Stress Wave Inspection of Bridge Timbers and Decking

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Final Report
July 1987

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in cooperation with the
United States Department of Transportation
Federal Highway Administration

STRESS WAVE INSPECTION

OF

BRIDGE TIMBERS AND DECKING

by

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Bridge Condition Survey Office

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16. Abstract

This report is designed to provide information to guide inspectors of wood highway structures in the use of stress wave inspection technology. It explains the methods and instruments used to measure the velocity of stress waves (sound) in wood. The characteristic behavior of sound waves in wood of various species, moisture content, preservative treatment and infection by wood destroying organisms is described. The important effects of the anatomy of wood and the orientation of grain and annual rings to the wave path are discussed to aid in the interpretation of measurements.

Characteristics of the instrumentation essential to its calibration are explained and instruction is provided in the appropriate use of these tools.

This report has been written to serve as a manual for "on site" stress wave inspection of the kind of wood structures found in highway systems. It is a compendium or experience in the field inspection of many wood buildings and highway bridges.

Original research conducted to fill in voids in the published studies, is described in the Appendices.

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INTRODUCTION

Stress wave velocity measurement has been used for the inspection of wood and concrete structural members over a period of ten or fifteen years in the United States. Its use in concrete inspection was practiced in England, at least on an experimental basis, for a longer period of time. As a research tool, it has been used to measure wood elastic modulus for over twenty years at Washington State University and the U.S. Forest Products Laboratory. A number of consulting engineers in the Pacific Northwest have employed the technique for wood building inspection. Individuals at Colorado State University and the University of Maryland have employed it in the inspection of old buildings, utilities poles, wood piling and glulam structures. Faculty and students at Washington State University have inspected schools, stadiums and bridges for practical decisions on replacement versus repair over a period of ten years.

A stress wave is a disturbance of the particles of matter in a piece of material. This disturbance is propagated through the material at a velocity related to the elastic modulus and density of the material. The disturbance can be caused by a blow or impact. The velocity can be determined by measuring the time for the disturbance to travel a known path length. The velocity in undecayed wood of any species can be computed on the basis of its density and elastic character. Measured velocities in a structure that differ substantially from the theoretically appropriate velocity are evidence of possible deterioration of the wood. This takes the form of decay or insect damage, or internal checking due to seasoning processes.

The interpretation of the measurements is a crucial aspect of stress wave inspection. High travel time or, stated another way, low velocity, is a signal to expect some type of deterioration. The interpretation involves a fairly good conception of the anatomy and mechanical properties of wood on the part of the inspector. It is also important to visualize the stress wave phenomena correctly and to understand the influence of environmental variables and physical and geometric features of the structure being inspected.

The operating principles of the measuring equipment must be clear to the user. A "black box" concept is unacceptable for effective use of the stress wave velocity technique. No mystery need, or should, prevail.

Although this method has been in use for a number of years, very little in the way of an explanatory treatment of the subject has been collectively presented. It is the object of this study to gather together as much information as possible, to explore areas where relationships have been less than clear, and to expand the investigators' experience that they might offer guidance to others who care to employ the stress wave method.

Stress wave inspection is just another tool for the knowledgeable inspector. It is a means of probing the interior of timber members nondestructively, rapidly, and with simple lightweight and portable instruments. It quantifies wood properties that have been traditionally sensed by audible sound, hardness or resilience, color, texture and moisture content. The method may have its greatest value in identifying undecayed parts of the structure and concentrating the inspectors attention on suspect areas where he may still employ traditional methods of evaluation (taking cores or plugs, boring holes to sense resistance or to examine the condition of chips, or use of picks).

Experience has proven that stress wave inspection is useful in determining the extent of deterioration or the absence thereof, in such a manner as to avoid sweeping condemnation of a structure with limited actual amounts of decay, thus minimizing the extent and cost of unnecessary replacement.

STRESS WAVE TIMER AND TIMER CHARACTERISTICS

An impact upon a piece of material imparts motion to the particles of wood at the point of impact. This stimulates the adjacent particles to motion and this disturbance travels in the direction of motion along the length of the piece. When it reaches the end it is reflected back toward the source of the disturbance.

The form of this disturbance can be quite varied, depending on the shape of the impactor, the energy it imparts to the piece of material and the properties of the material itself. The speed at which the disturbance travels is a function of the material's elastic properties and its density, according to the relationship:

$$V = \sqrt{\frac{E_D\, g}{\rho}} \quad \text{inches/sec} \qquad [1]$$

where E_D = dynamic elastic modulus of the material in psi

ρ = density in lbs/in^3

g = acceleration of gravity in $inches/second^2$, 386.4

The dynamic elastic modulus is slightly larger than the value obtained by static testing, since the static test value is based on stress at some arbitrarily chosen strain, at a lower rate of loading than is the case for a dynamic test. This is related to the materials creep properties, since the shape of the stress-strain curve below the elastic limit is dependent on the rate of loading and the material's creep properties (see Figure 1). In this discussion the ratio of dynamic to static modulus is 1.06 for compression and 1.16 for flexural elastic modulus. This is mentioned in Appendix A.

Typical values of stress wave velocity in various materials of good quality, computed from equation [1] are given in Table 1.

DETERMINING STRESS WAVE VELOCITY

The most direct method of determining the stress wave velocity is to time the wave as it moves a measured distance through the material. Accelerometers are used for sensing the stress wave as it starts at one point and arrives at another. The timer displays time in microseconds (millionths of a second). The stress wave velocity is then calculated as:

$$V = \frac{1000\ L}{t}\ \text{inches/millisecond (in/ms)} \qquad [2]$$

where L is the path length in inches and t, the time in microseconds.

The method employs two accelerometers, one to start the timer and the other to stop it. The accelerometers may be placed on the material at a measured spacing, L, to obtain the wave transit time between them. This is shown in Figure 2. This accelerometer arrangement is employed with the Metriguard 239A Stress Wave Timer and is useful in laboratory work, or for industrial applications for measuring stress wave velocity in pieces of discrete length or width. It is not the preferred method for field inspection of highway structures. Instead, an impact tool or hammer with a START accelerometer built into the hammer head has proven more convenient, combining the function of the pendulum in Figure 2 and the START accelerometer. The

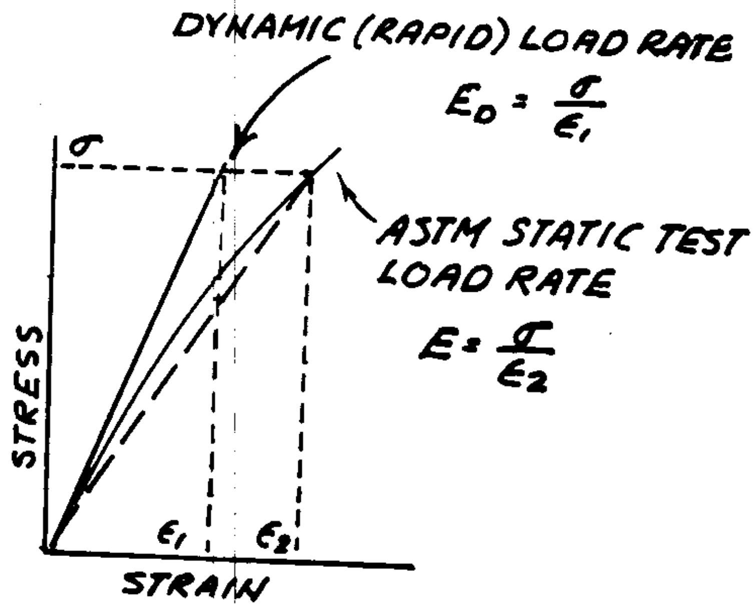


Figure 1. Static and Dynamic Elastic Modulus

Table 1. Typical Stress Wave Velocity Values for Several Materials

Material	Stress Wave Velocity (inches/millisecond)		
Wood, longitudinal:			
Douglas-fir, dry	208		
Douglas-fir, wet	182		
Loblolly pine, dry	198		
Loblolly pine, wet	176		
Wood, transverse:	Radial	Tang.	45°
Douglas-fir, dry	54	44	20
Douglas-fir, wet	48	38	17
Loblolly pine, dry	54	44	20
Loblolly pine, wet	48	40	18
Steel	196		
Aluminum	209		
Concrete:			
2500 psi	128		
3500 psi	139		
4500 psi	148		
8000 psi	171		
Air*	13		

*Equation [1] does not apply to fluids.

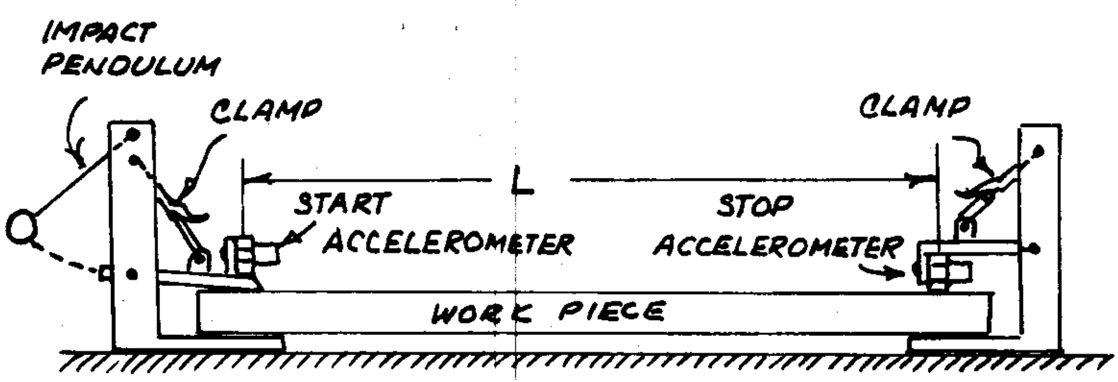


Figure 2. Laboratory Testing Arrangement

STOP accelerometer may be clamped to the member or hand held using a grip as shown in Figure 3. The accelerometer must be aligned in the direction of the wave path and has a front end which must face the source of the wave.

The arrangement shown in Figure 3 is highly practical for the inspector, most of whose work will be taking readings in the transverse, across-the-grain, direction whether the material be rectangular beams and columns, decking, or round poles and piling.

Another instrument which is often used for stress wave measurement is the James V-Meter. It employs two accelerometers as does the timer shown in Figure 4, but they are somewhat larger. Instead of a pendulum or hammer impactor, the James equipment has a piezoelectric crystal built into one of the accelerometer cases. This crystal can be electrically actuated to cause an impulse and actuate the START accelerometer. These accelerometers are applied to the wood on their broad flat faces. In the form in which they are currently available, they are difficult to align with the stress wave. The broad flat face may not couple well to wood surfaces unless a grease is used to improve the contact. But with some attention to these design problems the equipment should be able to serve the purpose well. Some good research has been reported using the James V-Meter.

ADJUSTING THE GAIN SETTING

The accuracy of the timer reading depends on the GAIN setting of the timer. An explanation is offered. An accelerometer placed in contact with a material, senses the acceleration of the particles in contact with it. Accelerometers are constructed to sense accelerations above some minimum value. Lower accelerations will not affect them.

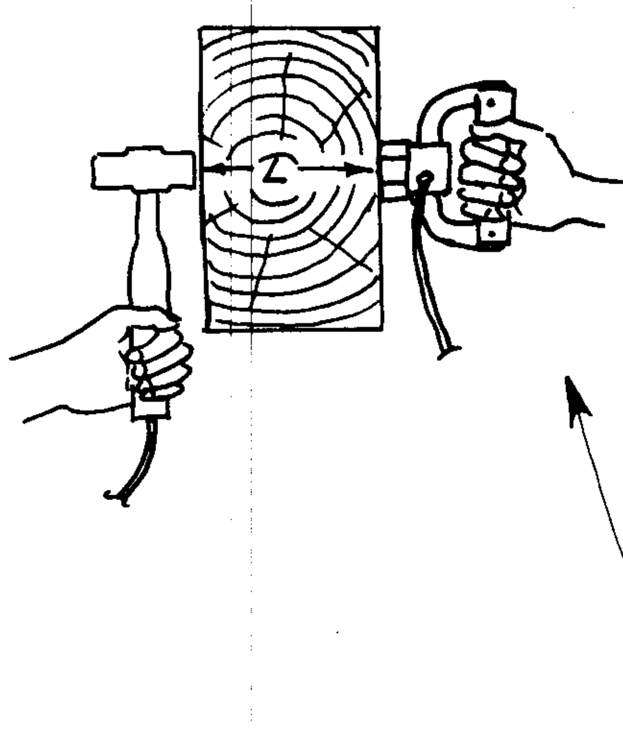


Figure 3. Field Inspection Tools

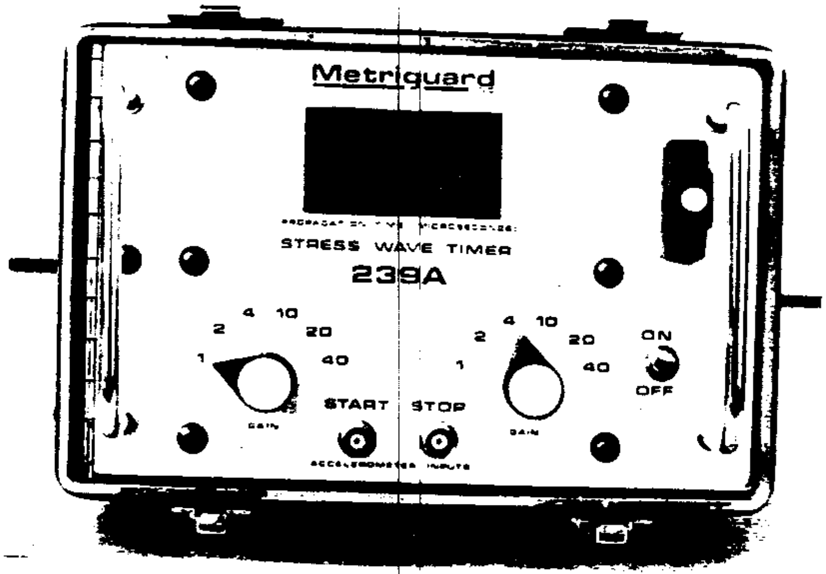


Figure 4. Stress Wave Timer

Stress waves attenuate (diminish in amplitude, or dampen) as they are propagated through a material. Over a sufficiently long path of travel a stress wave may attenuate so much that it fails to activate the stop timer, i.e., the accelerometer may not sense it. The sensitivity of the accelerometer to the wave can be increased by adjusting the GAIN settings on the instrument. Increasing the GAIN lowers the acceleration level that will start the timer. An appropriate timer setting is necessary, not only to trigger the STOP accelerometer, but to do so at the same point on the wave front that sets off the START accelerometer.

The effect of the GAIN setting is shown in Figure 5 which is based on studies made as a part of this project. For short travel paths the measured stress wave velocity appears to differ from that for longer paths in the same material, unless the STOP accelerometer gain was set at some optimum level. In most inspection work the path length has been less than 20 inches so a very substantial error can occur with improper gain setting. The reason for this has been explained by Metriguard engineers, who had encountered the same phenomenon in other applications.

The stress wave particle acceleration has a form somewhat as shown in Figure 6. The particle velocity at any point rises at an increasing rate to a maximum, then falls off at a decreasing rate to zero, as the wave moves past the point. The slope of the curve is the particle acceleration.

Figure 6 shows particle velocity versus time after the disturbance begins. The solid curve is for a point near the impacted end where the disturbance is strong. The dashed curve is for a point farther along the wave path where the disturbance is weaker. In this figure it has been attenuated 50%.

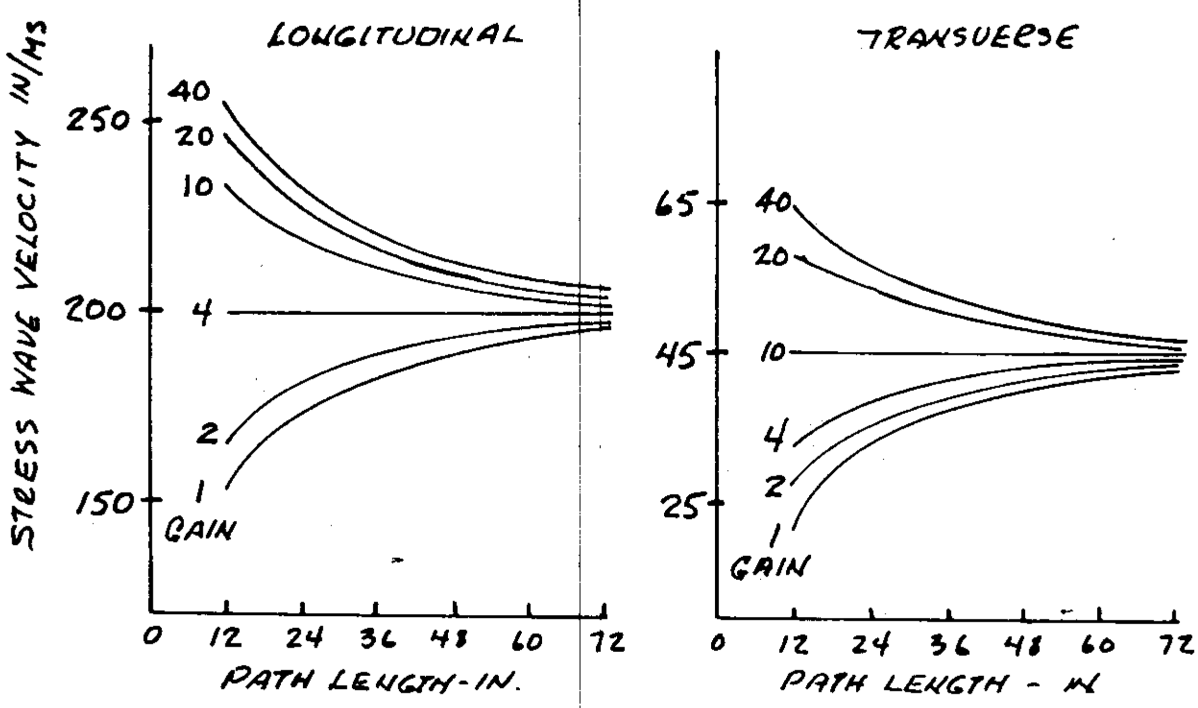


Figure 5. Effect of Gain Setting and Path Length on Stress Wave Velocity

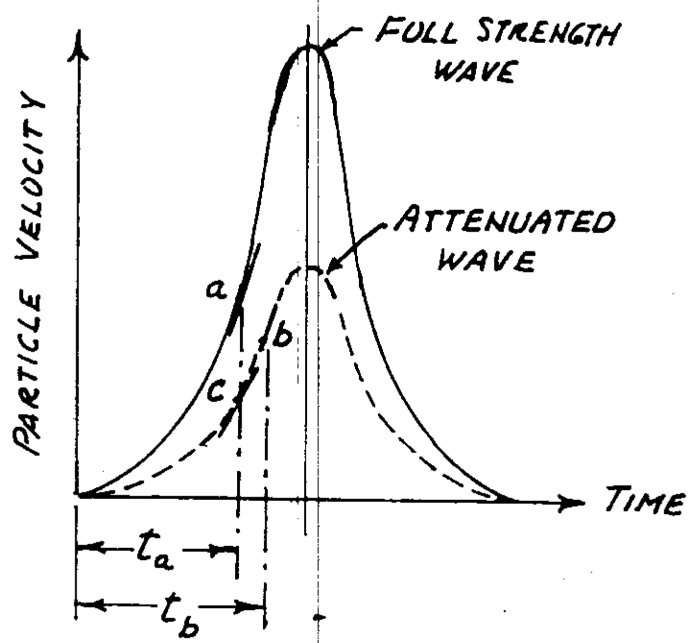


Figure 6. Particle Velocity vs. Time for Full Strength and Attentuated Wave

At "a" and "b" the slopes of the curves are equal, but "a" occurs at time "t_a" after the wave reaches the START accelerometer and "b" occurs at time "t_b" after the wave reaches the STOP accelerometer position.

If the gain settings of both accelerometer circuits are the same, the timer will measure a travel time which errs on the high side by the time $t_b - t_a$. This leads to a reduced apparent stress wave speed.

If the gain of the STOP accelerometer was set at "2" (see Figure 4) then half the acceleration required at a setting of "1" would trigger the timer. In Figure 6, where the attenuation was 50%, the acceleration (slope of the dashed line) at "c" would be half that at "a" and the gain of "2" would amplify this signal to actuate the STOP timer. This would occur at $t_c = t_a$. No error would occur. While this is an idealized illustration, it describes the principle. The attenuation shown here is larger than would usually occur.

As the path is lengthened the time error becomes a smaller and smaller percentage of the total travel time which explains the leveling off of the curves in Figure 5. For the longitudinal stress wave velocity curve in Figure 5 a gain setting of "4" was suitable. In the case of the transverse wave path a gain setting of "10" on the STOP accelerometer was best.

An inspector is usually concerned with transverse travel paths of less than 20 inches, so proper gain settings are desirable, and the value shown is approximately correct.

The intensity of the impact is not critical because the attenuation for a particular material is a percentage of the amplitude, regardless of the initial amplitude or intensity of the impact (of course the impact must be sufficient to deliver a measurable signal at the STOP accelerometer, but beyond this minimum level the intensity is not critical).

The timer gain can be calibrated by measuring the time for successively greater path lengths and plotting them as in the example, Figure 7. A gain setting that produces a line passing through the origin is the correct one. If the choice of available gain settings does not give a curve that passes through the origin then a time correction can be make by subtracting the amount of the y-intercept from the observed readings. In the case of the lower curve this would be minus -13, or add 13.

The Metriguard Stress Wave Timer will display a black dot for the triggering of either accelerometer (one dot for the START and another for the STOP accelerometer). If these black dots fail to appear the accelerometer is not being triggered. Either the wave has been attenuated too much, and a stronger impact is necessary; or there may be an open circuit in the cables or their connectors. A light flick of the fingernail on the front end of the accelerometer can be applied to test the accelerometer.

For inspection work sturdy cables and connectors are required. It is easy to accidentally step on the cables, kink them, or stretch them and care should be taken to avoid this. We had some trouble, initially, with light cables, but these were replaced by stronger ones and no further problems were encountered during an entire season of field work.

If moisture enters the timer it may affect the circuits. In one instance, using the equipment in inclement weather, this occurred. We placed the timer in an oven for about an hour at 150°F, which drove off the moisture and eliminated the problem.

It is inconvenient to calibrate the instruments in the field. It is recommended that calibration work be done in the shop or lab. Some practice doing this will set up some target values for appropriate gain settings.

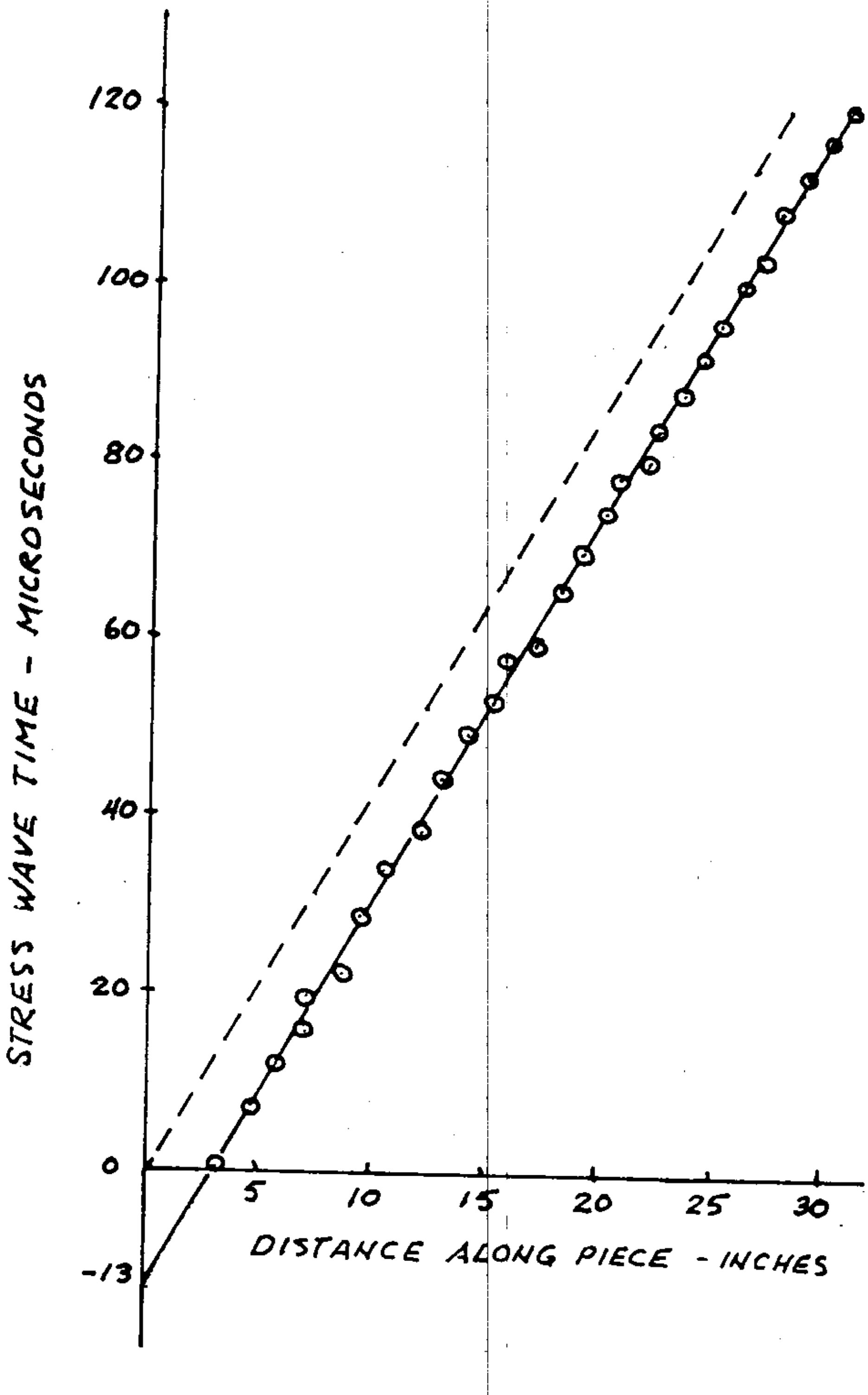


Figure 7. Zero Offset

When inspecting a structure with many equal thickness members, the existence of a gain setting error will not be a serious problem, since all readings will be for equal travel paths. The velocity in good undecayed wood may differ slightly from the theoretical value discussed in Appendix A and shown in Table 1, but the degrading effect of decay (Appendix E) will still be evident.

It is not necessary to clamp the STOP accelerometer to the member. Firm pressure against the member will establish a good contact. Even roughly sawn timbers can be coupled to the accelerometer with firm pressure. Old members are often coated with dirt or a mixture of dirt and wood preserving fluid. A wire brush, a scraper, or a wide putty knife is useful in cleaning off this accumulation.

It is sometimes convenient to clamp the STOP accelerometer to the member, especially if there is insufficient space behind the member to use the hand grip mounted accelerometer, or if an inspector must work alone. It is not practical for one person to hold the STOP accelerometer firmly against the beam while wielding the hammer on the opposite side, except for very thin easily accessible members, such as small columns.

A roundhead screw and a lock washer in the threaded hole in the front of the STOP accelerometer improves the contact and coupling. The screw should be short enough that it does not bear on the bottom of this threaded hole. If that should happen, the accelerometer may be damaged. This screw helps because it is difficult to hold the flat face of an accelerometer square with a flat surface or on an irregular round pole or piling surface.

TOOLS AND INSTRUMENTS

TIMER

The stress wave timer used in this work is the Metriguard 239A Stress Wave Timer. It is shown in Figure 4. It weighs about five pounds and is powered by one 9 volt battery. It displays the time in microseconds (millionths of a second) between actuations of the "start" and "stop" accelerometers, which are connected to it by cables. To check the functioning of the accelerometers, the display includes two black dots which appear when an accelerometer triggers the timer. One dot is for each accelerometer. Should either of these fail to appear on the display the accelerometer or its cable are not functioning correctly. A light tap on the front end of an accelerometer will actuate it for purposes of circuit checking.

Gain control switches are mounted on the timer panel. The numbers are gain multipliers, which indicate the reduction in threshold voltage needed to actuate the timer. At a gain setting of "2" the timer will recognize an accelerometer signal of half the amount it will recognize if the gain was set at "1." Thus "gain" increases timer sensitivity to accelerometer signal. The selection of an appropriate gain setting is discussed in the preceding section on Stress Wave Timer and Timer Characteristics.

As noted in the previous section, the timer should be protected for the entry of moisture into the instrument casing. Since it may be exposed to rain in routine use, suitable gaskets around all openings in the case are desirable.

ACCELEROMETERS

An accelerometer is a piezoelectric device which is very sensitive to acceleration. The two types used in this work are shown in Figure 8. The larger one (manufactured by Metriguard) has proven very acceptable for field work. The smaller one (manufactured by Columbia and supplied by Metriguard) has been useful in laboratory work. Either type may be used with the timer in Figure 4. If desired, one type can be used for the "start" function and the other for the "stop" function, but usually pairs of accelerometers of the same type are used together.

These devices should be treated with care. They are reasonably sturdy, but abuse could damage them. When they are placed firmly in contact with a piece of wood they will sense the passage of a stress wave.

In field inspection work it is convenient to have one accelerometer mounted in or on the hammer used to produce the stress wave. Figure 9A shows an impacting hammer with the larger type of accelerometer mounted inside the head. It is a very rugged tool with a padded handle to reduce mechanical shock to the operator.

Figure 9B is a common ball peen machinists hammer with the small Columbia accelerometer mounted on one side by means of a steel angle bracket welded to the hammer head. The wiring is external, running alongside the wood handle and taped to the handle. While we have used this extensively in field work, the exposed external mounting is more susceptible to abuse and has

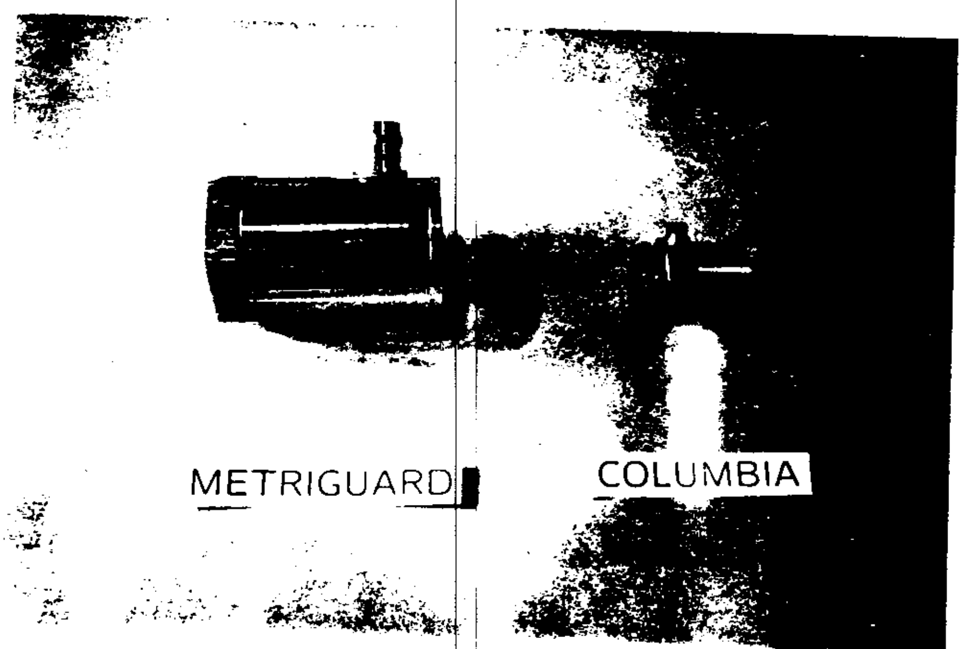
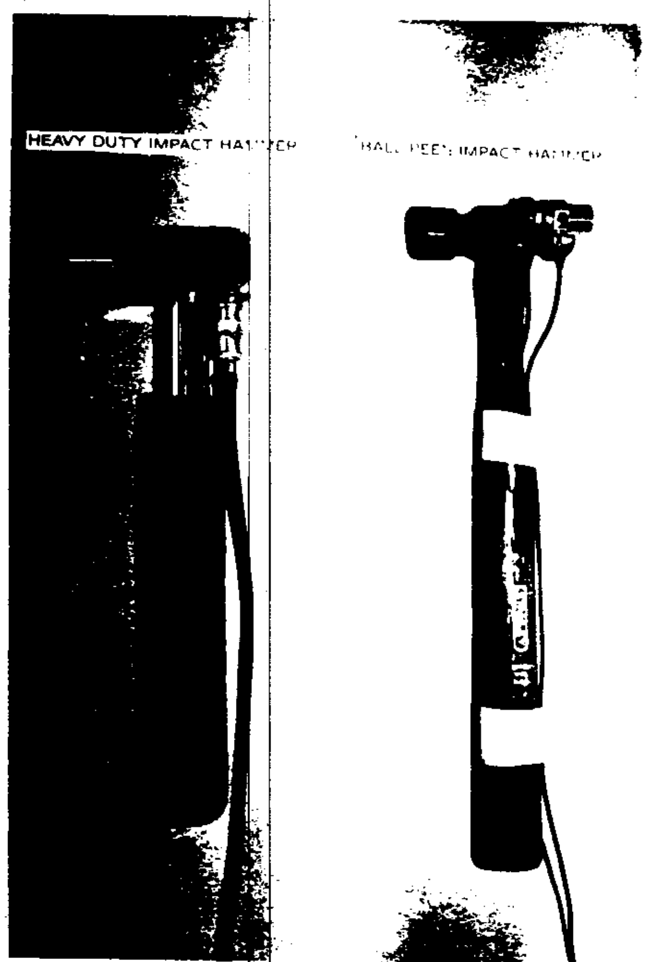


Figure 8. Accelerometers



(A) (B)

Figure 9. Impacting Hammers with Start Accelerometers

occasionally been damaged. With extended use the angle bracket may become deformed and the wiring may creep around the handle underneath the tape. The heavier type (A) of impacting hammer is generally more satisfactory.

Note that the front of the accelerometer faces the direction of the hammer face. When the blow is struck a stress wave travels back through the steel head to the accelerometer. The error induced by this small travel time through the hammer head is very small.

The "stop" accelerometer is held firmly against the material being inspected. Figure 10 shows hand grips with "stop" accelerometers of the large type (A) and of the small type (B). Both of these have been effective but type (A) is preferred for sturdiness. Problems, should they occur, are usually in the cable connections.

Figure 11 shows one of the small accelerometers fitted with an adjustable bar clamp. This is used to attach a "stop" accelerometer to a member at a location where space may not permit using the hand grip units shown in Figure 10.

An accelerometer mounting device for measuring stress wave time in flat panels is shown in Figure 12. The serpentine steel structure must be long enough so the travel time through the steel, from the pendulum end where the "start" accelerometer is mounted, to the "stop" accelerometer, exceeds the time for the wave to travel directly through the wood from the anvil to the "stop" accelerometer.

Table 1 gives a steel stress wave velocity of 196 in/ms. Velocity parallel-to-grain in undecayed wood is almost the same. In decayed wood it is about 66 in/ms. So, the serpentine path through the steel should be about three or four times that through the wood, if the tool is to measure the

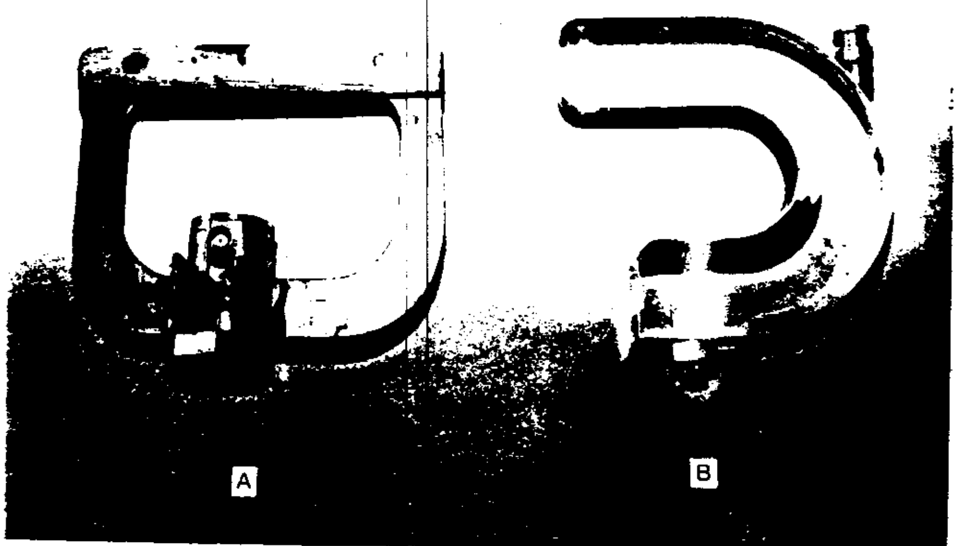


Figure 10. Stop Accelerometers with Handgrips

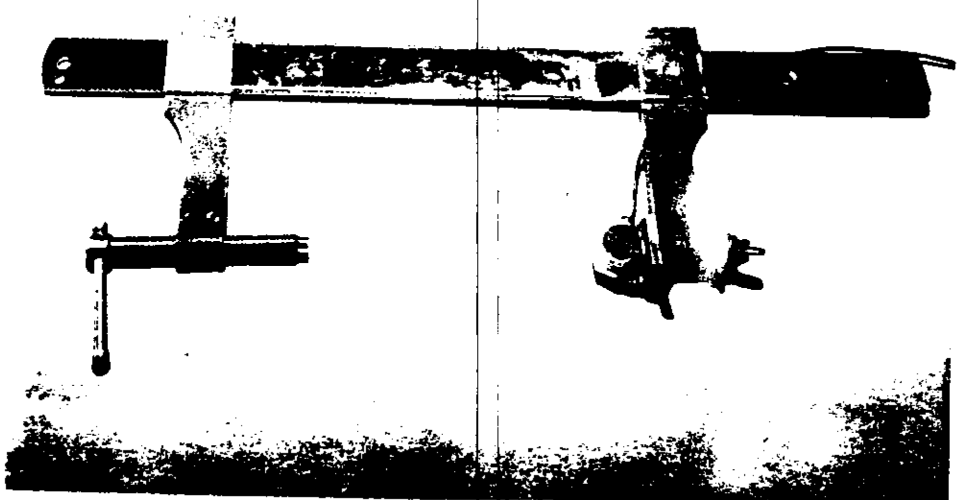


Figure 11. Stop Accelerometer with Adjustable Clamp

Figure 12. Serpentine Accelerometer Frame

velocity in decayed wood. As shown in Figure 12 the path length in the steel is adequate.

Velocity perpendicular to grain is about 53 in/ms in sound wood and possibly as low as 17 in/ms in decayed wood. To use this device for transverse stress wave measurements to find decay, the path through the steel should be about twelve times as long as through the wood (i.e., 196/17).

The frame could be modified to obtain this extra length. Another way of increasing the travel time through the frame is to insert some high impedance shim of a material such as a silicone rubber or other similar material.

A device of this type would be useful in measuring the stress wave velocity, or time, in the transverse direction in decking which can only be reached from the lower face. A hammer might be used in lieu of the pendulum in such a tool.

OTHER USEFUL TOOLS

Wire brushes, scrapers and stiff putty knives are helpful in cleaning off dirt that have accumulated on timber surfaces. Wire brushing rough lumber is sometimes useful to obtain good accelerometer coupling, and to make the grain of the wood more visible.

Increment core borers are useful in probing timber areas where the stress wave results imply decay with marginal time or velocity determinations. Plug cutters have also been used to obtain samples. Augers can be used to obtain chips or to sense decay by observing the resistance to drilling as the auger penetrates. These tools are all well known to the bridge inspector.

Metriguard Inc. has a circuit checker which can be used for trouble-shooting cable and accelerometer malfunctions. We found this useful when we were using the small accelerometers in the field, but it has never been needed when the large accelerometers were used.

WOOD AS A STRESS WAVE MEDIUM

In this section of the report we wish to discuss stress wave behavior in wood, to help the inspector interpret readings. The appendices discuss the background in greater detail. They may be studied to enlarge upon the summarized discussion in this section.

UNDECAYED AND UNTREATED WOOD

Theoretical and measured stress wave velocities in sound wood have shown very good agreement. Theoretical velocity information is developed in some detail in Appendix A.

Longitudinal Wave Travel

Waves traveling parallel to the grain (fibers), i.e., longitudinally, have velocities of about 227 in/ms for completely dry wood, 200 in/ms in wood at 12% moisture content, and 174 in/ms at the fiber saturation point (FSP). FSP is usually in the range of 21% to 30%, according to Table A1.

These values are not greatly affected by species, being ±10% for most. They are fairly typical for the Douglas-fir and southern pine most commonly used in bridge construction.

While it is generally conceded that moisture in excess of fiber saturation has no effect on mechanical properties, there is a small decrease in stress wave velocity at these higher moisture contents. This is believed to be a dynamic effect which appears because the high particle velocities and wave propagation rates are affected by the mass of the free water in the cell cavities. The stress wave velocity decreases as moisture rises, to about 0.9 times the FSP velocity at 80% to 100% moisture content.

In above-ground bridge structures such high moisture content would be unusual. In piling, underwater or near the water line velocities in undecayed wood of 90% of the FSP velocities could be expected. See Appendix C for further discussion.

Transverse Wave Travel

Velocities in either the radial or tangential directions are about one-fourth to one-fifth of those obtained along the grain. Velocities in the radial direction exceed those tangentially by about 25%.

Poles and piling are commonly inspected by passing the stress wave transversely through the diameter. In a solid pole this path is perpendicular to the annual rings (radial direction) and the undecayed wood velocities are about 55 in/ms at 12% moisture content, 48 in/ms at FSP, and possibly 42 in/ms at 80% moisture content or more.

In solid timbers of good quality the shortest transverse wave path may be either radial or tangential, or some intermediate direction, depending on how the member has been sawed with regard to the pith (tree center).

Figure 13 shows possible paths in a pith center (boxed-heart) timber. It may be difficult to know what velocity to expect for paths that do not pass through a pith center, or are not clearly tangent to the annual rings.

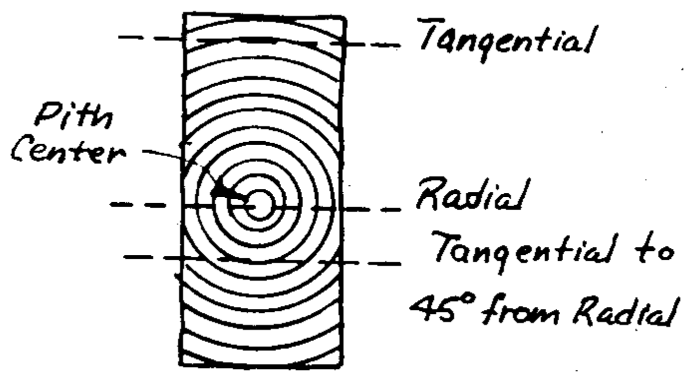


Figure 13. Transverse Stress Wave Paths Through a Rectangular Member

Our own work and that or others shows that the velocity along a path through the wood which intersects the annual rings at 45° is lower than the tangential value, and not at an average of the radial and tangential values (see Figure B7). The velocity through such material may be as low as half that in the tangential direction. So, for timbers, velocities of 30 in/ms at 12% and 24 in/ms at FSP, may occur in perfectly sound wood.

This leads to quite a lot of variation in transverse wave times in sawn timbers. However, as will be mentioned later, serious decay will result in even lower velocities.

The inspector should watch the annual ring orientation and relate it to the measured stress wave time, to interpret readings in sawn timbers and glulam beams.

Table 2 gives stress wave times versus path lengths for undecayed wood in the longitudinal and transverse directions at 12% moisture content. The larger transverse times will seldom be needed, except possibly in deck inspection--certainly not for pole or stringer inspection.

TREATED WOOD

The transverse stress wave velocity in Douglas-fir, completely penetrated with creosote or Penta-in-oil, is about 65% of that (53 in/ms) in untreated wood. This is the velocity to be expected near the ends of untreated poles or timbers. For Douglas-fir or southern pine, the radial velocity in completely penetrated treated wood will, therefore, be about 35 in/ms.

The transverse velocity through a treated pole can be estimated by the following formula (see Appendix F):

$$V = \frac{D}{0.0194t + 0.0189D} \qquad [2]$$

Table 2. Stress Wave Time in Microseconds in Undecayed Douglas-fir at 12% Moisture Content

Path Length inches	Longitudinal @ 200 in/ms	Transverse		
		Radial @ 55 in/ms	Tangential @ 44 in/ms	45° @ 20 in/ms
5	25	91	113	251
10	50	182	227	500
15	75	272	341	750
20	100	364	454	1001
30	150	545	682	1500
40	200	727	909	2000
50	250	909	1136	2501
60	300	1091	1363	3000
70	350	1273	1590	3500
80	400	1455	1817	4001
90	450	1636	2045	4500
100	500	1818	2273	5000

where D = diameter in inches

t = penetration of preservative in inches

Table 3 gives estimated velocities for poles of different diameters and penetration depths, based on an untreated wood velocity of 53 in/ms and a treated wood velocity of 35 in/ms.

These estimates imply greater precision that is actually justifiable, but they do show that the effect of treatment for penetrations typical of Douglas-fir poles, is not great. The conclusion is that treatment only reduces the velocity in undecayed poles by 4% to 8% and can be ignored for all practical purposes, in pole inspection.

The effect of treatment of Douglas-fir timbers is generally not more than a 10% reduction in stress wave velocity, except at ends where full penetration of the treating fluid causes a reduction of 35%.

Dip treatments in Penta-in-oil cause less than 10% reduction in the stress wave velocity, in most cases considerably less than 10%.

We do not have data for the effect of water-borne salt treatments. The salt treatments do not materially affect the mechanical properties of the wood, and since the moisture is largely lost upon redrying after treatment, we believe the effect of these treatments on stress wave velocity, is negligible.

DECAYED WOOD

Decay in wood causes a loss of weight and a loss of strength and stiffness (elasticity). As decay proceeds in the interior portion of a timber or pole with a dry or treated exterior shell, a void may be left in the center of the pole. However, long before the void develops, the effect of decay on the elastic properties of the wood will manifest itself as a markedly reduced stress wave velocity. Equation [1] states:

Table 3. Estimated Transverse Stress Wave Velocity for Douglas-fir Poles at Locations Away from End Penetration Effects for Various Penetrations of Penta in Oil or Creosote

Diameter	Penetration in Inches		
	1	1½	2
10	47.5	45.5	43.5
12	48.2	46.4	44.8
14	48.7	47.1	45.7
16	49.1	47.7	46.4
18	49.4	48.2	47.0
20	49.7	48.5	47.5
22	49.9	48.8	47.9
24	50.1	49.1	48.2

$$V = \sqrt{\frac{E_D\, g}{\rho}}$$

If E_D and ρ remained proportional, one to the other, V would be unchanged by decay, but they do not remain proportional. The dynamic or static elastic moduli are degraded much more rapidly than the density. This is illustrated in Tables E1 and E4. The longitudinal velocity decreased 29% with very little weight loss. The accompanying loss in dynamic elastic modulus was about 50% and the strength loss about 30%. A 56% velocity loss was associated with a 27% weight loss, an 86% loss in dynamic elastic modulus, and over a 99% strength loss. A 70% velocity loss was associated with a 57% weight loss, a 99.5% loss in dynamic elastic modulus, and over 99% strength loss.

Also in Table E5 for transverse stress waves in southern pine, one observes a 49% velocity loss associated with a 53% loss in dynamic modulus of elasticity and a 50% strength loss. For small specimens, which could be weighed, a 56% velocity loss was associated with a 63% loss in dynamic elastic modulus and 79% strength loss, with a 50% weight loss. An 11% velocity loss was associated with a 30% loss in E_D and a 29% strength loss.

Either longitudinal or transverse stress wave measurements will detect decay. Velocities which are half those of sound wood imply very extensive decay. Velocities which are 75% of sound wood values signify harmful decay. Usually a timber does not decay uniformly throughout its volume. Measurements at different locations will provide contrasting sound wood and decayed wood signals.

The transverse stress wave readings are most useful in identifying decayed areas because if decay is present at all, it is likely to occupy a substantial portion of the total stress wave path.

Longitudinal paths can be long and decayed regions may cover a large part of the cross-section, but a relatively small portion of the total path length. If longitudinal measurements are made, they should be made over successive short increments so the decay effects will be prominent.

TERMITE DAMAGED WOOD

Termites can produce considerable damage in wood without producing a detectable reduction in longitudinal stress wave velocity.

In the case of transverse stress waves, termite damage has been observed to cause a pronounced loss in stress wave velocity. This may be due, in large part, to the destruction of the shortest path between accelerometers, and diversion of the route through a longer path, with attendant "apparent decreased velocity."

Usually termite damage and decay coexist in actual structures, if they are present at all, whereas in laboratory infected specimens the termite damage may not be accompanied by decay damage.

Some additional study of the effect of termite damage on transverse stress wave velocity would be very desirable.

Termites occur in the Northwest, but are not the scourge they present in more southerly regions.

Table E1 provides some termite damage data. Figure E5 contains some observations on carpenter ant damage.

TEMPERATURE EFFECTS

Temperature affects the elastic properties of wood. The effect is quite small. Table C1 and Figures C1 and C2 provide some direct illustrations of the effect.

In dry wood a 200°F temperature increase results in a 14% loss of elastic modulus and 6% loss in stress wave velocity.

In wet wood the loss in elastic modulus is 25% with an accompanying 14% loss in velocity for the same 200°F temperature change.

The velocity versus temperature relationship is nearly linear. An inspector would not need to be concerned with temperature affecting the measurements in the range of zero to 100°F at usual wood moisture contents in highway structures.

Table C2 provides adjustment factors that combine the effects of temperature and moisture content.

ESTIMATING STRESS WAVE VELOCITIES

Most highway structures are treated with either Penta-in-oil or creosote. In the Pacific Northwest they are also usually Douglas-fir or possibly western red cedar (for piling). Stringers and decking will be Douglas-fir.

Round Members

Treated poles have a shell of preservatively treated material about 1 to 1½-inch thick, which will not decay. Decay, should it occur, will be in the untreated core. The expected velocity of a stress wave passing transversely through a treated pole can be estimated for a variety of assumed conditions.

Case 1. Determine the stress wave velocity for a treated Douglas-fir pole, 14 inches in diameter, with one inch of treatment penetration. Assume there is no decay and the moisture content in the above-ground portion of the pole is 16% to 18%.

Referring to Figure 14, the stress wave path is radial. The velocity in the treated part is about 35 in/ms and 53 in/ms in the untreated part. By

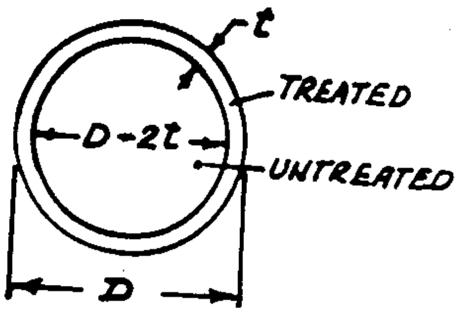


Figure 14. Case I: Velocity and Time for a Treated Wood Pole Without Decay

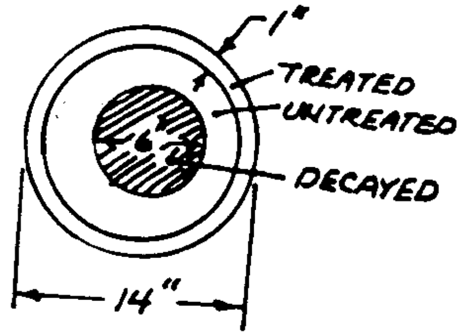


Figure 15. Case II: Velocity and Time for a Treated Wood Pole With Moderate Decay

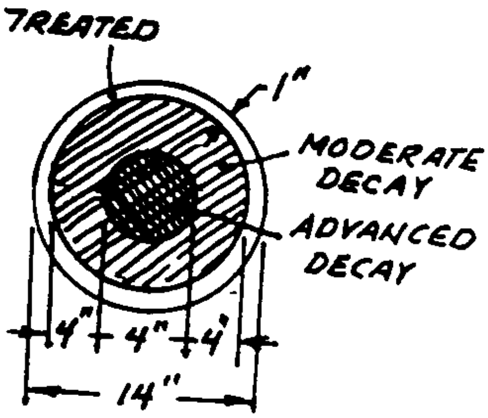


Figure 16. Case III: Velocity and Time for a Treated Wood Pole With Advanced Decay

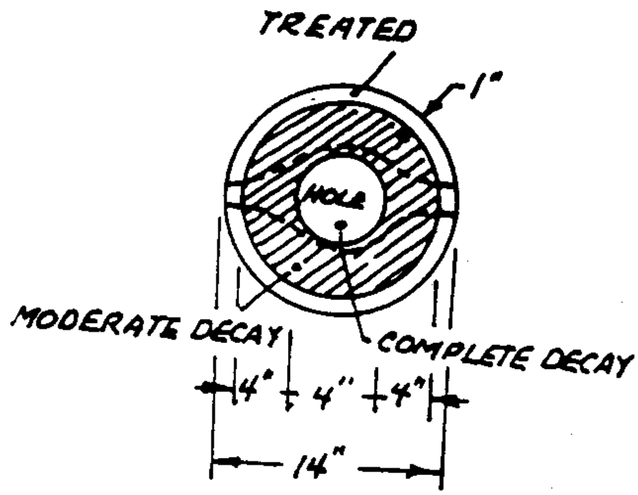


Figure 17. Case IV: Velocity and Time for a Treated Wood Pole With a Decayed Void in the Core

equating the total travel time through the treated and untreated parts to that through each of these parts, separately, an equation can be written which may be solved for the expected stress wave velocity.

$$\frac{D}{V_a} = \frac{2t}{V_t} + \frac{D - 2t}{V_u} \qquad [3]$$

where V_a = average stress wave velocity through the pole, in/ms

V_t = stress wave velocity in the treated shell = 35 in/ms

V_u = stress wave velocity in the untreated core = 53 in/ms

D = diameter in inches = 14

t = preservative peretration in inches = 1

$$\frac{D}{V_a} = 0.0571t + 0.0189D - 0.0377t$$

$$V_a = \frac{D}{0.0194t + 0.0189D}$$

For this problem, V_a will be 49.3 in/ms and the expected timer reading will be 284 microseconds.

Case 2. Determine the stress wave velocity if the pole in Case 1 was moderately decayed, so the velocity in the central decayed region was half the velocity in sound wood and the inner six inches of the pole's diameter was affected, as shown is Figure 15.

$$\frac{14}{V_a} = \frac{2}{V_t} + \frac{6}{V_u} + \frac{6}{0.5V_u} = \frac{2}{35} + \frac{6}{53} + \frac{6}{26.5}$$

$$V_a = 35.3 \text{ in/ms}$$

The expected reading of the timer would be 398 microseconds.

Case 3. Determine the stress wave velocity if the pole in Case 2 was more severely decayed, such that the velocity in the center four inches was 20% of that in sound wood and the velocity in the part between the treated shell and this severely decayed core was 45% of V_u. This is illustrated in Figure 16.

$$\frac{14}{V_a} = \frac{2}{V_t} + \frac{8}{0.45V_u} + \frac{4}{0.2V_u} = \frac{2}{35} + \frac{8}{23.85} + \frac{4}{10.6}$$

$$V_a = 17.6 \text{ in/ms}$$

The expected timer reading would be 795 microseconds.

These three cases show how the decay produces large changes in stress wave velocity and very noticeable increases in timer readings.

It is not likely that an inspector will make calculations like this. Possibly, after an inspection, when some timer readings are available, he might find these calculations useful in helping with the interpretation.

Case 4. Sometimes advanced decay leaves a hole in the untreated core which can not propagate a stress wave. Assuming the central four inches of the pole in Case 3 was void, what would the stress wave velocity and time be?

Figure 17 illustrates the conditions. The stress wave would follow a path around the hole. The shell distance will still be be about 2 inches. The path through the decayed wood is about 12.6 inches. One could assume that one third of this 12.6 inch path would be through decayed wood nearly perpendicular to the annual rings, one-third through decayed wood at about 45° to the annual rings and one-third though decayed wood about tangential to the annual rings.

For undecayed wood we assume:

V_u in the radial direction is 52 in/ms

V_u at 45° to radial is 19 in/ms

V_u in the tangential direction is 41 in/ms

For decayed wood use 45% of these values.

$$\frac{14}{V_a} = \frac{2}{35} + \frac{4.2}{23} + \frac{4.2}{8.6} + \frac{4.2}{18.4}$$

$$V_a = 14.7 \text{ in/ms}$$

The expected timer reading, in this case is 953 microseconds.

These calculations for round members are fairly uncomplicated because the angle of path to the plane of the annual rings is usually 90°. In sawn timbers and glulam beams this will not so often be the case.

Rectangular Members

Bridge stringers are rectangular members of solid sawn Douglas-fir, treated with creosote or Penta-in-oil. They are 5 to 6 inches wide by 15 to 19 inches deep. Occasionally wider stringers are used. Solid sawn stringers are usually cut with annual rings as shown in Figure 18.

It is usually convenient to pass the stress wave through these stringers transversely and horizontally at the mid-height and near the top and bottom.

Decay is, if present at all, likely to be in the middle or at the bottom where the stringers bear on a pile cap. If water has penetrated the deck decay potential may exist along the top, but we found that decks were generally tight and dry.

If decay is absent, the expected stress wave velocities can be taken for the annual ring orientation to the wave path. Near mid-height the wave path is usually radial, that is, perpendicular to the annual rings. With one inch of preservative penetration the expected velocity for 6-inch wide stringer can be estimates as follows:

$$\frac{6}{V_a} = \frac{2}{V_t} + \frac{4}{V_u}$$

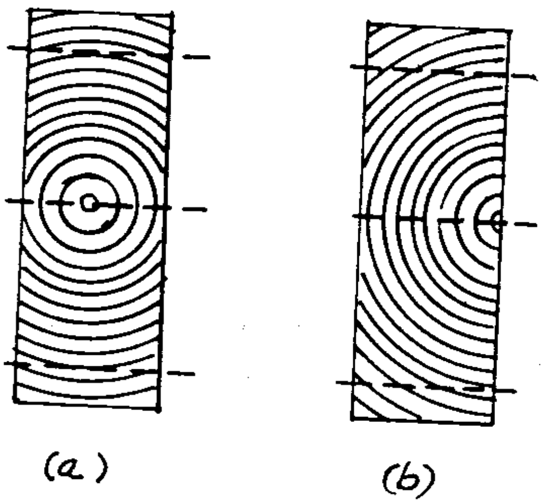


Figure 18. Transverse Stress Wave Paths and Annual Ring Orientation in a Rectangular Member

At 12% moisture content, $V_u = V_R = 55$ in/ms, from Table A3. V_t is 0.65 V_R or 36 in/ms. This yields $V_a = 47$ in/ms, or a timer reading of about 128 microseconds.

For a transverse path near the upper or lower edge of the member, where the rings are almost parallel to the wave path, $V_u = V_{tangential}$ from Table A3 for a value of 44 in/ms. $V_t = 0.65\ V_{tangential} = 29$ in/ms.

V_a, if the path is through 2 inches of treated wood and 4 inches of untreated wood, is 37 or 38 in/ms and the timer reading should be about 160 microseconds.

At a location where the annual rings are at about 45° to the wave path, $V_{45} = 20$ in/ms $= V_u$, $V_t = 0.65$, $V_{45} = 13$ in/ms, and V_a computes as 17 in/ms or a timer reading of 353 microseconds.

The reason these computed times are explained is to illustrate the sensitivity of the reading you obtain to annual ring orientation, even in decay-free wood. At three locations in this stringer, readings of 128, 160, and 353 are possible.

An early experience in using the stress wave method will show the variety of readings one may get at a single section of good wood. The inspector has to anticipate that these variations will occur. To locate decay he must compare transverse readings taken at various sections along a member, to search out abnormally large ones that suggest decay.

Severe, advanced decay in any of these sections will be shown by a dramatic increase in the timer readings.

Values of V_u for a decayed area would be less than 50% of those for undecayed wood in the preceding examples. For the wave path transversely through the center, the computed expected velocity would be 29 in/ms, for a timer reading of 207 microseconds. For the two other paths previously evaluated the results using decayed wood core properties would be V_a = 24 in/ms for the location near the top or bottom, and 11 in/ms for a path that traverses the annual rings at an angle of 45°. Thus for decayed wood the readings would be 207, 250, and 467 microseconds. These values are listed in Table 4, together with values for a member in an even more advanced state of internal decay.

Inspecting the surface of a timber will help visualize the annual ring orientation within, and perhaps the variation among readings taken at one cross-section. In Figure 19 are sketches of the cross-sections and the figure on the broad face of members with different annual ring patterns. Checks are often present, following radial lines into the members. Pith centers often display numerous face checks and sometimes abnormally shrunken wood (juvenile wood). Knots are also clues to ring orientation. Round knots are on a tangential face. Long narrow wedge-shaped knots (called spike knots) appear on radial or nearly radial faces. Oval shaped knots are on faces which are more nearly at 45° to the annual rings. Juvenile wood associated with pith centers often contains numerous very small knots representing small branches that formed when the tree was young and became intergrown with the wood which later formed around them. Some of the these characteristics are shown in Figure 19.

Longitudinal Stress Wave Velocity Measurements

The detection of decay in a long member using longitudinal stress wave time measurements is less successful than when using transverse measurements. If access to the ends for applying the impact is possible, a "stop" accelerometer placed at any position along the length will sense the arrival

Table 4. Stress Wave Velocity (in/ms) Along a 6-inch Path Transverse to Grain in Douglas-fir, Creosote Treated to 1-inch Penetration (numbers in parentheses are travel times in microseconds)

Direction of Stress Wave Path	No Decay	Moderate Decay	Advanced Decay
Radial	47 (128)	29 (207)	20 (300)
Tangential	38 (160)	24 (250)	17 (372)
45° to Annual Rings	17 (353)	13 (467)	11 (533)

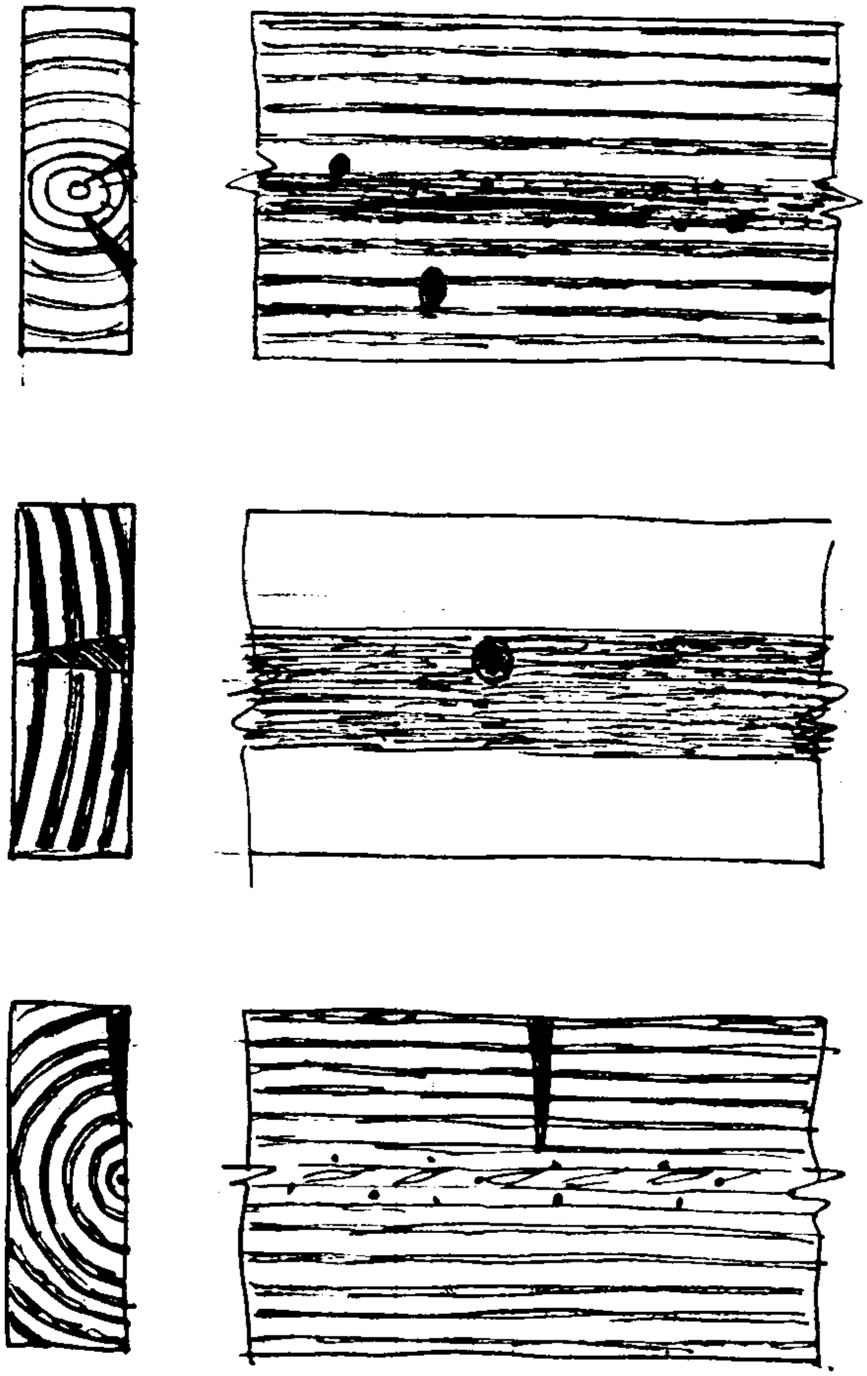


Figure 19. Appearance of Figure as an Aid to Inferring Ring Orientation

of the stress wave. The "stop" accelerometer must be placed so the front end faces the approaching stress wave.

Interior decay will impede the stress wave in that decayed region. The wave may proceed, unaffected, through the treated and undecayed shell, to which the accelerometer is attached. The wave velocity along the undecayed shell would not be affected by the decayed interior material. Thus, the stress wave may bypass the decayed portion with very little change in velocity.

This behavior was illustrated in a test described in Appendix E. A decayed 12 by 12 was used to determine travel times, than subdivided into longitudinal sticks and retested. Tables E2 and E3 show the very pronounced reductions in transverse velocity in the decayed regions either in the 12 by 12 or the 2 by 12 sizes. Table E4 shows that longitudinal velocities, while diminished by the decay, were not as markedly affected as was the case in the transverse direction.

Longitudinal measurements are useful, but not as definitive as transverse measurements in the detection of decay.

Hardware Influences

Bolted connections sometimes afford traps for water. Decay may develop near bolted connections if the bolts are loose and if the holes penetrate into untreated wood. Testing near bolt holes is important.

It is a concern that steel bolts might provide an avenue by which stress waves could bypass decayed regions. The stress wave velocity in steel is about the same as the longitudinal velocity in good wood, and four times that transversely in good wood. Thus a "short circuit" seems feasible, especially when testing in the transverse direction.

We tested many lap joints in bridges where 10 by 20 inch Douglas-fir stringers were joined together over bearing caps, as in Figure 20.

The bolts were checked for tightness and, if necessary, tightened. We found that the velocity through a 20-inch thickness consisting of two tightly bolted 10-inch members, was the same as through single 10-inch members. There was no effect of proximity to the bolt holes, or of the interface between the members.

In another field inspection of glulam timber with steel end hardware, shown in Figures E1 and E2, we found no effect of hardware on velocities measured transversely through individual laminae.

In yet another project we measured the longitudinal stress wave times in mechanically laminated beams with continuous steel connectors of the type shown in Figure 21. The steel plates which paralleled the laminae, did not short circuit the stress wave paths through the wood. Distinct measurements were obtained from stress waves passed longitudinally along laminations. These were used to compute the individual dynamic elastic moduli of each lamina. The results obtained agreed with those made for the unassembled members of the beams. These were for beam lengths of 16 to 20 feet.

Glulam Members

Transverse stress waves in glued-laminated members have been found to be reliable measures of the properties of each lamination, even though the laminations are very intimately adhered to one another. With the "start" and "stop" accelerometers placed on one lamina, the characteristics of that lamina can be obtained.

In glulam beams a transverse path through a lamina may pass through wood with annual rings oriented perpendicular, parallel or at some intermediate

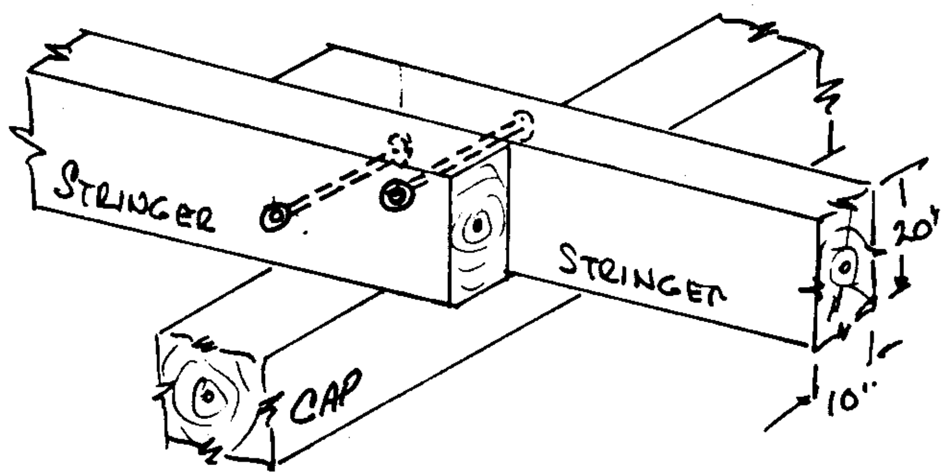


Figure 20. Bolted Lap Joint Between Two Stringers

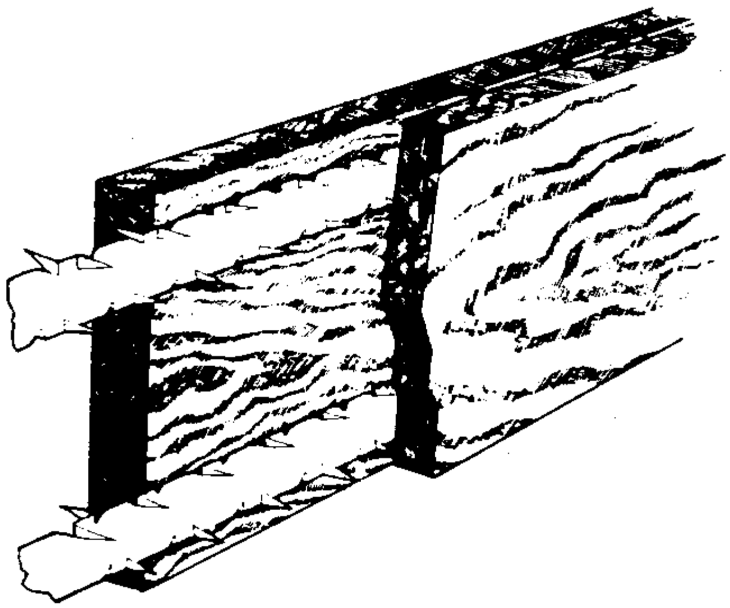


Figure 21. Steel Reinforced Wood Beam

angle to the rings. Each lamina would have its characteristic stress wave time as indicated in Figure 22 for Douglas-fir at 12% moisture content.

In glulam beams, fungi may have difficulty penetrating glue lines, and the susceptibility of adjacent lamina to decay, may differ. Sometimes decay is confined to particular lamina, but not always. Our experience has been that decay may occur in one lamina without affecting the stress wave velocity in the adjacent lamina.

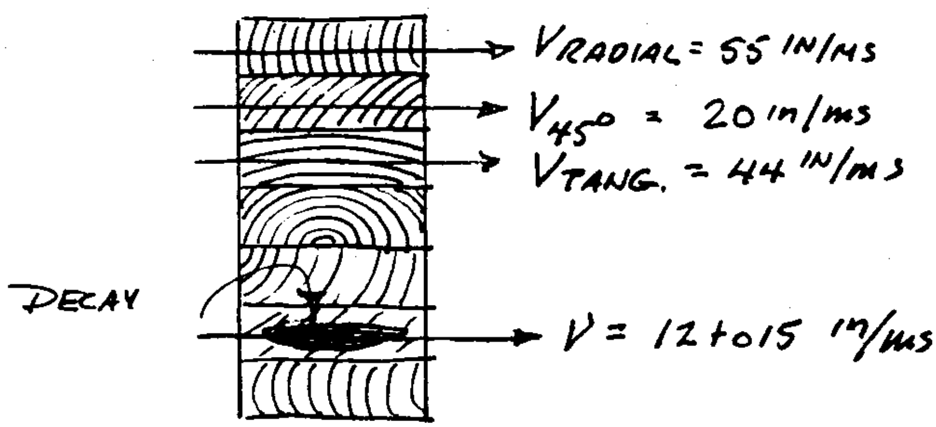


Figure 22. Transverse Stress Wave Velocities in a Glulam Beam

LITERATURE CITED

Citations from the literature are made in Appendices A, B, C, and E. The last page of each of these appendices presents the literature cited in that appendix.

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We have developed a comprehensive bibliography from our literature review, which includes all the publications or privately printed materials that are relevant to the stress wave inspection topic. This bibliography follows.

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APPENDIX A

THEORETICAL STRESS WAVE VELOCITIES IN CLEAR WOOD

An understanding of the relationship between stress wave velocity and wood properties can be gained from theoretical considerations. The general equation used in this discussion is:

$$E_D = \frac{\rho V^2}{g} \qquad [A1]$$

in which E_D = dynamic elastic modulus in psi

V = stress wave velocity in inches per second

ρ = actual wood density in lbs. per cubic inch but excluding any water above fiber saturation

g = gravity constant of 386.4 inches per second per second

Values of the static modulus of elasticity can be found in the Wood Handbook [1974] or in ASTM D2555 [1973]. These values were obtained from bending tests. They should be increased by 10% to obtain the true static modulus of elasticities. Dynamic modulus of elasticity is measured by very short time tests, whereas static tests require several minutes to perform. Static test results include the effect of wood creep and their elastic modulus results need to be increased about 6% to obtain dynamic values. For these reasons values of elastic modulus taken from the Wood Handbook or ASTM D2555 must be multiplied by 1.166 for use in the above equation.

The values of static modulus of elasticity for Douglas-fir given in the Wood Handbook are 1,560,000 psi for green wood and 1,950,000 psi for wood at 12% moisture content. The dynamic values, E_D, are 1,819,000 psi and 2,273,700 psi.

The specific gravity of various species are also found in the Wood Handbook and ASTM D2555. They are listed for the green condition and for 12% moisture content. They are based on the volume at either green or 12% moisture content, and the oven dry weight. Thus the Wood Handbook and ASTM D2555 values are not the actual specific gravities at these two conditions. To obtain the density from these specific gravity values the following procedure is necessary.

Coast Douglas-fir specific gravity listed in the Wood Handbook [1974], is 0.48 at 12% moisture content. One cubic inch of this wood contains 0.48 * 62.4/1728 = 0.01733 pounds of dry wood plus 12% of that weight in the form of water. So its true density is 1.12 * 0.01733 = 0.0194 lbs/in^3.

Green Coast Douglas-fir has a listed specific gravity of 0.45. "Green" means any moisture content equal to or exceeding the fiber saturation moisture content. The absorbed water in wood occurs in two forms; that which resides in the cell walls and that which is in the cell cavities. In living trees both the cell walls and the cavities are occupied by water. When lumber or poles dry (season) they lose the cavity water first, then the cell wall water. Loss of the cell cavity water has no effect on the volume or the mechanical properties (strength and elastic properties). Loss of the cell wall water causes reduced mechanical properties and shrinkage.

When wood is green the cell walls are saturated and varying amounts of cell cavity water may be present. The cell wall substance is fully swollen and at its maximum volume at any moisture content upward from the fiber saturation moisture content. Fiber saturation moisture content is commonly called the fiber saturation point (FSP).

To determine the density of green wood we need to know the FSP. It varies according to species. Table A1, the most comprehensive table available, from "Mechanics of Wood and Wood Composites" by Bodig and Jayne [1982] lists FSP values for many structural woods. When data is not available for a species use 28% for low extractive woods such as true firs and spruces, 25% for woods of average extractive content, such as white pine, and 20% for woods of high extractive content, such as locust or possibly bald cypress.

It is also important to know that the density in the stress wave formula does not include the weight of cell cavity water.

The value of density for green coast Douglas-fir, FSP of 26% from Table A1 is calculated as:

$$\rho = \frac{1.26 * 0.45 * 62.4}{1728} = 0.0205 \text{ lbs/in}^3$$

These densities and elastic moduli may be used to determine the longitudinal stress wave velocities for coast Douglas-fir, green and at 12%. The equation is:

$$V = \sqrt{\frac{E_D \, g}{\rho}} \qquad \text{[A2]}$$

At the green condition, V is calculated to be 185 inches/millisecond, and at 12% moisture content it is 213 inches/millisecond.

To obtain values of velocity at other moisture contents it is necessary to determine the density and dynamic elastic modulus at those moisture contents. To obtain density, the shrinkage coefficient must be known and may be found in Table 3.5 of the Wood Handbook [1974]. For coast Douglas-fir the

Table A1. Fiber Saturation Point of Different Woods at Room Temperature (Bodig and Jayne)

Species	Fiber Saturation Point, %	Species	Fiber Saturation Point, %
Ash, White	24.0	Pine, Klinki	32.5
Basswood	32.0	Loblolly	21.0
Birch, Yellow	27.0	Longleaf	25.5
Cedar, Alaska	28.5	Red	24.0
Western red	22.0	Slash	29.0
Douglas-fir	26.0	Shortleaf	30.0
Eucalyptus	30.0	Redwood	22.5
Fir, Red	30.0	Spruce, Sitka	28.5
Hemlock, Western	28.0	Red	27.0
Larch, Western	28.0	White	30.0
Mahogany	24.0	Tamarack	24.0
Oak, White	32.5	Teak	22.0
Swamp	31.0	Yellow poplar	31.5

volumetric shrinkage factor is 12.4% for moisture change from FSP to zero moisture. The change is considered linear with percent change in moisture.

Volume at zero moisture content is 1 - 0.124 = 0.876 times the volume green. Density at zero moisture therefore is:

$$\rho_0 = \frac{0.45 * 62.4}{0.876 * 1728} = 0.01855 \text{ lbs/in}^3$$

The volume at 20% moisture content is:

1 - (6/26)(0.124) = 0.971 times the green volume,

so the density at 20% is:

$$\rho_{20} = \frac{1.2 * 0.45 * 62.5}{0.971 * 1728} = 0.0201 \text{ lbs/in}^3$$

Values of E_D are required if the velocities are wanted at these other moisture contents. The Wood Handbook contains the necessary equation on page 4-32:

$$E_D = E_{D12}\left(\frac{E_{D12}}{E_{DG}}\right)^{\left(\frac{12 - M}{FSP - 12}\right)}$$

where E_{D12} = E_D at 12%

E_{DG} = E_D at FSP

M = moisture content at which E_D is wanted

At zero moisture content:

$$E_D = 2{,}273{,}700\left(\frac{2.2737}{1.819}\right)^{(12/14)} = 2{,}745{,}142 \text{ psi}$$

At 20% moisture content:

$$E_D = 2{,}273{,}700\left(\frac{2.2737}{1.819}\right)^{(-8/14)} = 2{,}001{,}500 \text{ psi}$$

Corresponding stress wave velocities are calculated as before.

At zero moisture content:

$$V = \sqrt{\frac{2,745,142 * 386.4}{0.01855}} = 239 \text{ inches/millisecond}$$

At 20% moisture content:

$$V = \sqrt{\frac{2,001,500 * 386.4}{0.0201}} = 196 \text{ inches/millisecond}$$

The stress wave velocities calculated above are all for the longitudinal or parallel-to-grain travel path. If velocities are wanted for other travel directions the value of E_D in those directions is needed. Values of modulus of elasticity in the longitudinal, radial and tangential directions are given by Bodig and Jayne in a fairly comprehensive table in this appendix. This is included as Table A2 along with their fiber saturation points in Table A1.

For coast Douglas-fir the ratio of radial to longitudinal E or E_D is 0.067 and tangential to longitudinal is 0.043. The radial and tangential velocities can be calculated using 0.067 E_D longitudinal and 0.043 E_D longitudinal. Or, more conveniently, multiplying V_L by the square root of either of these ratios. Thus,

$$V_R = 0.259\ V_L \quad [A3]$$

$$V_T = 0.207\ V_L \quad [A4]$$

Table A3 lists calculated values of stress wave velocity for a number of wood species likely to be encountered in wood structures. The longitudinal, radial and tangential velocities were obtained using adjusted static elastic modulus properties and densities computed by the methods of the foregoing discussion. The radial and tangential values are based on directional ratios from Table A2. The combined tangential-radial transverse velocities are based on literature [1935] findings which we simplified to the form:

$$0.40(V_R + V_T)/2 \quad [A5]$$

Table A2. Predicted Elastic Parameters for the Various Commercial Species Grown in the United States (12% Moisture Content) (Bodig and Jayne)

Species	Density (g/cm³)	E_L	E_R	E_T	G_{LR}	G_{LT}	G_{RT}
		(10⁶ psi)					
SOFTWOODS							
Baldcypress	.43	1.586	.1362	.0854	.1119	.1045	.01152
Cedar							
Alaska	.42	1.557	.1330	.0826	.1098	.1028	.01112
Atlantic white	.31	1.024	.0984	.0534	.0863	.0838	.00703
Eastern red	.46	.969	.1456	.0941	.1180	.1093	.01276
Incense	.35	1.143	.1110	.0636	.0950	.0909	.00845
Northern white	.29	.875	.0921	.0486	.0818	.0801	.00636
Port-Orford	.40	1.900	.1267	.0770	.1056	.0995	.01033
Western red	.33	1.221	.1047	.0585	.0907	.0874	.00773
Douglas-fir							
Coast	.45	2.141	.1424	.0912	.1160	.1077	.01234
Interior west	.46	2.010	.1456	.0941	.1180	.1093	.01276
Interior north	.45	1.964	.1424	.0912	.1160	.1077	.01234
Interior south	.43	1.633	.1362	.0854	.1119	.1045	.01152
Fir							
Balsam	.34	1.354	.1078	.0610	.0928	.0892	.00808
California red	.36	1.644	.1141	.0662	.0971	.0927	.00881
Grand	.35	1.729	.1110	.0636	.0950	.0909	.00845
Noble	.37	1.894	.1173	.0669	.0993	.0944	.00918
Pacific silver	.39	1.933	.1236	.0743	.1035	.0978	.00994
Subalpine	.31	.992	.0984	.0534	.0863	.0838	.00703
White	.37	1.644	.1173	.0669	.0993	.0944	.00918
Hemlock							
Eastern	.39	1.307	.1236	.0743	.1035	.0978	.00994
Mountain	.42	1.458	.1330	.0826	.1098	.1028	.01112
Western	.42	1.793	.1330	.0826	.1098	.1028	.01112
Larch							
Western	.48	2.049	.1519	.1000	.1221	.1125	.01360
Pine							
Eastern white	.35	1.353	.1110	.0636	.0950	.0909	.00845
Jack	.40	1.489	.1267	.0770	.1056	.0995	.01033
Lodgepole	.39	1.465	.1236	.0743	.1035	.0978	.00994
Ponderosa	.39	1.423	.1236	.0743	.1035	.0978	.00994
Red	.42	1.786	.1330	.0826	.1098	.1028	.01112
Spruce	.41	1.377	.1299	.0798	.1077	.1012	.01072
Sugar	.35	1.318	.1110	.0636	.0950	.0909	.00845
Western white	.37	1.654	.1173	.0669	.0993	.0944	.00918
Pine, Southern							
Loblolly	.47	1.975	.1487	.0971	.1200	.1109	.01318
Longleaf	.54	2.193	.1707	.1185	.1341	.1218	.01625
Pitch	.47	1.568	.1487	.0971	.1200	.1109	.01318
Pond	.51	1.926	.1613	.1091	.1281	.1172	.01490
Sand	.46	1.551	.1456	.0941	.1180	.1093	.01276
Shortleaf	.46	1.924	.1456	.0941	.1180	.1093	.01276
Slash	.54	2.249	.1707	.1185	.1341	.1218	.01625
Virginia	.46	1.671	.1456	.0941	.1180	.1093	.01276
Redwood							
Old Growth	.39	1.486	.1236	.0743	.1035	.0978	.00994
Second Growth	.34	1.206	.1078	.0610	.0928	.0892	.00808
Spruce							
Black	.38	1.672	.1204	.0716	.1014	.0961	.00956
Engelmann	.32	1.514	.1015	.0560	.0885	.0856	.00738
Red	.38	1.669	.1204	.0716	.1014	.0961	.00956
Sitka	.38	1.715	.1204	.0716	.1014	.0961	.00956
White	.38	1.474	.1204	.0716	.1014	.0961	.00956
Tamarack	.49	1.804	.1550	.1030	.1241	.1141	.01403
HARDWOODS							
Alder							
Red	.38	1.512	.1174	.0516	.0917	.0656	.02089
Ash							
Black	.45	1.752	.1435	.0675	.1116	.0812	.02469
Green	.53	1.813	.1743	.0875	.1350	.0998	.03334
White	.54	1.907	.1783	.0902	.1380	.1022	.03423
Aspen							
Bigtooth	.36	1.561	.1101	.0473	.0861	.0613	.01936
Quaking	.35	1.293	.1065	.0452	.0833	.0592	.01861
Beech							
American	.57	1.895	.1901	.0983	.1469	.1094	.03693
Birch							
Paper	.48	1.747	.1550	.0748	.1203	.0881	.02901
Sweet	.60	2.391	.2020	.1067	.1559	.1167	.03969
Yellow	.55	2.212	.1822	.0929	.1409	.1046	.03512
Cottonwood							
Black	.31	1.403	.0922	.0373	.0723	.0508	.01569
Eastern	.37	1.501	.1137	.0494	.0889	.0634	.02012
Elm							
American	.46	1.467	.1473	.0699	.1145	.0835	.02732
Slippery	.49	1.636	.1588	.0773	.1232	.0904	.02986
Hackberry	.49	1.309	.1588	.0773	.1232	.0904	.02986
Hickory							
Bitternut	.62	1.966	.2101	.1124	.1620	.1216	.04157
Mockernut	.64	2.436	.2181	.1182	.1681	.1266	.04346
Nutmeg	.56	1.868	.1861	.0956	.1439	.1070	.03602
Pecan	.61	1.891	.2061	.1095	.1590	.1191	.04063
Pignut	.67	2.484	.2304	.1272	.1773	.1341	.04635
Shagbark	.64	2.372	.2181	.1182	.1681	.1266	.04346
Shellbark	.63	2.079	.2141	.1153	.1651	.1241	.04251
Water	.63	2.230	.2141	.1153	.1651	.1241	.04251
Magnolia							
Cucumbertree	.44	1.993	.1398	.0651	.1087	.0789	.02567
Southern	.46	1.542	.1473	.0699	.1145	.0835	.02732
Maple							
Black	.52	1.778	.1704	.0850	.1320	.0974	.03246
Red	.50	1.810	.1627	.0798	.1261	.0927	.03072
Silver	.44	1.253	.1398	.0651	.1087	.0789	.02567
Sugar	.57	2.003	.1901	.0983	.1469	.1092	.03693
Oak - Red							
Black	.56	1.803	.1861	.0956	.1439	.1070	.03602
Cherry bark	.60	2.495	.2020	.1067	.1559	.1167	.03969
Laurel	.56	1.850	.1861	.0956	.1439	.1070	.03602
Northern red	.56	2.005	.1861	.0956	.1439	.1070	.03602
Pin	.58	1.895	.1941	.1011	.1499	.1118	.03785
Scarlet	.61	2.106	.2061	.1095	.1590	.1191	.04063
Southern red	.53	1.641	.1743	.0876	.1350	.0998	.03334
Water	.56	2.213	.1861	.0956	.1439	.1070	.03602
Willow	.55	2.089	.1822	.0929	.1409	.1046	.03512
Oak - White							
Bur	.60	1.136	.2020	.1067	.1559	.1167	.03969
Chestnut	.58	1.747	.1941	.1011	.1499	.1118	.03785
Overcup	.56	1.360	.1861	.0956	.1439	.1070	.03602
Post	.60	1.657	.2020	.1067	.1559	.1167	.03969
Swamp chestnut	.60	1.941	.2020	.1067	.1559	.1167	.03969
Swamp white	.64	2.230	.2181	.1182	.1681	.1266	.04246
White	.60	1.936	.2020	.1067	.1559	.1167	.03969

Table A3. Calculated Values of Stress Wave Velocity for Several Species of Wood

	Longitudinal			Radial			Tangential			Tangent/Radial		
	0	12	FSP	0	12	FSP	0	12	FSP	0	12	FSP
Douglas-fir:												
Coast	239	213	185	62	55	48	50	44	38	22	20	17
Interior W and N	230	203	178	62	54	48	50	44	39	22	20	17
Southern Pine:												
Longleaf	221	194	171	62	54	48	51	45	40	22	20	18
Slash	220	194	166	61	53	46	51	45	38	22	20	17
Loblolly	225	198	176	62	54	48	50	44	40	22	20	18
Shortleaf	218	196	167	60	54	46	48	43	37	22	20	17
Cedar, Western red	226	197	176	66	58	52	50	43	39	23	20	18
Fir, Grand	243	217	187	61	55	47	47	42	36	22	20	17
Pine, Red (Norway)	237	199	178	64	54	48	51	43	38	23	20	17
Oak, Northern red	215	180	155	66	55	47	47	39	34	25	19	18
Average	227	200	174	63	55	48	50	43	38	23	20	17

The purpose of this discussion is to show that velocities are not highly variable among species. Low density cedar and grand fir velocities are not greatly different than high density longleaf pine or Douglas-fir, particularly in the transverse direction.

In inspection work it is most useful to measure the velocity in a transverse direction, i.e., across the grain. The reason for this will be appreciated if one thinks about how decay develops in structures. It is often localized. It occurs at points where conditions are especially favorable. One part may harbor moisture, as at the bearing location of a beam, and the rest may be too dry to support decaying organisms. Points of exposure, bottoms of pilings, unprotected overhangs, rails and rail posts, tops of poles, bases of columns in ground contact, waterline regions of freshwater piles, and in buildings where accident or poor design or construction have permitted wet conditions, are almost invariably localized.

In the case of treated timbers, centers may decay leaving sound treated wood at all exposed faces. Longitudinal stress waves may propagate very nicely through the sound shell of the member, giving no evidence whatsoever of the decayed central region. Or if the decayed area is short any effect it may have will be masked by the good travel path in the remaining good wood. Transverse measurements will detect the unsound core when longitudinal waves will not.

Measurements made transversely enable the inspector to identify and locate decayed areas. Longitudinal measurements do not lend themselves to this interpretation, unless the member is very badly deteriorated. In another part of this report the effect of decay on stress wave velocity will be discussed in specific terms. Then it will be noted that decay has a large effect on elastic modulus, larger than its effect on density, especially in the early stages. Stress wave velocity is very sensitive to this elastic property change.

In pole and piling inspection, transverse stress wave paths tend to be radial. Decayed centers divert the path toward the tangential and lower velocity material. In sawn timbers and glulam beams paths tend to be a composite of the radial and tangential. Table A3 indicates that the tangential, radial or composite T/R paths have characteristic velocities, the radial being about 25% higher than the other two. Significant decay, we find, markedly reduces these velocities.

Table A4 lists elastic property ratios.

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Table A4. Elastic Modulus Ratios

	E_R/E_L	E_T/E_L
Douglas-fir		
Coast	0.067	0.043
Interior IN & N	0.072	0.047
Southern Pine		
Longleaf	0.078	0.054
Slash	0.076	0.053
Loblolly	0.075	0.049
Shortleaf	0.076	0.049
Cedar, Western red	0.086	0.048
Fir, Grand	0.064	0.037
Pine, Red, Norway	0.074	0.046
Oak, Northern red	0.093	0.048

APPENDIX B

EFFECT OF GRAIN DIRECTION ON STRESS WAVE VELOCITY

Grand Fir

This study determined the stress wave velocity versus grain angle at two moisture contents. Data was obtained at 28%, which is close to the fiber saturation point, and at 17% moisture content. We used grand fir because it was available green from a mill, and Douglas-fir was unavailable.

Nominal (rough) 2 by 4's were surfaced and glued green into a panel approximately 42 by 44 by 1½ inches thick, using a phenol-resorcinol adhesive. The annual ring orientations of the individual pieces in the panel varied from flat to edge grained.

Stress wave velocities were measured at selected angles to grain at each of the above moisture contents. We used the Metriguard Model 239A Stress Wave Timer with a gain setting of 1:20.

Table B1 lists the data gathered. Figures B1 and B2 are plots of this data. We fitted Hankinson type equations to this data. The Hankinson equation has been found useful in describing properties as functions of grain direction and is described in many references on wood technology and timber design. K. Y. Kim published a useful note on this equation in Wood and Fiber [1986]. This type of equation was applied to wood crushing strength in 1935

Table B1. Stress Wave Velocity vs. Angle to Grain at Two Moisture Contents for Grand Fir

Angle	28%	17%	Angle	28%	17%
0	175	196	31	80	84
0	---	192	31	78	87
10	158	170	40	64	70
10	157	169	40	65	70
10	159	169	48	41	59
20	112	123	61	37	26
20	112	118	61	43	39
22	103	115	75	22	25
23	103	109	75	28	28
23	101	107	90	27	23
31	78	88	90	21	21
31	79	86			

Hankinson: $$V_\Theta^2 = \frac{V_\parallel^2 \quad V_\perp^2}{V_\parallel^2 \ \sin^{3.5}\Theta + V_\perp^2 \ \cos^{3.5}\Theta}$$

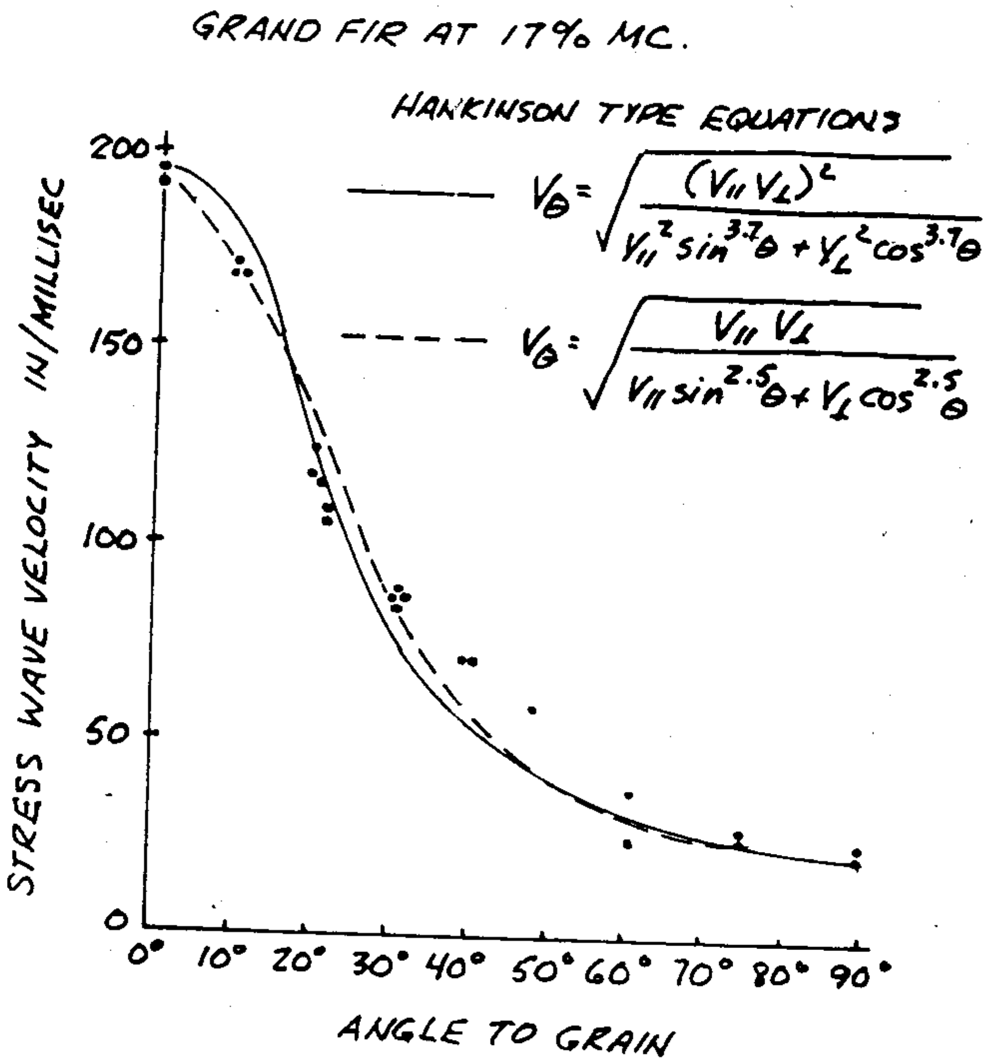

Figure B1. Stress Wave Velocity vs. Angle to Grain of Stress Wave Path in Grand Fir (17% Moisture Content)

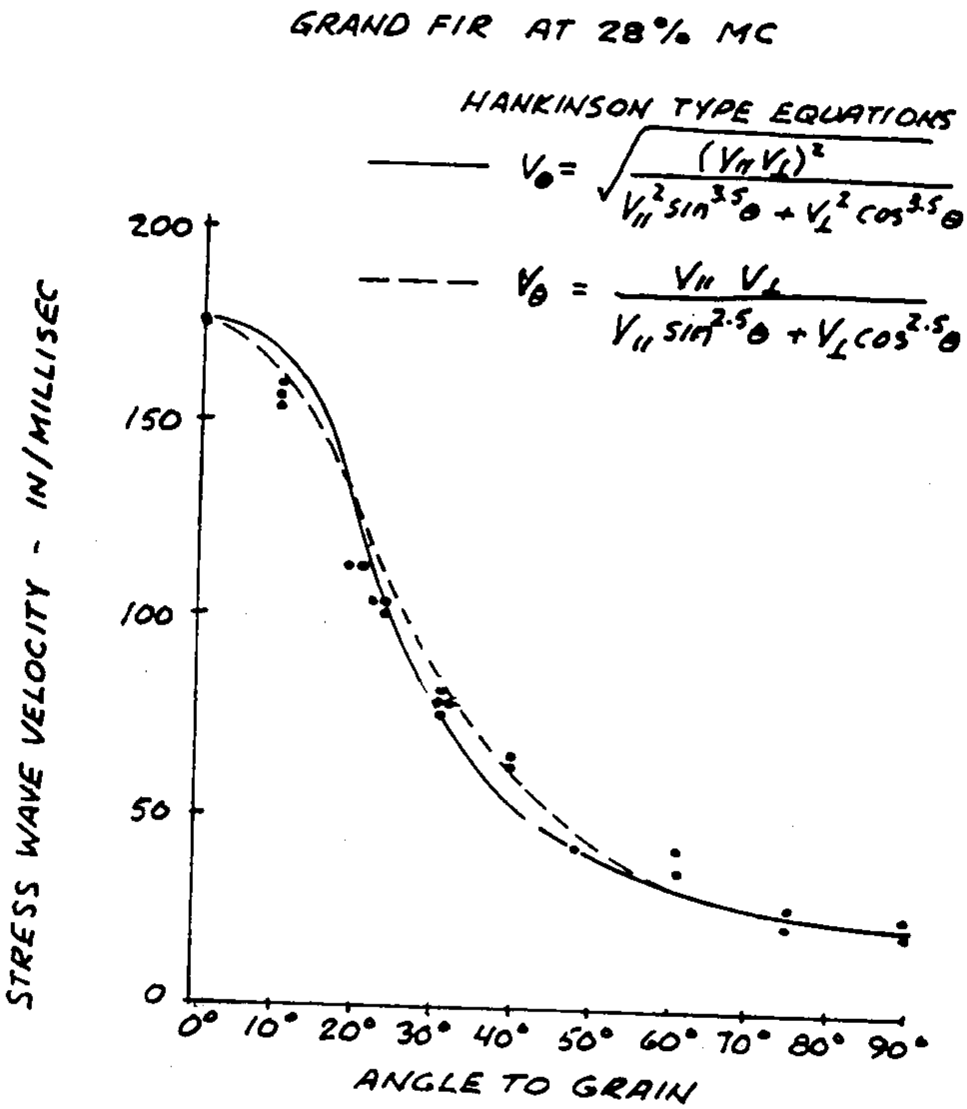

Figure B2. Stress Wave Velocity vs. Angle to Grain of Stress Wave Path in Grand Fir (28% Moisture Content)

[Markwardt and Wilson] and has subsequently been found useful in describing many property-grain relationships for wood. These are described in the Wood Handbook, page 4-27 and Figure 4-3 of that reference. The form we first examined was based on the equation in the Wood Handbook for elastic modulus, using V^2 instead of E, since the stress wave equation defines E as proportional to V^2. We then used an equation of the form:

$$V_\Theta = \frac{V_\parallel \quad V_\perp}{V_\parallel \ \sin^n\Theta + V_\perp \cos^n\Theta} \qquad [B1]$$

with good results.

Jung [1979] and McDonald [1978] have each obtained similar velocity versus grain angles relationships for other species of wood at other moisture contents.

Using stress wave and density data available from this test we calculated the dynamic elastic modulus, E_D, using densities of 0.0158 lbs/in^3 at the green condition and 0.0153 lbs/in^3 at the 17% condition. We obtained:

	17%	28% (green)
Dynamic E parallel-to-grain	1,490,245 psi	1,252,636 psi
Dynamic E perpendicular	19,164 psi	25,553 psi
Ratio perpendicular/parallel	0.013	0.019

As these ratios were considerably lower than those anticipated from other published information on grand fir we cut specimens from the test panel for a static test of the perpendicular-to-grain elastic modulus. The tests showed this value to be 16,528 psi static, which converts to a dynamic value of about 18,000 psi. This indicated that the particular material we were working with did, indeed, have a somewhat low perpendicular-to-grain elastic modulus. The value found in the literature for typical grand fir is $E\ /E\ \ \ = 0.05$.

Douglas-fir and Southern Pine

Two panels measuring 48 by 48 by 3/4 inches, one southern pine and the other of Douglas-fir were evaluated for stress wave velocity and grain angle. The ring orientation of the individual pieces composing each panel was randomized, from flat to edge grain. Moisture content at the test condition was 10% and densities were 0.0191 lbs/in^3 for the southern pine, 0.0185 lbs/in^3 for the Douglas-fir.

Test results appear in Table B2 and curves plotted from those data appear in Figures B3 and B4. Values of dynamic elastic modulus derived from the measurements at zero and 90° to grain are presented in Table B3. These values display ratios in general agreement with what might be inferred from published data. Ratios of radial to longitudinal and random radial-tangential to longitudinal are probably similar. Based on McDonald's [1978] Table B4, the Douglas-fir ratio appears low. It is of the proper order of magnitude, and it is necessary to acknowledge that these panels may differ from the norm obtained with larger samples of wood. It is noted that the longitudinal elastic modulus for the Douglas-fir in McDonald's study is quite low for the species.

In each of these cases the material used was not selected to be representative of the species. This was not important since the stress wave velocities are proportional to $(E/\rho)^{\frac{1}{2}}$. E varies with ρ within a species and the ratio is not highly sensitive to within-species properties variations. The grain angle effect which was being investigated would not be expected to

Table B2. Stress Wave Velocities at Various Angles to Grain for Douglas-fir and Southern Pine (10% Moisture Content)

Angle to Grain	Douglas-fir (velocity in inches/millisecond)	Southern Pine (velocity in inches/millisecond)
0	170	200
0	170	210
0	197	210
0	180	180
7	170	170
7	170	190
7	177	190
7	180	180
15	150	153
15	150	160
15	150	150
15	150	150
21	130	130
21	127	130
21	120	130
21	120	130
28	110	110
28	110	110
28	100	110
33	95	94
33	93	99
38	85	72
52	61	63
57	47	59
62	44	52
62	43	52
62	44	55
69	37	49
69	40	48
69	37	49
69	35	48
75	31	46
75	33	46
75	31	46
75	31	46
83	30	44
83	33	45
83	29	45
83	31	44
90	30	42
90	32	44
90	32	44
90	30	44

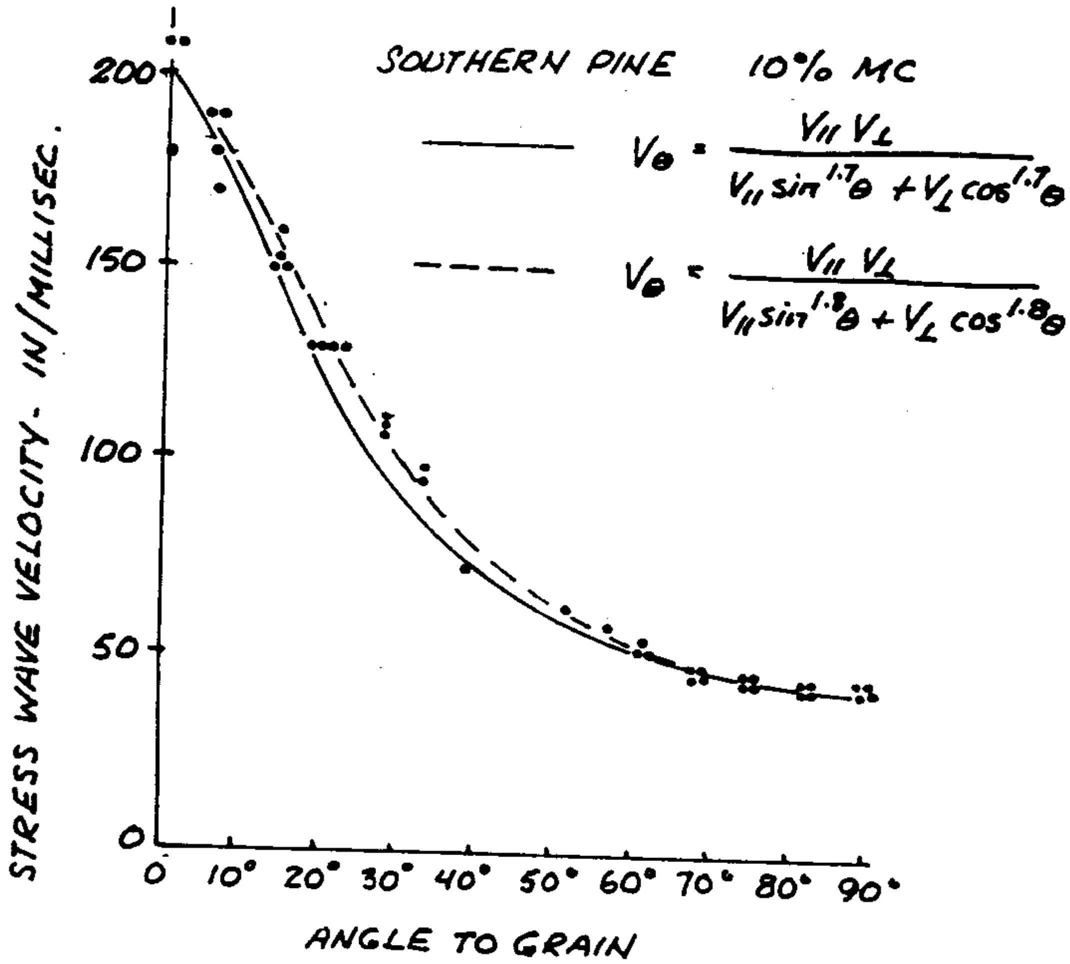

Figure B3. Stress Wave Velocity vs. Angle to Grain of Stress Wave Path in Southern Pine (10% Moisture Content)

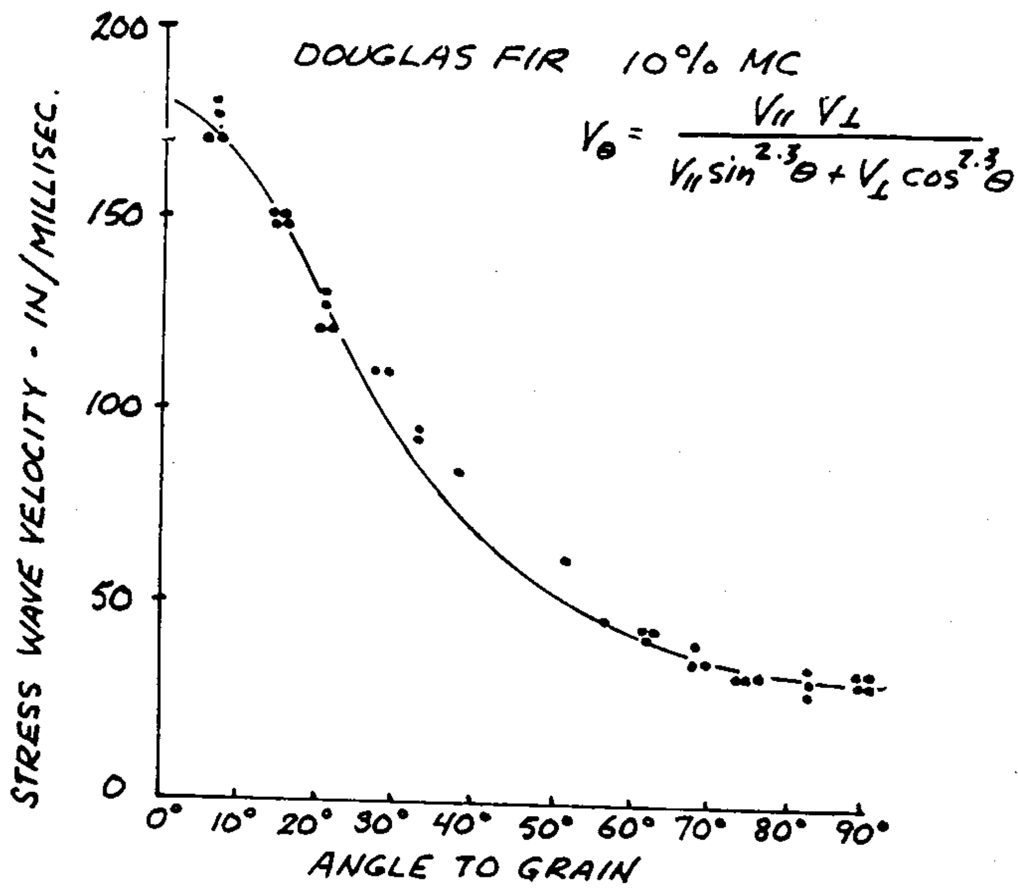

Figure B4. Stress Wave Velocity vs. Angle to Grain of Stress Wave Path in Douglas-fir (10% Moisture Content)

Table B3. Elastic Constants for Douglas-fir and Southern Pine Derived from Stress Wave Velocities and Density

	Douglas-fir	Southern Pine
Parallel-to-Grain E_D	1,534,054 psi	1,977,226 psi
Perpendicular E_D	46,011 psi	91,397 psi
Ratio Perpendicular/ Parallel	0.030	0.046

Table B4. Stress Wave Velocities in Dry Wood Reported by McDonald

	Longitudinal	Radial	Tangential	T/R
Douglas-fir (dry)	171	78	70	68
Western red cedar (dry)	230	85	78	75
Eastern white pine (dry)	171	97	61	73
Ponderosa pine (green)	173	64	57	56
Beech (dry)	260	78	70	68
Hickory (green)	207	89	66	71
Red oak (green)	162	80	70	69

be sensitive to the choice of the material as long as it was normal wood in sound condition and of reasonable quality.

Other Tests

J. Jung [1979] conducted research on the grading of ¼-inch thick red oak veneer and reported the results depicted in Figure B5. The wood was at 12% moisture content. While they do not cover the entire range from longitudinal to transverse, the curves are quite similar to others obtained in our studies. Jung does not present any measurements for transverse-to-grain stress wave velocity. He used the James V- Meter and both James and Metriguard accelerometers, obtaining results within ±8%.

Kent McDonald [1978] conducted studies on 3/4-inch thick boards submerged in water. He used a through transmission ultrasonic technique similar to the James V-Meter approach. Immersion in water was to obtain good "coupling" between the wood and the accelerometers. He tested several species and reports the velocity measurements (converted to inches/millisecond) taken from 2 inch cubes cut to get longitudinal, radial and tangential grain velocities as shown in Table B4.

The "dry" moisture content is not given in the report. It is implied that immersion in water was not long enough to alter the wood moisture content during the tests.

The McDonald data is the only reference material on transverse stress wave velocity, at different annual ring orientations. It is probably on species not commonly used for highway bridges, and the values are larger than those we have usually observed for softwood species. Probably the specimens were very dry when tested, and we know they were very small in size.

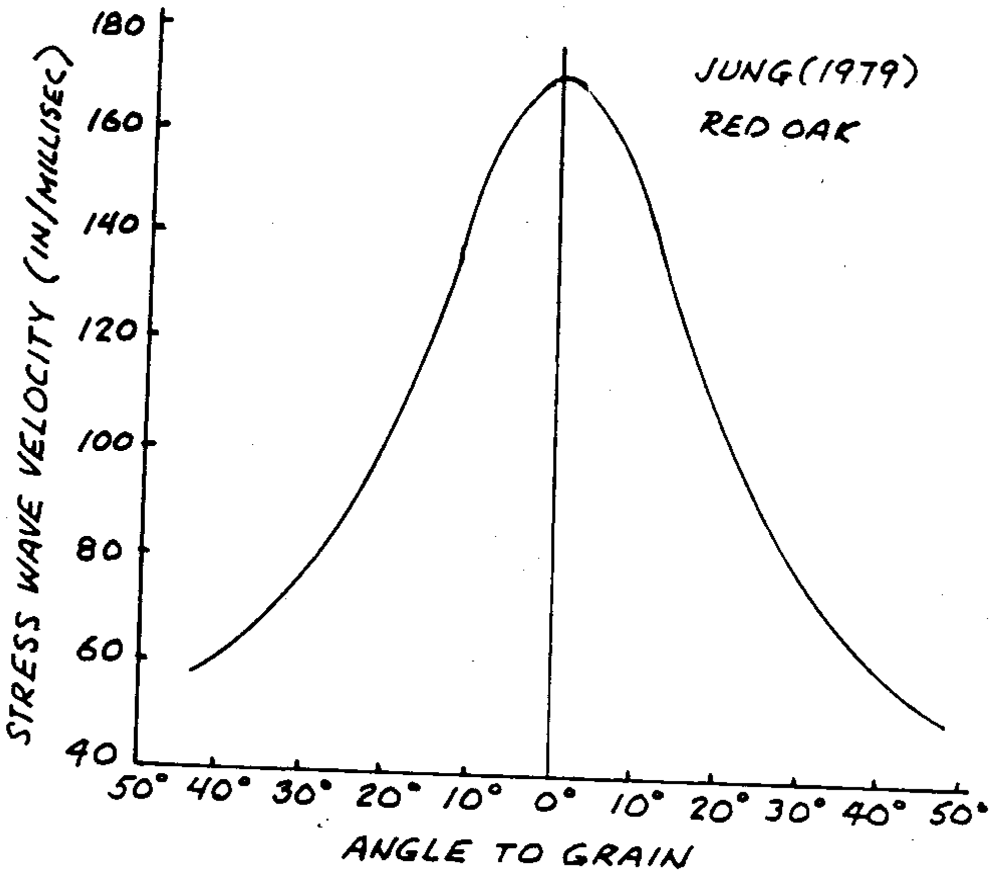

Figure B5. Stress Wave Velocity vs. Angle to Grain in 1/4-inch Thick Red Oak Veneer (Jung)

Other references [Bodig, 1982; Markwardt, 1935; FPL, 1944 and 1974] provide values for elastic modulus in compression perpendicular to grain and at various ring orientations. Theoretical values of stress wave velocity calculated from these data are presented in Figure B8.

McDonald's grain angle effects were shown on graphs, reproduced in Figures B6 and B7. They are not identified as to species, probably representing an average of the various species tested. Figure B6 is similar to our results for Douglas-fir, southern pine and grand fir, but McDonald's parallel-to-perpendicular velocity ratio is only 2.5, whereas ours were 3, 5 and about 8, respectively.

Figure B7 is an important relationship, showing the tangential velocity to be less than the radial, and 45° to either to be less than either. This is the only information we are aware of on this relationship and we have attempted to use it in our interpretations.

Figure B8 is more likely to represent the relationship in softwoods at usual in-service moisture conditions.

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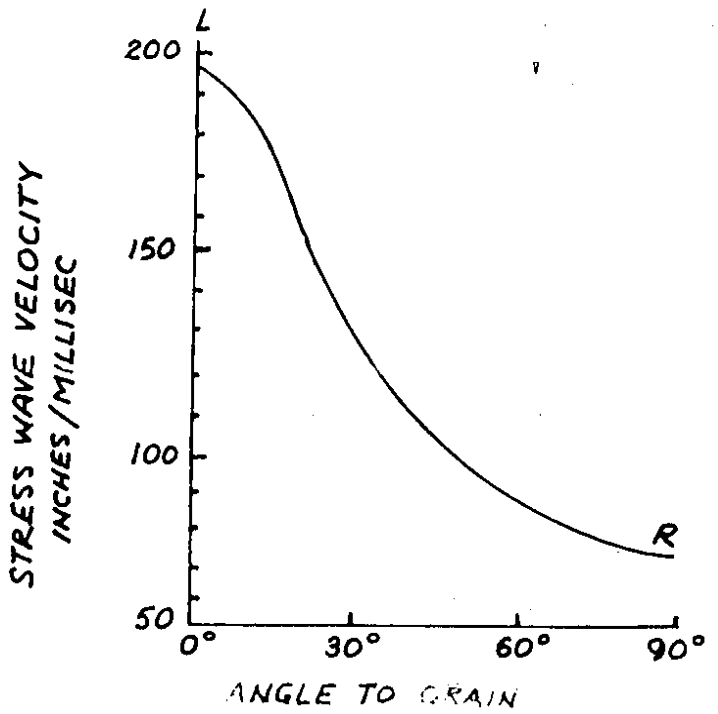

Figure B6. Stress Wave Velocity vs. Angle to Grain, Longitudinal to Radial, for 2-inch Diameter Specimens of Various Species (McDonald)

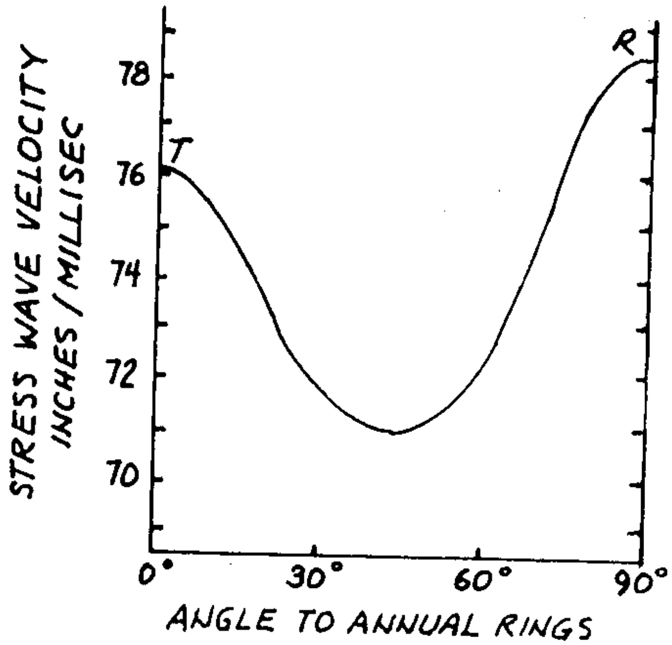

Figure B7. Transverse Stress Wave Velocity vs. Angle to Annual Rings; Tangential (0°) to Radial (90°) for 2-inch Diameter Specimens of Various Species (McDonald)

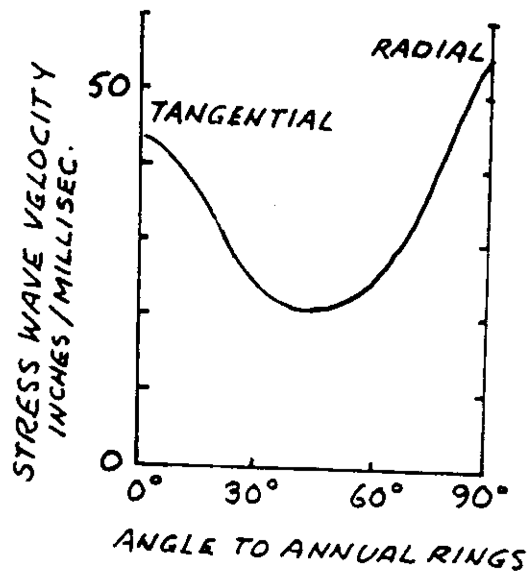

Figure B8. Transverse Stress Wave Velocity vs. Angle to Annual Rings; Tangential (0°) to Radial (90°) for Various Species from Literature (Markwardt and Wilson)

McDonald, K. A. 1978. Lumber Defect Detection by Ultrasonics. Forest Products Lab Report 311.

U.S. Army Engineering Div. 1921. Investigation of crushing strength of spruce at varying angles to the grain. Air Service Information Circular 3(259):3-15.

APPENDIX C

MOISTURE AND TEMPERATURE EFFECTS ON STRESS WAVE VELOCITY

One would expect that moisture and temperature effects on elastic modulus (E) and density (ρ) would be reflected in stress wave velocity according to the equation:

$$V = \sqrt{\frac{E\ g}{\rho}} \qquad [C1]$$

where g is the gravity constant, 386.4 inches/sec^2. This appears to be approximately true within the range of zero to fiber saturation, but not with precision. This review of available information has been made to determine how adjustments should be made for these two environmental factors.

James [1961] made a very carefully executed study in the 0-160°F temperature range and the oven-dry to fiber saturation (0-27%) moisture content range on Douglas-fir. He used 280 specimens approximately 2 by 2 by 40 inches long, in 40-specimen groups, each conditioned to a different moisture content at 80°F. After measuring stress wave velocities he changed the temperature with no change in moisture content and measured the velocities at 0, 38, 120, and 160°F. The log-decrement for longitudinal sound waves was obtained and the velocities and dynamic moduli of elasticity were calculated.

At the time he did this, the type of equipment we have been using was not yet developed.

Table C1 provides his results and Figures C1 and C2 show these graphically. These are very clearly defined relationships on one of the most commonly used species found in structures of all kinds. Using James results we prepared Table C2 which permits applying correction factors to any temperature and moisture condition likely to be encountered in wood structures which are not actually used wet.

The longitudinal stress wave velocity is 210 inches/millisecond at 12.8% moisture content and 80°F. This agrees with our theoretical value in Table A3 for coast Douglas-fir. Adjusting to the FSP using Table C2 factors gives 188 inches/millisecond, not too different from our theoretical value of 185 inches/millisecond. The factors also provide adjusted transverse velocity values that agree nicely with those computed from theory for Coast Douglas-fir. For the southern pines and red (Norway) pine agreement also appears reasonable when the Table C2 factors are used.

Burmester [1965] made a study of moisture content in a European pine, probably Scots pine, which is widely cultivated in Germany. His graph of longitudinal stress wave velocity versus moisture content appears as Figure C3. He obtained 224 inches/millisecond at 12.8%, and using the factors from Table C2 this would correct to 230 at 2% (he obtained 243) and 200 at 27% (he obtained 205).

The Burmester study included a point at 150%, well above the FSP. This indicates that longitudinal stress wave velocity decreases as moisture rises above FSP. The decrease is very small, about 0.2 inches/millisecond for each percent above fiber saturation. He did not assert that this relationship was

Table C1. Speed of Sound and Young's Modulus Averaged for Each Temperature and Moisture Content (James)

Moisture content	Gross[1] density	Speed of sound parallel to the grain[2]						Young's modulus parallel to the grain[3]					
		0° F. 10^3 in. per sec.	38° F. 10^3 in. per sec.	80° F. 10^3 in. per sec.	120° F. 10^3 in. per sec.	160° F. 10^3 in. per sec.	200° F. 10^3 in. per sec.	0° F. 10^6 p.s.i.	38° F. 10^6 p.s.i.	80° F. 10^6 p.s.i.	120° F. 10^6 p.s.i.	160° F. 10^6 p.s.i.	200° F. 10^6 p.s.i.
1.8	0.433	2.23	2.20	2.16	2.14	2.12	2.09	2.16	2.10	2.02	1.98	1.95	1.89
3.9	.438	2.22	2.18	2.15	2.12	2.10	2.07	2.16	2.08	2.02	1.97	1.93	1.88
7.2	.448	2.18	2.14	2.11	2.07	2.06	2.02	2.09	2.05	2.00	1.92	1.88	1.83
12.8	.424	2.17	2.13	2.10	2.07	2.04	2.00	2.00	1.92	1.87	1.82	1.76	1.70
16.5	.488	2.12	2.08	2.04	2.00	1.96	1.91	2.19	2.11	2.03	1.95	1.57	1.78
23.7	.494	1.99	1.96	1.92	1.85	1.82	1.74	1.96	1.90	1.82	1.69	1.64	1.50
27.2	.532	1.96	1.91	1.88	1.80	1.77	1.69	2.04	1.94	1.88	1.72	1.67	1.52

[1]Computed from (SG) (1+MC) (k), where SG is the average specific gravity. MC is moisture content in decimal form, and k converts specific gravity into units of mass per unit volume in a system where inches, pounds, and seconds are the respective units of length, force and time.
[2]Computed from the average length and resonant frequency of each group at each condition.
[3]Computed from the average density and speed of sound of each group at each condition.

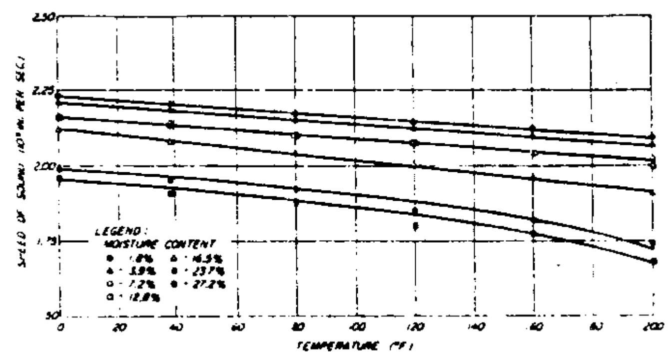

Figure C1. Plot of the Speed of Sound in Douglas-fir as a Function of Temperature for Various Levels of Moisture (James)

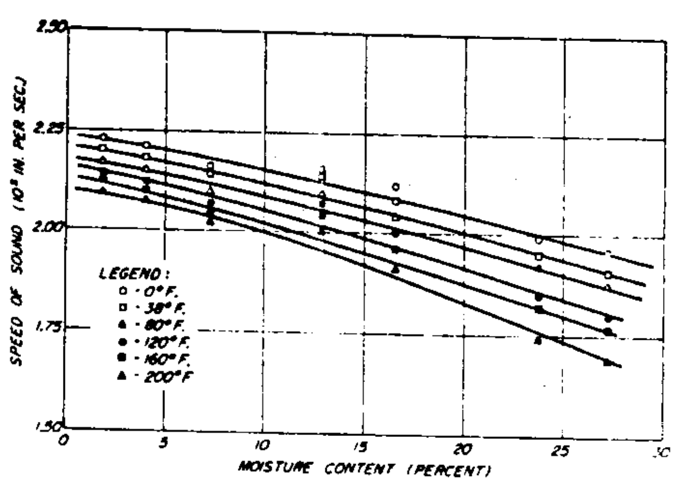

Figure C2. Plot of the Speed of Sound in Douglas-fir as a Function of Moisture Content for Various Temperatures (James)

Table C2. Stress Wave Velocity Adjustment Factors for Temperature and Moisture for Douglas-fir

Moisture Content %	Temperature °F 0	38	80	120	160	200
1.8	1.060	1.048	1.029	1.019	1.010	0.995
3.9	1.057	1.038	1.020	1.010	1.000	0.986
7.2	1.080	1.020	1.004	0.986	0.976	0.962
12.8	1.030	1.014	1.000	0.986	0.971	0.952
16.5	1.010	0.990	0.971	0.952	0.933	0.910
23.7	0.948	0.933	0.914	0.881	0.866	0.829
27.2	0.933	0.910	0.895	0.857	0.840	0.805

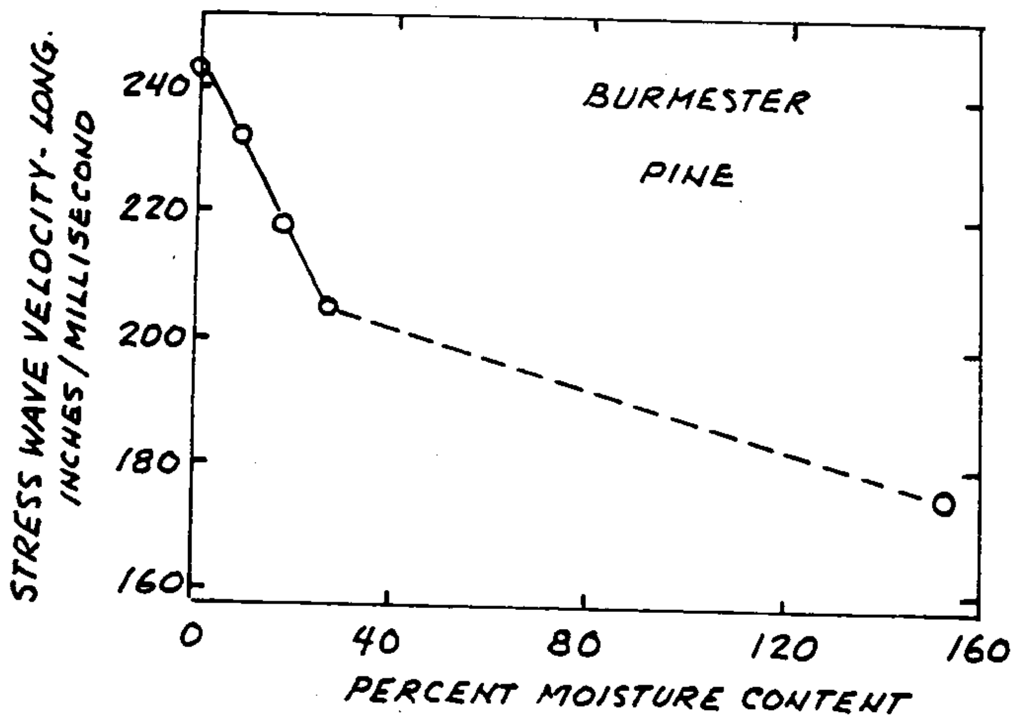

Figure C3. Longitudinal Stress Wave Velocity vs. Moisture Content in Pine (Burmester) linear, hence the dashed line in his graph. Other studies shows that it is not linear, but falls at a diminishing rate with increasing moisture content.

Gerhards' [1975] investigation on sweetgum (liquidamber styraciflua), a common species of hardwood found in the southern United States, is of interest mainly because of the paucity of any data on moisture effects. Sweetgum is not commonly used in structures which might require inspection. Its density and elastic properties are similar to interior Douglas-fir and loblolly (a southern) pine. Gerhards' curve is presented in Figure C4. His specimens were 96-inch long 2 by 4's. He used a stress wave timer like the Metriguard instrument, with similar accelerometers, for a longitudinal pulse.

Our Table C2 adjustment factors do not fit these sweetgum results. Sweetgum is a diffuse-porous hardwood and unlike the softwood species to which Table C2 adjustments appear reasonable.

Gerhards defines the stress wave velocity changes in the wet region, showing the change to occur at a diminishing rate with rising moisture content. He shows the same amount of change as Burmester (30 inches/millisecond from FSP to 150% moisture content). But most of this change occurs between FSP and 80%, very little thereafter.

This reduction in stress wave velocity at moisture levels above fiber saturation seems inconsistent with the commonly accepted idea that no volume or property changes occur in this range. Gerhards suggests possible moisture content gradients in his specimens might offer an explanation, but his method does appear to have been carefully executed and the conditioning carefully done. Perhaps the added weight of free water in the cell cavities, even though not affecting cell wall properties, does act as a mechanical impedance which shows up in dynamic measurements but not in static tests. In any event we must note and acknowledge these observations.

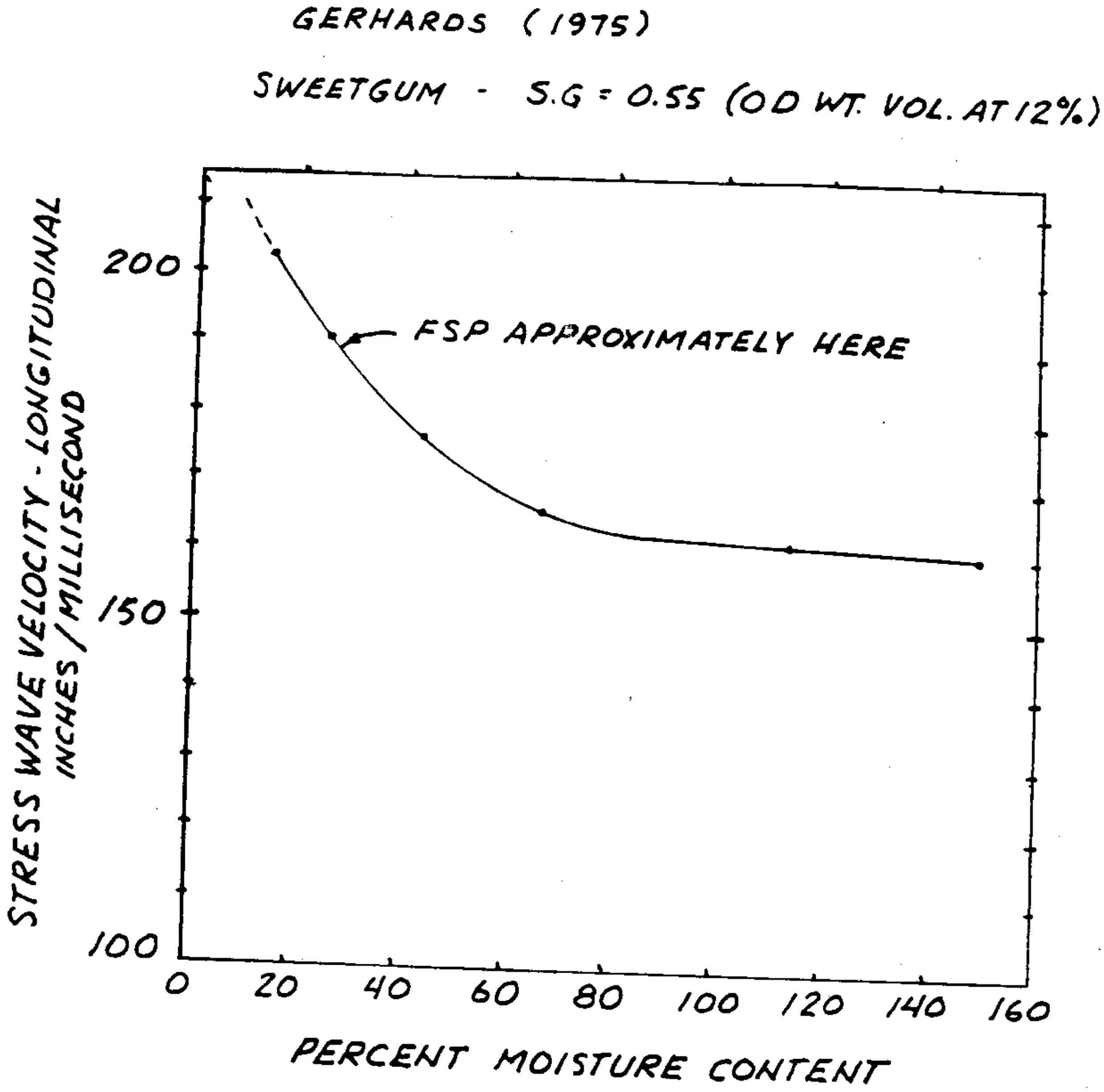

Figure C4. Longitudinal Stress Wave Velocity vs. Moisture Content in Sweetgum (Gerhards)

As a matter of further interest we include Figure C5 showing static bending elastic modulus obtained by applying a load at midspan with a span-depth ratio for the member of about 60. At this large value these elastic moduli should be very close to the true E. In the hygroscopic range (0 to FSP) the ratios of static to dynamic E are a little higher than we assumed in our theoretical computations of expected stress wave velocities, in Appendix A.

Gerhards obtained the upper curve in Figure C5, computing dynamic E from his stress wave velocities and density determinations. By omitting the weight of free water in computing, we modified his curve, to obtain the dashed line. Our choice of a fiber saturation was speculation, and is subject to question, but the general effect is interesting. We could find nothing in the technical literature on sweetgum FSP.

As a part of the current work, we studied the effect of temperature on four pieces of Douglas-fir lumber, 2 by 10 by 30 inches long. Velocities were measured longitudinally and transversely at 33, 70 and 110°F. The moisture content at 33 and 70°F was about 8%. At 110°F it was probably close to oven dry. The results are in Table C3. Figure C6 also shows these results. If the wood had not dried out in a substantial way (as it must have done, at 110°F) the stress wave velocity at that temperature would have been lower. The numbers in parentheses in Table C3 are adjusted values to 8% moisture at 110°F.

Aggour and Ragab [1982] produced a very useful study of piling using the stress wave technique. They examined piling, piling sections both treated and untreated, and small beam specimens cut from piling. Their research is very relevant and we cite some of their results on moisture content effects.

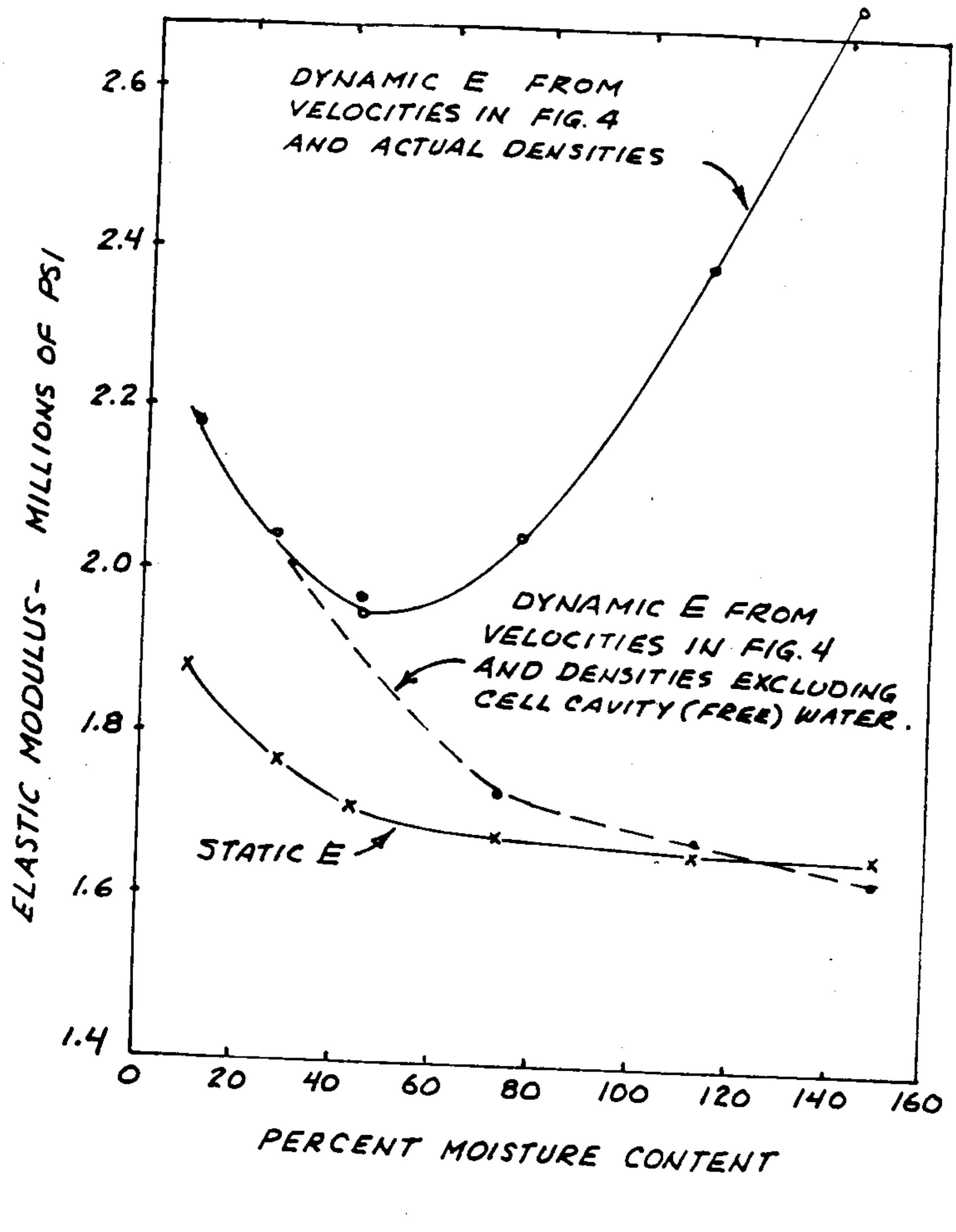

Figure C5. Dynamic Elastic Modulus by Stress Wave Measurement and Static Elastic Modulus (Gerhards)

Table C3. Stress Wave Velocity vs. Temperature for a Douglas-fir Sample

Temperature °F	Specific Gravity	Moisture Content %	Longitudinal SWV in/millisec	Longitudinal Dynamic MOE 10^6 psi	Transverse SWV in/millisec	Transverse Dynamic MOE 10^6 psi
33	0.48	12	214	2.04	71	0.23
70	0.48	12	205	1.87	67	0.20
110	0.47	0	205 (198)	1.84	65 (63)	0.19

Note: Numbers in parentheses are values adjusted to 8% moisture content.

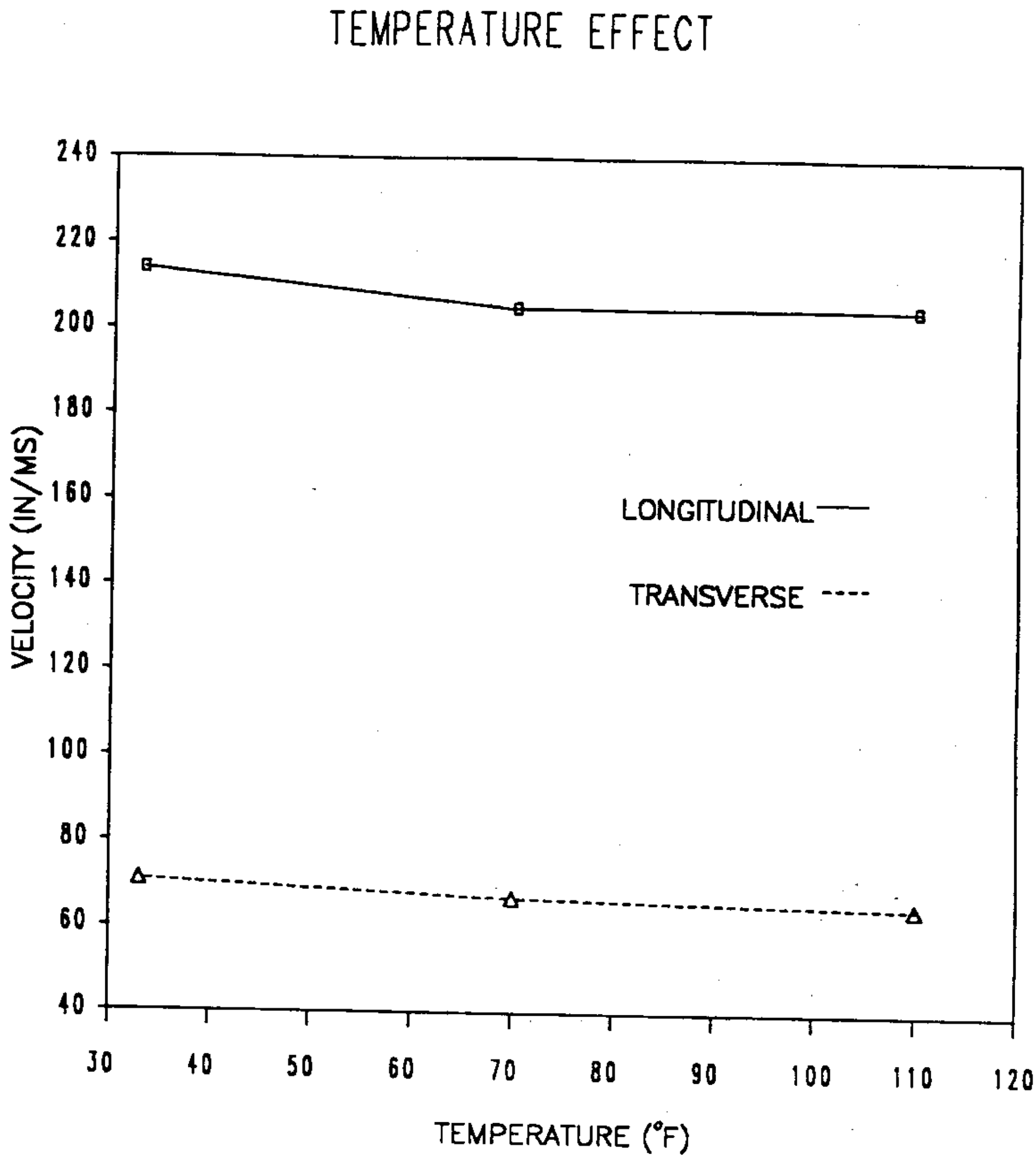

Figure C6. Effect of Temperature on Stress Wave Velocity in Douglas-fir

They used the James V-Meter with the piezoelectric pulsing unit and accelerometers. Their results were both longitudinal and transverse with transverse results tending to be radial velocities, owing to the circular shape of their research material.

Figure C7 shows their longitudinal stress wave velocities. The values for untreated red oak and southern pine are lower than our theoretical values. This may be a coupling characteristic of the James V-Meter transducers. Other than that, the shape of their curves support the findings of James and Burmester. Their southern pine values are lower than those of red oak. We would have expected them to be higher.

The longitudinal stress wave velocities in Figure C7 for untreated southern pine are about 15% greater than those for the southern pine treated with creosote solution to retention of about 10 lbs per cubic foot. We measured the velocities in southern pine lumber at 12% moisture content, then again after the specimens were treated with Penta in light petroleum solvent to a retention of 8 lbs per cubic foot and found that the velocities (in all the directions to grain) were 5% to 6% less for the treated material.

Figure C8 shows results for transverse stress wave velocities. It does not appear that the differences in treated and untreated southern pine is of much consequence for transverse paths of wave travel.

Aggour and Ragab obtained values of dynamic E by calculation from density and velocity data, shown in Figures C9 and C10, very much like those of Gerhards in the range above FSP. By discounting the free water in the cell cavities, we plotted the dashed lines. The loss of velocity with rising moisture content above FSP confirms Gerhards results for longitudinal wave paths. In the case of transverse paths the effect is present but small.

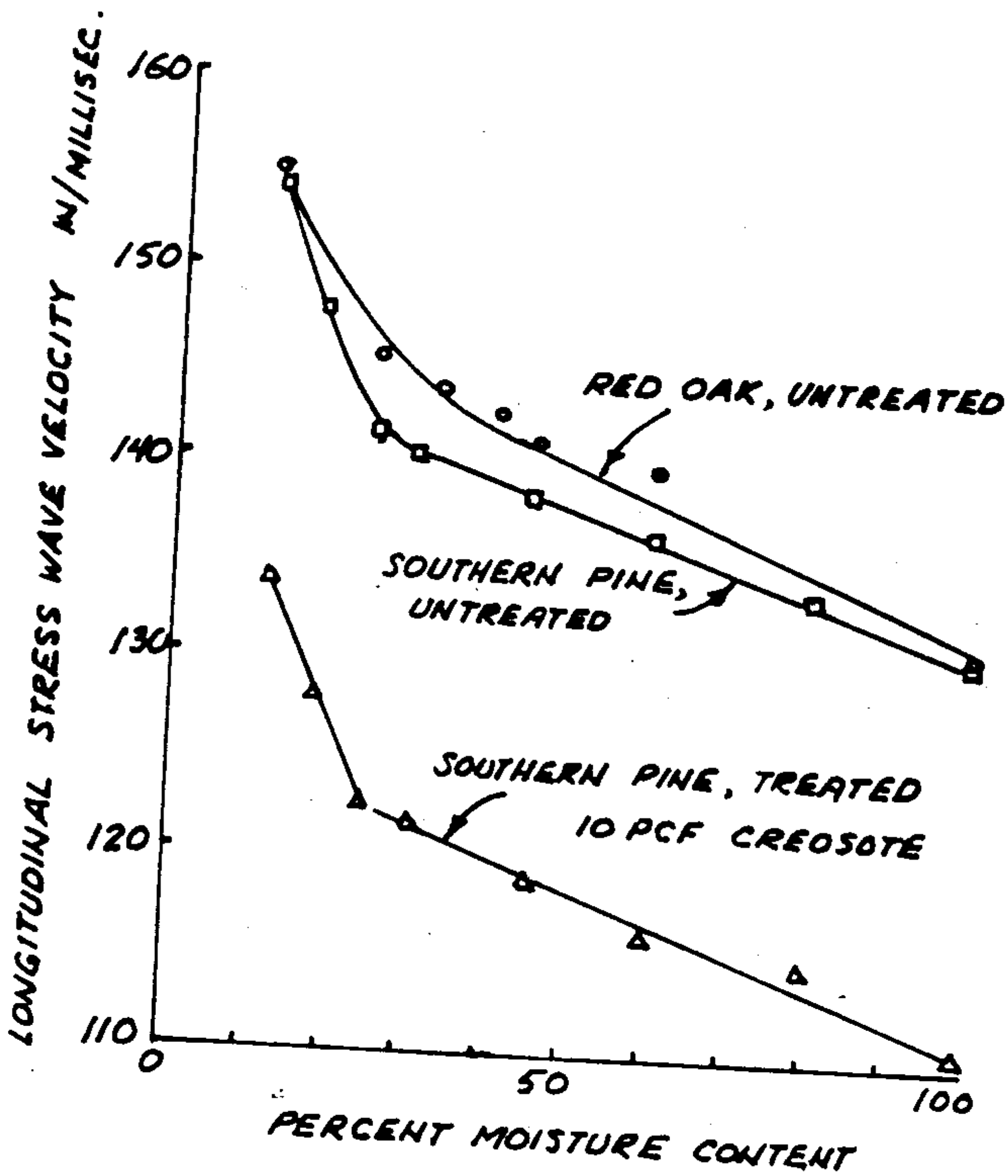

Figure C7. Longitudinal Stress Wave Velocity in Southern Pine and Red Oak Piling (Aggour and Ragab)

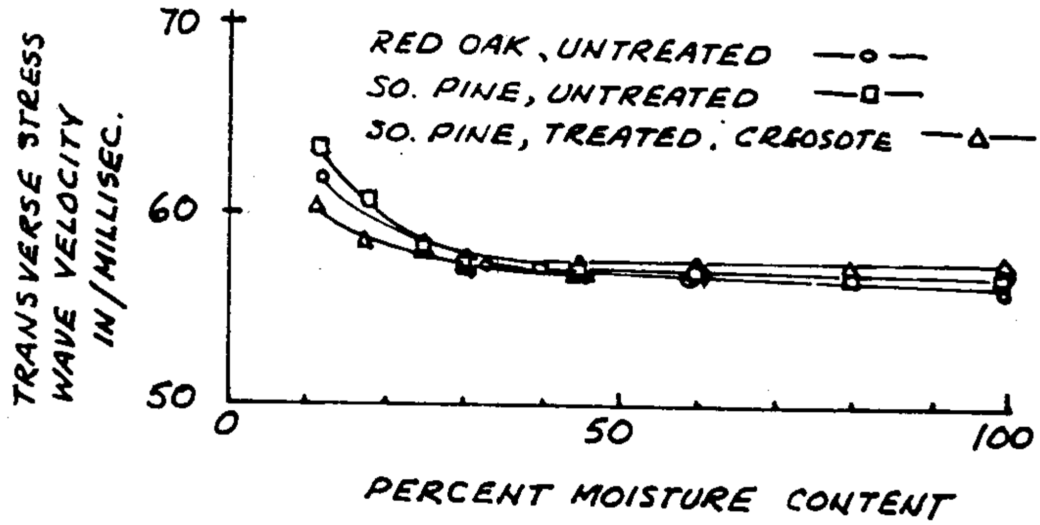

Figure C8. Transverse Stress Wave Velocity in Southern Pine and Red Oak Piling (Aggour and Ragab)

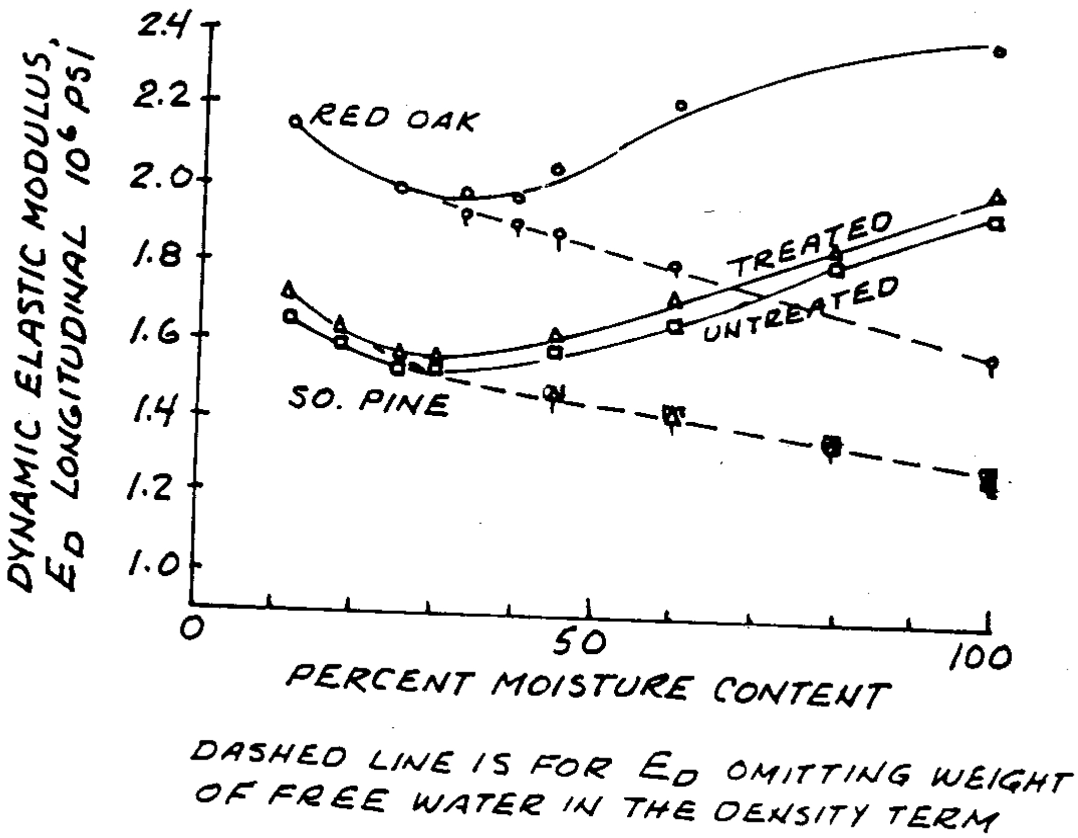

Figure C9. Longitudinal Dynamic Elastic Modulus, Southern Pine and Red Oak Piling (Aggour and Ragab)

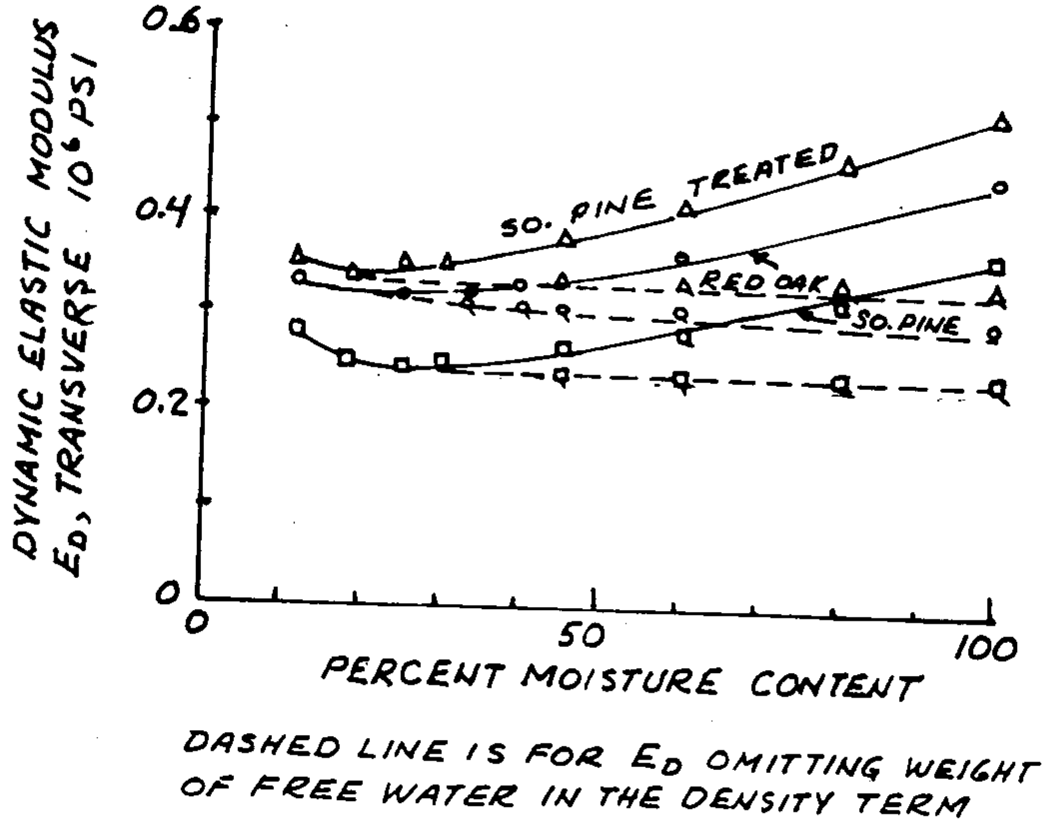

Figure C10. Transverse Dynamic Elastic Modulus, Southern Pine and Red Oak Piling (Aggour and Ragab)

Most inspection work will be accomplished by measuring velocities at 90° to the grain direction. The effect of moisture content above fiber saturation is almost too small to cause any misinterpretation of findings when decay is present.

In the range below fiber saturation for structures not immersed in water, the correction factors in Table C2 will be useful.

Treated wood should show velocities about 15% lower than sound untreated wood values for creosote and 6% less for Penta in light oil.

For water-borne salt treatments we do not believe there will be any significant effect of the treatment on the velocity. Wood so treated will be slightly wetter than untreated wood in the same environment, due to the hygroscopic nature of the salts. If much work is to be done on salt treated highway structures, some further study of the moisture effects and treatment effects might be desired. Usually for highway structures, oil-borne treatments or creosote are the preferred treatments because of their resistance to excessive air drying and attendant checking of the large members.

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APPENDIX D

EFFECT OF PRESERVATIVE TREATMENT

We prepared six specimens of southern pine, each 7/8 by 1½ by 38¼ inches long. We cut these from a large 44 by 48 inch edge glued panel cut so the grain direction were at 0°, 10°, 22.5°, 45°, 67.5° and 90° to the specimens long axis.

The material was conditioned to 12% moisture content. The stress wave velocity was measured for each piece at these conditions. The pieces were then immersed in a tank of Penta dissolved in light petroleum solvent (Diesel oil) for sufficient time to produce good penetration of the treating fluid. Because of the end-grain exposure and the sapwood content of the pieces we were able to obtain good penetration without the use of heat or pressure. The retentions are listed in the tables.

Upon completion of the treatment the stress wave velocity was measured immediately after removal from the treating solution and again, after two days of draining and evaporation at room temperature.

The results appear in Table D1. The effect of the treatment was to reduce the stress wave velocity about 8%. The amount of retention did not have a distinct effect on this reduction. Evaporating and draining off of the excess treating fluid apparently did not affect the amount of fluid in the

Table D1. Effect of Penta Treatment on Stress Wave Velocity in Southern Pine Wood at 12% Moisture Content and 70°F

			Freshly Treated			Treated after Drainage & Evaporation		
Grain Angle Degree	Density Untreated lbs/in^3	Velocity Untreated in/ms	Retention pcf	Velocity in/ms	SWV Change in %	Retention pcf	Velocity in/ms	SWV Change in %
0	0.0186	205	5.1	194	-5	2.9	191	-7
10	0.0184	156	9.5	139	-11	6.4	142	-9
22.5	0.0189	125	7.2	116	-7	4.6	119	-5
45	0.0222	85	7.3	78	-8	4.6	81	-1
67.5	0.0217	58	8.6	54	-7	5.6	57	-1
90	0.0215	50	8.2	47	-6	5.6	49	-2

in/ms = inches per millisecond; pcf = pounds per cubic foot cell wall substance of the wood. It is known that petroleum solvents do not have the same effect on properties that is caused by water, probably because it does not form hydrogen bonds with the cellulose.

The retention of treating fluid should not affect the static E of the wood. It may affect the dynamic value because a greater mass must be accelerated by the stress wave impulse.

Table D2 lists computed dynamic E using the stress wave velocity and density of the treated and untreated wood. We have not perceived any large effect of treatment on the dynamic E, only a tendency to increase with increasing density. Possibly, in the course of evaporation and drainage, some moisture was lost, thereby accounting for a small increase in elastic properties for the larger grain angle specimens, because of the large amount of end-grain exposure.

Research on treatment effects could provide a better understanding of this process. We have found very little of this in the relevant literature. It is probably not justified in terms of the objective of this project.

Water-borne salts (CCA, Wolman salts, Boliden salts, etc.) have little effect on stress wave velocities in sound wood. The weight of retained salt after these treated timbers have been dried is very small. Salts do have an affinity for water and will shift the equilibrium moisture content of the wood upward a few percent. Effects would be conventional moisture effects.

Table D2. Effect of Treatment on Dynamic Modulus of Elasticity

Grain Angle Degree	E_D Untreated 10^6 psi	Retention pcf	E_D 10^6 psi	Retention pcf	E_D 10^6 psi
0	2.023	5.1	2.084	2.9	2.067
10	1.159	9.5	1.185	6.4	1.143
22.5	0.764	7.2	0.797	4.6	0.781
45	0.415	7.3	0.413	4.6	0.418
67.5	0.189	8.6	0.199	5.6	0.206
90	0.139	8.2	0.149	5.6	0.152

APPENDIX E

THE EFFECT OF DECAY ON STRESS WAVE VELOCITY

Experience using the stress wave velocity method has shown that decayed material displays a very low velocity. Transverse wave travel paths give more reliable results, but, with good attention to correct technique either longitudinal or transverse measurements can be effective. High stress wave travel times of course, correspond to low stress wave velocity.

In 1978 Hoyle and Pellerin reported their use of the method for locating decayed regions in the exposed ends of glued-laminated arches in school buildings. These were Douglas-fir arches and they were not treated with any wood preservative. They were 5½ inches wide and 22½ inches deep. A Metriguard Stress Wave Timer was employed. The impulse was generated by a light blow from a hammer which had an accelerometer firmly attached to the head. A second accelerometer was fitted with a hand grip so it could be held firmly against the wood member. We employed this method on the ends of 38 arches, for distances from 5 to 12 feet from the ends, predetermined to be the problem area. Stress wave time was measured transversely, through each lamination, and plotted as in Figures E1 and E2. These values of velocity are a little higher than suggested, because, at the time this work was done, we had not learned to set the "Gain" correctly. Repairs were ordered on the

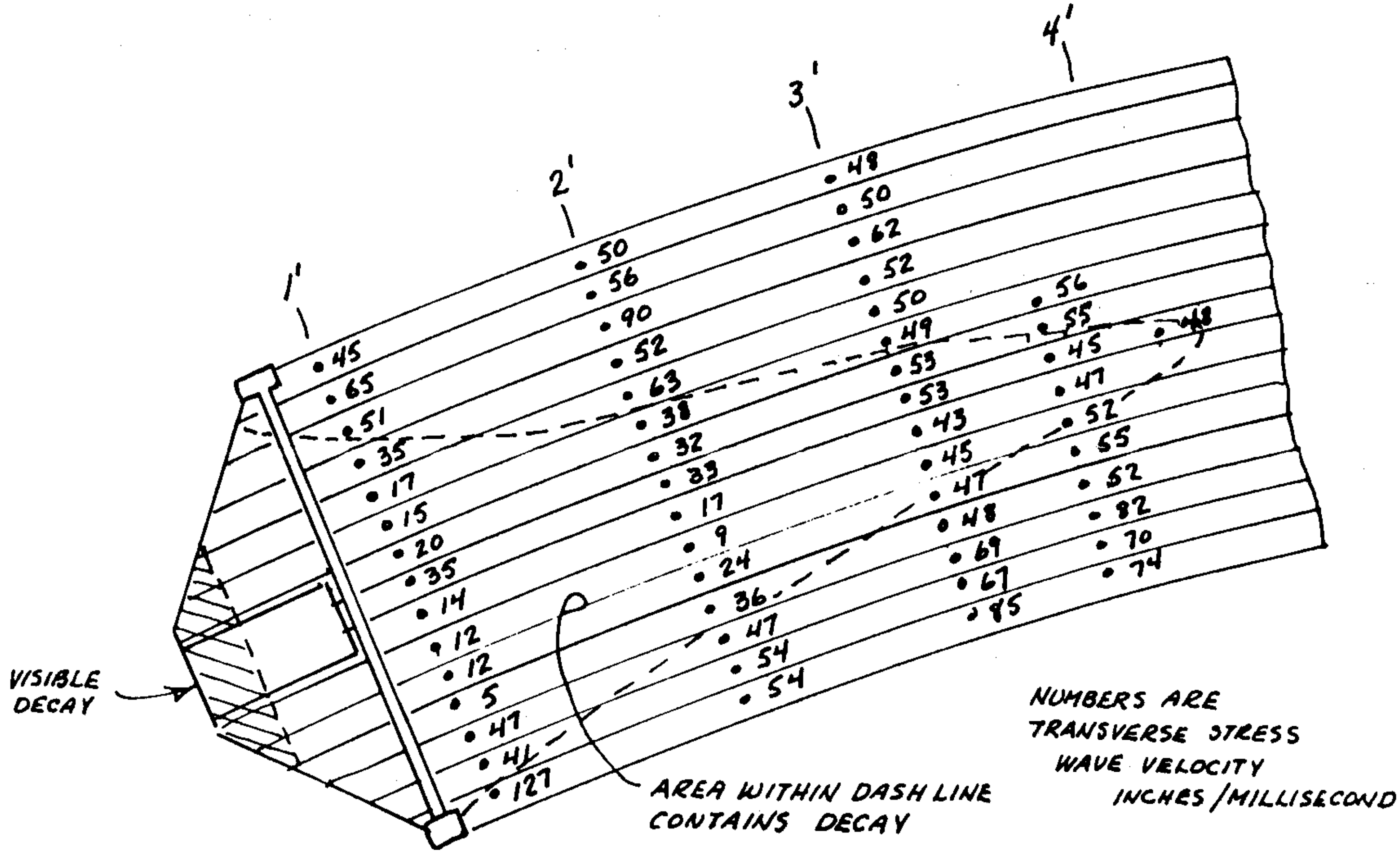

Figure E1. Transverse Stress Wave Velocities in Decayed Glulam Timber (Hoyle and Pellerin)

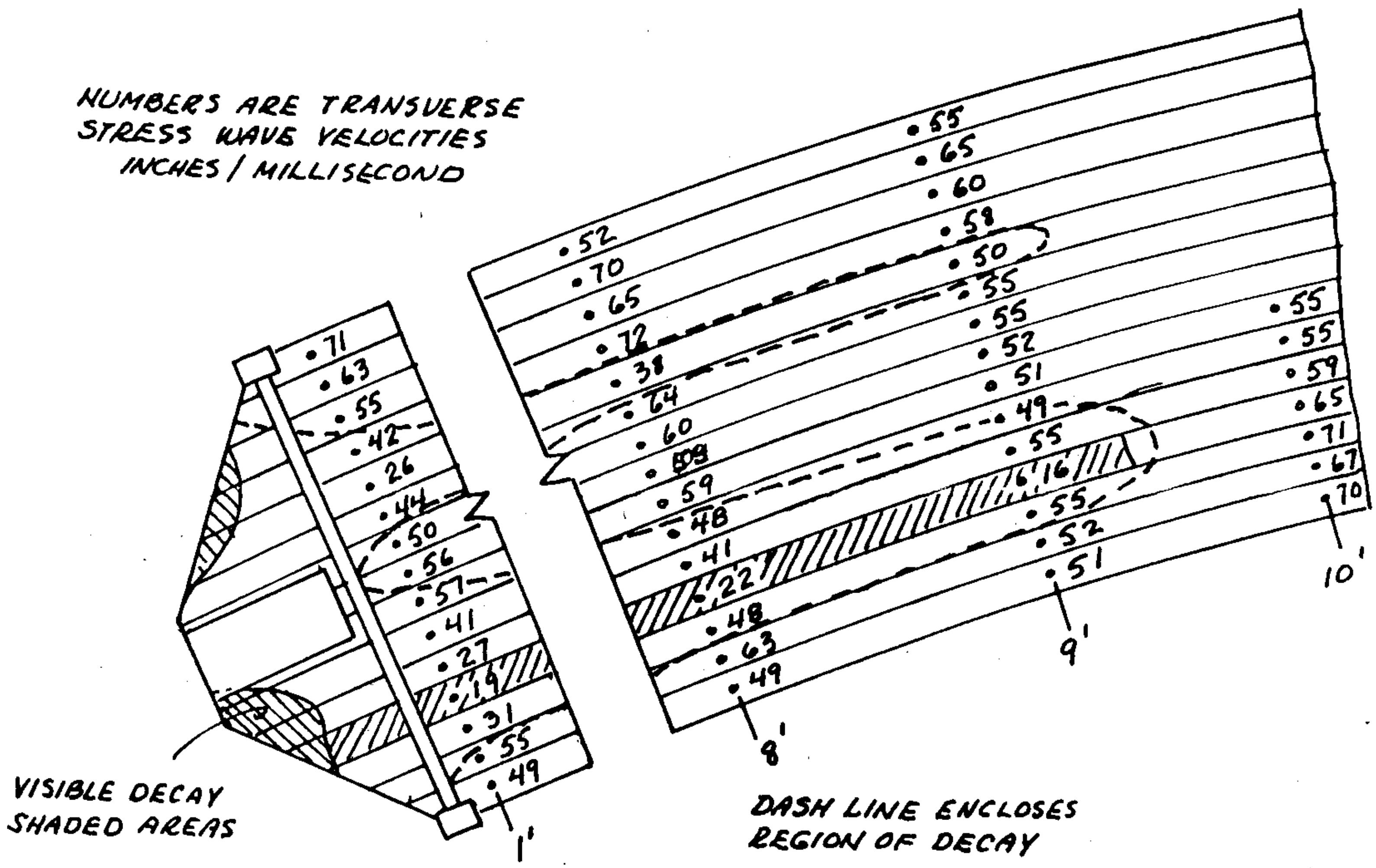

Figure E2. Transverse Stress Wave Velocities in Decayed Glulam Timber (Hoyle and Pellerin) basis of these results and inspection of the material removed and replaced showed that decayed areas were accurately located.

Velocities less than 50 inches/millisec. were considered to imply decay, and the degree of decay correlated inversely with the velocity (directly with the travel time). The transverse velocity readings for sound wood at 12% moisture content is, theoretically, about 46 inches/millisec. Figures E1 and E2 show how we identified the decayed regions.

In 1986 eighty-four bridge timbers [Hoyle, 1986] were inspected with similar equipment. At the time the gain settings were set somewhat differently than in the school inspection project and it was determined that stress wave velocities of 25 inches/millisec or less would imply decay. The members were solid sawn Douglas-fir treated with creosote in oil, to a penetration of 1 to 1½ inches. The structure had been in place for over 30 years.

The vast majority of readings were 40 to 70 inches/millisec. transversely through the 10-inch width of these 10 by 20 inch beams. Readings of less than 25 inches/millisec did show decay, rather minor at 20, and very severe at 10 inches/millisec.

Figure E3 shows a severely decayed and insect damaged section which was measured with results shown in Figures E4 and E5. The transverse readings in Figure E4 correlated well with the damage. The longitudinal readings in Figure E5 illustrated the superiority of the transverse wave readings. With the impulse applied at the center of the decay-free end (point 0) and received at points A, B, C and D we obtained sound wood indications for paths OB (186) and OC (219), and questionable readings for wood quality at OA (132) and OD (108). These longitudinal readings did not discern the damage nearly as well

Figure E3. Insect and Decay Damaged Douglas-fir Bridge Stringer

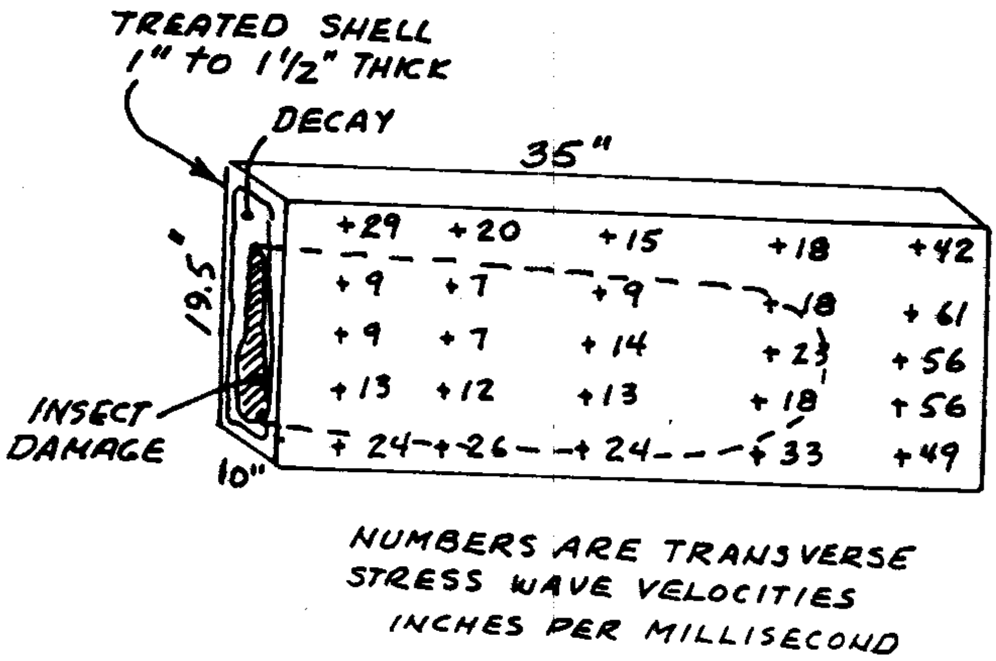

Figure E4. Transverse Stress Wave Inspection of Douglas-fir Timber With Decay and Insect Damage

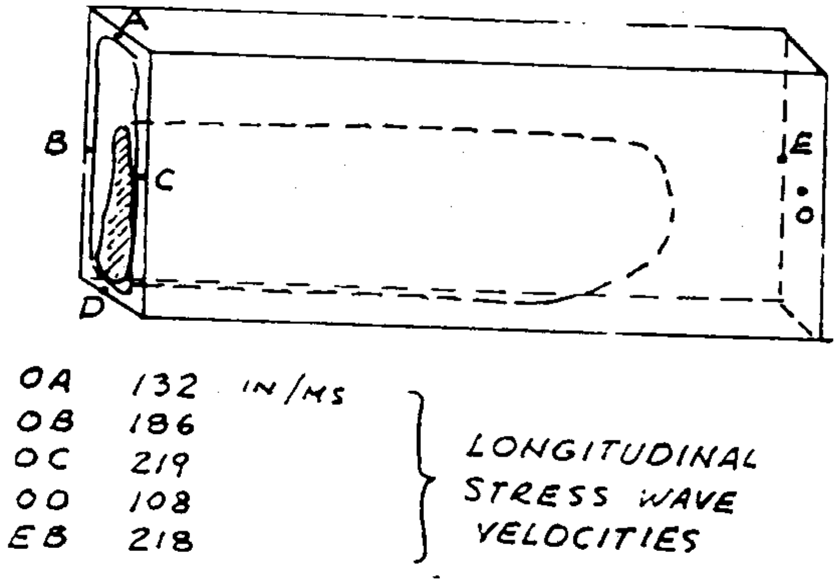

Figure E5. Longitudinal Stress Wave Inspection of Douglas-fir Timber With Decay and Insect Damage as the transverse values. The stress wave by-passed damaged areas when a direct path through good wood was open to it.

Field experience has shown that deep seasoning checks (splits) can cause low velocity readings (high travel times) which appear to be simply forcing the stress wave to follow a circuitous route from one accelerometer to the other. This may suggest decay when none exists, especially in large timbers or pilings. These checks are usually visible. By moving the accelerometers so the path of the wave is not interrupted by the seasoning check it can be determined whether the cause of the low velocity is the check or decay.

Decay has two effects. One is a reduction of the elastic modulus of the wood. The other is a decrease in density. If these effects were proportional to on the another the ratio E/ρ would be unchanged by the decay and the stress wave method would not show any velocity loss in the presence of decay. Fortunately these two effects are not proportional. Elastic modulus loss proceeds much more rapidly than weight loss.

Based on data by Wang, et al. [1980] it can be shown that a 14% loss in density would be accompanied by a 70% loss in elastic modulus. This would correspond to a 40% loss in velocity by the stress wave method.

Pellerin and Vogt [1986], and Pellerin, et al. [1985], carried out a detailed study of the effect of decay and termite damage on stress wave velocity. This work, completed in 1986, was sponsored by the U.S. Forest Products Laboratory, which prepared the decay and termite damaged specimens in their labs. They used 500 specimens of southern pine wood, 3/4-inch square by 12 inches long, conditioned to an initial moisture content of about 9%.

One group of 150 specimens was exposed to decay by the brown-rot fungus, Gloephyllum trabeum. Another groun 175 specimens was exposed to damage by subterranean termites. The remaining material was used for controls. During the exposure periods, 25 specimen sample lots were withdrawn at intervals and evaluated by longitudinal stress wave measurements and mechanical compression parallel-to-grain tests. The results are presented in Table E1 and Figure E6.

The decay process requires moisture levels above 19%, as does the termite degradation process. The exposure procedure is conducted in the presence of moisture which raises the wood to a moist condition favorable to the fungi and termites. Pellerin and Vogt computed dynamic elastic modulus values using stress wave velocities as measured, and the initial density of the specimens because they found that dynamic elastic modulus determined in this way provided a better correlation with deterioration in terms of weight loss. In presenting their results we have used the actual density rather than the initial density for our dynamic values. Pellerin and Vogt also measured the stress wave velocity at the decay moisture content, and made compression tests after reconditioning to 9%. Since "in situ" structures cannot be "conditioned" for inspection, we have used their unconditioned stress wave velocity determinations in this discussion.

Figure E6 reveals an initial velocity reduction which must be due partly to the moisture gain to induce decay, and partly due to the decay fungi attack on the wood substance. Southern pine at 25% moisture content would be close to fiber saturation and, if undecayed, would display a stress wave velocity of around 170 inches/millisec. This explanation notwithstanding, Figure E6 shows a high initial loss in velocity for a relatively small weight loss. Wang, et al., observed a similar rapid initial elastic modulus loss with little weight loss, and the calculated velocity loss from their data would be equally rapid.

Figure E7 also shows the initial rapid change in dynamic elastic modulus, not entirely explained by moisture change. The compression strength and

Table E1. Longitudinal Stress Wave Velocity and Weight Loss Due to Decay and Termite Attack (Pellerin and Vogt)

Decay				Termite Attack			
Percent Weight Loss	SWV in/ms	Dynamic MOE 10^6 psi	Ultimate Compression psi	Percent Weight Loss	SWV in/ms	Dynamic MOE 10^6 psi	Ultimate Compression psi
0	211	2.05	6,745	0	173	1.55	8,609
0.6	151	1.04	4,770	5.2	173	1.47	9,529
8.7	144	0.87	3,226	8.0	177	1.49	8,992
27.2	93	0.29	467	9.6	178	1.48	8,007
36.1	70	0.14	295	17.0	176	1.33	5,342
43.1	66	0.11	443	30.6	177	1.13	2,480

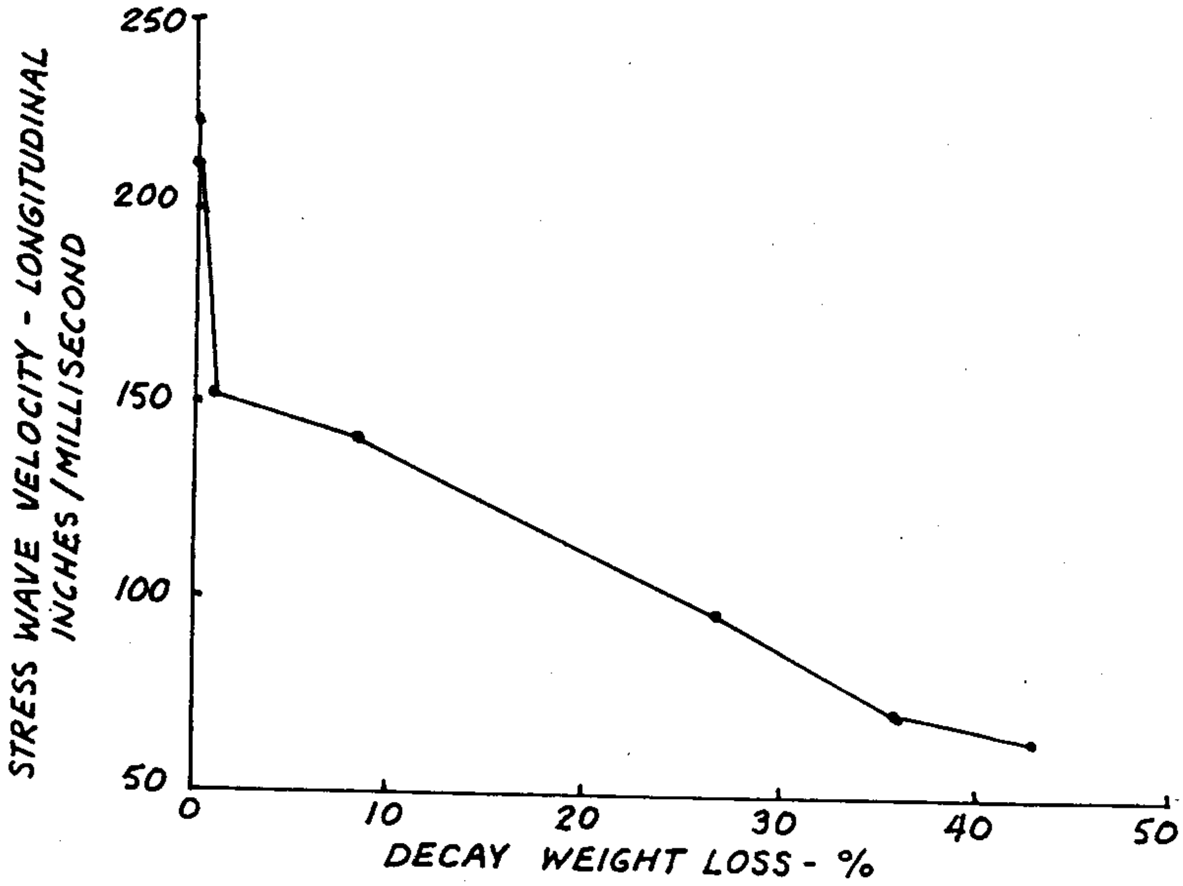

Figure E6. Weight Loss vs. Longitudinal Stress Wave Velocity (Pellerin and Vogt)

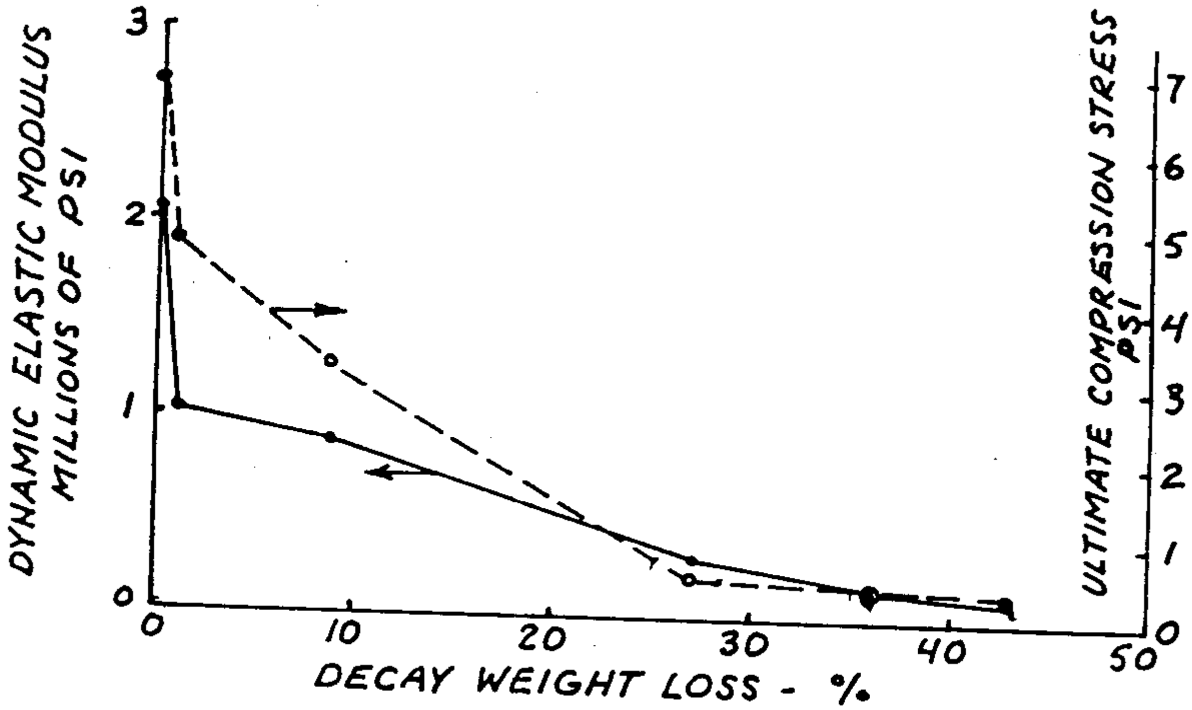

Figure E7. Weight Loss vs. Dynamic Elastic Modulus and Ultimate Compression Strength Parallel to Grain (Pellerin and Vogt) dynamic modulus of elasticity curves fall to lower values as decay weight loss proceeds, in a tandem manner. Thus, it is evident that the effect of decay on stress wave velocity is a consequence of changes produced in both E and ρ.

A 50% drop in stress wave velocity at 9% moisture content would imply a very seriously decayed condition with only a 25% weight loss. An 80% reduction in elastic modulus and an 85% reduction in compression strength would accompany this velocity loss.

A 25% reduction in stress wave velocity accompanies a very small weight loss, but a substantial strength strength and stiffness loss. Allowing for a 25% moisture content of the decaying material, the reduction due to decay would be 70% in elastic modulus and compression strength.

It is rarely possible to conveniently determine weight loss by field inspection methods.

We could anticipate similar effects of decay on stress wave velocity across the grain. To test this assertion another study like that of Pellerin and Vogt has been conducted as a part of this project (see Appendix G). In that study only the effects of brown-rot fungus (not termites) were examined. The species was Douglas-fir. The specimens have been made with the grain oriented at 90° to the long axis, so that transverse stress waves may be applied in the long specimen direction. Appendix G shows that the SWV in decayed wood is less across than along the grain. Sound wood tested in the radial and tangential directions displayed SWV's of 40 to 50 in/ms., while the SWV at 45 degrees to the annual rings was 25 to 30 in/ms. For moderate decay the SWV along tangential and radial paths was 30 to 40 in/ms and 20 to 25 in/ms at 45 degrees to the annual rings. For severe decay tangential and radical velocities were about 20 or less, and there was not a great difference between this and the 45 degree direction. Fifteen in/ms is certainly indicative of a very severe decay problem.

Termite damage in Pellerin and Vogt's study, had little effect on stress wave velocity according to the results shown in Table E1. The termite damage occurred primarily in the low density earlywood (spring-wood) portions of the annual rings. It is apparent that the compressive strength and stiffness are affected by the termite attack but to a lesser degree than the brown-rot fungus decay. The stress waves are able to propagate through the more or less intact latewood (summerwood) even though the earlywood has been extensively degraded. The extent to which this insensitivity of longitudinal stress wave velocity to termite damage might occur for the transverse direction is not known. In the field observations on the carpenter ant damaged Douglas-fir bridge stringer, mentioned previously, the transverse velocity was markedly affected by the insect damage. Hunt and Garratt [1938] note that carpenter ants preferentially attack earlywood, as do the termites. A study of insect damaged wood's reaction to transverse stress waves is desirable to clarify this matter.

As part of the current project, a section of Douglas-fir bridge timber which had been in ground contact and was partially decayed, was examined in detail. The member was approximately 12 by 12 by 27 inches long. Its gross density was 29.3 lbs/cubic foot as collected, partially decayed.

Referring Figure E8, measurements were made transversely and longitudinally. The results listed in Table E2 are for the transverse direction.

The timber was then sawed into boards approximately 2 by 12 by 27 inches long and the stress wave velocity was measured in each board, transversely, with results listed in Table E3. The poor condition of boards 5 and 6 is

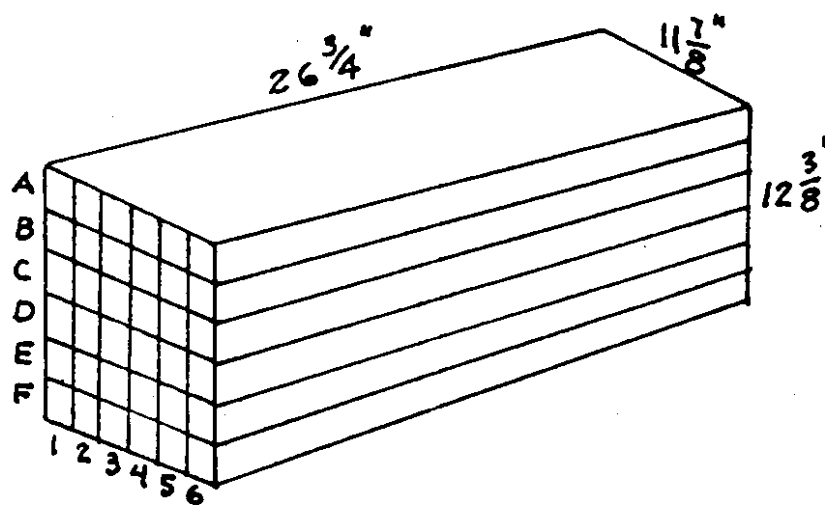

Figure E8. Partially Decayed Timber Used to Develop Information on Longitudinal and Transverse Stress Wave Velocity Options

Table E2. Transverse Stress Wave Velocity in 12 by 12 Douglas-fir Bridge Timber

Path	Velocity in/ms	Path	Velocity in/ms
1-1	31	A-A	11
2-2	30	B-B	22
3-3	27	C-C	14
4-4	20	D-D	13
5-5	6	E-E	7
6-6	3	F-F	20

Table E3. Transverse Stress Wave Velocity in 2 by 12 Boards Cut from 12 by 12 Douglas-fir Bridge Timber

Board	Weight lbs	Stress Wave Velocity (in/ms)		
		Center	End 1	End 2
1	11.3	28	29	15 decay
2	11.8	32	19 split	18 decay
3	11.2	31	16 split	16 decay/split
4	10.8	25	17 split	12 decay
5	10.0	--	--	--
6	6.6	--	--	--

Missing data is for boards too fragile to measure.

reflected in the low velocities obtained for path 5-5 and 6-6 and reported in Table E2. It is evident that the decay in this part of the timber was selectively identified before the timber was cut into boards. The board weights in Table E3 indicate decay increasing in severity toward the bottom board number 6.

Table E4 lists stress wave velocities at various longitudinal paths through the timber before it was cut into 2 by 12-inch boards and after it was cut into 2 by 2-inch sticks. With each reduction in piece size the alternate paths for stress wave travel become more confined. The object of this exercise was to see if this isolation caused any change in the velocities along particular paths.

Velocities in the 2 by 2-inch specimens were measured immediately after cutting from the 2 by 12-inch boards and again, after they had air dried for several days to approximately 12% moisture content.

This timber specimen was about 18% to 22% average moisture content when it was taken from its location on the ground, under the bridge. The piece was partially decayed and in some places where fungi were active, it may have been at the higher end of this moisture content range, while at other places (the exposed top) it probably was less than 15%.

Portions marked 5 and 6 were near the ground contact side and were most badly decayed. When cut into 2 by 12's and 2 by 2's, these pieces tended to fall to pieces, although some of them could be measured with the stress wave timer. Table E4 shows low velocities for some of the portions marked 5 and 6.

A longitudinal velocity for sound wood would be about 185 to 190 inches/millisec. at 15% to 22% moisture content. The velocity in much of this piece showed only 70% of the sound wood value. As with the transverse stress wave measurements, the decay in this member is evident.

Table E4. Longitudinal Stress Wave Velocity in Douglas-fir Timber Containing Decayed Portions: (a) as 12 by 12, (b) as 2 by 12's, and (c) as 2 by 2's

Position of Accelerometers	Stress Wave Velocities (in/ms)					
	12 x 12	2 x 12	2 x 2		2 x 2 Conditioned	
			SWV	WT. LBS	SWV	WT. LBS
A1	188	182	182	1.73	179	1.70
B1	174	170	177	1.87	184	1.79
C1	149	157	157	1.79	167	1.69
D1	135	167	175	1.61	179	1.51
E1	150	178	177	1.66	177	1.59
F1	170	177	185	1.88	180	1.85
A2	192	201	199	1.70	209	1.63
B2	192	205	205	1.89	223	1.72
C2	163	184	191	2.03	204	1.74
D2	141	164	163	1.82	184	1.59
E2	154	170	174	1.72	183	1.58
F2	178	188	182	1.87	183	1.80
A3	148	164	159	1.32	180	1.23
B3	161	177	182	1.54	205	1.33
C3	164	184	182	1.86	199	1.49
D3	163	178	173	2.02	203	1.66
E3	160	180	178	1.78	196	1.61
F3	172	183	183	1.94	189	1.86
A4	166	155	161	1.26	162	1.12
B4	136	155	166	1.50	184	1.19
C4	166	161	167	1.74	202	1.37
D4	143	142	147	1.79	180	1.42
E4	154	161	165	1.89	192	1.59
F4	157	153	---	---	---	---
A5	99	---	89	1.35	104	0.82
B5	88	---	89	2.08	154	0.94
C5	177	---	148	1.77	184	1.28
D5	122	---	---	---	---	---
E5	98	---	88	1.45	81	0.51
F5	160	---	158	1.84	154	1.71
A6	91	---	---	---	---	---
B6	170	---	---	---	---	---
C6	120	---	---	---	---	---
D6	---	---	---	---	---	---
E6	---	---	---	---	---	---
F6	166	---	---	---	---	---

A comparison of velocities taken before and after subdividing the pieces showed that decay detection is as effective in the large size as in the subdivided size.

Aggour and Ragab [1982] compared the properties of decayed and undecayed bridge piling samples, with results shown in Table E5. The stress wave velocities for the decayed samples were about one-half of those for the undecayed samples. This was true both for piling sections 6 to 12 inches in diameter and small specimens approximately on inch square.

The relative dynamic moduli, decayed and undecayed, were one-to-two. The strengths bore the same ratio, one to the other. The small specimens showed a somewhat larger ratio, probably because the decay material in the small pieces occupied their volume more completely. The piling sections usually contained considerable volumes of sound or only slightly decayed wood.

Aggour and Ragab found that there was a difference in longitudinal wave velocities for piling and for 1 by 1-inch specimens. The velocity in the small specimens was about 88.5% of that in the 6 to 12-inch round pile sections.

The effect of decay is pronounced. Even incipient decay has a deleterious effect on stress wave velocity. This has been demonstrated in the laboratory and the field. A 25% reduction in velocity implies a serious decay problem, and severe decay will reduce velocity to 25% or 30% of that displayed by sound wood.

Decay may occur in pockets, spreading from one location to another. This spread is most rapid along the grain. The untreated central cores of timbers and poles may decay leaving the shells of treated wood to propagate the stress waves. Exploratory tests using transverse stress waves at stations distributed along the length of a member, will permit comparative examination

Table E5. Properties of Decayed and Undecayed Southern Pine, Treated With Creosote (12 to 16 pcf) (Aggour and Ragab)

Condition	Piling Sections			1" x 1" x 4" Specimens			
	Velocity Transverse in/ms	Dynamic E_L 10^6 psi	Ult. Comp. Stress psi	Velocity Transverse in/ms	Dynamic E_L 10^6 psi	Ult. Comp. Stress psi	Density lb/in^3
Excellent	---	---	---	72.8 (4.0)	2.22 (0.16)	7,400 (517)	0.023 (0.0009)
Good	58 (7.3)	1.41 (0.13)	2,685 (254)	64.5 (4.5)	1.55 (0.15)	5,320 (495)	0.0183 (0.0017)
Decayed	30 (13.9)	0.66 (0.19)	1,330 (310)	32 (11.5)	0.81 (0.3)	1,585 (775)	0.0115 (0.0025)

Numbers in parentheses are standard deviations.

E_L = longitudinal dynamic modulus of elasticity of decayed and sound wood. Use of this technique is shown in several figures in this appendix.

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APPENDIX F

STRESS WAVE VELOCITY IN TREATED WOOD POLES OR PILING

The preservative treatment of wood poles is a process that has been successfully carried out from the very inception of the wood treating business. The quantity of poles treated exceeds that of any other product. Treated wood poles are used in electric utility structures as poles, in highway bridges and marine structures as piling, and in certain types of buildings as structural framing and foundations.

In highway structures we are interested in inspecting at the ground line and the water line, especially, but also at the pile caps which support the bridge stringers.

We inspected a quantity of poles with various oil-borne treatments at a modern treating plant to gather a body of data on stress wave velocity in these treated materials.

Thirty poles treated with pentachlorophenol in light petroleum solvent were examined near their ends where penetration was completely through the section and at four feet from the ends, where only a shell of wood, perhaps 1½-inch wide, was penetrated.

Table F1 presents the velocities measured through these thirty poles. At the thoroughly treated and penetrated ends the average velocity was 33

Table F1. Stress Wave Times and Velocities for Douglas-fir Poles Pressure Treated with Penta in Oil

Diameter inches	Time - microseconds (Velocity - in/ms) Distance from End					
	6 inches	12 inches	24 inches	36 inches	48 inches	96 inches
9.375*	290 (32.3)	215 (43.6)	235 (39.9)	195 (48.0)	186 (50.4)	
10.25*	385 (26.6)	350 (29.2)	270 (38.0)	225 (45.5)	233 (44.0)	
9.25*	260 (35.5)				200 (46.3)	
8.625*	420 (20.5)				186 (46.3)	
8.625*	330 (26.1)				173 (50.0)	
10.0	240 (41.7)				280 (35.7)	
9.5	370 (25.7)				210 (45.2)	
11.0	350 (31.4)				220 (50.0)	
11.875	330 (36.0)				270 (44.0)	
10.25	570 (18.0)				310 (33.0)	
10.5	285 (36.8)				300 (35.0)	
10.75	260 (41.3)				230 (46.7)	
10.0	285 (35.1)				210 (47.6)	
11.0	385 (28.6)				300 (36.7)	
10.5	310 (33.9)				225 (46.7)	
10.0	310 (32.3)				245 (40.8)	
11.75	338 (34.8)				224 (52.5)	212 (55.4)
12.0	280 (42.8)				205 (58.5)	
11.25	310 (36.3)				240 (46.9)	
10.0	303 (33.0)				270 (37.0)	
10.25	288 (35.6)				195 (52.6)	
11.25	280 (40.2)				220 (51.1)	
10.5	330 (31.8)				225 (46.7)	
11.25	430 (26.1)				280 (40.2)	
10.5	315 (33.3)				220 (47.7)	
11.75	305 (38.5)				220 (53.4)	
10.0	350 (28.6)				250 (40.0)	
10.5	270 (38.9)				260 (40.3)	
11.25	245 (45.9)				210 (53.6)	
9.5	345 (27.5)				265 (35.8)	

*Distances measured from top end.

inches/millisec., and at the partially treated sections four feet from the ends it was 45 inches/millisec. Treatment reduced the velocity by about 37% of the untreated wood stress wave velocity, at the fully penetrated end and by 14% at portions of the poles where end penetration effects were absent. Coefficients of variation of velocity were 20% at ends and 14% at 4 feet from the ends.

Reasons for the variation are understandable. Penetration is never exactly the same along all diameters, due to checks, branch knots and variable sapwood widths. Each test was along a particular diameter. Wood permeability is also variable. The treater endeavors to provide a carefully specified minimum penetration and retention of preservative, and in so doing will treat some poles in excess of this amount.

Moisture content also affects the penetration and the velocity of the stress wave. A moisture content of the shell of the pole may be 12% to 18% and could be greater (usually is) in the center of the pole. Seasoning checks are common and unavoidable. They affect interior dryness and may impede the path of the stress wave through the pole. We attempted, insofar as possible to take measurements in such a way as to permit an unobstructed stress wave path along a pole diameter. Star shaped checking rather limits the avenues of free stress wave travel.

Small diameter poles may contain a greater relative amount of permeable sapwood than larger diameter poles, which can contribute to variability of treated shell width in poles.

Considering the opportunities for variability, these coefficients of variation are considered quite reasonable.

In two of the poles in Table F1 velocities were measured at five locations from the top end, to illustrate the reduced effectiveness of end penetration. These results are only approximate, since there are many variables which have not been entirely sorted out. However, on the assumption of a center moisture content of 18%-20% and an untreated Douglas-fir wood velocity of 52 inches/millisec., and with the velocity at the ends considered to be for completely penetrated wood, rough estimates of penetration are possible. For these two poles these estimates are shown in Figure F1. Let us emphasize that these results may not be perfectly accurate. We could not cut the poles to compare actual penetrations to estimated values, which would need to be done to establish the utility of this technique.

Usually inspectors are examining poles where the penetration is not very deep, except as seasoning checks may provide access to the inner portions of poles by the wood preserving fluid.

Table F1 data show stress wave time at fully penetrated sections to be increased by a factor of 1.59 times that for untreated wood; normally treated penetrations away from the ends increased about 1.16 times that for untreated wood in 10 inch diameter poles. For larger diameters this increase would be less, because the treated portion of the path length is smaller in larger diameter poles. This will be illustrated when we present the data on some 24-inch diameter creosote treated poles.

The effect of decay in the untreated center of a pole, on the velocity of a stress wave through the pole, would be far greater than the effect of treatment on velocity. Hence it should be easy to distinguish decay despite the somewhat similar effect of treating chemicals on stress wave velocity.

Table F2 contains data taken of Penta pressure treated poles, of incised Douglas-fir (coastal variety, as is all Douglas-fir in this report). Incising promotes permeability. The computed penetration for these poles at four feet from the end, was 2.9 inches, showing the desired effect of incising. For the

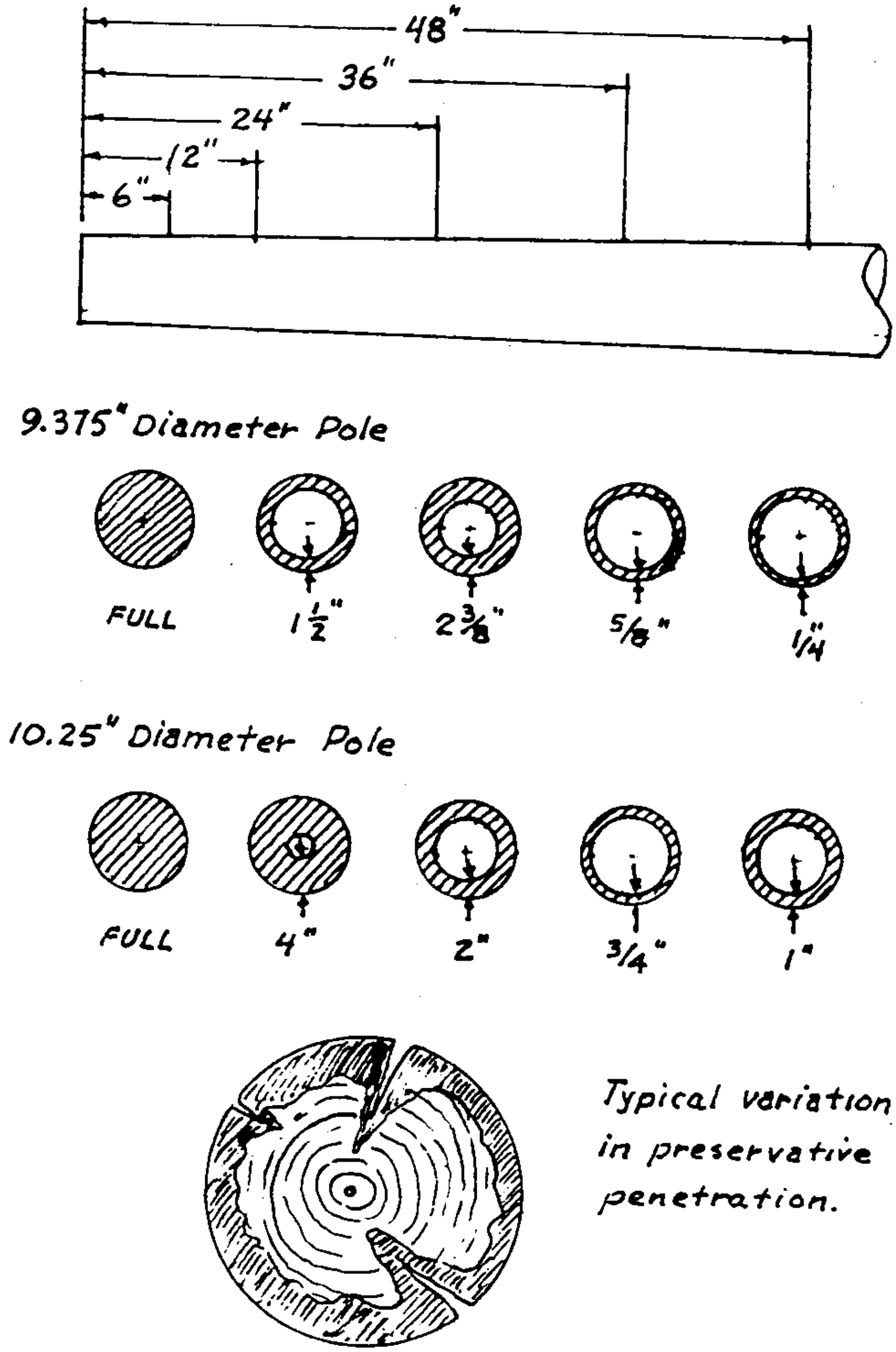


Figure F1. Sketches Showing Preservative Penetration Along the Length of a Pole

Table F2. Stress Wave Times and Velocities for Incised Douglas-fir Poles With Penta in Oil Pressure Treatment at Various Distances from the Butt End

Diameter inches	Time (Velocity) 6 inches	48 inches	Diameter inches	Time (Velocity) 6 inches	48 inches
9.75	316 (30.9)	240 (40.6)	10.5	275 (38.2)	218 (48.2)
11.0	400 (27.5)	300 (36.7)	11.0	345 (31.9)	250 (44.0)
10.5	340 (30.9)	280 (37.5)	10.75	300 (35.8)	280 (38.4)
10.5	330 (31.8)	250 (42.0)	10.0	455 (21.9)	270 (37.0)
10.75	260 (41.3)	255 (42.2)	10.0	400 (25.0)	230 (43.4)
9.75	375 (26.0)	190 (51.3)	10.25	372 (27.6)	258 (39.7)
10.25	390 (26.2)	370 (27.7)	11.25	450 (25.0)	266 (42.3)

Table F3. Stress Wave Times and Velocities for Incised Douglas-fir Poles With Creosote Pressure Treatment at Various Distances from the Butt End

Diameter inches	6 inches from Butt	72 inches from Butt
25.0	520 (48.0)	488 (51.2)
23.5	750 (31.3)	455 (51.6)
23.5	735 (32.0)	550 (42.7)
24.0	535 (41.0)	425 (56.5)

fully treated ends the travel time was 1.69 times that for untreated wood, for a corresponding velocity reduction factor of 0.6.

These poles had an average diameter of 10.4 inches. For poles of a much larger diameter the effect of treatment on velocity would be less. For 16-inch diameter poles with the same penetration the velocity at four feet or more from the end would be increased by a factor of 1.08 times that for 10.4-inch poles and for 20-inch poles by a factor of 1.22. In terms of the untreated wood's stress wave velocity the velocities in 10.4-inch poles at locations away from end penetration effects would by 73%; for 16-inch poles would be 79%; and for 20-inch poles would be 89% of that for untreated wood.

Table F3 contains measurements on creosote treated, incised, Douglas-fir poles. These were fully incised and pressure treated and had an average diameter of 24-inches. The treatment had very little effect on stress wave time at six feet form the butt. This does not imply poor treatment, but only that the path of the stress wave along the pole's diameter was probably 90% through untreated wood.

An approximate calculation of penetration has been made using the following equation:

$$\frac{D}{V} - \frac{D}{V_{ut}} = 2t\left(\frac{1}{V_{ft}} - \frac{1}{V_{ut}}\right) \qquad \text{[E1]}$$

where D = diameter, inches

V_{ft} = velocity at fully penetrated end, inches/millisec.

V_{ut} = velocity in untreated wood, inches/millisec.

V = velocity at section of interest, inches/millisec.

t = thickness of shell penetration, inches.

Example: For incised creosoted Douglas-fir with an average diameter of 24 inches in Table F3, V_{ft} = 38, V = 50.5, and V_{ut} is assumed to be 52 for 18% moisture content:

$$\frac{24}{50.5} - \frac{24}{52} = 2t(\frac{1}{38} - \frac{1}{52})$$
$$t \quad = 0.97 \text{ inch}$$

Table F4 has results for butt treated poles of western red cedar, using pentachlorophenol in light oil. This is a soak treatment. The portion of the length from 3 feet above the butt to 8 feet above the butt is incised to improve penetration. The stress wave velocity in this incised region at six feet above the butt end was less than at the end, indicating better penetration.

Conclusions

The results are summarized in Table F5 for convenient comparisons.

1. Data from ends represents wood completely penetrated by preservative. The velocity in Penta-treated Douglas-fir was 63% of that in untreated wood (52 in/ms for D.-fir). The velocity in creosote-treated wood was 73% of that in untreated wood. A t-test for comparison of different size groups showed no significant difference between the velocities in creosoted and Penta-treated poles.
2. Data from locations where end penetration was not a factor (4 feet or more from the ends) showed the velocity in Penta-treated wood at 86% of that in untreated wood. In creosote treated wood the velocity was 97% of that in untreated wood. A t-test showed no significant difference in velocities.

Table F4. Stress Wave Times (microseconds) and Velocities (in/ms) for Cedar Soaked Butt-Treated Poles Incised Between 3 and 8 feet from Butt With Penta in Oil

Diameter inches	6 inches	72 inches	120 inches
15.0	700 (21.4)	850 (17.6)	300 (50.0)
14.0	590 (23.7)	600 (23.3)	400 (35.0)
13.0	425 (30.5)	770 (16.9)	360 (36.1)
14.0	387 (36.1)	570 (24.6)	700 (20.0)

Table F5. Summary of Results in Tables F1 to F4

Data From	Type	Diameter inches	Quan.	Velocity at End		Velocity 4 ft.		V/V-Untreated	
				Average in/ms	SD in/ms	Average in/ms	SD in/ms	Normal Pen.	Full Pen.
Table F1	Pressure treated Douglas-fir, Penta	10.36	30	33.1	6.5	45.2	6.5	0.87	0.64
Table F2	Pressure treated Douglas-fir, Penta incised	10.4	15	30.8	6.2	37.7	12.9	0.73	0.59
Table F3	Pressure treated Douglas-fir, creosote incised	24.0	4	38.0	8.0	50.5	5.7	0.97	0.73
Table F4	Soak treated cedar butt treatment, incised, Penta	14.0	4	27.9	6.7	20.6*	3.9	0.4	0.54**

*6 feet from butt instead of 4 feet.

**End penetration may be limited because no pressure was used.

The large value for the creosote treated poles was influenced by the fact that these poles were 24-inch diameter while those for the Penta-treated poles were only about 10-inch diameter.

3. The velocity in incised cedar poles was more affected by soak treatment than pressure treatment for Penta in Douglas-fir. Cedar is more permeable than Douglas-fir. However, the t-test showed no significant difference between the incised, soaked-in-Penta cedar (14-in diameter) and the pressure treated Douglas-fir, either when fully penetrated (at 6-in from the end) or normally treated (4 to 6 ft from the ends). The lack of significance is because of the rather large coefficients of variation in the velocities.

4. Preservative treatment reduces stress wave velocity, but has less effect than advance decay in the untreated centers of poles. This is based on measurements of velocity in decayed poles reported elsewhere.

APPENDIX G

EFFECT OF DECAY ON STRESS WAVE VELOCITY PERPENDICULAR TO THE GRAIN

This discussion is based on Paul S. Rutherford's masters degree thesis, "Nondestructive Stress Wave Measurement of Decay in Douglas-fir" dated August 1987, Washington State University and some additional tests conducted by Hoyle.

Decay should result in losses in weight, elastic modulus and compressive strength. Rutherford's thesis contains no data on weight loss, although he did measure it and employed the information in his computation of dynamic elastic modulus. Weight losses were very small and volume changes were also small. Decay did not permeate his transverse grain specimens to the degree that the longitudinal grain specimens used by Pellerin and Vogt in a previous study, had been infected.

This reduced spread on the decay is logical. Fungi could easily feed along the grain, especially through the springwood (earlywood) of longitudinal grain specimens. For transverse grain specimens inoculated at their mid-length, there are some with longitudinal paths from end to end where fungi can move transversely through the cell walls of the springwood tissue, but even this is a more difficult direction of decay propagation. In other transverse grain specimens there are no longitudinal paths through springwood tissue and fungi must travel through the summerwood (latewood) tissue which is more dense than the springwood tissue. Since the incubation time for the various groups of specimens in Rutherford's study were the same as those for the Pellerin and Vogt study, it is only reasonable that the spread of the decay in the Rutherford study was more limited.

In planning research on cross-grain stress wave velocity (SWV) in decayed wood, greater periods of incubation time should be considered. This does not mean that the experiment did not yield useful information. Pellerin and Vogt have observed that considerable loss of strength and elastic character does occur before weight loss becomes significant. This is evident in Rutherford's results, although none of his specimens lost more than 30 percent of their strength or elastic modulus. The effect of these property changes were evident in terms of the reduction of measured stress wave velocity.

An examination of Table G1 shows a relationship between SWV and ultimate compression strength (UCS). Rutherford obtained a correlation coefficient of 0.702 for SWV vs. UCS for conditioned speciments. Conditioning consisted of a one week exposure to a 12 percent equilibrium moisture content environment at 75 degrees Fahrenheit. He also measured SWV in specimens at the end of the decay period and prior to any conditioning treatment, obtaining a correlation coefficient of 0.673. His results are shown in Figure G1.

In this study each exposure (0, 3, 6, 9, and 12 weeks) was applied to a different set of 24 specimens (approximately 1" x 1" x 8.75"). The 24 specimens were subdivided into six subgroups according to annual ring orientation. The subgroups in each exposure group were matched to subgroups

Table G1. Subgroup Average Properties

Exposure weeks	Specimen Group psi	UCS ksi	MOE Static in/ms	SWV Conditioned in/ms	SWV Exposed	Approximate Angle
0	A	414.0	26.7	43.2	43.2	
3		333.0	20.7	39.3	30.0	
6		334.0	20.9	38.0	30.5	45°
9		344.0	20.2	38.2	32.8	
12		317.5	18.9	37.2	29.3	
0	B	484.0	25.2	38.5	38.5	
3		393.0	18.0	37.3	28.8	
6		416.0	20.3	36.5	32.2	45°
9		411.0	20.0	36.5	29.8	
12		412.0	20.5	35.0	28.2	
0	C	546.0	36.1	47.8	47.8	
3		445.0	27.8	44.5	35.3	
6		450.0	29.9	41.5	37.8	67°
9		361.0	26.1	42.3	31.5	
12		443.0	29.4	42.5	33.0	
0	D	612.0	50.3	61.3	61.3	
3		574.0	47.4	60.5	48.3	
6		473.0	39.9	51.3	45.3	90°
9		485.0	40.8	54.8	44.3	(radial)
12		474.0	39.5	51.0	40.3	
0	E	640.0	44.4	51.0	51.0	
3		584.0	35.3	46.5	39.5	
6		558.0	35.8	45.3	38.5	0°
9		553.0	35.5	46.8	38.3	
12		506.0	31.6	42.3	38.3	
0	F	560.0	32.9	47.3	47.3	
3		522.0	26.4	44.0	33.5	
6		483.0	24.1	39.8	31.8	22°
9		461.0	23.7	42.8	31.3	
12		460.0	24.3	39.3	33.3	

Each number is the average of 4 specimens.

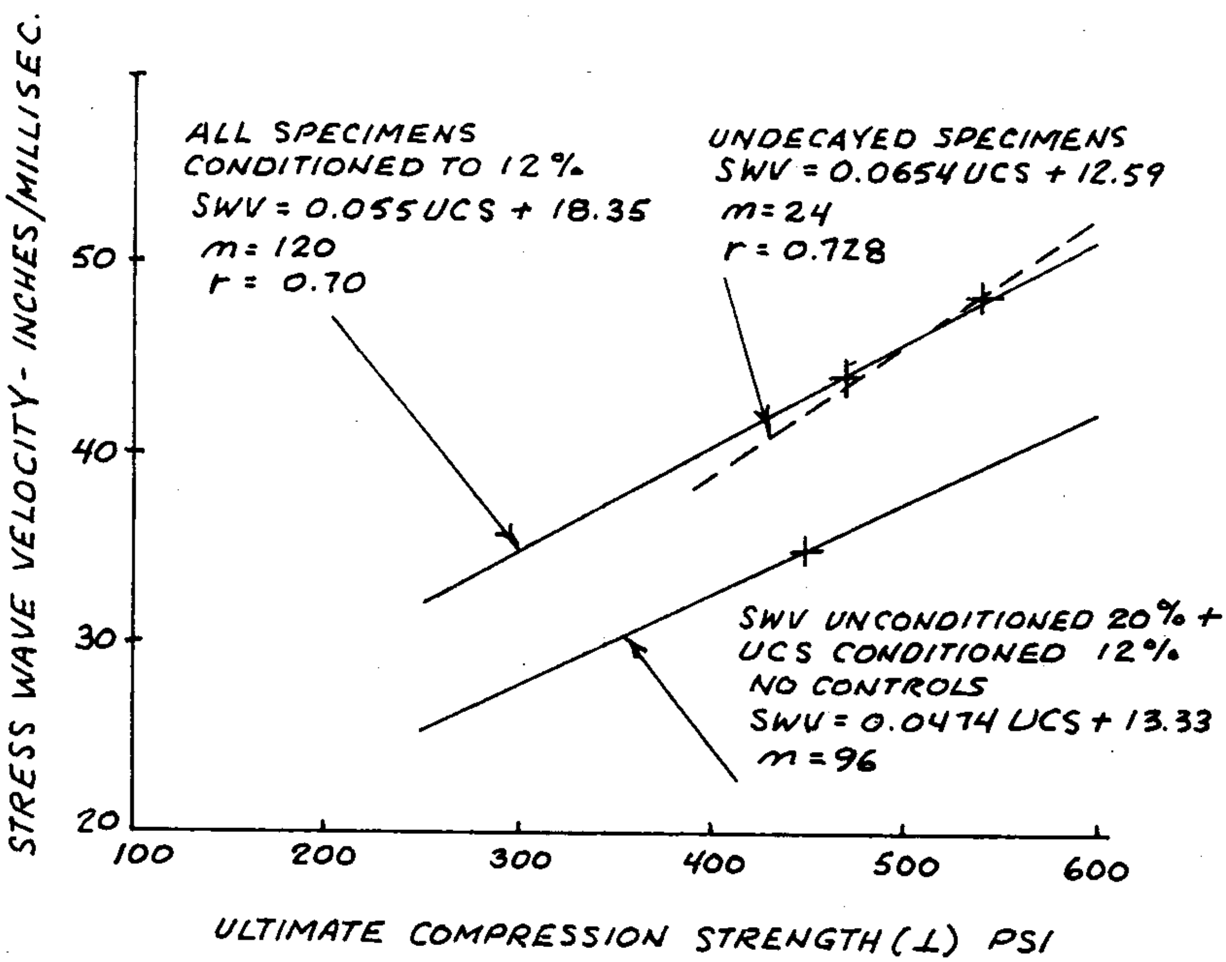


Figure G1. Regressions - Stress Wave Velocity vs. Ultimate Compressive Strength Decayed and Sound Douglas Fir in other exposure groups. Matching was according to board origin and hence, to ring orientation.

[In retrospect, it might have been desirable to have performed the nondestructive tests on the samples that were exposed for 12 weeks at periods of 0, 3, 6, 9, and 12 weeks. Compression strength could not be obtained except after final exposure, but at least the progressive change in SWV on the same specimens could have been measured.]

The test results show a relationship to annual ring orientation very much like that reported by Bodig and Jayne and in the 1940 Wood Handbook. These results appear in Figure G2A where the average subgroup UCS's are plotted versus ring orientation. There are two curves, one for controls (zero exposure time) and one for specimens having the greatest exposure to decay. Figure G2B shows static modulus of elasticity versus annual ring orientation. Definite differences are observed between control and decayed specimens values even though the decay was not severe enough to produce significant weight loss or great degradation of the wood.

The relationships between SWV and UCS are shown in Figure G1. UCS and static modulus of elasticity (MOE) are the wood properties which responded to decay in this study. Density did not change very much. Each of these responsive properties was affected as shown in Table G2.

In Figure G1 we show compression strength as the independent variable because we are attempting to determine the SWV that should be anticipated for the degraded wood. Since the UCS was determined for the conditioned wood, it is logical that the regression lines for all specimens (upper solid line) and controls (dashed line) are close together. The regression line for all specimens with unconditioned SWV (lower solid line) is depressed since the decayed specimens before conditioning were wetter and denser than after

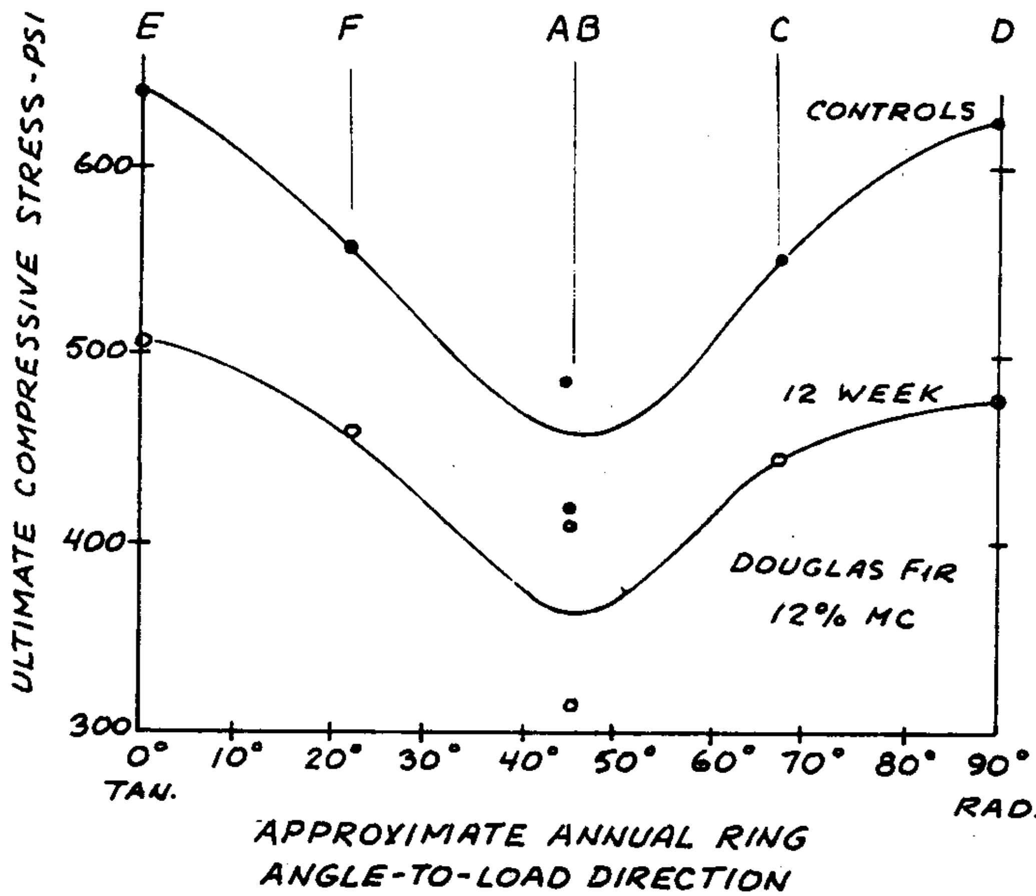


Figure G2A. Ring Orientation vs. UCS for Controls (Undecayed) and 12-Week Exposure (Decayed) Specimens

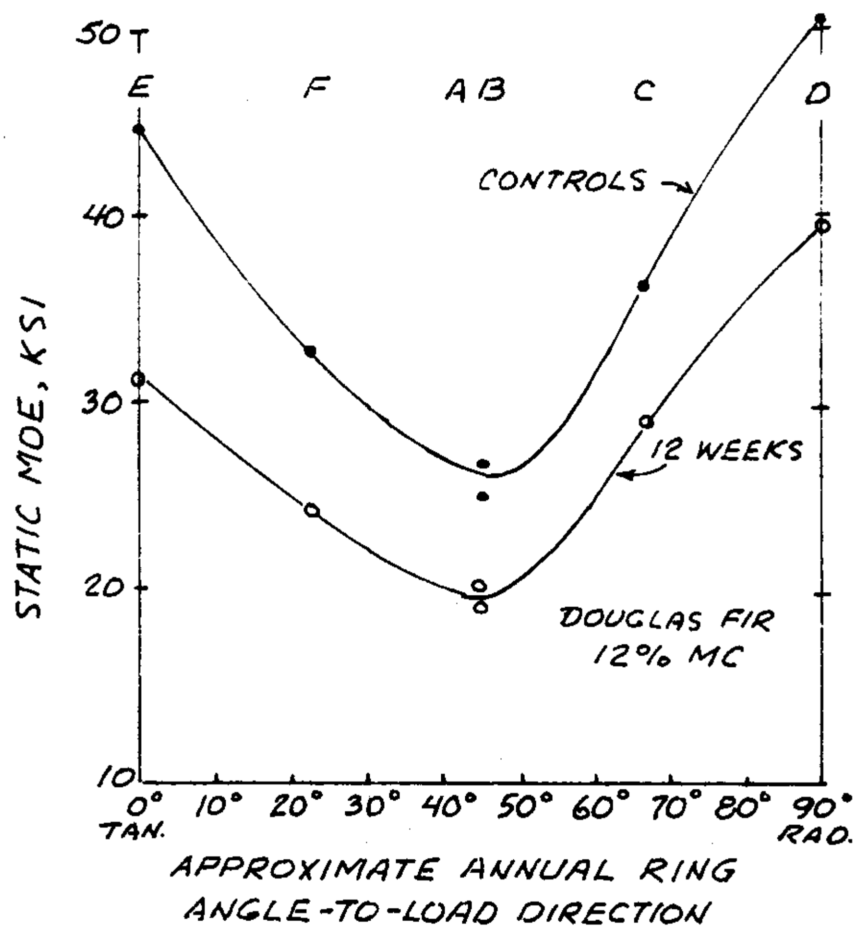


Figure G2B. Ring Orientation vs. Static MOE for Controls (Undecayed) and 12-Week Exposure (Decayed) Specimens

Table G2. Ratio of Properties After 12-Week Exposure to Values of Controls

Ring Orientation	Ult. Comp. Stress	Static MOE
0°(T)	0.79	0.71
22°	0.82	0.74
45°	0.81	0.76
67°	0.81	0.81
90°(R)	0.77	0.79

conditioning. Moisture content was probably about 20 percent or more. There were no controls at the high unconditioned moisture content. The correlation coefficients are not high because the degree of decay was not great.

The results show a very good relationship between SWV and strength. The useful consideration is strength, and the low strengths in Figure G1 are due to decay. The dashed line, which only extends from 400 to 600 psi, is for undecayed wood. Decayed wood had lower strengths. Had the experiment contained more thoroughly decayed material the strengths would have become much lower and, as the graph suggests, would have shown SWV's as low as 15 to 20 inches per millisecond, or lower.

As mentioned before, the decay in these specimens was concentrated near their mid-length. This means that these SWV's are the averages of velocities through decayed centers and undecayed ends. By cutting off the undecayed ends and assembling short decayed centers into longer specimens we obtained the results shown in Table G3. These are more indicative of the true SWV's in decayed wood.

Note that the velocities are all below 30 inches per millisecond and as low as 16 inches per millisecond. The effect of annual ring orientation is not as pronounced as reported for the original specimens, Figure G3. The lowest values are not for the 45 degree ring orientation. There was no great variation in the amount of decay in the pieces which had been cut from the centers of the original specimens, thus the decay periods are relatively meaningless for these artificially constructed decayed specimens.

Figure G4 shows a very unexpected relationship between static and dynamic MOE. The large ratio of dynamic to static values, about 3, was not expected. We think it could be due to high creep properties for perpendicular-to-grain loading. The literature contains no information about perpendicular-to-grain

Table G3. Stress Wave Velocities in Uniformly Decayed Portions of Specimens*

Specimen Number	Ring Angle	6-Week Spec. Grav.	6-Week SWV in/ms	9-Week Spec. Grav.	9-Week SWV in/ms	12-Week Spec. Grav.	12-Week SWV in/ms
A	45°	0.50 (0.53)	20	0.50 (0.58)	28	0.55 (0.56)	24
B	45°	0.52 (0.55)	18	0.54 (0.54)	21	0.51 (0.54)	25
C	67°	0.51 (0.58)	27	0.50 (0.54)	28	0.53 (0.54)	28
D	90°	0.46 (0.54)	25	0.46 (0.51)	25	0.47 (0.52)	23
E	0°	0.58 (0.63)	16	0.59 (0.64)	16	0.55 (0.56)	22
F	22°	0.54 (0.58)	16	0.53 (0.63)	16	0.50 (0.53)	19

*At 6% M.C. The numbers in parentheses are for the undecayed ends of the specimens from which the decayed wood was cut. The other specific gravity values are from the decayed or partially decayed portions.

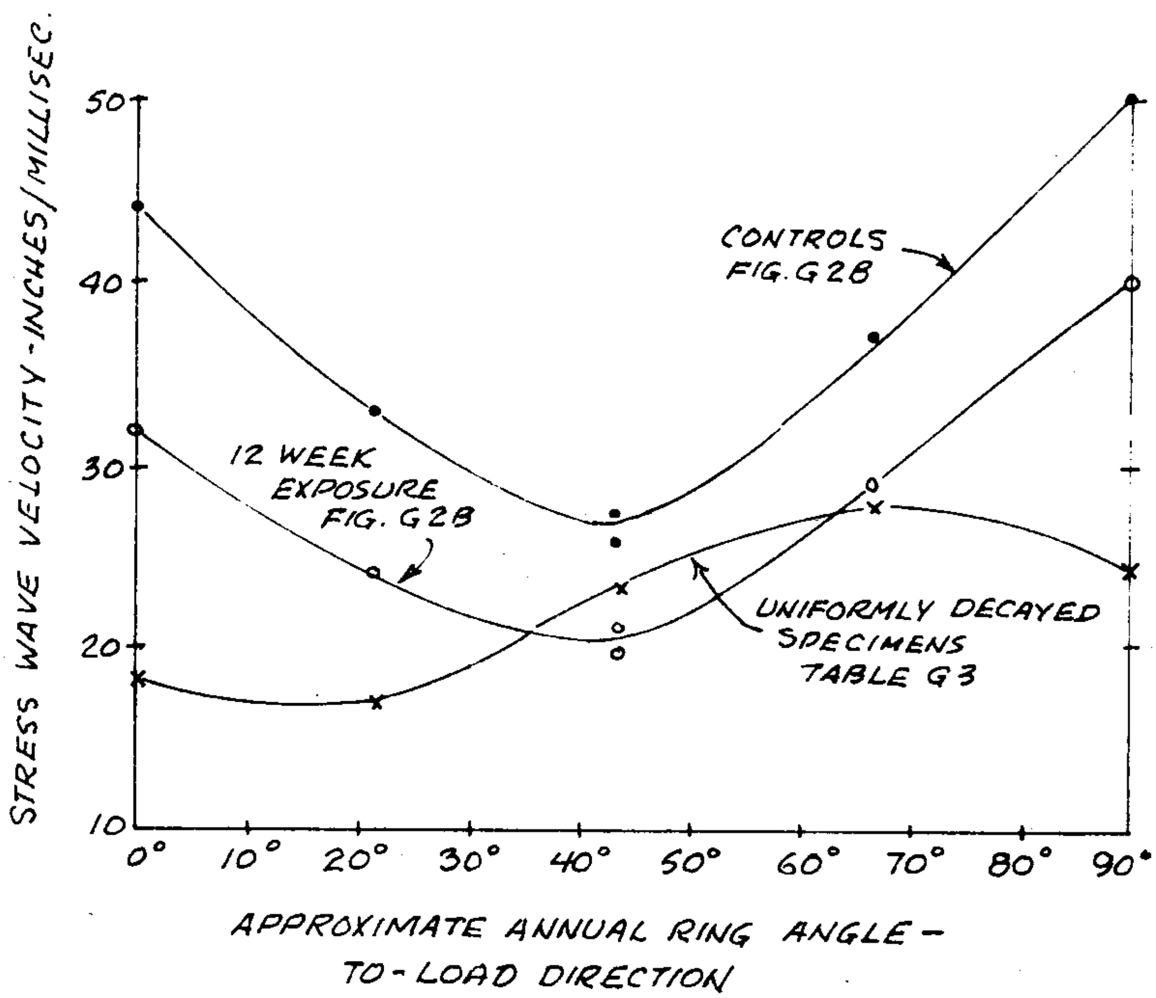
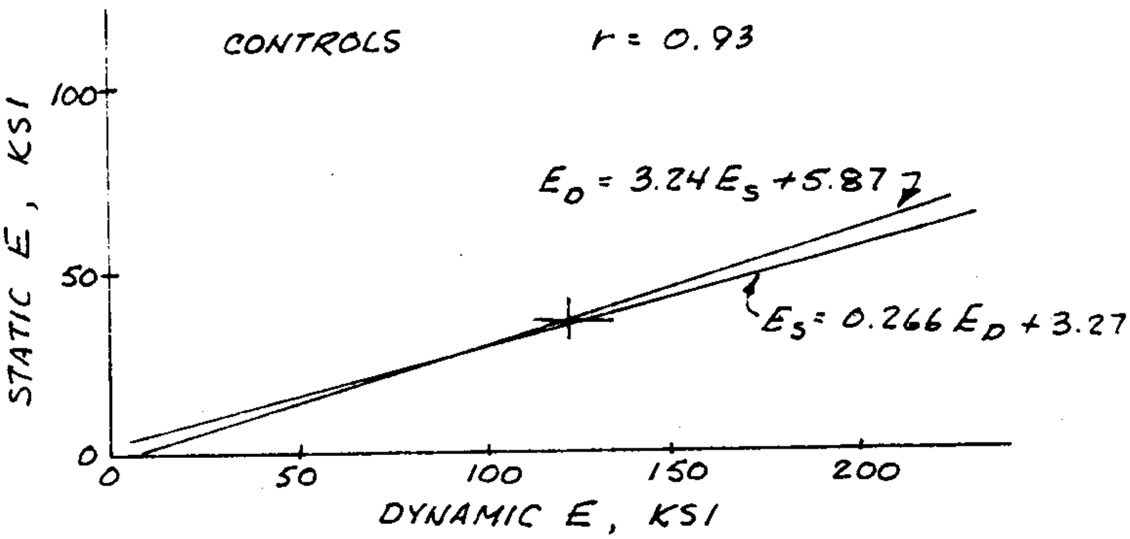


Figure G3. Stress Wave Velocity vs. Ring Angle



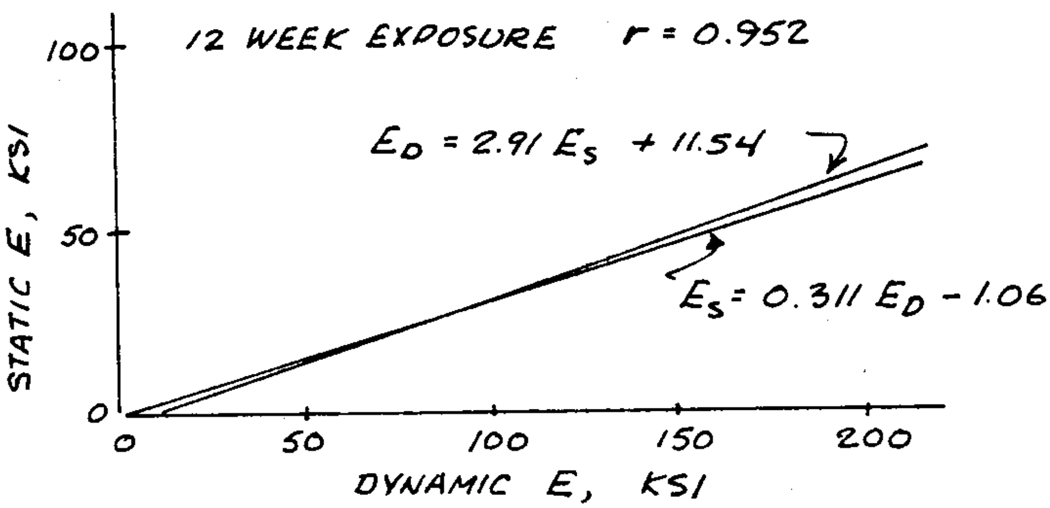


Figure G4. Static vs. Dynamic Elastic Modulus for Undecayed and Decayed Douglas Fir creep properties, but tests by Rutherford indicate that creep is, indeed, larger for perpendicular-to-grain than for parallel-to-grain loading. Rutherford used a lower load rate in his tests for static MOE than had been suggested by the appropriate ASTM Standard tests, although there seems to be no applicable ASTM Standard test for this measurement.

The effect of this discovery suggests the values for transverse velocities in Tables 1 and 2 may well be higher than those predicted. Table 1 and 2 values were calculated on the assumption that dynamic MOE was 1.06 times the static values, which may be correct for parallel-to-grain loading but may be too low for perpendicular-to-grain loading. If dynamic MOE is truly three times the static value, our estimated transverse velocities could be markedly affected. This would be a good topic for further exploration.