 1991). For example, sounding-, pick-, or probing-type tests are used by inspectors of wood structures to indicate the condition of a structural member. The underlying premise for the use of such tests is that degraded wood is relatively soft and will have a low resistance to probe penetration. A quantitative test based on this premise was developed by Talbott (1982). Talbott examined withdrawal resistance of a threaded probe, similar to a wood screw, inserted into a member, which could be correlated to the residual strength of the wood member.

Based on the extensive literature review performed by Ross and Pellerin (1991), the following conclusions on the state-of-the-art NDE techniques for assessing wood structures were reached:

1. Laboratory investigations have established relationships between

NDE parameters and the performance of wood members, and the relationships have been verified using a wide range of wood-based materials and a variety of NDE techniques.

2. Laboratory studies of the predictive relationships for biologically degraded wood typical of that actually found in structures have been limited in regards to both the NDE evaluation techniques employed and the biological agents of deterioration studied.

3. In-place assessment efforts have focused primarily on adaptations of stress-wave NDE techniques. These techniques have shown considerable promise, are relatively easy to use, and have low equipment costs. However, the application of stress wave NDE techniques to complicated structures and the effect of structure boundary conditions has not been adequately addressed. Further, little information exists on the relationship between excitation system characteristics and wave behavior.

EXPERIMENTAL PROCEDURE

Before beginning the NDE of a bridge, base wave transit times to be expected depending on the member dimensions are determined. A threshold velocity for rot of 635 meters/second is used to establish the transit times. After a quick visual inspection of the timber structure, its members are initially marked at a set interval which is usually 600 mm. The marks are started as close as possible to a member end. NDE of the members is done at the marks vertically through the centerline and horizontally at the top, center, and bottom. If an anomaly is found, sample spacing is densified to 300 mm intervals and 50 mm o.c. vertically and horizontally. In glulam members each lamination is sampled. This close space sampling is continued until the readings again indicate sound timber. The stress wave transit times are recorded directly on sketches of the members as shown in Figure 6.

To verify the stress wave velocity information, increment cores of the timber may be taken at one sound location as well as those locations that stress wave velocity readings indicate are unsound. The increment core data, stress wave velocity data, and moisture contents are transferred to a scale drawing which can then be used in calculating the remaining strengths of the structure and determination of the extent and cost of repairs required.

CASE STUDY

A one lane bridge consisting of two "Howe" deck trusses spanning 36.6 meters over the Coquille River in the Wet coastal climate of Powers, Oregon was evaluated. The deck was nail laminated timber of 38 mm x 235 mm dimensions. The top and bottom chords and diagonals were 250 mm wide Douglas fir glulams pressure treated with 50-50 creosote petroleum. All verticals were steel rods and the panel point connections were steel gussets with shear plates. The bridge was 32 years old when inspected with the S.W.V. equipment. The S.W.V. equipment revealed extreme rot in the trusses lower and upper chords.

Figure 7 shows the extent of rot in one section of the lower chord. Readings of the stress wave times were taken at 305 mm intervals across each lamination. Figure 7 also shows locations of the core samples taken. The stress wave time of 1233 microseconds corresponds to a 250 mm horizontal core sample that only showed 50 mm of "sound" timber. The rot at the top chord was so extensive through the centerlines of the chords that we were not able to obtain readings there near the tops of the chords.

The stress wave velocity equipment's capability to map the extent of rot was used to determine a lower chord repair system that allowed the bridge to be used at a derated capacity for log hauling. The inspection of the 248 plus members took a crew of 3 people 3 days.

In many instances, only one face of a bridge component is available for evaluation. In order to deal with these instances, current research is underway to utilize reflected stress waves for the nondestructive evaluation.

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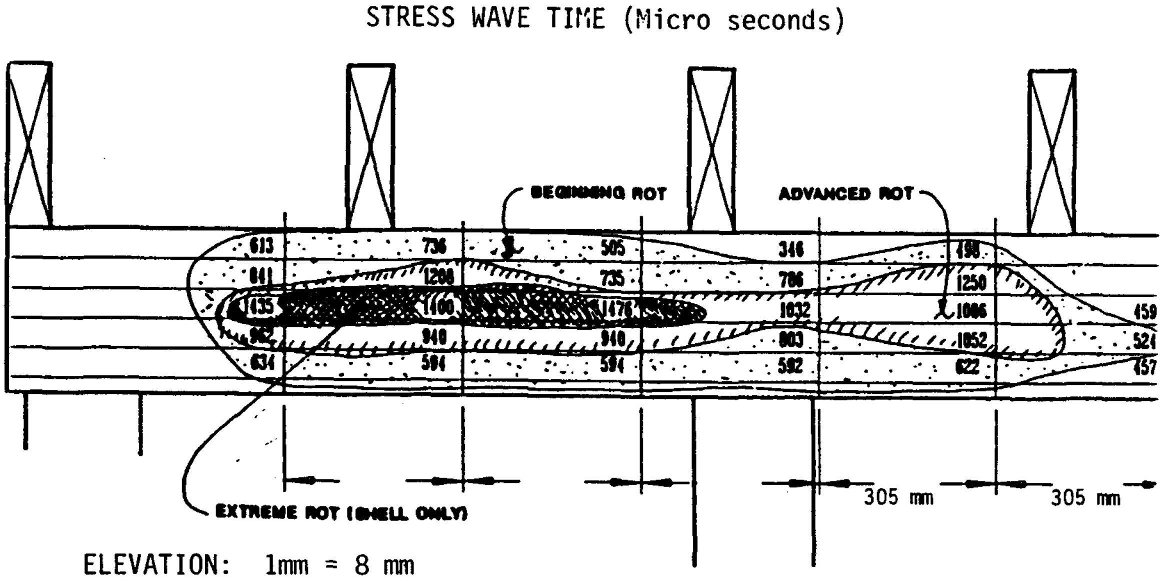

Figure 6. Stress wave times for degraded beam.

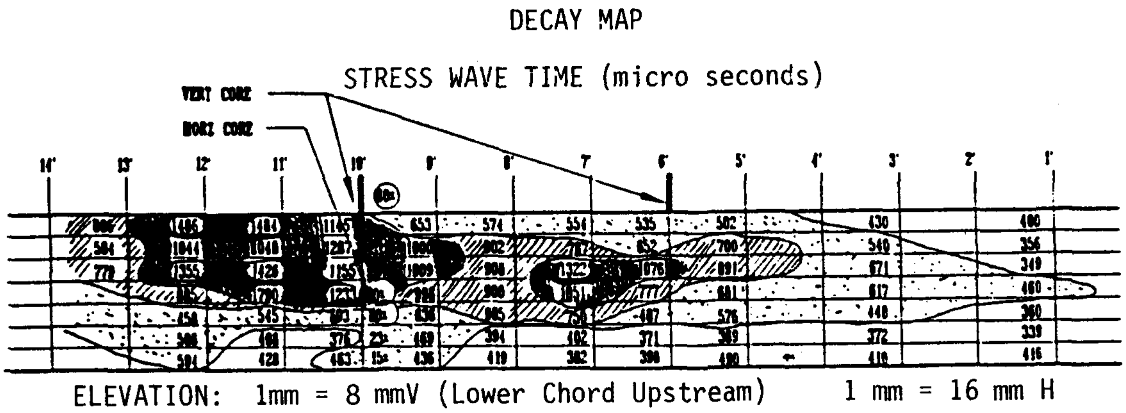

Figure 7. Decay map of case study chord.

In: PTEC 94 Timber shaping the future: Proceedings of Pacific timber engineering conference; 1994 July 11–15,Gold Coast, Australia. Fortitude Valley MAC, Queensland, Australia: Timber Research Development and Advisory Council: 458–464. Vol. 2.