Liro Forestry Solutions

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LOG SORTING USING ACOUSTICS TECHNOLOGY: APPLICATIONS AND LIMITATIONS

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1. Executive Summary

Main finding: This study has found that the direct integration of acoustic technology for the purpose of log sorting according to stiffness is limited. The problems that lead to this conclusion include: poor correlation between log stiffness and acoustic signal; lack of robustness of the technology; limited application potential prior to log-making; and difficulty of automation of measurements.

New Zealand's main commercial tree species, Radiata pine, has a high variability in wood quality properties resulting in a high level of raw product segregation. The stiffness and stability of the lumber is one such criteria. It is therefore desirable to sort stems and logs according to stiffness as soon as possible in the processing chain. This work focused on the application and limitations of acoustic technology in the stump to mill processing chain to provide such segregation. The key operational and technology findings were:

Operational

- Acoustic technology relies on a relationship between the speed of the stress wave through wood, and the square root of the Modulus of Elasticity divided by the density. Density is normally not known, although it is assumed that fresh logs have a density of close to 1kg / 1000 cm^3.
- Timber acoustic properties are very sensitive to density, grain angle, moisture content and slenderness ratio, and material imperfections such as knots.
- Therefore, log grading is likely to be relative to the batch of logs, and not to some determined absolute standard.
- It is perceived to be unfeasible to test a whole stem and obtain meaningful results, unless stress wave timing is used over smaller sections of the stem.
- Although testing should be ideally completed on stems prior to log-making, the most likely integration potential is when log sorting at the skid. The logs are still saturated allowing more consistent grading. This may not be the case when attempting to log sort at the mill.
- The best grading that can be achieved, under ideal conditions, is sorting into two stacks whereby the absolute difference in Modulus of Elasticity of 10%. Over 30% of all logs would have been graded erroneously.
- The cost of implementation is likely to be in the order of $1 to $4 per log, depending on the method chosen.

Technology:

- Acoustic technology relies on highly sensitive componentry to carry out testing. Very high sample rates (50,000 per second), and delicate cabling (co-axial) and connectors (BNC) are required. It is sensitive to external signal sources, making it difficult to incorporate anywhere in a working environment.
- A transducer/accelerometer requires firm fixing into the timber to obtain a positive, readily identifiable signal. This represents a major operational constraint because of the time requirement involved.

- Laboratory testing at ***Forest Research*** of 84 Radiata pine 5m logs showed that acoustics can explain 62% of the variation ($r^2 = 0.62$). However, it is known that integration into a continuous mill supply chain could reduce the r^2 value to 0.35, which is an extremely poor correlation.
- Although a test rig for carrying out acoustic measurements in the field has been constructed, in-field testing has been unsuccessful because of the above mentioned limitations.
- In-field testing is likely to be based on resonance measurements because it integrates the logs' properties, and also because of the difficulty of carrying out stress-wave timing in an operational setting.

Acoustic technology, at this stage, does not appear to be robust enough for in-field log evaluation requirements. This technology may improve to the point where it can be used in a rugged environment. The inherent accuracy limitations of using acoustic technology on non-homogenous materials such as Radiata pine logs means that only limited incremental gains in sorting can be expected. Neither the stress wave timing method nor the resonance method has a strong enough correlation with timber stiffness to get really excited about this technology at this stage.

2. Table of Contents

3. Report Overview

The introduction (Section 4) states the basis for this study which attempts to integrate acoustic technology into forestry for the purpose of logs stiffness segregation. A review of the relevant literature can be found in Section 5. It refers to a long history of acoustic methods for testing and discusses the significance of results from over 90 studies.

The fundamental Section (Section 6) discusses the various stress wave types and their governing equations. Measuring techniques are presented, as are the factors that influence the stress-wave speed to stiffness correlations. Most importantly, this leads to a presentation of accuracy limitations.

Section 7 provides a review of implementation possibilities in the stump to sawmill supply chain. Section 8 shows the design considerations, both at the technical level for the measurement of stress wave or harmonics and also the implementation onto appropriate machinery. The building of a test set-up to be used for in-field measurements in described in Section 9.

The large Appendix A is a complete copy of a report entitled "Non-destructive Testing for Assessing Wood Members in Structures" by Ross and Pellerin (1991, USDA Forest Service). It provides a comprehensive overview of non-destructive testing methods, reference list and summarises study results from over 80 published acoustic experiments. It has been included for completeness of this report and avoids the need for unnecessary replication.

4. Introduction

The use of acoustic technology has been used for determining material properties, particularly material stiffness, for over three decades. Most successful experiments have been carried out on either homogenous material, or thin strips of non-homogenous material. In most of these tests stress-wave timing has been used to obtain the results and a correlation range from r^2=0.92 for homogenous materials such as processed wood products to as low as r^2=0.32 for non-homogenous materials such as logs.

Very few studies have been completed on logs and results indicate that, although feasible in the laboratory type settings, only coarse grading is possible. There is no published literature to suggest this technology can be used on stems when using resonance. Using the stress wave timing technique along a part of the stem or logs' surface has resulted in considerably lower correlation. This is because of the localised influence grain angle, knots, moisture content.

An example of the use of this technique is the FAKOPP which has been used for inventory purposes in standing trees. However both the reliability of the equipment and the results means it is not widely used.

However, it is recognised that even a small incremental gain in log stiffness sorting (segregation) prior to milling into lumber could result in net revenue gains for the industry. The current limitations to the integration of this technology to date is that it is not very robust and is highly susceptible to interference from machinery and electronic circuitry of almost any kind.

By developing a system to implement acoustic log grading technology on to the skid site, it may be possible to grade individual stems or logs according to their stiffness (preferably on stems prior to logmaking). The ability to grade stems prior to logmaking or downgrade low stiffness logs prior to sawmilling has a net revenue potential by increasing stress-grade averages, thereby increasing recovery percentages.

It should be noted that no cost benefit calculations have been completed to date to indicate improved margins of this technology. However, the marketing manager of ***Forest Research*** is confident that a premium can be obtained without a value loss for the down-graded logs (Christie, *pers com*).

Stiffness grading at the lumber stage in the mill using sophisticated grading machinery can still only grade with limited accuracy. Machine stress rated timber (MSR) and machine evaluated lumber (MEL) methods in the mill have reduced the coefficient of variation relative to the visual stress rated (VSR) timber from 25% to 11% and 15% respectively. The advantage of grading logs prior to sawmilling is to increase the outturn of structural timber meeting minimum specifications, and thereby reduce the volume of reject lumber.

In addition to mechanical stress grading and the use of acoustic technology to determine stiffness, rapid development has been made in the use of both Near Infra-Red (NIR) and Visible Infra-Red (VIR). These techniques 'scan' the surface of the material, and the reflected spectrum is analysed for material properties.

5. Literary Review

Non-destructive tests using acoustic principles (also referred to as sonar or stress-waves) have been available for 30 years (Deng, 1992). A comprehensive review of "Non-destructive Testing for Assessing Wood Members in Structures" completed by the USDA Forest Service (Ross and Pellerin, 1991) presents many of the currently available testing techniques. It also lists 73 references of non-destructive tests that have been carried out including a summary of the materials used and the type of tests carried out.

Where appropriate, the MoE and the correlation coefficients between the particular acoustic test and the value obtained from bending tests are also summarised. Statistical correlation results (r^2) are between 0.5 and 0.92 showing that in laboratory testing situations there is a strong correlation between the acoustic signal and the stiffness properties of wood. However the r^2 values for tests carried out on species such as southern Pine are considerably lower (0.32 - 0.72), as are r^2 values for tests carried out on larger lumber. It is not intended to repeat or summarise the Ross and Pellerin (1991) document. A copy of it has been appended and the remainder of this section will focus on relevant and more recent literature not covered there.

Three recent pieces of work have been carried out using Radiata pine as test material. Deng (1992) completed a research report on both the use of a stress wave timer for estimating the stiffness (E_{mod} = Modulus of Elasticity) of Radiata pine. Four pieces of 100 x 50mm air dried timber were tested and the E_{mod} determined using the stress wave timer was within 10% of the E_{mod} determined in bending tests for the four samples that ranged from 7 to 15.5 GPa. Deng also showed that the E_{mod} remained relatively constant along the one metre length of the pieces of timber when testing different segments. This indicates that the testing location over a very short piece of timber is not critical to determining the E_{mod} for a given piece of timber. However, almost no correlation was found between the strength of the finger jointed timber and the acoustic signals.

The second work completed in conjunction with this project focused on log segregation methods for structural lumber yield improvement (Ridoutt *et al*, 1999). Branch Index (BIX), Pilodyn and acoustics were used to classify a series of 84 five metre logs and the results are reported relative to the improvements in structural lumber recovery. A satisfactory relationship (r^2 = 0.67) was found between the axial frequency and the E_{mod} when including branch index (BI) or large end diameter (LED). The E_{mod} was determined by milling the log into lumber, stress grading the individual pieces, and averaging all the pieces that made up that log.

In a small test on the skid with a chainsaw as a sound source and signals recorded using a tape recorder, it was shown that fundamental frequencies could be isolated using Fast Fourier transformations (Parker, Liro Filenote 1997). Liro - Forestry Solutions, together with DOTSE (Parker, Gibbons & Riddle,1998), indicated that Radiata pine has acoustic behaviour which is similar to that of other species.

The most successful use of acoustic testing has been specific laboratory projects such as the stress wave grading of veneer sheets (Jung, 1979), as well as predicting localised E_{mod} and tensile strength in finger jointed laminated lumber (Bender et al, 1990).

Two non-contact analysis methods are also available which use the shear waves (vibration of the lumber) to determine stiffness properties. New research in Norway uses TV Holography to detect vibration modes, though it is in the prototype stage (Skatter and Dyrseth, 1997). A signal processing unit isolates features on the surface of the log and monitors the transverse vibrations. The second method uses the free vibration of a length of timber, excited by a small impulse (hammer tap), and with the resonance signal picked up using a microphone (Sobue, 1982b). This system would be very sensitive to external sounds, and therefore limited to laboratory type set-ups.

6. Fundamentals

Types of waves and fundamental equations

Longitudinal Stress Wave

The primary wave that is being considered when attempting to grade the stiffness of timber is the longitudinal stress wave. It is an acoustic wave front passing through the medium, where the speed of the wave is dependant only on the density and the stiffness of the medium it is going through.

Assuming that the wave front is normal to the direction of travel, then the stress wave equation can be presented as the product of the velocity of the wave squared (V), the density (ρ) and divided by acceleration due to gravity (g).

$$E_{\mathrm{mod}} = \frac{V^2 \cdot \rho}{g} \qquad \textbf{(1)}$$

Rearranging equation 1 for the longitudinal resonance frequency of a known length of timber, we obtain:

$$f = \frac{1}{2 \cdot L} \cdot \sqrt{\frac{E_{\mathrm{mod}}}{\rho}} \qquad \textbf{(2)}$$

The main advantage of longitudinal vibration is that it is not affected by shear or rotary inertia effects.

Transverse Vibration

A transverse vibration wave can be generated by supporting the lumber or log at the two end points (i.e. guitar string). Internal shear leads not only to dampening of magnitude but also of frequency. The resonance of the freely vibrating log can be measured using microphone (Sobue, 1982b), transducer or optical methods (Skatter and Dyrseth, 1997).

The primary equation governing the behaviour of a beam freely supported at its ends is:

$$E_{\mathrm{mod}} = \frac{f^2 \cdot W \cdot L^3}{2.46 \cdot I} \qquad \textbf{(3)}$$

Where: W is the weight of the beam (N)

I is the moment of inertia (m4)

Basic frequency dampening equations to compensate for internal friction (shear) are presented in Ross and Pellerin (1991).

Flexural Vibration

Flexural vibration can be considered the to be the combination of longitudinal and shear waves down the beam. It is difficult to generate such a wave, and its governing equation is also complex:

$$E_{\mathrm{mod}} = \frac{f_{F,n}^2 \cdot \rho \cdot S \cdot L^4}{A_n^2 \cdot I} \qquad \textbf{(4)}$$

Where: S is the cross-sectional area

A is a coefficient that depends on the resonant frequency of the flexural node (see Parker *et al*, 1998).

Stress wave timing and resonance measuring techniques

There are two primary ways in which to convert a stress wave in a log or piece of lumber into a measure of stiffness. The first uses the velocity of the stress wave passing through the timber, whereas the second uses the resonance set up in the log by an energy source (see diagrams on pages 14 and 15 of Appendix A).

The advantage of the stress wave is that it is simpler concept although harder to measure - it is independent of log length but very specific to the area tested. For the frequency option, the wave passes through the whole log or lumber piece and is therefore an integration of the logs' characteristics.

It requires the measurement of the time it takes for a stress waves to cover a known distance along or through the object. Stress wave timers have been commercially available for a long time. They are primarily a transducer at either end, with a fast data capture rate to accurately time the signal (e.g. Gerhards, 1982). The signal can be generated (a) beyond the first transducer, (b) the first transducer can be mounted on the hammer, or (c) the first transducer can act as a transponder and send its own known signal. Should the object have a square end, then by placing the receiving transducer on the end where the signal commences, it is possible to receive the reflected stress wave. It should be noted that such a signal is considerably weaker, and more filtering needs to be done to remove reflected signals from branches or other boundaries along the object.

To automate the signal processing requires filters to determine the 'departure' and 'arrival' of the stress wave. That is thresholds must be set to know when to commence timing and what signal to accept as the true wave. Even in laboratory settings this poses a problem, and manual signal interpretation is required. When contemplating an automated system on a piece of forestry equipment it must be recognised that vibrations and shock signals covering almost the whole frequency range are common.

The second method it to measure the frequency. Sobue (1986b) showed that when measuring the longitudinal vibration using short beams, a Fast Fourier transformation of the resulting signal clearly provides the resonance frequencies. Importantly, the method of supporting the beam was altered from a single central support to multiple supports without altering the response spectrum.

For these experiments, Sobue used just an amplified microphone signal after tapping the end of the log. However, transducers such as accelerometers are more adapt to accurately measuring the signal, especially when relying on more complex energy sources. Such data can be captured and analysed on an oscilloscope, or conversely using a data capture card and signal processing using Fast Fourier transformation software.

Flexural vibration can be measured using transducers, and also using optical methods. However, to set up vibration in a log or stem it must be suspended off the ground. Such a method may be feasible if sorting with a grapple. The support location, the log's length and its cross-sectional characteristics must be known exactly for this method to be successful.

Stress wave speed in Radiata

The complexity of establishing relationships according to the fundamental equations 1 and 2 is that timber has neither a homogenous density nor stiffness. While there is no problem in applying these concepts to materials such as steel or plastics, timber is a complex medium consisting primarily of unidirectional grain wood fibre and moisture. Both the dry wood density and the saturated wood density are known to change within a stem depending on location. Trends have been established for density relative to height and diameter.

The summarised Ross and Pellerin (1991) data show that the speed of a basic longitudinal stress wave varies between 3000 and 6000 m/sec for the full range of timber species tested. Tests completed on fully saturated Pinus radiata indicate the speed (thin straight beam) to be approximately 3760 m/sec.

As can be seen in all equations presented in section 5.1, frequency is related to the square root of the ratio of E_{mod} divided by density. Therefore any relationship between the measured acoustic signal and the stiffness of the lumber/log will only be valid if either the density is known and can be taken into consideration, or the density remains constant. Fortunately, for the purpose of grading logs prior to milling, the moisture content of the timber is such that combined with the dry wood density (ranges from 350 to 490 kg / m^3), the sum of the two results in fully saturated density of 930 to 990 kg / m^3 which is a relatively narrow range.

Factors affecting stress wave speed

There are some key factors affecting the speed of the stress wave passing through the non-homogenous and non-uniform logs. Most of these factors have been investigated and there is relevant information presented below. Their effect on accuracy is discussed in the following section.

Slenderness Ratio

As previously mentioned, acoustic theory is based on a slender beam. The larger the diameter of the test object relative to its length, the slower the resulting stress wave. Combining the theory and laboratory trials in Japanese species and Douglas-fir indicate stiffness/density acoustic behaviour (Sobue 1986a, 1986b) and that of Liro - DOTSE (Parker *et al*, 1998), the following figure can be generated to provide compensation for the slenderness ratio (Figure 1).

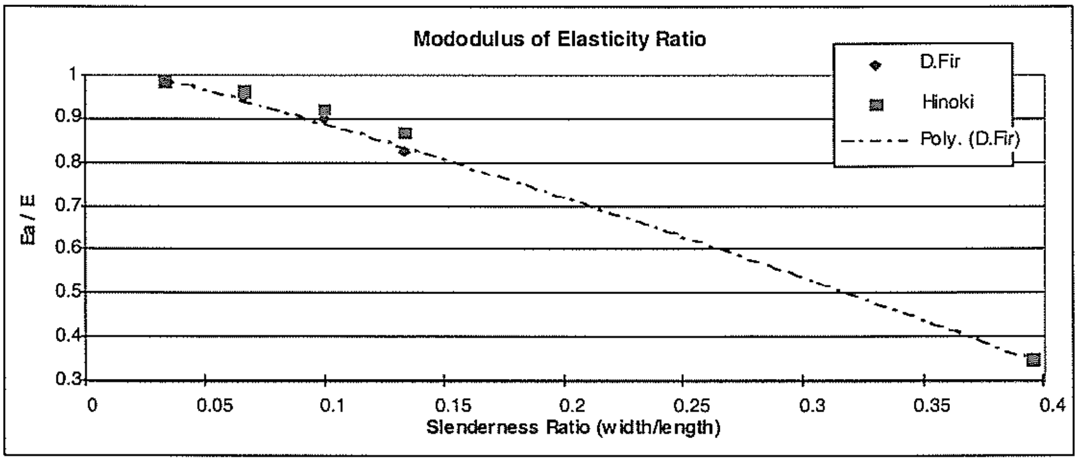


Figure 1. Slenderness ratio effect on Emod

The figure shows the ratio for the Emod. If we take the square root of the Ea/E axis we get the effect on the stress wave. In absence of better data, a simple equation can be formulated whereby the influence of the slenderness ratio (s.r) on the stress wave speed can be shown as:

$$\text{Stress wave speed reduction} = 100 - (\text{slenderness ratio} * 50) \qquad \textbf{(5)}$$

Under normal operating conditions the slenderness ratio is likely to be less than 0.1. Additionally, when grading a certain specification of log, then the slenderness ratio will be in a relatively narrow range.

Moisture Content and Temperature

The effect of changing moisture content on stress wave speed can most readily be explained through the corresponding increase in density of the timber. Gerhards (1982) combined available data, and produced the following chart showing the effect of changing moisture content and temperature (Figure 2). By compiling data from a number of references, the relative speed of the stress wave through the timber decreased by 1 percent for each degree temperature increase. The exact cause-effect relationship due to temperature is unclear, however it is thought the higher 'excitement' state of the timber at higher temperatures slows down the stress wave.

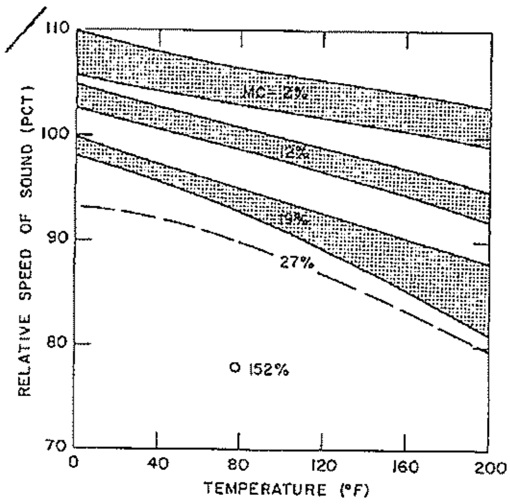


Figure 2 Temperature and moisture content effect on stress wave speed (after Gerhards, 1982b)

Grain Angle

Grain angle delays the signal through the timber, and equations have been formulated to make corrections (Armstrong et al, 1991, Gerhards, 1982). With regard to the grain angle of the timber, the relative longitudinal speed decreases by approximately one percent for each degree of grain angle (Figure 3). This only holds true up to a grain angle of 30 degrees, after which the effect is reduced and tapers off to approximately 50%, and with a high variation shown between timbers and tests.

Knots

Gerhards (1982a) completed a comprehensive study on the effect of knots in timber on the stress wave propagation. The key finding was that a knot severely retards the stress wave (due to the perpendicular boundary conditions), but the wave can pass around the knot and over a longer distance return to reform an almost linear stress wave front. For a simple board with a knot, a reduction in speed of 16% was shown relative to a similar but knot-free board.

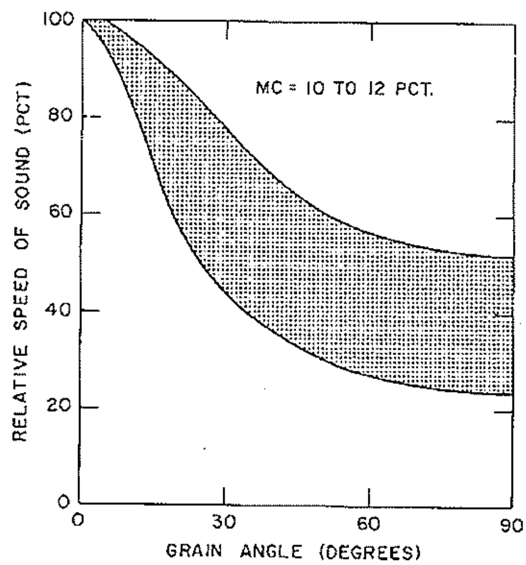


Figure 3. Stress wave speed reduction with increasing grain angle (after Gerhards, 1982b).

No literature has been found regarding the stress-wave passing a whorl of knots in a log. The similarity with the above mentioned tests would mean it is of the order of 10 to 15%.

Effects on accuracy (theory)

It is already known that there is considerable variation of density and stiffness within a stand of trees compared with regional variation, yet to produce structural grade lumber only the logs with higher stiffness characteristics provide a higher out-turn when milling.

Knowing that average log E_{mod} values range from 4.5 to 10.5 GPa for logs that meet sawmilling specification, to make a realistic differentiation to log properties we should be aiming to differentiate at the 10% (15% ?) level. If we are aiming to make a 10% differentiation in E_{mod} then we are aiming to find a 5% change in resonant frequency or stress wave speed (since it is related to the square root of frequency).

In the previous section it has been noted that the speed of the stress wave is reduced by 1% for approximately every 1 degree increase in temperature and every one degree in grain angle. Increase in moisture content also decreases stress wave speed at a rate of approximately 1% for every 1 % change in MC. However this approximation only holds at low moisture contents (2 to 25%). Little is known about MC influence at higher moisture content, although the effect is considerably reduced. The presence of knots slow down, but do not inhibit the stress wave which passes around the knot (Gerhards, 1982). The only experiments are on narrow short boards and indicate a speed reduction of 15%. There is little other known data on the effect of knots in logs.

The other known effect is from the slenderness ratio, and the basic relationship is that in percent, the stress wave speed reduces by 100 - (s.r. * 50). This can be compensated for if the diameter can be measured. A typical range of correction factors is shown in Table 1.

By considering the above factors and their respective influence on stress wave speed, it would indicate that log or stem grading can only be completed on a similar set of logs/stems in the same conditions. It would appear that it is not possible to provide absolute grading scales. This means that at any site a series of logs would need to be tested and retrospectively graded relative to the average for all the logs.

	Log Length		
Log diameter	4 m	8 m	12 m
20 cm	97.5	98.75	99.17
30 cm	96.25	98.13	98.75
40 cm	95	97.5	98.33
50 cm	93.75	96.87	97.92

Table 1. Correction factor (%) for slenderness ratio

Effects of Accuracy (Test results)

In a parallel and partnership study, 84 5 metre logs were tested for a number of properties. Acoustic tests were completed on the logs, and they were subsequently milled and each individual piece stress-graded. The 62 % of the variation was explained in the relationship between the two.

As part of this project, these data have been further analysed to provide a better idea of the benefits of segregation based on acoustic results. It should be noted that these results will represent the absolute upper end of the accuracy we can expect for testing on the skid.

Figure 4 shows the effect on average MoE after grading the logs according to the acoustic results. The average MoE was 7.2 Mpa, and this could be increased to 7.8, 8.1 or 8.3 by taking the top half, third and quarter respectively.

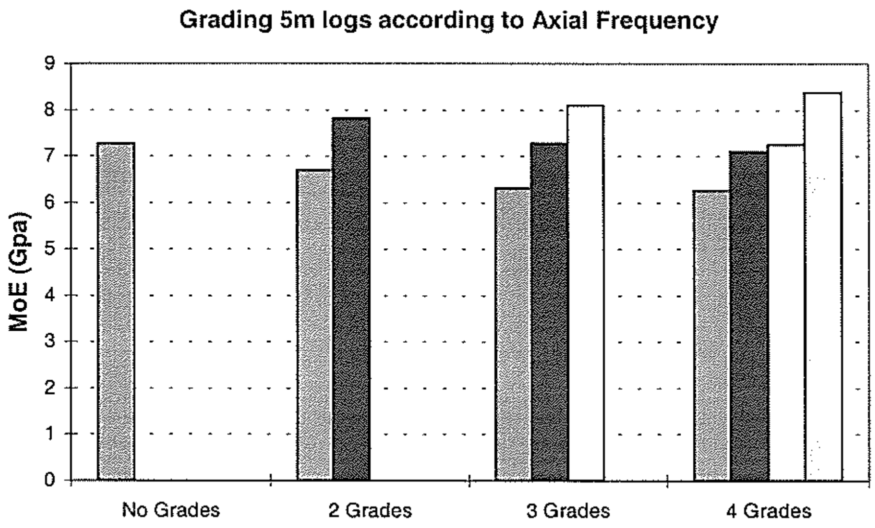


Figure 4. Grading 5m logs according to Axial Frequency (using evenly spaced intervals)

Figure 5 shows the raw data, and illustrates the effect of grading with a correlation co-efficient of r^2=0.62. The data points in sector 1 would represent the logs correctly graded as 'high' MoE, whereby sector 2 represents those graded incorrectly as being of 'high' stiffness. Similarly, the logs represented by the points in sectors three are those correctly rejected for being of 'low' density, while those in sector 4 have been rejected as 'low', when in fact they are of 'high' density. In total, almost 70% of all the logs have been graded correctly.

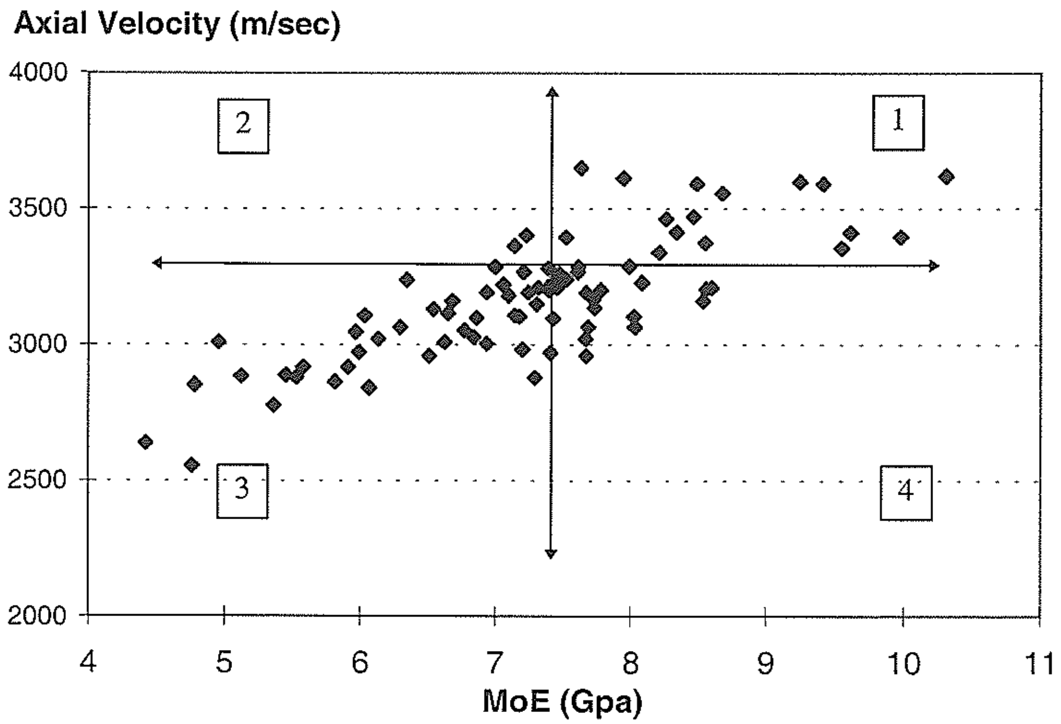


Figure 5. Axial velocity plotted against MoE.

7. Applying acoustic technology in the forest-to-mill chain

Seven basic operational steps are reviewed regarding the possible implementation options in the forest to mill supply chain. Both opportunities and limitations of this technology are important with regard to designing a successful system.

Forest-to-Mill Chain

Inventory

Using the stress wave timer set up, it is possible to determine the 'stiffness' of the outer layer of the standing tree (Note: accuracy limitations using this technique are discussed in section 5). Because the inter-stand variability is greater than between stands, a large number of trees would need to be sampled to successfully grading a stand, and it would be of little benefit except in areas where regimes or climate conditions indicate a potentially large difference in average E_{mod} stand values.

At the individual tree level, each tree would need to be graded and tagged in such a fashion as to allow that information to be available when log-making. However, using exactly the same measuring concept it is feasible to measure the stems on the landing where the information can be used directly for log making and or log sorting. The benefit of carrying out the measurements prior to felling would be unrestricted access to the trees. The FAKOPP tool is designed for this purpose, although some hardware (cabling) and correlation problems have been reported.

Felling

There are two main felling methods, mechanical or motor-manual. With motor manual felling there is no apparent way to integrate sonar testing equipment. There is certainly the potential to incorporate a system within a harvesting head, although it would need to measure stress wave speed and not resonance. Resonance measurement would be extremely inaccurate because of the unknown length and the number of branches at the top of the tree. If the felling head was to fell and delimb, then after topping the tree, the length can be determined and it could be possible to obtain a resonance.

A measuring concept similar to the FAKOPP, whereby two probes must penetrate beyond the bark and into the outer layer of the wood, would need to be mounted within the head. The components of this system would need to be robust to survive even harder conditions than that would be experienced at a log sorting phase (impacts and vibrations).

Extraction

Extraction is typically carried out using either a skidder or a yarder. While there is some possibility of mounting something on the blades of a grapple skidder, unknown length and limited marking capability limits any potential. Although the grapple of a forwarder may present some opportunity, their use in NZ is limited to thinning extraction.

Log-making

With the focus on value realisation, this would be the most obvious place to integrate a stiffness measuring system so that the data can be used to more selectively log-make the stem. The task of cross-cutting can either be undertaken motor-manually or by a mechanised processing head.

However, getting a meaningful signal back from a long tapered log is not a proven concept/technology.

If the length of the stem is unknown, or it is shown that there is no or only a very poor correlation between the stem's resonance and the actual stiffness of the logs, the using a stress wave timer concept is the only feasible option. A system similar to the FAKOPP could be used at discrete intervals along the stem. The bark would have to be removed at each location and the resulting information entered manually into the callipers. It requires more work to get a signal, and consideration needs to be given to the cost of implementing such technology.

The use the resonance technique, which would provide a better integrated result of the stiffness of the whole log, has two requirements. The stem length must be known, such as by integrating it with the TimberTech callipers. Secondly (as above) a correlation between the signal and stiffness is established. Because of the need to identify the fundamental resonance, some computing power is also required to complete an FFT, and filter out the dominant signal within the expected range. The current TimberTech system is based on a Psion computer which does appear to have enough computing power to undertake such a transformation.

Fleeting / Sorting

After the stems have been made into logs, the logs are fleeted one at a time into stacks. Although the logs have already been formed, there is an opportunity to grade them because:

- the length of the log is known and relatively short (clear signal),
- only the saw logs need to be graded,
- the logs can be separated into different stacks,
- there is opportunity to attach the measuring system to either the grapple head to the body of the excavator,
- the problem of attempting to assign stiffness values to a sawlog some way down the stem is removed.

Considering the inherent difficulties in obtaining a useful signal from a stem using the fundamental frequency, preliminary consideration identifies the grapple of a knuckle boom loader as a logical 'location' in the stump to mill chain for the introduction of a potential grading system.

Loading out

Logs are generally loaded out en masse (multiple logs per loading action) which provides no opportunity for individual log grading. If the logs were to be loaded just one at a time and graded at that point, the logs that do not meet the grade will have to be replaced onto the stack or a separate stack.

Logyard

For stem extraction to a log yard, the same comments as made for the cross-cutting and fleeting and sorting apply. Some efficiencies of scale may apply where a larger number of stems are processed at the one site, allowing of the possibility of a specialised crew to make the measurements. The instrument need not be as robust, and can be of higher weight because of the ease of access to the butts of the logs. The system cost can also spread over more logs per day, reducing the cost per log.

8. Implementation Considerations

Key aspects to consider are:

- technical requirements
- data interpretation and presentation
- robustness of the technology
- system design
- signal interference from machine vibrations
- the cost of implementation

Technical Considerations

The hardware used to measure the acoustic signal must have data capture rates that exceed the requirements of the level of accuracy we are trying to achieve. That is: our ability to accurately measure the signal, either as a absolute signal return or the resonance, limits the accuracy with which we can classify or grade the logs. The speed of sound through a saturated Pinus radiata log is approximately 3760 m/sec.

	Speed (millisec.)	Resonance (Hz)
3m Log	1.59	1253
25m Stem	6.67	301

Table 2. Log length effect on stress wave speed and resonance in Radiata pine.

Example: Trying to grade an 4 m log, the transverse stress wave return signal from the end of the log would take 0.00213 sec. A 10% increase in MoE would increase the stress wave speed by 4.8 %, and the signal would return in 0.00455 sec. The difference to measure is therefore 0.00020 sec (5000 Hz). To adequately define a pulse or a resonance, we need at least 10 (preferably 20) points per cycle to isolate the peak of the cycle. Hence the need to sample at a rate of 50kHz.

Using the resonance measuring technique, a data capture board with 50kHz sampling capability must be sourced. When considering stress wave timing there must be the ability to measure two transducers simultaneously and a minimum data capture rate of 100 kHz is required. It should be noted that most data capture boards will effectively only have a data capture rate of 70% of that stated when using more than one channel.

The key hardware components for a successful system, including their specifications are:

1. Two transducers (accelerometer)
2. Stable -5 to +5 Volt excitation for the transducers
3. Co-axial cabling BNC connectors for connecting the transducer to the data capture board
4. Data capture board with 100kHz sampling capability (at least 50kHz for two channels)

5. Filtering componentry (signal conditioning), either separate or integrated into the data capture board. Likely to require variable filtering depending on what machinery it is required to work in the vicinity of.
6. DAQ board capable of high accuracy (small step) analogue to digital conversion
7. High speed data transfer from DAQ to computer, although if the DAQ has data storage capability then delayed transfer at a lower rate is possible.
8. Software for signal analyses. Commercial software is available but for the purpose of commercialising this, a special timer chip with appropriate filters could do the task in an automated fashion.
9. Output screen of some sort. Initially in the prototype phase this can be just the computer screen. For a operational system this will need to be a more user friendly information screen.

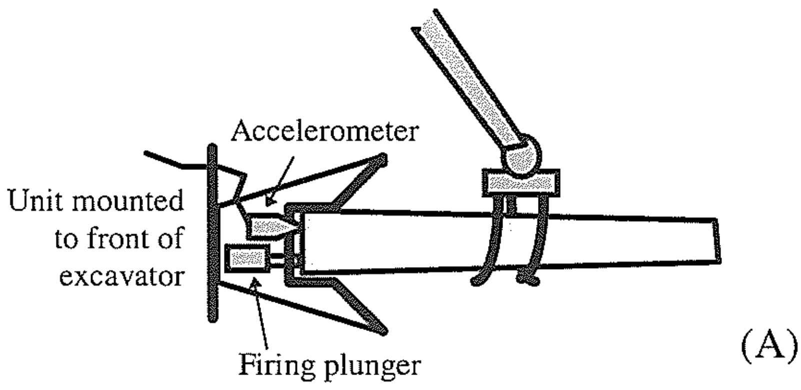
System design options

The section on implementation possibilities highlighted the most appropriate location for the integration of this technology to be at the log sorting stage on the skid. There are two consideration which leads our preferred design towards the integration of acoustic log testing onto the excavator. This design addresses the compatibility of the components and component layout as intended for use in a grapple loader / fleeting / sorting excavator on the skid.

There are a number of key design considerations:

- Transducer (accelerometer) type and location on the grapple
- Wiring to a suitable data manipulation collection device (including shielding from external signals)
- Hardware for processing / interpreting the signal (for experimental stage likely to be a laptop computer with an analog data capture card)
- Software for processing / interpreting the signal (for example DOTSE software or oscilloscope)
- 'Sound' energy source and the 'target' area (possibly airgun or hydraulic ram)

Figure 6 shows two alternative design options. Considering the problems to date with robustness regarding cabling and data transfer from the accelerometers to a data processing unit, the first design option appears to be most viable.



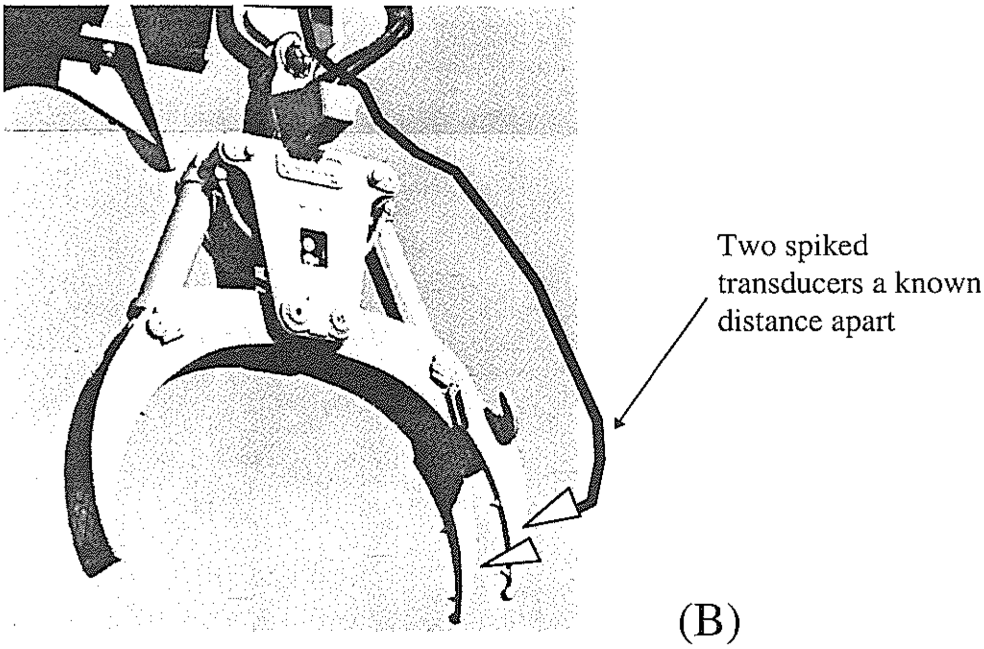


Figure 6. Acoustic measuring concepts for an excavator

Another factor to consider is the way the transducers are 'connected' to the log. While in the above diagrams they are shown as spiked probes that will penetrate into the wood, it is known that a screw attachment improves the signal reception considerably. Ideally, the stress wave peak signal will be sinusoidal with an emphasis on identifying the peak. An 'imperfect' connection will act as a one way filter as shown in Figure 7. Without increasing the design complication considerably, such a system is not likely to be feasible for the grapple.

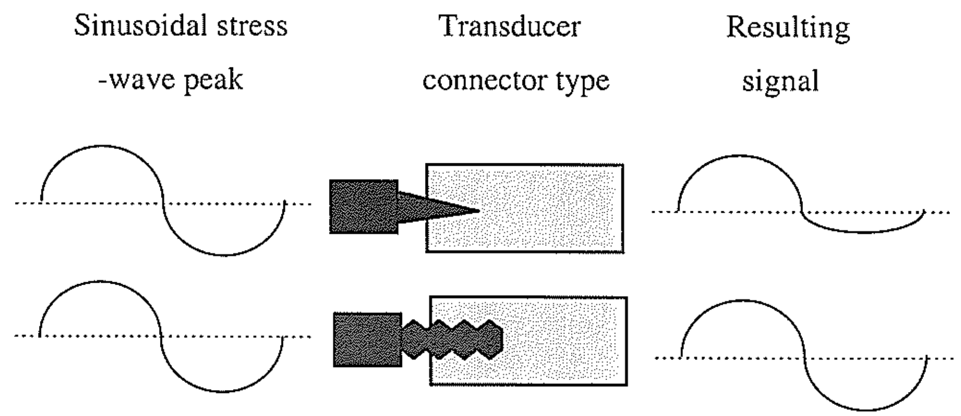


Figure 7. Effect of 'imperfect' transducer connection

Cost of Implementation

Without a full trial, the cost of implementation can only be estimated. However, when log-making the time to complete a single test will be in the order of a minute. At an approximate cost of $50 per hour for the person and the cost and on-going maintenance of the equipment, this would mean a cost per log of $1. If using the stress-wave timing option and a number of tests had to be completed to grade a single log, then a cost approaching $4 per log can be anticipated.

With regard to integrating the system into a grapple, although a single functioning unit is likely to cost in the order of $10,000 to $15,000 dollars, the high on-going maintenance costs would still have the grading cost at $1 per log. Particularly the accelerometers and the cabling will be features that require the intensive maintenance.

Validation of new Technology

Stiffness of Test Log

To accuracy of the new design must be tested. Although some relationships between the acoustic signal and the stiffness of the timber has been completed, these tests have been carried out in laboratory type situations. The 'quality' of the grading is highly dependant on the correct identification of either the return of the stress wave or the first resonance peak of the Fast Fourier Transformation (FFT). Just testing the system for a signal is not valid since the acoustic result to stiffness correlation can not be assumed.

To complete a test of any new system, both the acoustic test and the determination of the stem or log stiffness must be carried out on a series of test logs. There are two methods for determining the stiffness of the log:

The first if the more 'usual' method of sawing the log into lumber (typically 100 x 50mm lumber) and stress grading each individual piece. The 'logs' stiffness is then calculated by averaging all the results. This method is associated with high costs in both time and resources.

The second method is a simple bend test (apply known force and measure deflection) which can be carried out on a skid on each log that is graded (Figure 8). The log should be supported at each end and a known weight applied to the centre. The stiffness can be calculated using a spreadsheet developed by the author (and is available from Liro) which takes into account the taper of the log.

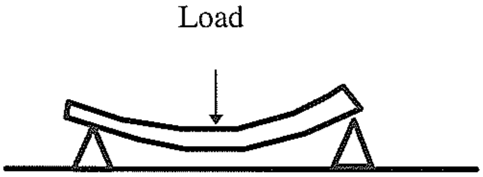


Figure 8. Simple bend test on log to grade for stiffness.

9. Building a Test Rig

A Data Acquisition Card (DAQ 112) with 100kHz data acquisition capability was purchased from the company IOTEC and used in conjunction with a number of transducer types, mainly from the company Sensotec. The board was successfully incorporated into a 486 computer, along with all the necessary software.

Although a single channel could be monitored (although not consistently), multiple channel monitoring was only sporadically successful. Major constraints were the appropriate filtering of external signals such as mains power and machinery, as well as minimising cross-talk between channels.

Because of these problems, no tests were completed outside of the laboratory. Although this was disappointing, obviously the robustness of. The only way field tests could have been completed would have been using an oscilloscope, which would have not met either robustness, automation or cost criteria.

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Appendix A

United States
Department of
Agriculture

Forest Service

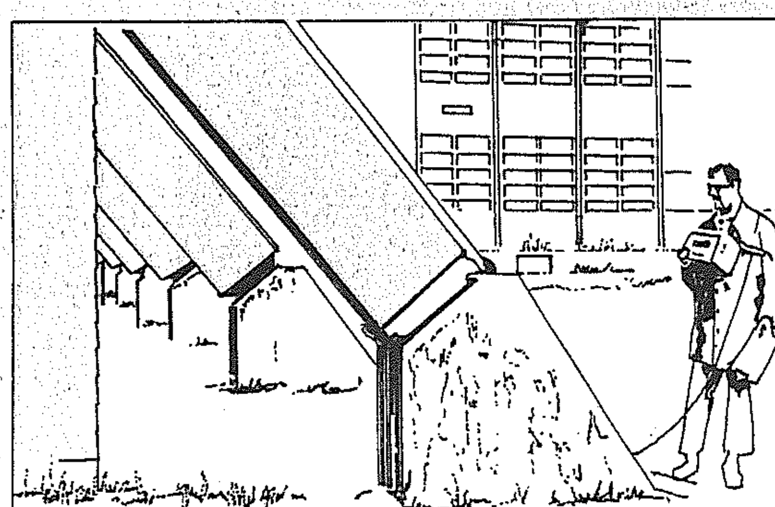
Forest
Products
Laboratory

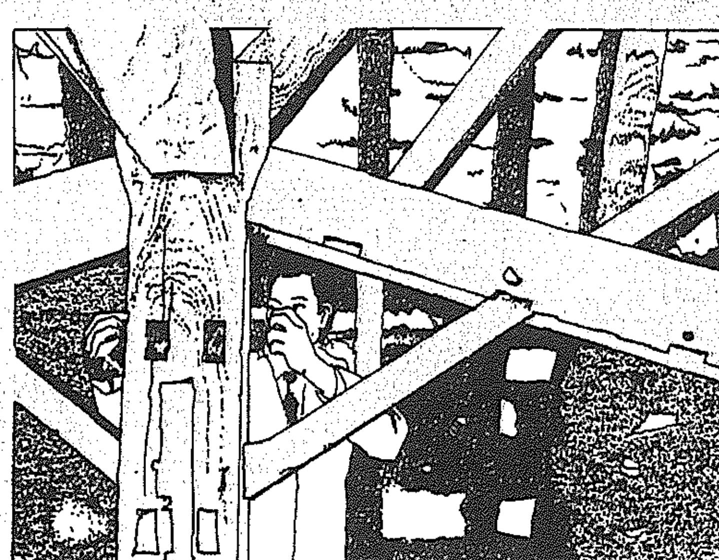
General
Technical
Report
FPL-GTR-70

Nondestructive Testing for Assessing Wood Members in Structures

A Review

Robert J. Ross
Roy F. Pellerin





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Abstract

Numerous organizations have conducted research to develop nondestructive testing (NDT) techniques for assessing the condition of wood members in structures. This report presents a comprehensive review of published research on the development and use of NDT tools for in-place assessment of wood members. It examines the fundamental hypothesis behind NDT of wood, reviews several widely used NDT techniques, and summarizes results of projects that focused on laboratory verification of the fundamental hypothesis. Results obtained from projects that used NDT techniques for in-place evaluation of wood members are presented. In addition, recommendations are given for future in-place assessment NDT research.

Keywords: Nondestructive testing, structures, literature review, wood

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August 1991

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The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Contents

Nondestructive Testing for Assessing Wood Members in Structures

A Review

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Executive Summary

The USDA Forest Service, Forest Products Laboratory (FPL), and Washington State University (WSU) have been actively developing nondestructive testing (NDT) techniques for wood products for more than 30 years. Their individual and combined efforts of research and technology transfer activities have yielded a variety of NDT tools and techniques that are commonly used by manufacturers and users of forest products throughout the world.

Recently, individuals and organizations have shown considerable interest in the use of NDT for assessing the performance of wood members in structures. Both the FPL and WSU have received numerous requests for background information that illustrates use of NDT techniques for in-place member assessment. Questions are frequently asked about fundamental NDT concepts and about previous NDT research that might be extended to a particular application.

We prepared this report to provide a synthesized information base to aid in addressing such requests. This report is a compilation of various published research and application efforts that have focussed on NDT of wood products. The report begins by examining fundamental concepts for NDT of wood. It then reviews pertinent laboratory investigations designed to explore fundamental concepts and presents several examples of how to apply these concepts to in-place assessment of wood members. Recommendations are also given for future in-place assessment NDT research.

Introduction

By definition, nondestructive materials evaluation is the science of identifying physical and mechanical properties of a piece of material without altering its end-use capabilities. Such evaluations rely upon nondestructive testing (NDT) techniques to provide accurate information pertaining to the properties, performance, or condition of the material in question.

Historically, the wood products community has developed and used NDT techniques almost exclusively for sorting or grading structural products. Two excellent examples are machine stress rating (MSR) of lumber and ultrasonic grading of veneer. As currently practiced in North America, MSR couples visual sorting criteria with nondestructive measurements of the stiffness of a piece of lumber to assign it to an established grade (Galligan and others 1977). Similarly, laminated veneer manufacturing facilities use stress wave NDT techniques to sort incoming veneer into strength classes prior to processing into finished products. Veneers are assigned to strength categories, which are established through empirical relationships between stress wave velocity and strength, based on the velocity at which an induced stress wave travels through the veneer (Sharp 1985).

However, a need also exists for NDT techniques to be used in the evaluation of wood in structures. This need is expanding because an increasing amount of resources are being devoted to repair and rehabilitation of existing structures rather than to new construction. As more resources are devoted to repair, an increasing emphasis must be placed on the in-place assessment of structures. This, in turn, requires accurate, cost-effective NDT techniques.

This report presents a review of literature on NDT techniques used for in-place evaluation of wood in structures. Reports of work utilizing NDT techniques for in-place evaluation of wood in structures are also discussed.

Fundamental Hypothesis

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

This concept led researchers to vigorously examine several NDT techniques for grading structural lumber and evaluating the quality of laminated materials (Bell and others 1950; Galiginaitis and others 1954; Jayne 1955, 1959; James 1959; Hoyle 1961b; McKean and Hoyle 1962; Senft and others 1962). Two significant developments evolved from their efforts: MSR of lumber, and perhaps more significant, the evolution of a hypothesis based on fundamental material properties for establishing relationships between measurable NDT parameters and static mechanical properties.

The fundamental hypothesis for NDT of wood materials was initiated by Jayne (1959). He proposed that the energy storage and dissipation properties of wood materials, which can be measured nondestructively by using a number of NDT techniques, are controlled by the same mechanisms that determine the static behavior of such material. As a consequence, useful mathematical relationships between these properties and static elastic and strength behavior should be attainable through statistical regression analysis.

To elaborate on Jayne's (1959) hypothesis, consider how the microscopic structure of clear wood affects its static mechanical behavior and energy storage and dissipation properties. Clear wood is a composite material composed of many tube-like cells cemented together. At the microscopic level, energy storage properties are controlled by orientation of the cells and structural composition, factors that contribute to static elasticity and strength. Such properties are observable as frequency of oscillation in vibration or speed-of-sound transmission. Conversely, energy dissipation properties are controlled by internal friction characteristics, which bonding behavior between constituents contributes to significantly. Rate of decay of free vibration or acoustic wave attenuation measurements are frequently used to observe energy dissipation properties in wood and other materials.

Statistical regression analysis methods are used to establish mathematical relationships between NDT parameters and performance characteristics. As shown in Figure 1, the closer data are grouped around the regression line and the lower the variability, the more successful an NDT parameter is at predicting performance. In the literature we reviewed, most researchers reported on the quality of an NDT parameter in terms of a correlation coefficient r. Correlation coefficients can range from −1 to 1. A correlation coefficient nearing 1 suggests a strong positive relationship, and a coefficient near 0.7 indicates a positive relationship. A correlation coefficient of zero reveals that no relationship exists, positive or negative.

NDT Techniques

The following sections briefly describe several techniques used to nondestructively evaluate wood-based materials.

Static Bending Techniques

Measuring modulus of elasticity (MOE) of a member by static bending techniques is the foundation of MSR of lumber. As currently employed for MSR, this relatively simple measurement involves utilizing the load-deflection relationship of a simply supported beam loaded at its midspan (Fig. 2). Modulus of elasticity can be computed directly by using equations derived from fundamental mechanics of materials and used to infer strength.

Transverse Vibration Techniques

Transverse vibration techniques have received considerable attention for NDT applications. To illustrate these methods, an analogy can be drawn between the behavior of a vibrating beam and the vibration of a mass that is attached to a weightless spring and internal damping force (Fig. 3). In Figure 3, mass M is supported from a rigid body by a weightless spring whose stiffness is denoted by K. Internal friction or damping is represented by the dashpot D. A forcing function equaling $P_0 \sin \omega t$ or zero is applied for forced and free vibration, respectively. When M is set into vibration, its equation of motion can be expressed by the following:

$$M(\frac{d^2x}{dt^2}) + D(\frac{dx}{dt}) + Kx = P_0 \sin \omega t \qquad (1)$$

;quation (1) can be solved for either K or D.

ı solution for K will lead to an expression for MOE
/here

$$\text{MOE} = \frac{f_r^2 W L^3}{12.65 I g} \qquad (2)$$

ɔr a beam freely supported at two nodal points and

$$\text{MOE} = \frac{f_r^2 W L^3}{2.46 I g} \qquad (3)$$

or a beam simply supported at its ends.

n Equations (2) and (3),

MOE is dynamic modulus of elasticity (lb/in^2 (Pa)),

f_r resonant frequency (Hz)

W beam weight (lb (kg·g)),

L beam span (in. (m)),

I beam moment of inertia (in^4 (m^4)), and

g acceleration due to gravity (386 in/s^2 (9.8 m/s^2)).

Solving Equation (1) for D leads to an expression ıf the internal friction or damping component. The ogarithmic decrement of vibrational decay δ is a neasure of internal friction and can be expressed in he form (for free vibrations)

$$\delta = \frac{1}{(n-1)} \ln \frac{A_1}{A_n} \qquad (4)$$

vhere A_1 and A_n are the amplitudes of two oscillations ı $- 1$ cycles apart (Fig. 4).

For forced vibrations,

$$\delta = \frac{\pi \Delta f}{f_r} \frac{1}{\sqrt{(A_r/A)^2 - 1}} \qquad (5)$$

vhere

Δf is the difference in frequency of two points of amplitude A on each side of a resonance curve,

f_r the frequency at resonance, and

A_r the amplitude at resonance (Fig. 4b).

Sharpness of resonance Q is frequently used to measure damping capacity; Q is defined as the ratio of f_r/f. Note that if the value $0.707A_r$ (half-power point method) is substituted for A in Equation (5), the equation reduces to

$$\delta = \frac{\pi \Delta f}{f_r} \qquad (6)$$

and

$$Q = \frac{\pi}{\delta} \qquad (7)$$

Stress Wave Techniques

Several techniques that utilize stress wave propagation have been researched for use as NDT tools. Speed-of-sound transmission and attenuation of induced stress waves in a material are frequently used as NDT parameters.

To illustrate these techniques, consider application of one-dimensional wave theory to the homogeneous viscoelastic bar (Fig. 5). After an impact hits the end of the bar, a wave is generated. This wave immediately begins moving down the bar as particles at the leading edge of the wave become excited, while particles at the trailing edge of the wave come to rest. The wave moves along the bar at a constant speed, but its individual particles have only small longitudinal movements as a result of the wave passing over them. After traveling the length of the bar, this forward-moving wave impinges on the free end of the bar, is reflected, and begins traveling back down the bar.

Energy is dissipated as the wave travels through the bar; therefore, although the speed of the wave remains constant, movement of particles diminishes with each successive passing of the wave. Eventually all particles of the bar come to rest.

Monitoring the movement of a cross section near the end of such a bar in response to a propagating stress wave results in waveforms that consist of a series of equally spaced pulses whose magnitude decreases exponentially with time (Fig. 6). The propagation speed C of such a wave can be determined by coupling measurements of the time between pulses Δt and the length of the bar L by

$$C = \frac{2L}{\Delta t} \qquad (8)$$

The MOE can be computed using C and the mass density of the bar ρ:

$$\text{MOE} = C^2 \rho \tag{9}$$

Wave attenuation can be determined for the rate of decay of the amplitude of pulses using Equation (4) for logarithmic decrement.

Note that wave attenuation calculated using this formula is highly dependent upon characteristics of the excitation system used. Thus, results reported by various researchers cannot be directly compared because several excitation systems were employed. As their results show, energy loss characteristics as measured by stress wave techniques provide useful information pertaining to the performance of wood-based materials.

A more rigorous treatise on the measurement of energy loss by stress wave techniques is presented by Kolsky (1963). In general, a more appropriate method for evaluating energy loss would be to determine the quantity of energy imparted into a member and the corresponding rate of loss of energy. Loss of energy would be calculated using an integral of a waveform, as is done for determining the energy emitted during acoustic emission testing of materials (Harris and others 1972). This is defined as the root mean square (RMS) value.

Wood is neither homogeneous nor isotropic; therefore, the usefulness of one-dimensional wave theory for describing stress wave behavior in wood could be considered dubious. However, several researchers have explored application of the theory by examining actual waveforms resulting from propagating waves in wood and wood products and have found that one-dimensional wave theory is adequate for describing wave behavior. For example, Bertholf (1965) found that the theory could be used to accurately predict dynamic strain patterns in small wood specimens. He verified predicted stress wave behavior with actual strain wave measurements and also verified 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-dimensional theory. Similar results were obtained with clear lumber in tests conducted by Kaiserlik and Pellerin (1977).

An interesting series of experiments designed to explore wave behavior in lumber was also conducted by Gerhards (1981, 1982). He observed changes in the shape of a wave front in lumber containing knots and cross grain by measuring the change in wave speed in the vicinity of such defects. He concluded that a stress wave traveling in lumber containing knots and cross grain does not maintain a planar wave front.

One commonly used technique that employs stress wave NDT technology utilizes simple time-of-flight-type measurement systems to determine speed-of-wave propagation (Figs. 7,8). In these measurement systems, a mechanical or ultrasonic impact is used to impart a longitudinal wave into a member. Piezoelectric sensors are placed at two points on the member and used to sense passing of the wave. The time it takes for the wave to travel between sensors is measured and used to compute wave propagation speed.

Several research projects designed to examine application of one-dimensional theory to wave propagation in clear wood, lumber, and veneer have been conducted using this type of measurement. These projects examined relationships between MOE values obtained from stress wave measurements and those measured using static testing techniques. Note the strong correlative MOE relationships found in these research projects (Table 1).

Considerable research activity has focused on development of techniques to measure stress wave attenuation in wood products. For example, Ross and Pellerin (1988) used an inexpensive velocity meter to measure wave attenuation. Others (Beall 1987, Patton–Mallory and De Groot 1989) examined coupling acoustic emission (AE) and ultrasonic techniques to measure wave attenuation.

Acoustic emission techniques have also been extensively researched for application to wood-based materials. These techniques rely upon the application of stress to a member to generate a stress wave. An excellent review of AE techniques and research related to their application to wood-based materials is presented by Beall (1987).

Other Techniques

Several other NDT techniques have been investigated for use with wood. For example, the attenuation of x-rays has been investigated for detecting internal voids in wood (Mothershead and Stacey 1965) and for inspecting utility poles and trees (Monro and others 1990).

Screw withdrawal (Talbot 1982) and pick- or probing-types tests have also been examined. These inexpensive techniques provide information about a member at a point and are consequently of limited value for inferring strength for large members. However, they are useful for detecting surface damage of members.

The Pilodyn test is also used to detect surface damage. The Pilodyn instrument consists of a spring-loaded pin device that drives a hardened steel pin into the wood.

epth of pin penetration is used as a measure of degree f degradation (Hoffmeyer 1978).

.aboratory Verification of ·undamental Hypothesis

everal research organizations have examined applicaion of fundamental concepts under laboratory condiions. The following sections summarize results preented by these organizations.

:lear Wood and Lumber Products

nitial laboratory studies to verify the fundamental ypothesis were conducted with clear wood and lumber roducts using a variety of NDT techniques. For xample, considerable research activity was conducted n the early 1960s to examine relationships between he static bending MOE and ultimate strength of oftwood dimension lumber. Results obtained from arious projects designed to examine this relationship re summarized in Tables 2 to 4. Note that useful orrelative relationships were found between MOE nd the bending, compressive, and tensile strengths f dimension lumber obtained from various softwood pecies.

Research using transverse vibration and stress wave echniques is summarized in Table 5. Jayne (1959) lesigned and conducted one of the first studies that tilized transverse vibration NDT techniques for valuating the strength of wood. He was successful n demonstrating a relationship between energy torage and dissipation properties, measured by forced ransverse vibration techniques, and the static bending roperties of small, clear wood specimens. He utilized n experimental setup similar to that illustrated in Figure 9. With this setup, Jayne was able to determine he resonant frequency of a specimen from a frequency esponse curve. In addition, sharpness of resonance energy loss) was obtained using the half-power point nethod. Pellerin (1965a,b) verified the hypothesis ising free transverse vibration techniques on dimension umber and glulam timbers with the apparatus hown in Figure 10. After obtaining a damped sine vaveform for a specimen (Fig. 3), he analyzed it tilizing equations for MOE and logarithmic decrement. Measured values of MOE and logarithmic decrement vere then compared to static MOE and strength alues. O'Halloran (1969) used a similar apparatus and btained comparable results with softwood dimension umber.

Kaiserlik and Pellerin (1977) furthered the hypothesis y using stress wave techniques to evaluate the tensile strength of a small sample of clear lumber containing varying degrees of slope of grain (Fig. 11). They utilized the one-dimensional wave Equation (9) to compute MOE and the equation presented by Pellerin (1965b) for logarithmic decrement.

Wood-Based Composite Materials

The fundamental hypothesis was verified using stress wave techniques on wood-based composites (Suddarth 1965, Pellerin and Morschauser 1974, Ross 1984, Fagan and Bodig 1985, Vogt 1985, and Ross and Pellerin 1988) (Table 6). Pellerin and Morschauser (1974) used the setup in Figure 7 to show that stress wave speed, a measure of energy storage properties, could be used to predict the flexural behavior of underlayment grade particleboard. Ross (1984) and Ross and Pellerin (1988) revealed that wave attenuation, a measure of energy dissipation properties, is sensitive to bonding characteristics and is a valuable NDT parameter that contributes significantly to the prediction of tensile and flexural mechanical behavior of wood-based particle composites. Vogt (1985) furthered the application of the hypothesis to wood-based fiber composites. In an additional study, Vogt (1986) found a strong relationship between internal bond and stress wave parameters of particle and fiber composites. Suddarth (1965) verified the hypothesis by using forced transverse vibration techniques to locate poorly bonded or debonded areas in wood components for missiles.

Biologically Degraded Wood

Verification of the hypothesis with wood subjected to different levels of deterioration by decay fungi, which adversely effect the mechanical properties of wood and are frequently found in wood structures, has been limited to studies that have employed only energy storage parameters (Table 7). Wang and others (1980) found that wood decay significantly affected the frequency of oscillation of small, eastern pine, sapwood, cantilever bending specimens (Fig. 12). Pellerin and others (1985) showed that stress wave speed could be successfully used to monitor the degradation of small clear-wood specimens exposed to brown-rot fungi. They showed a strong correlative relationship between stress wave speed and parallel-to-grain compressive strength of exposed wood. Rutherford and others (1987) showed similar results. They also revealed that MOE perpendicular to the grain, measured using stress wave NDT techniques, was significantly affected by degradation from brown-rot decay and could be used to detect incipient decay. Chudnoff and others (1984) reported similar results from experiments that utilized an ultrasonic measurement system (Fig. 8) and several hardwood and softwood species. Patton–Mallory and

De Groot (1989) reported encouraging results from a fundamental study dealing with the application of acousto-ultrasonic techniques (Fig. 13). Their results showed that energy loss parameters may provide useful additional information pertaining to early strength loss from incipient decay caused by brown-rot fungi.

Acoustic emission techniques were also investigated for use in decay detection. Utilizing a small sample of clear, white fir specimens infected with brown-rot fungi, Beall and Wilcox (1986) were able to show a relationship between selected AE parameters and radial compressive strength (Fig. 14).

In-Place Assessment of Wood Members

Several organizations have published research results on the use of NDT techniques for in-place evaluation of wood members (Table 8). The following summarizes research conducted on the use of several NDT techniques for such evaluations.

Static Bending Techniques

Measuring flexural MOE by static bending techniques has been successfully employed to grade lumber by using machines that approximate simply supported boundary conditions. Such machines consistently maintain these conditions. However, an in-place environment yields boundary conditions that may vary considerably in even the simplest structure. Consequently, application of this technique for in-place assessment of wood members has been limited.

Abbott and Elcock (1987) developed an in-place NDT technique for measuring the stiffness of in-service poles (Fig. 15). A bending load was applied to individual poles above the ground line. Load and resulting deflections were recorded and used to compute flexural stiffness. From these measurements, inferences pertaining to pole strength were made, and predicted and actual values were compared.

Transverse Vibration Techniques

Transverse vibration techniques are also significantly influenced by boundary conditions. Most researchers conducting laboratory studies with this technique devote considerable time to insuring that simple end conditions are attained. As discussed previously, such conditions frequently do not exist with wood members in structures. Consequently, use of this technique has also been limited for in-place evaluations.

Murphy and others (1987) developed a technique based on transverse vibration NDT techniques for evaluating wood poles. Their technique involved measuring the vibrational response of a pole after it is tapped by a rubber mallet. Resonant frequency of the pole was identified and used to infer pole strength.

Stress Wave Techniques

Longitudinal stress wave NDT techniques have also been investigated by researchers for assessing wood members in structures. The influence that boundary conditions have on speed-of-sound transmission measurements has been shown to be significantly less than that for static bending or transverse vibration techniques. Thus, many researchers have examined longitudinal stress wave NDT techniques for in-place assessment of wood members. The following briefly describes stress wave NDT techniques that have been used in projects.

Eighteenth Century Mansion

Lee (1965) was one of the first to examine use of stress wave techniques for in-place evaluation. He assessed the roof structure of an 18th century mansion, using an ultrasonic impact and measurement system similar to that illustrated in Figure 8. He measured propagation speed of stress waves in wood members both parallel and perpendicular to the grain. To obtain an estimate of strength loss, sections from purlins were evaluated statically in a laboratory, and a chart relating stress wave velocity and strength was prepared. Strength of the remaining timbers was then inferred.

University Football Stadium

Washington State University's football stadium, Pullman, Washington, was also inspected using stress wave NDT techniques. This stadium was originally constructed in the 1930s; the north and south grandstands were replaced after a fire in the 1960s. The portion of the stadium that was inspected for its structural integrity in the early 1980s was the horseshoe section that joined the north and south grandstands. This horseshoe section was part of the original stadium and was constructed from large solid-sawn timbers. The reason for inspection was that large crowds were anticipated for the upcoming football season, thus requiring use of the horseshoe section. The university administration hired consulting engineers to inspect and assess the structural integrity of the stadium. The consulting engineers reported that the section was structurally sound. However, an informal inspection by graduate students enrolled in a NDT wood course revealed that the structural members in the horseshoe section were badly decayed and probably would not be able to carry the load from the anticipated crowd. Further evaluation using stress wave equipment (Fig. 16) showed that speed-of-sound transmission was significantly lower in decayed members than in sound wood. Subsequent probing of those areas indicated that the decay was so extensive that only a thin shell of sound wood remained. These results led to the dismantling of the horseshoe section of the stadium. The decay of the timbers was so advanced that when the stress-skin effect of the seating was removed, the substructure collapsed under its own weight.

School Gymnasium

Another structure evaluated with stress wave NDT techniques was a school gymnasium, constructed with laminated barrel arches (Hoyle and Pellerin 1978). These laminated arches were the main support structure for the gymnasium (Fig. 17). Each arch end was exposed to the weather and rested in a metal stirrup fastened to a concrete pier foundation. These conditions and the heavy nonbreathing paint that was used on the exposed portions of the arches created an environment that would support the growth of decay fungi. Cracking and peeling of paint were the first indications that decay was present in the arch ends. When the condition of the gymnasium was realized by school personnel, the problem was one of determining where decay was present and where the wood was sound and did not require replacement. It was not necessary to pinpoint the decayed areas with great precision but to establish how far in from the arch ends that the decay had progressed. The repair procedure was then to replace those ends of the arches with structurally sound material.

The method of inspection was the same as described for the football stadium. To insure that the stress wave travel times were measured in straight lines through individual laminates, a paper, on the third arch from the near end of the gymnasium, containing a grid of 1.5 in. (38 mm) squares, was fastened to each side of the arch and used as a map for taking stress wave time measurements (Fig. 18). The recorded times were then used to determine the extent of the decay (Fig. 19).

Piers

Stress wave techniques were also used to inspect the structural integrity of several piers. Currently limited to inspection of structural components that are above the water line, stress wave techniques were used to inspect a Seattle, Washington, pier that is owned and operated by the U.S. Coast Guard. The pier is constructed of large wood beams and stringers supported on wood piling. Although details of the inspection are not published, NDT techniques similar to those described previously were used.

Bridges

A report by Hoyle and Rutherford (1987) describes the evaluation of wood bridges for the Washington State Department of Transportation using speed-of-sound transmission as an index of deterioration. Previously described stress wave NDT techniques were used. About twelve bridges were evaluated and only one revealed signs of decay. Similarly, Aggour and others (1986) used ultrasonic techniques to evaluate the residual compression strength of timber bridge piles. Relationships between speed-of-sound transmission and residual compressive strength showed excellent correlation.

TRESTLE

TRESTLE was constructed between July 1976 and February 1979 and is one of the largest known glue-laminated structures in the world. It is located at Kirtland Air Force Base, New Mexico. TRESTLE was built as a test stand for aircraft that weigh 550,000 lb (250,000 kg). It has a 50- by 394-ft (15- by 120-m) access ramp and a 200- by 200-ft (61- by 61-m) test platform, and the top surface is 118 ft (36 m) above the ground (Fig. 20).

In the early 1980s, the U.S. Air Force wanted to test aircraft that were considerably heavier than had previously been tested, so they requested a structural evaluation of TRESTLE. One evaluation method relied upon speed-of-sound transmission measurements. Figure 21 shows one stress wave technique that was used. Measurements were taken both longitudinally and transversely to the length of the laminated beams. Neal (1985) and Browne and Kuchar (1985) reported that a total of 484 glulam members (representing approximately 5 percent of the structural members) were evaluated. They concluded that the structural framework of TRESTLE had not measurably degraded, but the exposed deck system was significantly degraded.

Barn Structure

Stress wave techniques were also used to evaluate the wood members of a barn, constructed in 1925 for the College of Agriculture, Washington State University, Pullman, WA (Lanius and others 1981). The structure evaluated was primarily used as an animal shelter on the ground floor and for hay storage on the second floor. The inspection was confined to the nominal 2- by 12-in. (standard 38- by 286-mm) floor joists in the south bay of the barn where hay storage was believed to be the primary use. Speed-of-sound propagation parallel to the grain was measured on 50 percent of the members of the structure. These values were then related to an allowable extreme fiber stress in bending and used to judge remaining strength.

Water Cooling Towers

Stewart and others (1986) used stress wave techniques to evaluate the wood members of several water cooling towers. Using the instrumentation illustrated in Figure 22, approximately 7,700 4-ft- (1.2-m-) long nominal 2- by 4-in. (standard 38- by 89-mm) redwood columns were evaluated. Using the information obtained from a correlation between stress wave parameters and column strength of 74 test specimens and that obtained from the in-place evaluation, individual column strengths were predicted. Columns not meeting desired reliability limits were identified for replacement. This effort resulted in salvaging a substantial portion of the columns that would have otherwise required replacement.

Wood Utility Poles

Anthony and Bodig (1989) reported on the use of sonic stress wave spectral analysis techniques that they had developed and used for inspection of wood structures. Their equipment was designed on the concept that stress waves propagate at different speeds and attenuate differently at various frequencies in wood-based products. Anthony and Bodig collected a time record of a wave propagating through a member, converted it to a frequency spectrum, and then correlated various characteristics to strength using multiple regression analysis techniques (Fig. 23).

Dunlop (1983) utilized an electronic system (Fig. 24), sweeping through a selected range of excitation frequencies, to develop an acoustic signature of a pole. Resonant frequencies were examined for use as NDT parameters.

Other NDT Techniques

Simple mechanical tests are frequently used for in-service inspection of wood members in structures. 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 the same underlying premise was developed by Talbot (1982). His test differed from the probing-type test in that instead of evaluating probe penetration resistance, Talbot examined withdrawal resistance of a threaded probe, similar to a wood screw, inserted into a member. Talbot believed that a correlative relationship between withdrawal resistance and residual strength should exist and would be relatively easy to implement. To determine if such a relationship existed, he conducted an experiment using several small Douglas-fir beams that were in various stages of degradation as a result of exposure to decay fungi. Prior to testing to failure in bending, probe withdrawal resistance was measured at the neutral axis of the beams. Bending strength and corresponding probe resistance values were then compared. Talbot's results revealed that a relationship does exist (Fig. 25). He used this test in conjunction with stress wave techniques to assess the extent of damage to the solid-sawn timbers of Washington State University's football stadium.

Concluding Remarks and Future Research Directions

Considerable effort has been devoted to developing NDT techniques for assessing the performance of wood structural members. This report reviewed literature pertaining to NDT of wood, with an emphasis on techniques used for in-place assessment. Based on our review, we conclude the following:

1. A fundamental hypothesis for establishing relationships between NDT parameters and performance of wood members has been established and verified using a wide range of wood-based materials and a variety of NDT techniques.
2. Laboratory investigations on validity of the fundamental hypothesis for establishing predictive relationships for biologically degraded wood, as is sometimes found in structures, have been limited in regards to both the NDT techniques employed and the biological agents of deterioration studied.
3. In-place assessment efforts have focused primarily on adaptations of stress wave NDT techniques. These techniques have shown considerable promise, are relatively easy to use, and have low equipment costs.

Future in-place assessment NDT research should focus on furthering the application of stress wave techniques. Stress wave NDT techniques have been extensively investigated under laboratory conditions and used by inspection professionals on a limited basis. However, many questions remain unanswered regarding the effectiveness of stress wave NDT techniques to evaluate members in complicated structures. No published work documents how wave behavior is affected by the varied boundary conditions found in wood structures. In addition, little information has been published on the relationship between excitation system characteristics and wave behavior. Research efforts in these two areas would advance state-of-the-art inspection techniques considerably.

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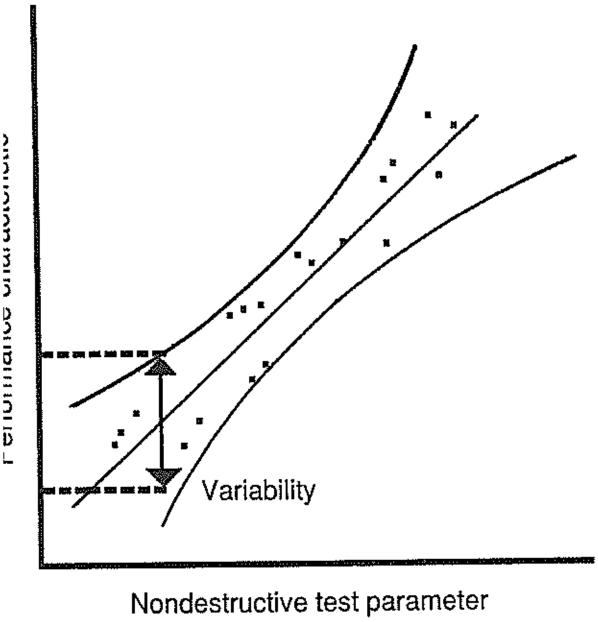

Figure 1—Typical relationship between nondestructive testing parameter and performance.

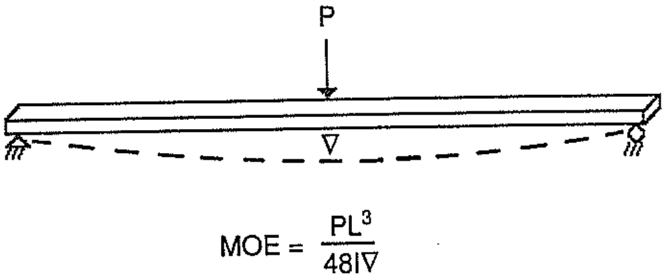

Figure 2—A simply supported beam loaded at its midspan and the mathematical equation relating modulus of elasticity to load and deflection.

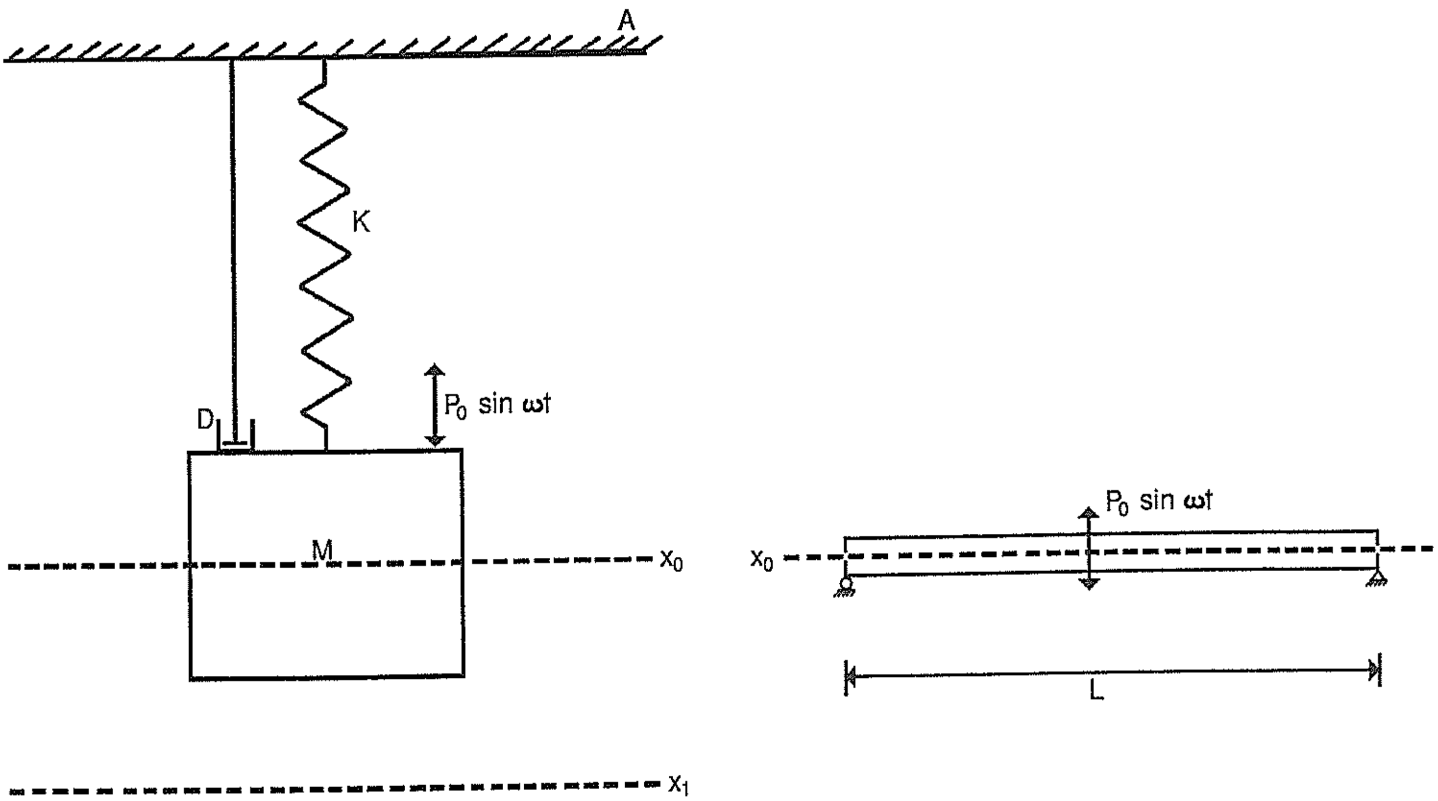

Figure 3—Mass-spring dashpot vibration model (left) and transversely vibrating beam (right).

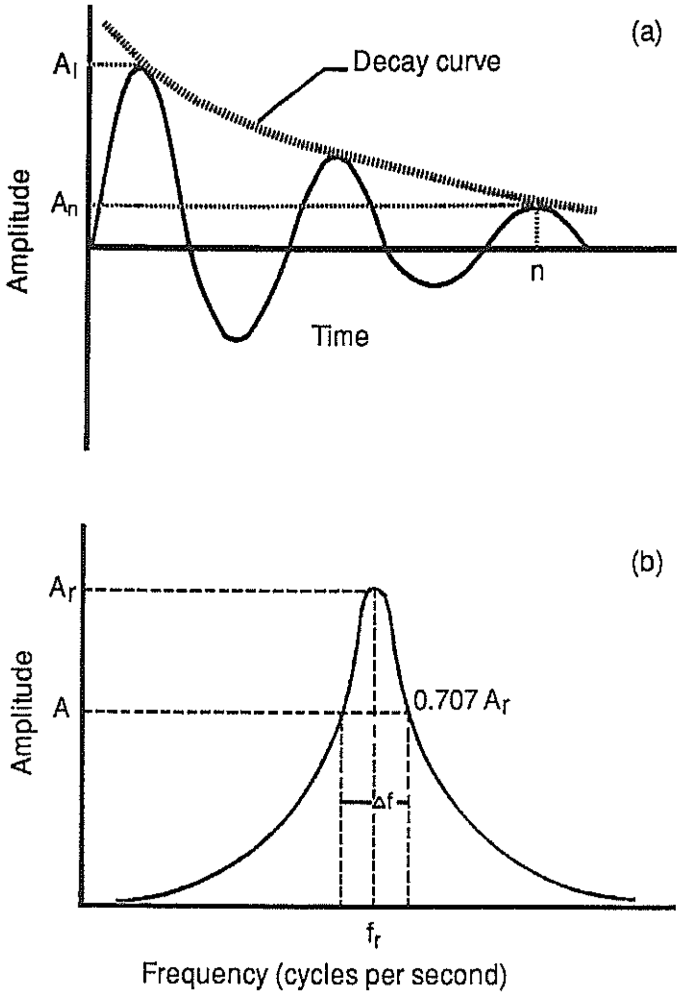

Figure 4—Free vibration of a beam: (a) damped sine wave, (b) frequency response curve.

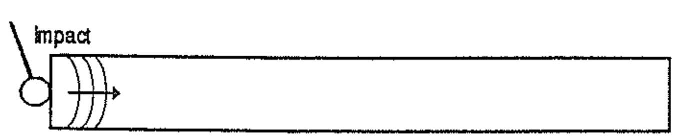

Figure 5—Viscoelastic bar of length L subjected to an impact.

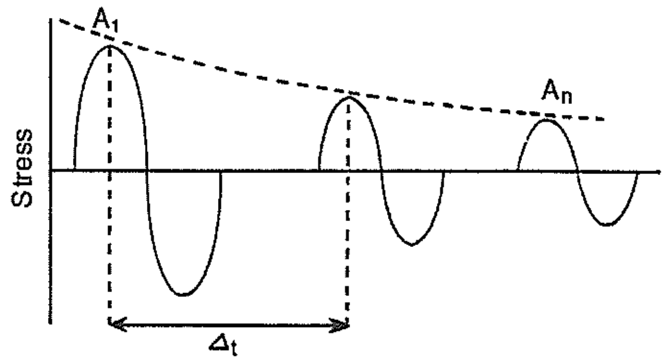

Figure 6—Theoretical response of the end of a viscoelastic bar in response to a propagating stress wave.

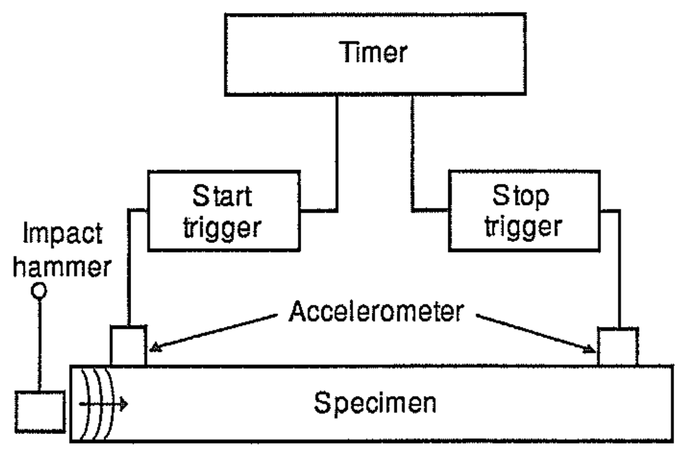

Figure 7—Technique utilized to measure impact-induced stress wave propagation speed in various wood products.

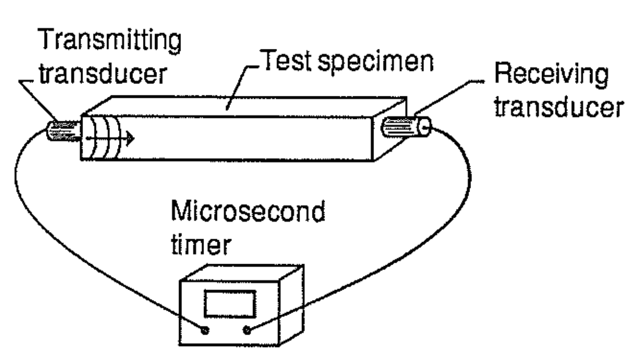

Figure 8—Ultrasonic measurement system used to measure speed-of-sound transmission in various wood products.

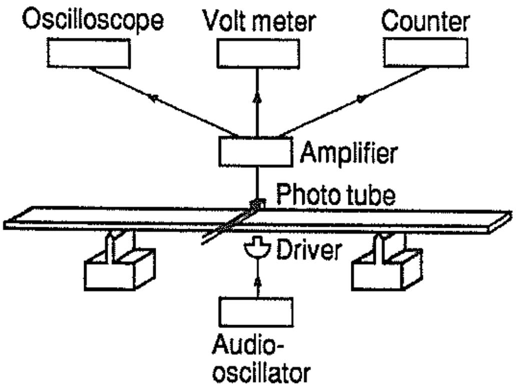

Figure 9—Experimental setup utilized to measure the response of wood beams to forced transverse vibration.

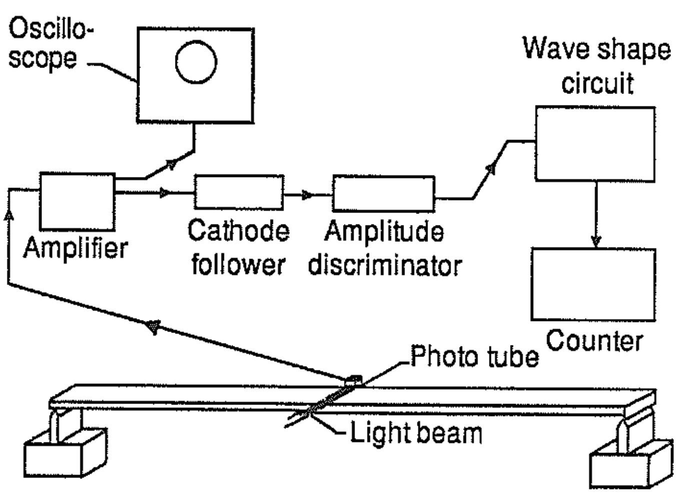

Figure 10—Apparatus used to examine free transverse vibration characteristics of lumber specimens (Pellerin 1965a,b).

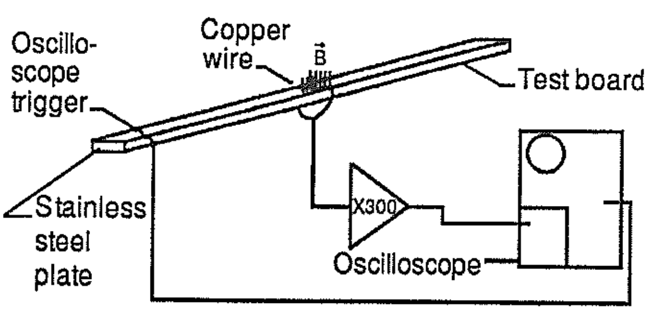

Figure 11—Instrumentation developed to observe stress wave behavior in lumber (Kaiserlik and Pellerin 1977).

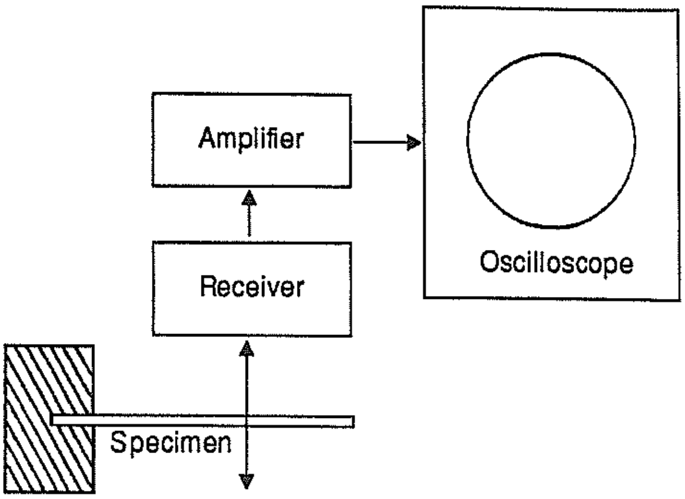

Figure 12—Experimental setup developed to observe free vibration response of decayed specimens.

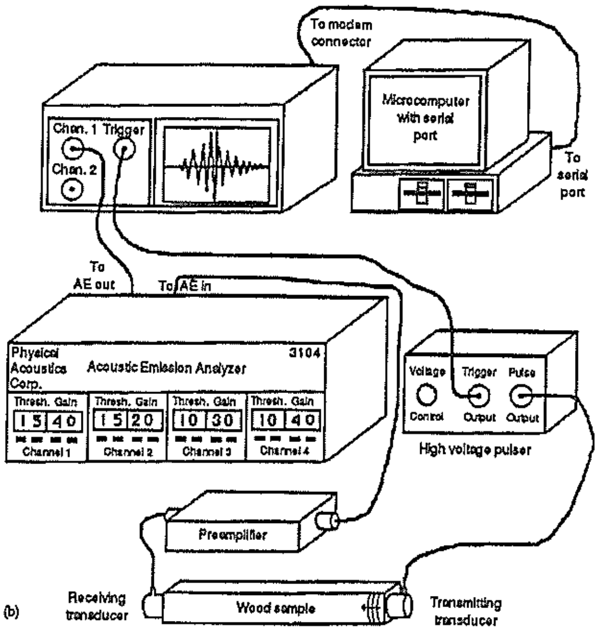

Figure 13—Acousto-ultrasonic equipment (Patton-Mallory and De Groot 1989).

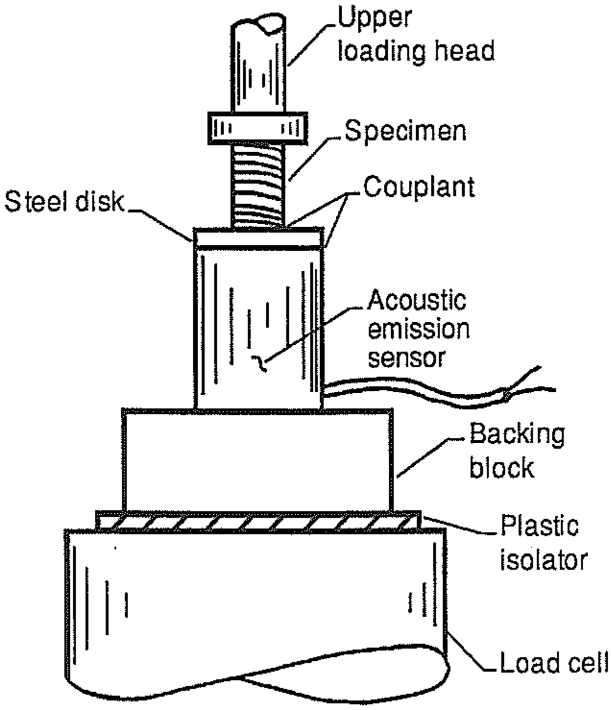

Figure 14—Experimental setup to monitor acoustic emissions from decayed specimens subjected to a compressive force.

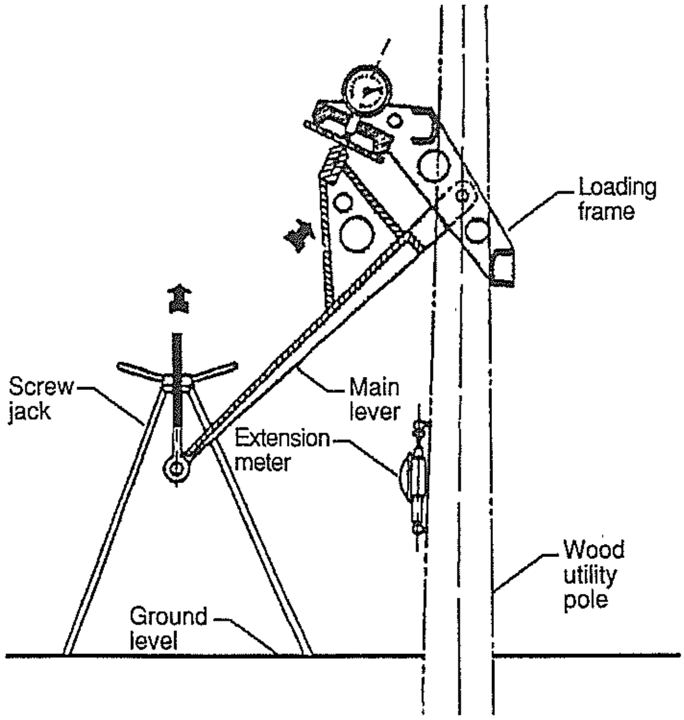

Figure 15—Setup developed to evaluate poles.

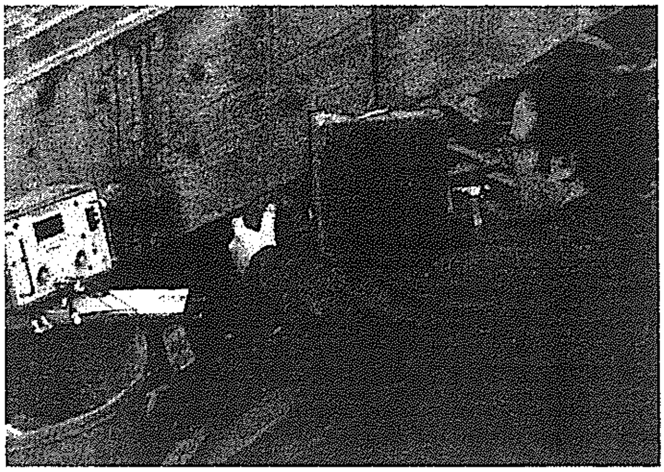

Figure 16—Stress wave equipment used to evaluate university football stadium.

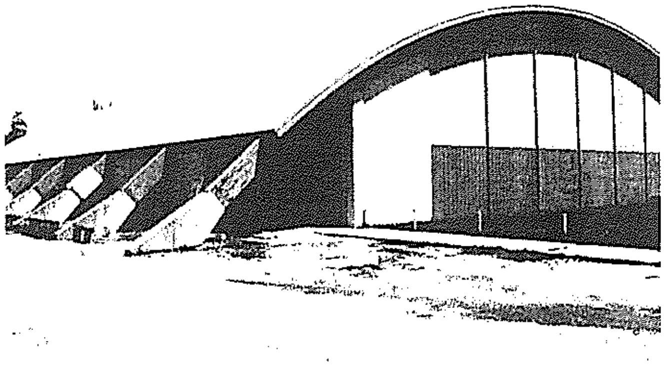

Figure 17—School gymnasium evaluated by Hoyle and Pellerin (1978).

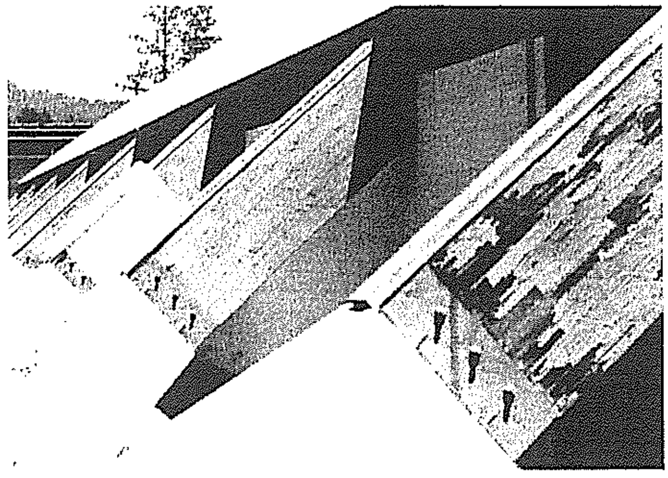

Figure 18—Third barrel arch contains map for stress wave reading.

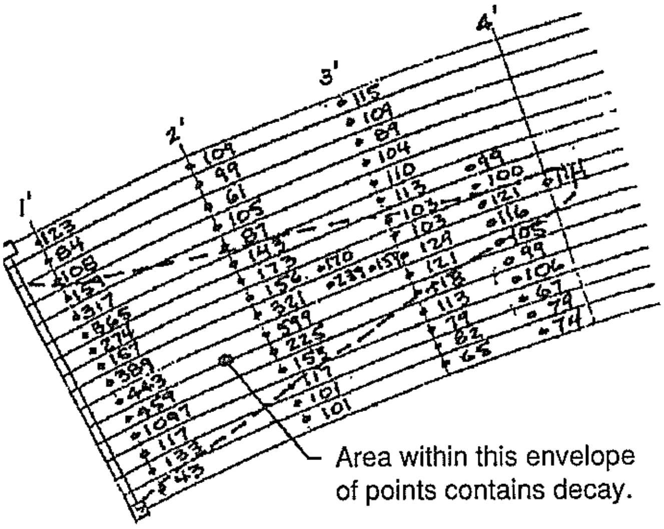

Figure 19—Inspection diagram showing stress wave travel time (μs).

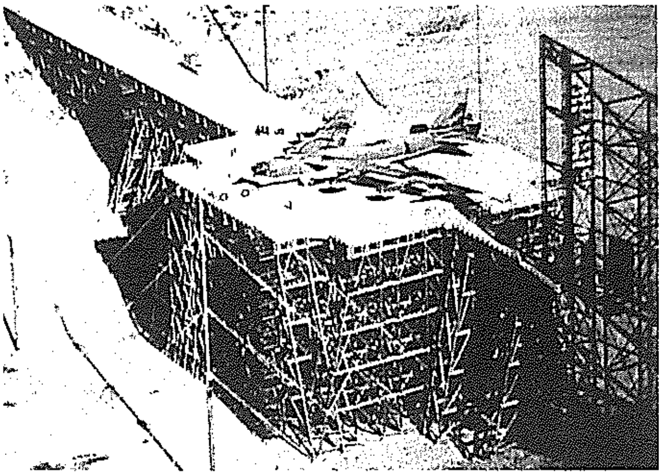

Figure 20—TRESTLE test stand for aircraft.

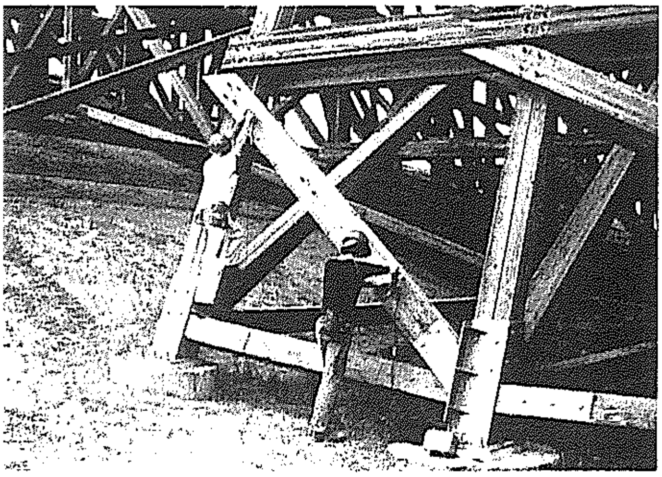

Figure 21—Stress wave evaluation of wood members of TRESTLE.

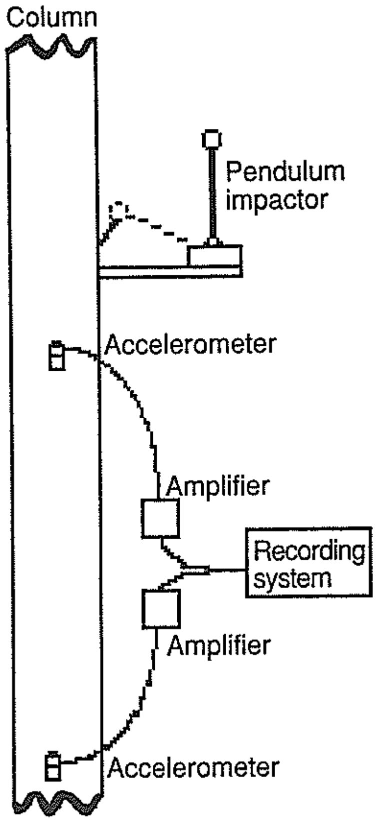

Figure 22—Instrumentation utilized to test wood members in water cooling tower.

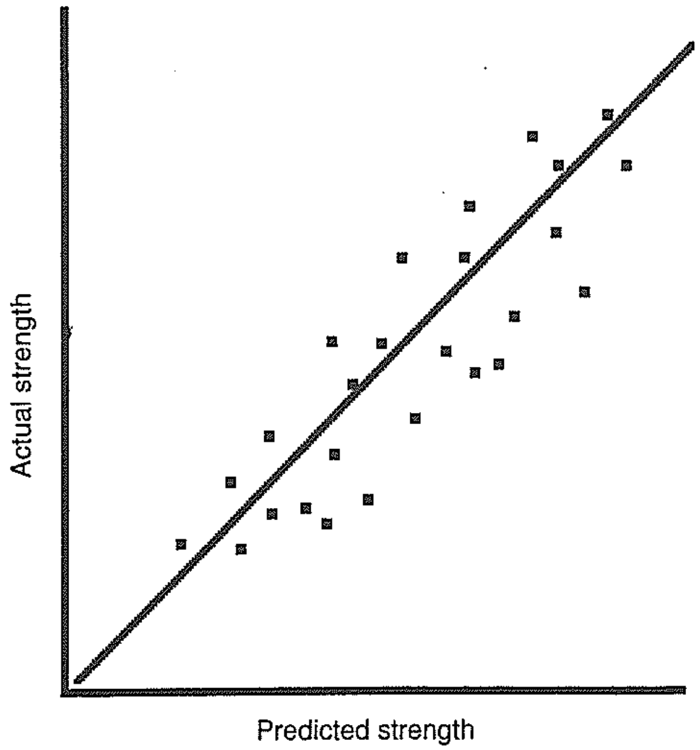

Figure 23—Relationship between predicted and actual strength of utility poles.

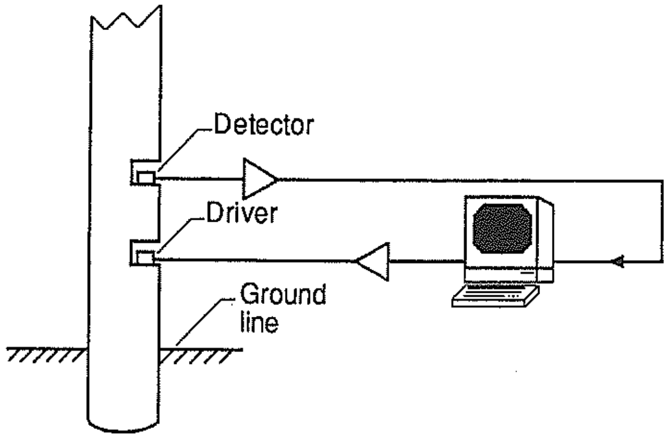

Figure 24—Electronic system to analyze poles.

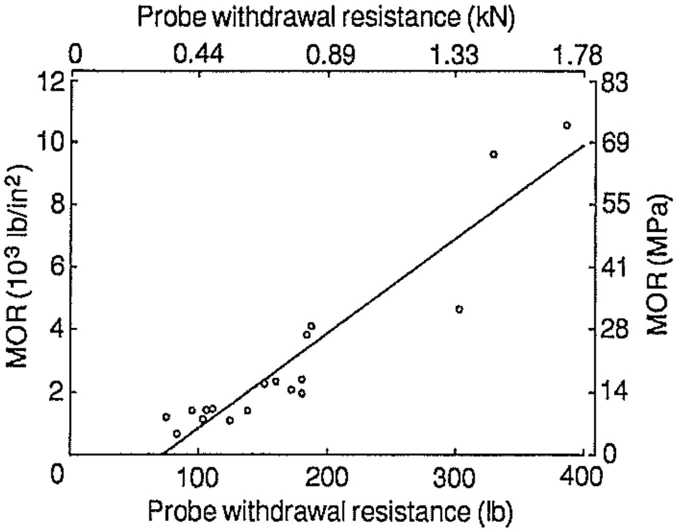

Figure 25—Relationship between probe withdrawal resistance and residual bending strength of Douglas-fir specimens.

Table 1—Research summary on the correlation between stress wave modulus of elasticity values obtained from time-of-flight-type measurements and static modulus of elasticity of various wood materials

Reference	Material	Static loading mode	Correlation coefficient, r
Bell and others (1954)	Clear wood	Compression	0.98
		Bending	0.98
Galligan and Courteau (1965)	Lumber	Bending	0.96
Koch and Woodson (1968)	Veneer	Tension	0.96 – 0.94
Porter and others (1972)	Lumber	Bending	0.90 – 0.92
Pellerin and Galligan (1973)	Lumber	Bending	0.96
	Veneer	Tension	0.96
McAlister (1976)	Veneer	Tension	0.99
Gerhards (1982)	Knotty lumber	Bending	0.87
	Clear lumber	Bending	0.95

able 2—Research summary on the correlation between modulus of elasticity (tested flatwise) and flatwise bending trength of softwood dimension lumber

Reference	Species	Nominal moisture content (percent)	Grade[a]	Nominal width (in.)[b]	Growth location	Correlation coefficient, r
Ioyle (1961b)	Douglas-fir	12	SS,C,U	4,6,10	Western Oregon, Washington	0.79
					Idaho, Washington	0.72
	Western hemlock	12	SS,C,U	4,6,10	Western Oregon, Washington	0.74
	Western larch	12	SS,C,U	4,6,8	Idaho, Washington	0.70
Ioyle (1962)	Grand fir	12	C,S,U	8	Idaho	0.72
Iofstrand and Howe (1963)	Grand fir	12	C,S	4,6,8	Idaho	0.75
ellerin (1963b)	Douglas-fir	12	Combination of visual grades	4,8	Idaho	0.76
Ioyle (1964)	Southern Pine	12	1D,1,2D,2,3	4,6,8	Southeastern United States	0.76
ramer (1964)	Southern Pine	12	1D,2,3	4,6,10	Southeastern United States	0.88
ohnson (1965)	Douglas-fir	10	SS,C,U	6	Western Oregon, Washington	0.85
	Western Hemlock	10	SS,C,U	6	Western Oregon, Washington	0.86

[a]Grades are by regional rules in use at time of research. Western Products Association and West Coast Lumber Inspection Bureau Grades: SS = Select Structural, C = Construction, S = Standard, U = Utility. Western Wood Products Association grades: 1, 2, 3. Southern Pine Inspection Bureau Grades: 1D = No. 1 Dense, 1 = No. 1, 2D = No. 2 Dense, 2 = No. 2, 3 = No. 3.

1 in. = 25.4 mm.

Table 3—Research summary on the correlation between modulus of elasticity (tested flatwise and on edge) and edgewise bending strength of softwood dimension lumber

Reference	Species	Nominal moisture content (percent)	Grade[a]	Nominal width (in.)[b]	Growth location	Correlation coefficient, r
Hoerber (1962)	Douglas fir	12	SS,C,U	4,6,8	Idaho, Eastern Washington	0.65
Hoyle (1962)	Grand fir	12	C,S,U,SS	8	Idaho	0.59 - 0.70
Hoyle (1964)	Southern Pine	12	1D,1,2D,2,3	4,6,8	Southeastern United States	0.57
Sunley and Hudson (1964)	Norway spruce and Scots pine (pooled)	—	—	4,7	Great Britain	0.68
Corder (1965)	Douglas-fir	12	SS,C,S	4,6,10	Inland Northwestern, United States	0.64
Johnson (1965)	Douglas-fir	10	SS,C,U	6	Western Oregon, Washington	0.80 - 0.87
	Western Hemlock	10	SS,C,U	6		0.84
Littleford (1965)	Douglas-fir	10	—	6	British Columbia, Canada	0.74
	Western Hemlock	12	—	6		0.70 - 0.77
	Noble fir	12	—	6		0.66
	Western white spruce	12	—	6		0.79
	Lodgepole pine	17	—	6		0.80
Miller (1965)	White spruce	12	—	6	Eastern Canada	0.78 - 0.84
	Jack pine	12	—	6		0.69 - 0.73
Doyle and Markwardt (1966)	Southern Pine	12	1D,1,2D,2,3	4,6, 8,10	Southeastern United States	—
Hoyle (1968)	Southern Pine	12	1D,1,2D,2,3	4,6,8	Southeastern United States	0.67

[a]Grades are by regional rules in use at time of research. Western Products Association and West Coast Lumber Inspection Bureau Grades: SS = Select Structural, C = Construction, S = Standard, U = Utility.
Western Wood Products Association grades: 1, 2, 3. Southern Pine Inspection Bureau Grades:
1D = No. 1 Dense, 1 = No. 1, 2D = No. 2 Dense, 2 = No. 2, 3 = No. 3.
[b]1 in. = 25.4 mm.

Table 4—Research summary on the correlation between modulus of elasticity (tested flatwise) and the compressive and tensile strength of softwood dimension lumber.

Strength property	Reference	Species	Nominal moisture content (percent)	Grade[a]	Nominal width (in.)[b]	Growth location	Correlation coefficient, r
Compressive	Hofstrand and Howe (1963)	Grand fir	12	Ungraded	4,8	Idaho	0.84
	Pellerin (1963a)	Douglas-fir	12	SS,S,E	4,8	Idaho	0.78
	Hoyle (1968)	Southern Pine	12	1,2,3	4,8	Southeastern United States	0.67
Tensile	Hoyle (1968)	Douglas fir	13	1.0,1.4,1.8,2,2	4,8	Idaho	0.74
		White fir	14			Idaho	0.75
		Western Hemlock	15			Western Oregon, Washington	0.81

[a]Grades are by regional rules in use at time of research. Western Products Association and West Coast Lumber Inspection Bureau Grades: SS = Select Structural, S = Standard, E = Economy.
Western Wood Products Association grades: 1, 2, 3. Machine Stress Grades: 1.0, 1.4, 1.8, 2.2.
[b]1 in. = 25.4 mm.

Table 5—Summary of results that verify the fundamental hypothesis that used transverse vibration and stress wave nondestructive testing (NDT) techniques on clear wood and lumber products[a]

Reference	NDT technique	Material	NDT parameters measured	Static test	Reported properties	Comparison of NDT parameters and static properties (correlation coefficient, r, unless noted)
Jayne (1959)[b]	Forced transverse vibration	Small, clear sitka spruce specimens	Resonant frequency, E_d, Q	Bending	E_{sB}, MOR	E_{sB} and E_d — ±100,000 lb/in^2 MOR and E_d — ±1,000 lb/in^2 MOR amd E_d — ±1,000 lb/in^2 MOR and density/Q — ±1,000 lb/in^2 MOR and E_d/δ — ±900 lb/in^2
Pellerin (1965a)	Free transverse vibration	Douglas-fir glue-lam	Natural frequency, E_d, δ	Bending	E_{sB}, MOR	Predicted relative strength of three glue-laminated members.
Pellerin (1965b)	Free transverse vibration	Inland Douglas-fir dimension lumber	Natural frequency, E_d, δ	Bending	E_{sB}, MOR	E_{sB} and E_d — 0.98 MOR and E_d — 0.67–0.93 MOR and $1/\delta$ — 0.46–0.88 MOR and E_d/δ — 0.68–0.92
O'Halloran (1969)	Free transverse vibration	Lodgepole pine dimension lumber	Natural frequency, E_d, δ	Bending	E_{sB}, MOR	E_{sB} and E_d — 0.98 MOR and E_d — 0.89 MOR and $1/\delta$ — 0.82 MOR and E_d/δ — 0.91
Kaiserlik and Pellerin (1977)	Longitudinal stress wave	Douglas-fir boards	C, E_d, δ	Tension	UTS	UTS and E_d — 0.84 UTS and combination of E_d and δ — 0.90

[a] C = Speed of sound.
δ = Logarithmic decrement.
E_d = Dynamic modulus of elasticity obtained from either transverse vibration or stress wave measurements.
E_{sB} = Modulus of elasticity obtained from static bending test.
MOE = Modulus of elasticity.
MOR = Modulus of rupture.
Q = Sharpness of resonance.
UTS = Ultimate tensile stress.
1 lb/in^2 = 6.9×10^3 Pa.
[b] Correlation coefficients were not reported by Jayne. However, he did report 95 percent confidence intervals.

'able 6—Summary of results that verify the fundamental hypothesis using wood-based composites[a]

Reference	NDT technique	Material	NDT parameters measured	Static test	Reported properties	Comparison of NDT parameters and static properties (correlation coefficient, r, unless noted)
uddarth (1965)	Forced transverse vibration	Laminated wood (missile noise fairing)	E_d, δ			Mapped out debonded or poorly bonded areas.
'ellerin and Morschauser (1974)	Longitudinal stress wave	Underlayment particleboard	C	Bending	E_{sB}, MOR	E_{sB} and C^2 — 0.93–0.95 MOR and C^2 — 0.87–0.93
ꞌoss (1984), Ross and Pellerin (1988)	Longitudinal stress wave	Underlayment and industrial particleboard, structural panel products	C, E_d, δ	Tension	E_{sT}, UTS	E_{sT} and C^2 — 0.98 E_{sT} and E_d — 0.98 UTS and C^2 — 0.91 UTS and E_d — 0.93 UTS and $1/\delta$ — 0.63 UTS and combination of E_d, $1/\delta$ — 0.95
				Bending	E_{sB}, MOR	E_{sB} and C^2 — 0.97 E_{sB} and E_d — 0.96 MOR and C^2 — 0.93 MOR and E_d — 0.92 MOR and $1/\delta$ — 0.70 MOR and combination of E_d, $1/\delta$ — 0.97
				Internal bond	IB	IB and combination — 0.79
agan and Bodig (1985)	Longitudinal stress wave	Wide range of wood composites	C	Bending	MOR	Simulated and actual MOR distributions were similar.
'ogt (1985)	Longitudinal stress wave	Medium-density fiberboard	C, E_d, δ	Tension	E_{sT}, UTS	E_{sT} and C^2 — 0.90 E_{sT} and E_d — 0.88 UTS and C^2 — 0.81 UTS and E_d — 0.88 Combination — 0.88
				Bending	E_{sB}, MOR	E_{sB} and C^2 — 0.76 E_{sB} and E_d — 0.72 MOR and C^2 — 0.96 MOR and C^2 — 0.92 Combination — 0.97
'ogt (1986)	Stress wave (through transmission)	Underlayment and industrial particleboard, structural panel products	C_t, E_{dt}	Internal bond	IB	IB and C_t^2 — 0.70–0.72 IB and E_{dt} — 0.80–0.99

C = Speed of sound.
C_t = Speed-of-sound transmission through thickness.
δ = Logarithmic decrement.
E_d = Dynamic modulus of elasticity obtained from either transverse vibration or stress wave measurements.
E_{dt} = Dynamic modulus of elasticity, through the thickness orientation.
E_{sB} = Modulus of elasticity obtained from a static bending test.
E_{sT} = Modulus of elasticity obtained from a static tension test.
MOR = Modulus of rupture.
UTS = Ultimate tensile stress.

Table 7—Research summary of correlation between nondestructive testing (NDT) parameters and properties of degraded wood[a]

Reference	NDT technique	Material	Degradation agent	NDT parameters measured	Static test	Reported properties	Comparison of NDT parameters and static properties (correlation coefficient, *r*, unless noted)
Wang and others (1970)	Free transverse vibration (cantilever bending)	Small, clear eastern white pine sapwood specimens	Brown-rot fungi (*Poria placenta* Murr.)	Natural frequency	None		Significant loss in frequency as early as 7 days after inoculation
Chudnoff and others (1984)	Longitudinal stress wave (parallel to grain)	Decayed and sound mine props; 26 species or species groupings	—	E_d	Compression parallel to grain	E_c, UCS	E_c and E_d — 0.84–0.97 (all species combined, hardwoods, maple, and oaks). E_c and E_d — 0.73–0.81 (all species combined, southern pines, lodgepole pine). UCS and E_d — 0.85–0.95 (all species combined, hardwoods, maple, and oaks).
Pellerin and others (1985)	Longitudinal stress wave (parallel to grain)	Small, clear southern yellow pine specimens	Brown-rot fungi (*Gloeophyllum trabeum*)	C, E_d	Compression parallel to grain	UCS	UCS and C: 0.47 (controls) 0.73 (exposed) 0.80 (control and exposed) UCS and E_d: 0.86 (controls) 0.86-0.89 (exposed) 0.94 (control and exposed)
			Termites (subterranean)	C, E_d			UCS and C: 0.65 (controls) 0.21 (exposed) 0.28 (control and exposed) UCS and E_d: 0.90 (controls) 0.79 (exposed) 0.80 (control and exposed)

Wilcox (1986)		Small, clear white fir specimens	Brown-rot fungi (*Poria placenta*)	AE	Compression	Stress at various levels	AE events were very sensitive to degree of mass loss and stress level.
Rutherford and others (1987a,b)	Longitudinal stress wave (perpendicular to grain)	Small, clear Douglas-fir specimens	Brown-rot fungi (*Gloeophyllum trabeum*)	C, E_d	Compression perpendicular to grain	E_c, UCS	E_c and C — 0.91 E_c and E_d — 0.94 UCS and C — 0.67–0.70 UCS and E_d — 0.79 UCS and MOE — 0.80
Patton–Mallory and De Groot (1989)	Longitudinal stress wave	Small, clear southern yellow pine specimens	Brown-rot fungi (*Gloeophyllum trabeum*)	C, root mean square voltage frequency content of received signal	Bending	Maximum moment, alkali solubility	C decreased in a linear fashion with increasing decay degradation. Signal strength decreased with increasing decay degradation. High-frequency components of signal were attenuated with very early stages of decay degradation.

[a] AE = Acoustic emission events.
C = Speed of sound.
E_c = Modulus of elasticity obtained from a static compression test.
E_d = Dynamic modulus of elasticity obtained from either transverse vibration or stress wave measurements.
MOE = Modulas of elasticity.
MOR = Modulus of rupture.
UCS = Ultimate compressive stress.

Table 8—Research summary of nondestructive testing (NDT) concepts for in-place evaluation of wood structures[a]

Reference	NDT technique	Type of structure	Location	Material	NDT parameters measured	Analysis performed—conclusions
Lee (1965)	Longitudinal stress wave	Eighteenth century mansion roof	United Kindgom	Solid-sawn timber	C	Developed empirical relationship between speed-of-sound transmission and residual strength.
Hoyle and Pellerin (1978)	Longitudinal stress wave (perpendicular to grain)	School building	Idaho	Curved glulam arches (span 120 ft, rise 33 ft)	C	Detected decay in exposed ends of arches. Mapped out areas of decay.
Lanius and others (1981)	Longitudinal stress wave	Barn	Washington	2- by 12-in. joists	C, E_d	Estimated residual strength of members.
Dunlop (1983)	Acoustic resonance	Wood poles	Australia	Wood utility poles	Resonant frequencies	Test diagnosed large percentage of poles in sample set correctly.
Browne and Kuchar (1985)	Longitudinal stress wave	Dielectric support stand for testing large aircraft in a simulated flight situation	New Mexico	Glulam, structural timbers	C, E_d	MOE determined, strength properties inferred.
Neal (1985)	Longitudinal stress wave (parallel and perpendicular to grain)	Large military test stand (TRESTLE)	New Mexico	Glulam	E_d	Structural framework was not degraded; exposed deck system was degraded.
		Small military test stand	New Mexico	Glulam	E_d	Structural framework and decks were degraded.
		Large military test stand	Arizona	Glulam, solid sawn timber	E_d	Accessible structural degradation had not occurred.
Aggour and others (1986)	Longitudinal stress wave (perdendicular to grain)	Bridge piling	Maryland	Piling	C, density	Correlation of density and C to compressive strength of pile ($r = 0.98$).

(1987)	MOE test			poles		MOE and residual strength of poles ($r = 0.68$).
Hoyle and Rutherford (1987)	Longitudinal stress wave (parallel and perpendicular to grain)	Timber bridges	Northwestern United States	Solid sawn timber	C, E_d	Revealed signs of decay in 1 of 12 bridges; reevaluation every 3 years.
Murphy and others (1987)	Vibration	Wood poles	Western Canada	Wood utility poles (Douglas-fir cedar)	Resonant frequencies	Comparison to pole stiffness ($r = 0.82$).
Anthony and Bodig (1989)	Stress wave	Wood cooling tower, poles	Texas, Western United States	Solid sawn timber, poles	C, δ, phase shifts	Determined rate of strength degradataion.
Pellerin (1989)	Longitudinal stress wave	University foot-ball stadium	Washington	Solid sawn timber	C	Found severe decay degradation; structure was dismantled. substructure collapsed under its own weight.
		Piers	Washington	Large wood beam, stringers supported by wood pilings	C	Replaced structural members containing decay.

[a] C = Speed of sound.
δ = Logarithmic decrement.
E_d = Dynamic modulus of elasticity obtained from either transverse vibration or stress wave measurements.
MOE = Modulus of elasticity.
r = correlation coefficient.
1 ft = 0.3 m, 1 in. = 25.4 mm.

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