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The conventional method for determining lumber strength depends on visual evaluation by lumber graders which often results in undergrading of lumber. Nondestructive proof testing is used less often and provides for only estimates of elastic moduli of elasticity and rupture. The evaluation of nondestructive variables such as proportional limit (PL) and acoustic emissions (AE), offers a possibility of not only improved predictions for elastic but also nonelastic moduli.

A microcomputer-controlled testing machine was used to pretest three machine-stress-rated grades of Douglas-fir lumber up to PL under an accelerated deflection rate. These specimens were then tested to failure. The load, deflection, and AE were continuously monitored throughout the testing. The observations from nondestructive testing were chosen for independent variables in regression models for predicting the destructive parameters.

It is found that PL can be determined in a microcomputer-controlled test, with the computer-detected PL highly correlated with PL determined from destructive testing ($r = 0.92$).

Although this computer-detected PL, in combination with modulus of elasticity, is a good estimator of lumber strength (r = 0.83), it results in a poor prediction of ultimate deflection (r = 0.54). However, not only is a combination of AE variables below the PL and physical properties strongly correlated with PL (r = 0.76), but the same combination is also strongly correlated to strength (r = 0.93) and ultimate deflection (r = 0.83).

Nondestructive Detection of Proportional Limit and Prediction of Destructive Parameters

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NONDESTRUCTIVE DETECTION OF PROPORTIONAL LIMIT AND PREDICTION OF DESTRUCTIVE PARAMETERS

I. INTRODUCTION

Wood has been and will continue to be a material often used in numerous types of structures from buildings to boats. In structures, such as houses where the strength, stiffness, and stability of wood components are critical, the component material must be able to withstand all the service loads that are likely to occur. This is assured by using the material that has a sufficient grade to keep the stresses and deflections below the values prescribed by codes. These stresses and deflections govern the selection of structural grades of lumber and wood-based products.

1.1 JUSTIFICATION

In the past, wood has been graded either into classes of probable strength visually on the mill green chain or mechanically by machine testing. The grades assigned to wood by visual grading are based on strength ratios that define the portion of strength left after accounting for defects. Visual grading is fairly accurate considering that it is based on human judgement and that it includes a wide range of strength variability. This wide range has resulted in undergrading to insure that most of the material meets the visual grade or in overgrading to increase mill profits. Such practices are economically wasteful and structurally inadequate, which can seriously undermine existing lumber markets. Thus, the development of a more reliable grading method is highly desirable.

Strength prediction by mechanical grading, also known as machine stress rating, is mostly limited to lumber going into specialty products such as glue-lams, but it is becoming more commonplace in industry. It is based on the high correlation between the nondestructive variable modulus of elasticity (MOE) and the destructive variable modulus of rupture (MOR). Although this correlation has reduced misgrading and narrowed the strength variability within grades, a great deal of variability still remains. Since lumber strength is dependent upon the critical flaw in a particular member and MOE is a material property, strength might be better predicted using variables which are more dependent on the critical flaw than MOE.

In addition to reducing intra-grade variability in strength prediction, methods are also needed which more accurately predict the nonlinear lumber stiffness in bending between the proportional limit and the ultimate load. Existing design practices consider only MOE and MOR. Although this is acceptable for traditional design procedures that are oversimplified, recent improved methods call for reliable definition of the nonlinear section of the load-deflection curve.

1.2 OBJECTIVES

The overall objective for this study is to better define the load-deflection curve of lumber exposed to bending, with particular interest in the region between the proportional limit and ultimate load. The specific objectives are:

1) To develop a nondestructive testing procedure and arrangement for detecting the proportional limit for lumber;

2) To determine the level of the minimum damage needed to detect the proportional limit and to determine if this damage has a negligible effect on lumber strength and stiffness; and

3) To use the variables from nondestructive bending tests to predict the variables that can be obtained only in destructive bending tests.

II. REVIEW OF LITERATURE

Presently, the most common practice of estimating lumber strength is visual grading. Strength ratios are assigned to lumber by multiplying clear wood strength by strength reducing characteristics, such as checks, wane, knots, cross grain, and decay. Additional adjustments can be made for conditions such as moisture content and load duration. The resulting strength ratios are the basis for sorting the lumber into strength groups or grades. At mills, graders estimate strength ratios of individual boards by visually estimating these charactristics. For instance, grades for structural lumber used as joists or planks have the following minimum strength ratios (43): select structural - 0.65, No. 1 - 0.55, No. 2 - 0.45, and No. 3 - 0.26.

In visual grading, lumber graders introduce human errors so that most grading rules allow that five percent of lumber be misgraded. Thus, the correlation between predicted and actual strength is poor. A potential for improving visual grading lies in correlating strength with nondestructively tested parameters that are not influenced by judgement decisions from lumber graders.

2.1 STATIC BENDING

A standard test for evaluating bending properties of full sized lumber is a third-point-load test as described in American Society for Testing and Materials (ASTM) designation D 198-76 (2), "Standard Methods of Static Tests of Timbers in Structural Sizes". The result of such a test is a load-deflection curve from which a stress-strain curve can be obtained. As illustrated in Figure 2.1, the typical stress-strain curve can be divided into four regions (8):

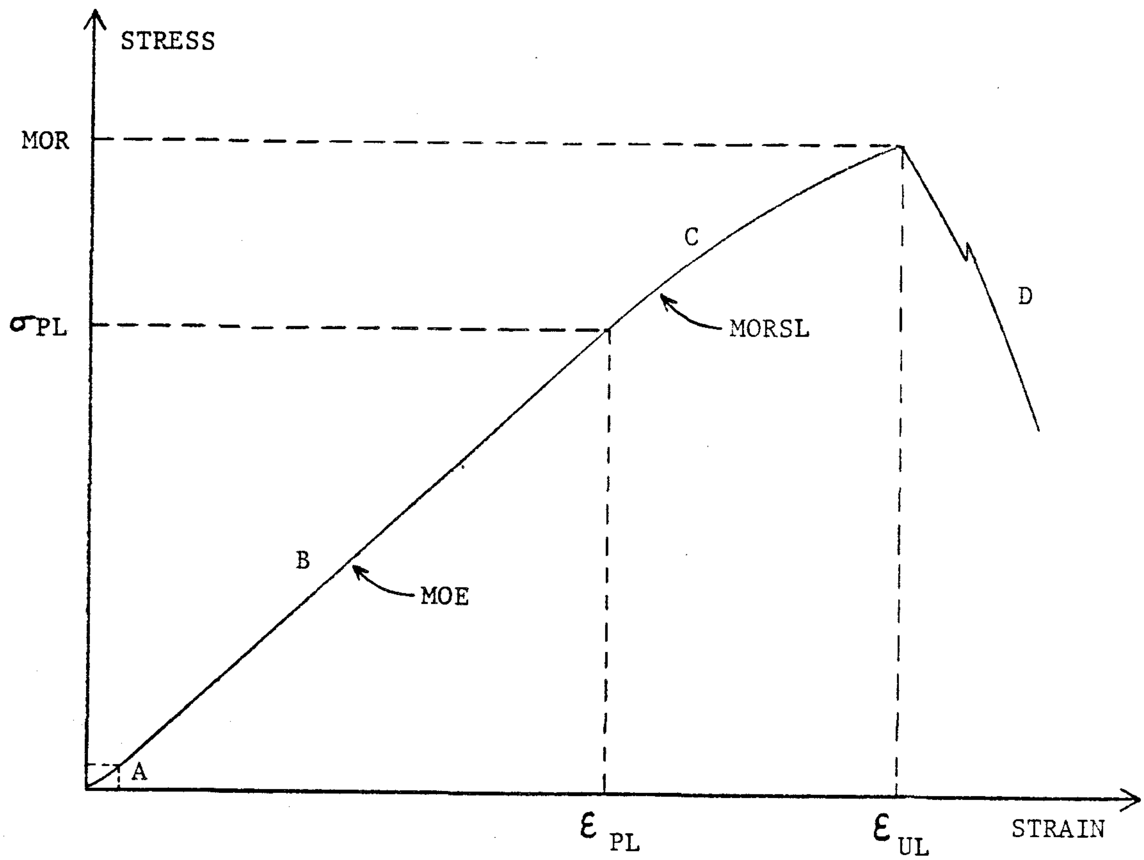

Figure 2.1. Characteristics of a typical stress-strain curve.

A, associated with initial alignment of specimen and testing machine, B, linear elastic region, C, curvilinear region, and D, post-failure region.

The initial alignment region is caused by imperfection of specimens and testing arrangements and can be made negligible by careful specimen manufacture and testing.

The linear elastic region is characterized by the straight trace of stress to strain. The traditional MOE is the slope of this trace. The point where stress in no longer proportional to strain is termed the proportional limit, PL, and is characterized by coordinates σ PL and ε PL.

Above PL, strain increases at a faster rate than stress, which produces a convex curvilinear trace. The inelastic curve in this region, which can be approximated by a straight-lined segment connecting the load at PL with the ultimate load, shall be referred to as MORSL. The maximum outer-fiber stress that the material attains at failure lies in this region of the curve. This is called the ultimate bending stress, σ UL, or MOR. The corresponding strain at the ultimate load, ε UL, is important in identifying the curvilinear trace. Although stress and strain are not linear in this region, researchers have found significant correlation between the parameters of linear and curvilinear regions (7,13).

The post failure region, although of importance in the ultimate load analysis of highly indeterminate wood structures, is seldom needed in wood design. Therefore, it is not in the scope of this study.

The PL has in the past been determined by visual examination of the load-deflection or stress-strain curve from destructive tests. The location at which linear behavior becomes curvilinear is often difficult to determine manually and possibly biased by the examiner. An improvement may consist of computer monitoring the load-deflection curve, in which the deviation from linearity can be mathematically defined allowing an unbiased definition of the PL.

A stochastic technique is commonly used for prediction of MOR from a nondestructive parameter (8). It is based on previously developed relations between MOR and a nondestructively evaluated variable, such as MOE (Figure 2.2). For the mean of the nondestructive variable, MOR is a random variable characterized by the previously determined probability density function (Figure 2.2). The nondestructive data are generally separated into several classes, with the mean value of each class used to predict MOR by regression analysis.

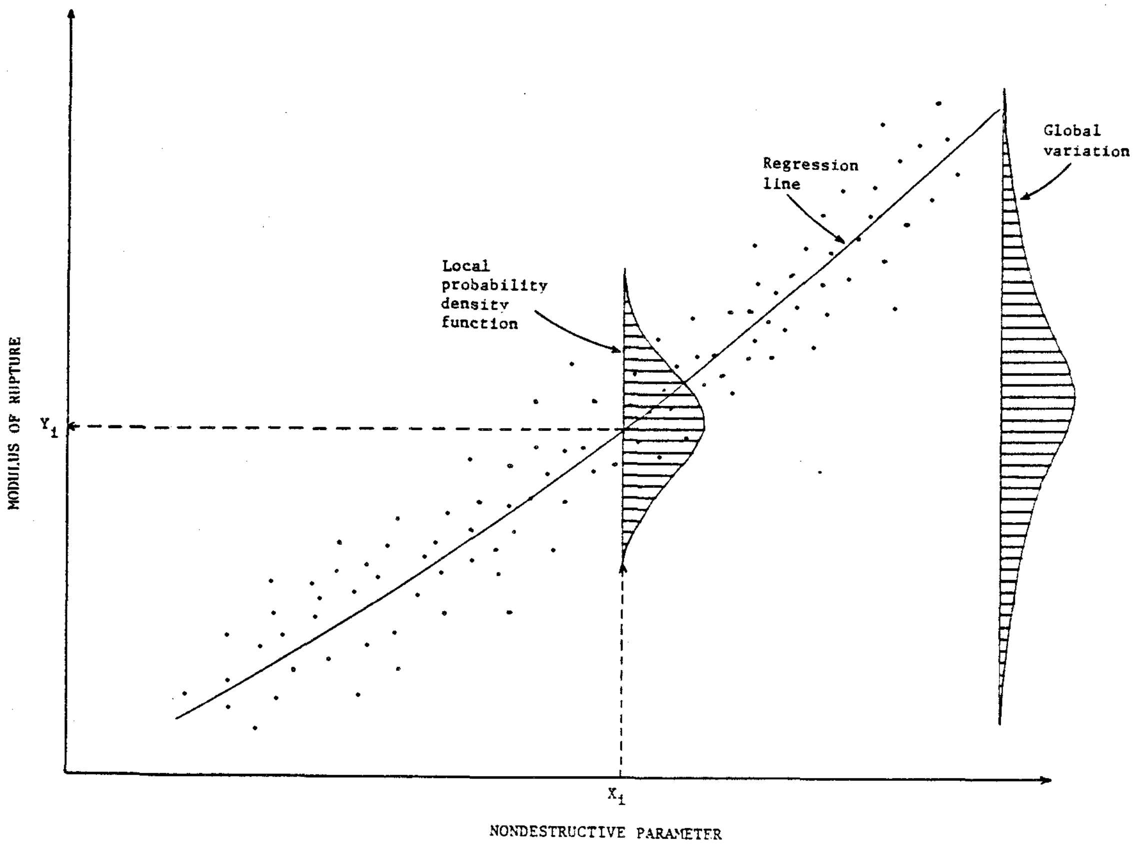

Figure 2.2. Prediction of individual modulus of ruptures from mean and local probability density functions.

Since full-sized lumber containing defects has to be tested to obtain the nondestructive variables, several correction factors used in the derivation of strength ratios for visually graded lumber are not needed in nondestructive in-grade testing on the production line. Examples of such factors are correction factors to account for defects, special grading, and lumber size (8). The use of nondestructive evaluation does not eliminate all sources of error associated with estimating variability. As indicated by the data in Figure 2.2, some variabilility remains about the fitted regression line. However, the variability in estimating MOR has been substantially reduced. This reduction contributes to much better utilization of individual pieces, since it assigns MOR´s and corresponding allowable unit stresses by the method which accounts for the variability about the mean (8). This reduced variability in MOR prediction can lead eventually to less variable grades which will result in a more efficent use of lumber (32).

The selection of nondestructive variables are of practical significance only if they are accurate, effective, rapid, safe, simple, and inexpensive (11). This means that variables should be closely related to strength and stiffness of lumber.

Intensive research of predicting bending strength from nondestructive variables did not begin until the late 1950´s. Shotgun approaches towards finding a significant nondestructive variable seemed to peak in the early 1960´s. Unsuccessful methods included sonic tests, use of photo-electric cells, static electrical fields, liquid penetrants, electrical and thermal conductivity, and hardness correlations (14). Various types of radiation treatments were also tried, but discontinued because of problems encountered. All the research suggested three viable variables: specific gravity (SG), MOE, and vibration (dynamic) modulus of elasticity.

Table 2.1 summarizes work that various authors have performed correlating dependent variable MOR with various nondestructive parameters appearing as independent variables. The correlation coefficient, r, measures the closeness of fit between two types of variables (41). The closer r is to +/-1, the better the correlation. Positive r's indicate a tendency of both variables to increase together and negative values of r indicate an increase in one variable with a decrease in the other variable. Although the correlation between SG and MOR is significant (Table 2.1), the corresponding r is rather small when compared with those of MOR with either MOE or dynamic modulus of elasticity, E. Investigations showed r values as high as 0.71 when correlating SG of small, clearwood specimen with MOR, but the correlation was weak with an r of 0.49 (11) for full-sized lumber.

In addition to SG for predicting MOR, regression relations with MOE from static bending tests have been well documented (Table 2.1). Correlation coefficients between MOR and MOE generally range between 0.65 and 0.85, a significant improvement over those of SG.

This high correlation between MOE and MOR has led to the development of machines that stress rate lumber, the first of which was commercially developed by Potlatch Forests, Inc. in 1963 (15). The machines were calibrated by visual-grade requirements as set forth by lumber products associations (45).

Bending stiffness, the property evaluated from deflection

Table 2.1. Summary of research correlating modulus of rupture (MOR) to specific gravity (SG), static modulus of elasticity (MOE), and vibrational modulus of elasticity (E).

ESTIMATED PARAMETER	ESTIMATOR	SPECIES	DIMENSIONS	SAMPLE SIZE	r	REFERENCE NO.
MOR(edge)	SG	S. pine	2x4	-	0.516	(11)
MOR(flat)	SG	S. pine	2x4	-	0.614	(11)
MOR	SG	Doug-fir	2x6	200	0.435	(39)
MOR	SG	Redwood	2x4	125	0.53	(38)
MOR	MOE(flat)	W.hemlock	2x6	244	0.79-0.85	(9)
MOR	MOE(edge)	W.hemlock	2x6	244	0.83-0.84	(9)
MOR(flat)	MOE(flat)	Doug-fir	2x6	486	0.83-0.86	(19)
MOR(flat)	MOE(flat)	W.hemlock	-	-	0.856	(19)
MOR(edge)	MOE(edge)	Doug-fir	-	250	0.71	(31)
MOR(edge)	MOE(edge)	E.spruce	-	250	0.74	(31)
MOR(edge)	MOE(edge)	Redwood	2x4	125	0.68	(38)
MOR(edge)	MOE(flat)	S. pine	2x4,6,8,10	1,349	0.655	(11)
MOR(edge)	MOE(edge)	Balt.redw.	2x4	-	0.836	(42)
MOR(edge)	MOE(flat)	Balt.redw.	2x4	-	0.784	(42)
MOR(edge)	MOE(edge)	Red pine	2x6	199	0.81-0.84	(26)
MOR(edge)	MOE(edge)	Doug-fir	2x4	150	0.66	(6)
MOR(edge)	MOE(edge)	S. pine	2x4,6,8	88	0.777	(44)
MOR(edge)	MOE(flat)	S. pine	2x4,6,8	88	0.789	(44)
MOR(edge)	MOE(edge)	Doug-fir	2x6	200	0.681	(39)
MOR	MOE(edge)	Spruce	2x6	110	0.835	(24)
MOR	MOE(edge)	Jack pine	2x6	109	0.729	(24)
MOR	MOE(edge)	Doug-fir	2x4	-	0.82	(1)
MOR	E(edge,free)	Red pine	2x6	194	0.827	(26)
MOR	E(edge,supp)	Red pine	2x6	197	0.833	(26)
MOR	E	S. pine	2x4,6,8	88	0.772	(44)
MOR	E	varied	varied	varied	0.67-.93	(21)
MOR	E(edge)	Spruce	2x6	110	0.806	(24)
MOR	E(edge)	Jack pine	2x6	109	0.702	(24)

measurements obtained in machine stress-grading, is often defined as the product of the moment of inertia and MOE. For structural lumber, the moment of inertia of a given size can be considered constant (8). As a result, MOE can be determined directly from deflection measurements.

Currently in the U.S.A., two types of machines for stress-rating lumber are most often used. They are the Continuous Lumber Tester (CLT-1) developed by Potlatch Forest, Inc., and the Stress-O-Matic (SOM) developed by the Western Pine Association.

In the CLT-1, boards are continuously fed through the machine at speeds ranging from 700 lineal feet per minute (fpm) to 1265 fpm (22). The machine measures the flatwise stiffness of each piece by continuously monitoring the force necessary to deflect sections of a board a fixed amount first in the downward and then in the upward direction (Figure 2.3). As lumber passes through the CLT-1, the computer simultaneously calculates the minimum and average MOE along each piece. The final MOE category is combined from both the minimum and average MOE (15). The CLT-1 can be programmed for any desired dimension of lumber to be graded.

The maximum feed rate for the present SOM is 600 fpm, but the actual operating speed is closer to 400 fpm (15). The SOM simulates the ASTM three-point load test. Thus, it uses a fixed load over a 4-foot span on a flat face in one direction only (Figure 2.4). The continuously monitored deflection is used to determine MOE. If the deflection exceeds a value that has been preset for the MOE classes, the applied load is reduced. The readings continue until the highest load per four foot section on the board is reached that will not

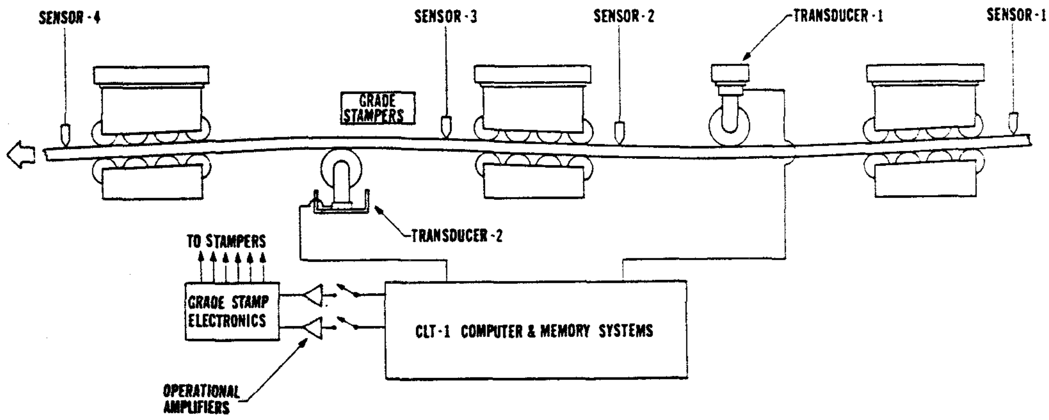

Figure 2.3. The CLT-1 machine for stress-rating of lumber in a production process (courtesy of (15)).

exceed the preset deflection limit. This load identifies the 4-foot section of the minimum MOE which is then assigned to the whole piece.

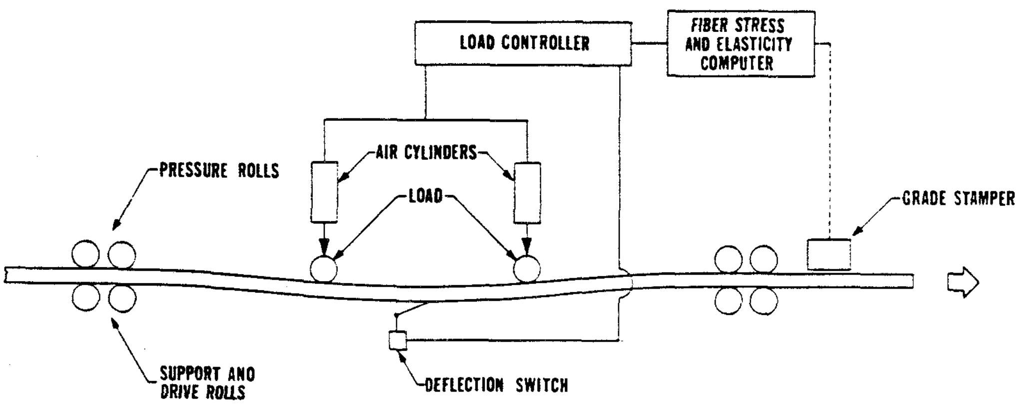

Figure 2.4. Operation of the SOM machine for stress-rating of lumber (courtesy of (15)).

Several authors have found that addition of a second nondestructive strength predictor to the MOR-MOE regression increases r. Orosz (29) reported that addition of strength ratio to the MOR-MOE relationship of Douglas-fir and Southern Pine dimension lumber numerically improved r by 0.06 to 0.23. However, the resulting r's were still below 0.80. Polensek and Atherton (31) also showed an increase in r when strength ratio was added to the MOR-MOE relationship. However, the increase in r was only from 0.71 to 0.74.

The addition of SG to the MOR-MOE relationship has been shown by several authors to not significantly contribute to r. Doyle and Markwardt (11) and Senft et al. (39) independently found that such an addition increased r from 0.68 to 0.70.

Thus, the addition of nondestructive variables, such as strength ratio and SG, to the MOR-MOE regression model adds little to the correlation. However, this does not negate the existence of other more significant variables.

A third nondestructive variable used to predict MOR is E, where E refers to the modulus of elasticity as determined by free vibration of boards. In 1959, Jayne adopted to wood the idea of using E to predict MOR (17). He proposed the hypothesis that energy storage and energy dissipation were related to the same properties that control mechanical properties. He demonstrated that transverse vibration of small clear specimens of wood showed a significant relationship between E and MOE. However, since both moduli measure the stiffness of the same deflection mode, the correlation should be high.

Various authors have researched the MOR-E correlation (Table 2.1) and have obtained r´s of approximately 0.8. Although these r´s appear higher than those of MOR–MOE, several authors presented data suggesting that the two correlations were about equal. Miller and Tardif (26) did both dynamic and static testing of 2" by 6" red pine to correlate E, MOE, and MOR. They found r for MOR–E to be 0.83. They also found r´s for the MOR–MOE relation between 0.81 and 0.84, as compared with results by Walters (44) who obtained r´s for MOR–E and MOR–MOE equal to 0.77 and 0.78, respectively. Orosz (30) ran a regression on edgewise MOE versus edgewise E and flatwise MOE versus flatwise E and obtained r´s of 0.98 and 0.99, respectively. Thus MOR prediction from dynamic E is just as reliable as from static MOE.

An MSR machine has been developed which utilizes E to predict MOR. This machine employs transverse vibration and is called the E–Computer. Although its capacity of ten boards per minute is much lower than the deflection MSR machines, it can grade a wide range of lumber stiffness and lumber containing bow or warp (15).

The past decade has produced limited research on the MOR–SPL relationship (Table 2.2). Results have been promising with r´s ranging from 0.82 to 0.92. All the investigators (1,6,13) found that the correlation between MOR and SPL was always higher than that of the corresponding MOR and MOE. Fernandez (13) and Atherton (6) also noted that addition of MOE to the MOR–SPL regression equations did not significantly improve the correlation.

Although SPL appears to be the best known predictor of MOR, there are a few problems associated with the practical application of this concept. The question of damage to the lumber when loaded to the PL comes into play. A logical application may consist of loading boards

Table 2.2. Previous work correlating modulus of rupture and stress at proportional limit.

SPECIES	GRADE	DIMENSIONS	SAMPLE SIZE	r	REFERENCE
Doug-fir	-	2x4	-	0.82	(1)
Doug-fir	Stud	2x4	150	0.88	(13)
Redwood	Utility	2x4	125	0.90	(6)
D-f & Redwood	Stud & Utility	2x4	275	0.92	(6)

as described in the ASTM designation D 198-76 (2) and stop at the PL. To estimate the effect of preloading, the following reasoning may be helpful. Assuming that the PL is at approximately 85 percent of the ultimate load and a rate of loading that takes five minutes to achieve the ultimate load, the estimated theoretical residual fractional lifetime according to Gerhards (16) is approximately 95 percent and the theoretical residual strength left is almost 99 percent. If the SPL is to be detected on a commercial basis from the load-deflection relations, then load rates must be fast. Therefore, Gerhards (16) further assumed that a load of 100 percent of the ultimate static strength is reached in two seconds with instantaneous load removal, for which he estimated theoretical fractional residual lifetime of almost 100 percent with little to no reduction in theoretical residual strength.

The main problem with the evaluation of SPL is its detection during testing. The PL can not generally be detected until the load exceeds the SPL. Thus specimens are stressed beyond the SPL resulting in wood damage and possibly failure. Atherton (6) suggested a constant monitoring of load and deflection during testing by a microcomputer to detect when a change in the slope of the load-deflection curve occurs. At this point, the load could be instantaneously removed with negligible or no damage to the lumber.

2.2 ACOUSTIC EMISSIONS

It has been known for many years that a solid subjected to sufficient stresses emits discrete acoustic waves, which can be detected by transducers in acoustic contact with the solid. The phenomenon of wave generation in materials under stress is termed acoustic emission (AE), or, alternatively, stress-wave emission (46).

AE differs from other nondestructive testing methods in two respects. First, the energy release that initiates the acoustic pulse in the solid also initiates the abrupt redistribution of internal stresses. Second, crack growth and plastic deformation are major sources of AE. Therefore, an active source of AE is also likely to significantly reduce the MOE and MOR of the solid (12).

The most common pulse characterization in an AE experiment is called "ring-down" counting (12). Figure 2.5 shows the time-amplitude trace of a pair of typical signal bursts at the transducer. A peak count is defined as any discrete event in which the voltage from the transducer exceeds a set threshold voltage level, Vo. The AE response pulse oscillates with a gradually decaying amplitude and, consequently, a single AE may cause a large number of peak counts. Further, this number is dependent upon the magnitude of the AE source pulse, because the larger the response signal, the larger the number of oscillations before the voltage level drops below the threshold level. Hence, the data taken represents not only the frequency of occurrence but also the strength of the AE pulses (12).

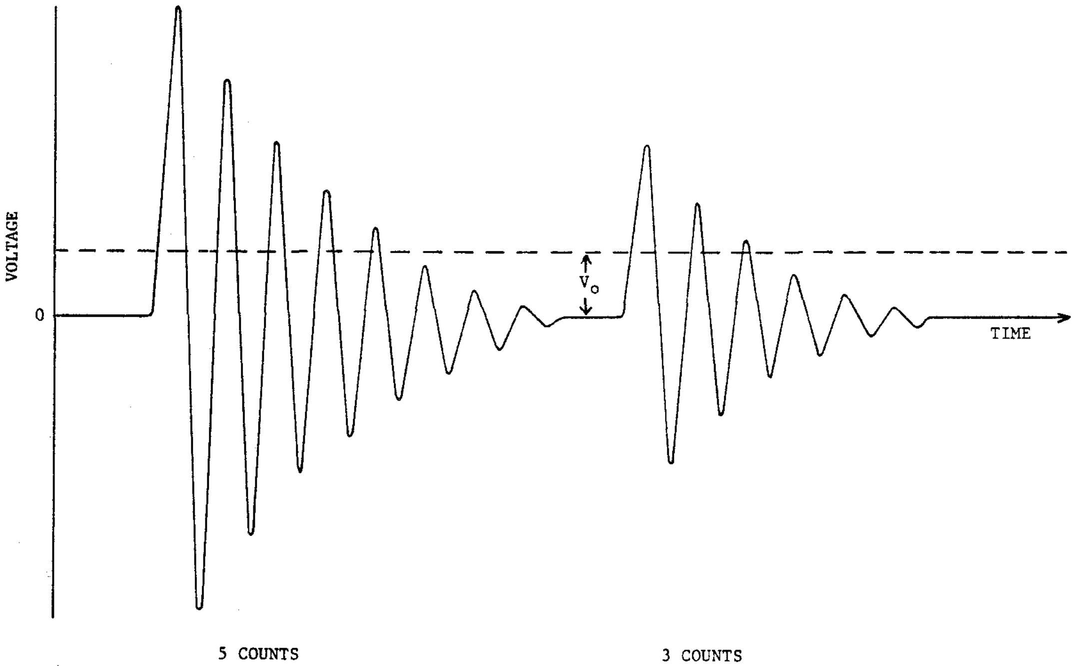

Figure 2.5. Ring-down counting with two bursts and eight peak counts.

In 1928, Joffe (18) related noise levels in a structure and stresses. However, Kaiser (20) in 1950 was the first one to clearly documented the AE phenomenon. He demonstrated not only that many materials, including wood, exhibited AE under stress, but also that many materials subjected to cycling loads demonstrated an irreversibility of AE; this is now known as the Kaiser effect. While the AE of metals and ceramics have been extensively researched, those of wood have received less attention.

While miners have long known the importance of audible sounds emitted by timbers as a warning of overstressing and possibly of impending failure, wood researchers have only recently paid attention to it. In 1963, Miller (25) studied the sounds produced when small, clearwood specimens of maple and Douglas-fir crossarms were stressed in bending. He used a contact microphone as the transducer and found that the maple specimens gave virtually no warning of failure. However, most of the Douglas-fir crossarms emitted detectible sounds when the loads were equivalent to their long-term strength.

Porter was the first to study wood AE in detail. In 1964, he (33) used a piezo-electric crystal, in conjunction with an amplifier, band-pass filter and an electronic counter, to study AE as correlated to crack extension and static bending. For cleavage specimens of Alaska yellow cedar, he found that there was a linear relation between cumulative AE count and crack length. For small Douglas-fir specimens, he found a possible relationship between the apparent PL and the number of AE.

Porter et al. (10) investigated flaw growth in western white pine. They concluded that in tension, bending, and cleavage, AE resulted from unstable crack extensions and that these extensions were activated at low average strain levels. In compression, applied loads closed cracks resulting in few emissions. In bending, they found a linear increase of emissions with strain up to the PL, when the rate of emissions decreased. The rate of AE increased again just prior to specimen failure.

In 1969, Adams (1) applied AE to investigate defect growth in nominal 2 in. by 4 in. beams of 50-in. span consisting of three western softwoods, which were subjected to two concentrated loads applied at third points. He reported that the rate of AE increased rapidly when reaching SPL. He also found that variables taken from AE count-deflection traces were not significant predictors of MOR.

Porter et al. in 1972 (34) measured AE to estimate the bending strength of 2 in. by 6 in. Douglas-fir finger joints. They found that cumulative AE count was most highly correlated with strength in the region of the PL. Applying the load to just beyond the SPL, a 10 percent absolute accuracy in estimating fracture loads was observed.

In 1982, Ansell (4) tested small, clear specimens in tension to characterize AE patterns for earlywood and latewood. He found that AE counts accumulated rapidly at low strain for latewood, whereas earlywood was characterized by a progression of gradual increases in AE, interspersed with rapid jumps in emissions. He also observed that with increasing grain angle, samples deformed with progressively fewer counts to failure, which reflected on the mode of failure by shear in planes of earlywood. In another publication, also in 1982, Ansell (5) reported that the proportion of earlywood to latewood has a marked effect on the shape of the AE count-strain traces. He also correlated MOE, MOR, and work to fracture with the AE count-strain data. Although the work to fracture is related to the total AE to failure, no direct proportionality exist between the two parameters.

Most recently, AE have been monitored to evaluate stress and defect propagation during lumber drying. Skaar et al. (40) found that it was possible to detect AE bursts in red oak during drying. They suggested a control system for a lumber dry kiln, in which AE would have controlled drying rate. Noguchi et al. (28) reported on AE bursts during drying on three species of hardwoods. They also found that rates of AE peak counts responded more to changes in the atmospheric humidity than to changes in the internal moisture of a specimen.

Researchers have recently characterized AE with regards to loading type and defect type. Sato et al. (37) reported that burst type AE were generated during plastic deformation during static-compression testing. They reported that the Kaiser effect was also present during static-tension testing. In 1984, Sato et al. (35) found for tension failure that slow rates of peak counts are probably generated with the opening of microcracks included originally in wood. They concluded that burst type AE corresponded to a ductile property in the fracture process of wood. In a subsequent study (36), they redefined burst type AE as coming from macro-cracks propagating across annual rings in the radial direction.

III. EXPERIMENTAL PROCEDURE

3.1 MATERIAL SELECTION

The specimens, 264 nominal 2- by 4-inch Douglas-fir boards of 12-foot length, were selected from a mill that cut lumber from logs coming from the growing area along the east and west side of the mid-Willamette Valley, Oregon. Three MSR grades of material were selected from the piles that had been dried to an average moisture content of twelve percent at the mill: 1350f, 1800f, and 2400f. After selection, the specimens were banded together, covered in plastic, and trucked to the Forest Research Laboratory at Oregon State University, where they were stickered and equilibrated in a room with an equilibrium moisture content of 12% for four months.

3.2 TESTING ARRANGEMENT

ASTM standard D198-76 (2) for the three-point bending test was followed whenever possible. Test types conducted in this project are summarized in Figure 3.1. For samples 1A, 2A, 3A, and 4, the deflection rate of 24 in/min was 50 times faster than the recommended ASTM rate of 0.5 in/min. The faster deflection rates were employed to emulate possible industrial applications, enhance research efficiency, and decrease specimen damage. Samples 4 and 5 contained approximately an equal number from each grade used.

3.2.1 TESTS TO EVALUATE PROPORTIONAL LIMIT

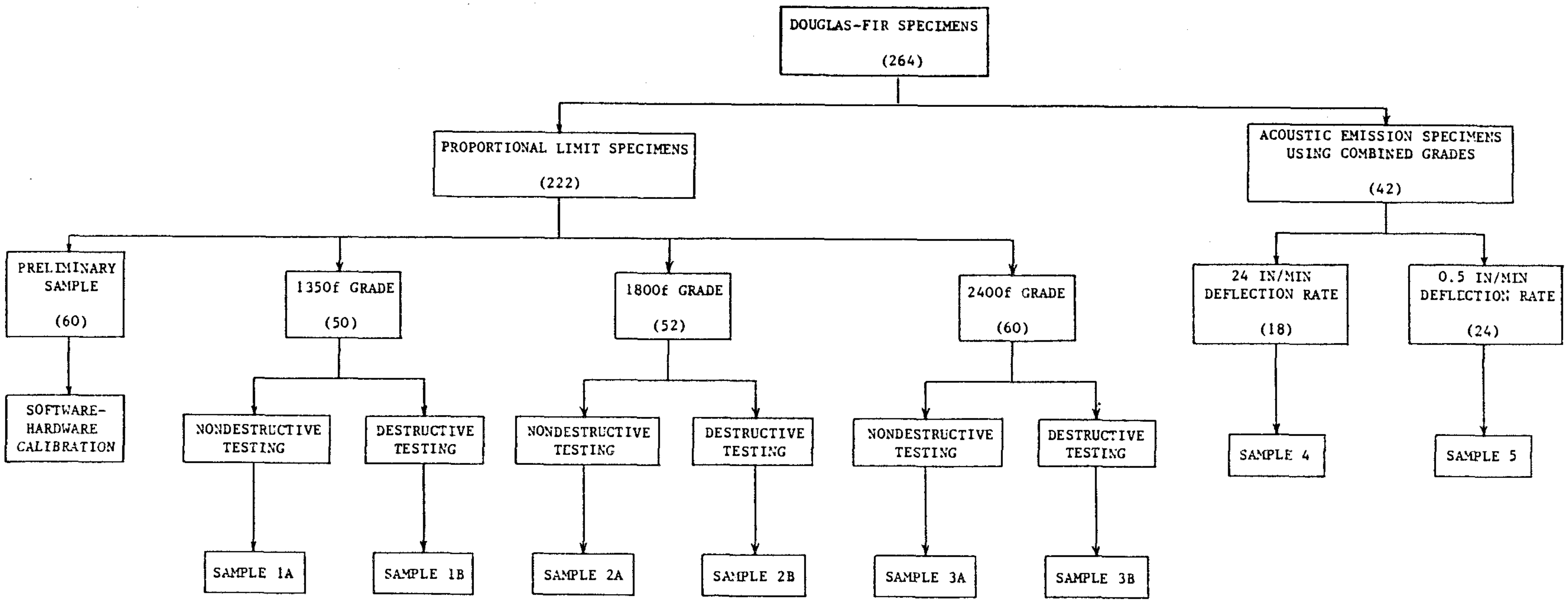

Figure 3.1. Description of experimental samples

Figure 3.2 depicts the research steps for the proportional limit evaluation. The dimensions and moisture content of each specimens were taken before testing. The width and thickness of the specimens were measured at each quarter length by a micrometer to the nearest 0.0025 inch. The average of the three measurements represented an effective cross section that was assumed constant along the specimen length. The moisture content was taken by an electric moisture meter with one reading at midspan. SG was based on full specimen average weight and volume. MOE, SPL, and PLD were continuously evaluated by microcomputer throughout the nondestructive tests. UL, UD, MOR, and MORSL were evaluated during the destructive bending tests.

Initially, specimens were nondestructively tested in bending up to the apparent PL in a conventional testing machine under third-point loading over a span of 114 inches in accordance with ASTM designation D 198-76 (2), at the testing rate of 24 ipm. Midspan deflection was monitored by a linear variable differential transformer and recorded as a function of load that was monitored by a load cell. The slope load and deflection was continuously evaluated by the microcomputer to detect the first change in rate which also indicated deviation from linearity on the load-deflection trace. 28 load-deflection data pairs were evaluated and checked per second.

Figure 3.3 illustrates the algorithm used to determine the PL associated with the first change of the load-deflection slope. Because the nonlinearity in region 1 represents specimen alignment, slope deviations in this region were ignored. In the next region, when the slope becomes constant, a linear regression analysis was

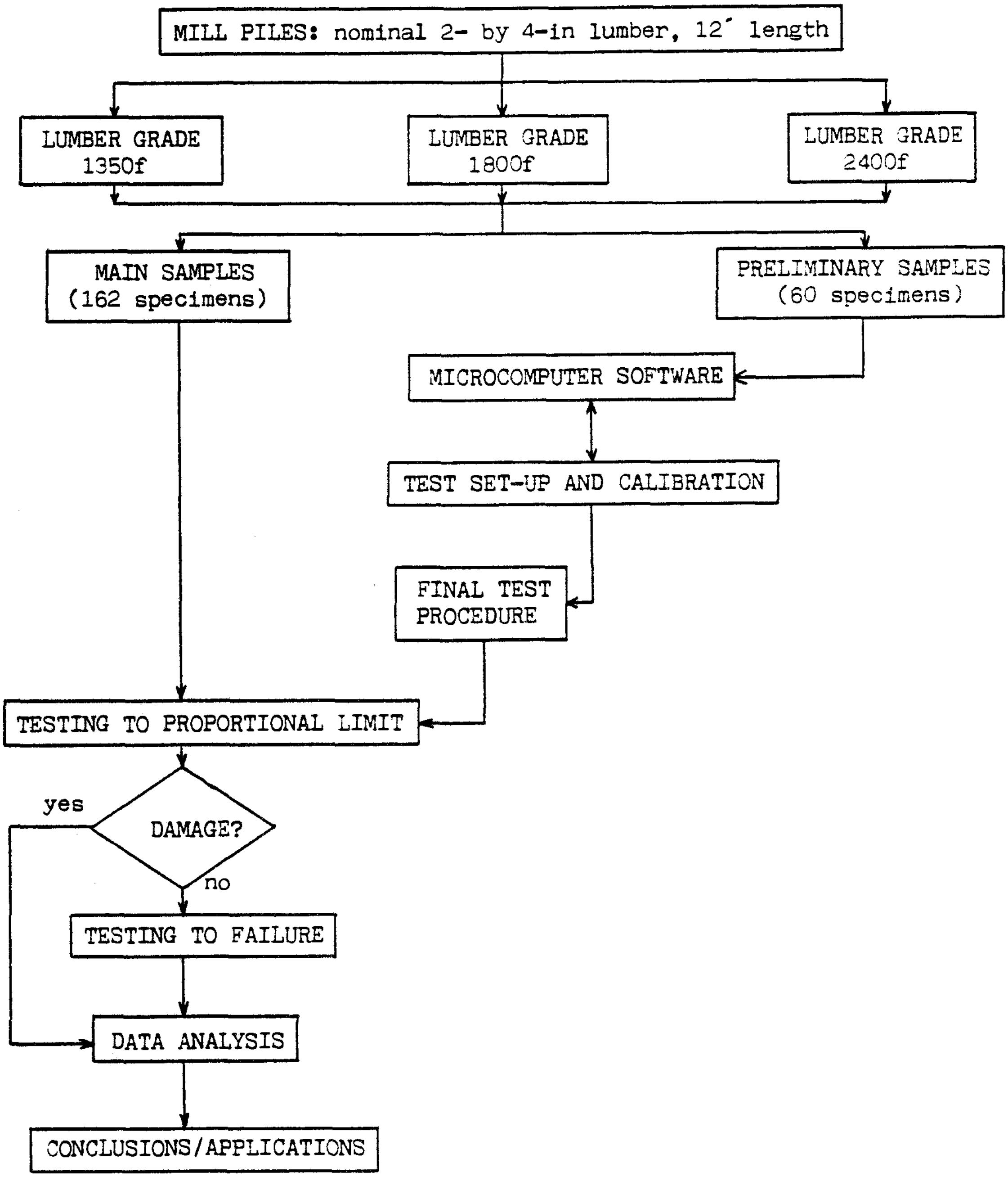

Figure 3.2. Flowchart of study procedure for bending tests.

carried out on the current data collected to obtain the overall slope of the trace. This regression line was then extended into region 3 in which the PL was to be encountered. The difference between the theoretical load as determined by the regression line and the actual load (shown as ΔL in Figure 3.3) was then calculated for each six pound load increment. The proportional limit was chosen (and thus the load was reversed) at the point when this difference exceeded eight pounds. As expected, region 2 varied among the three test types as follows: 280 to 360 lbs for sample 1A, 320 to 420 lbs for sample 2A, and 360 to 460 lbs for sample 3A.

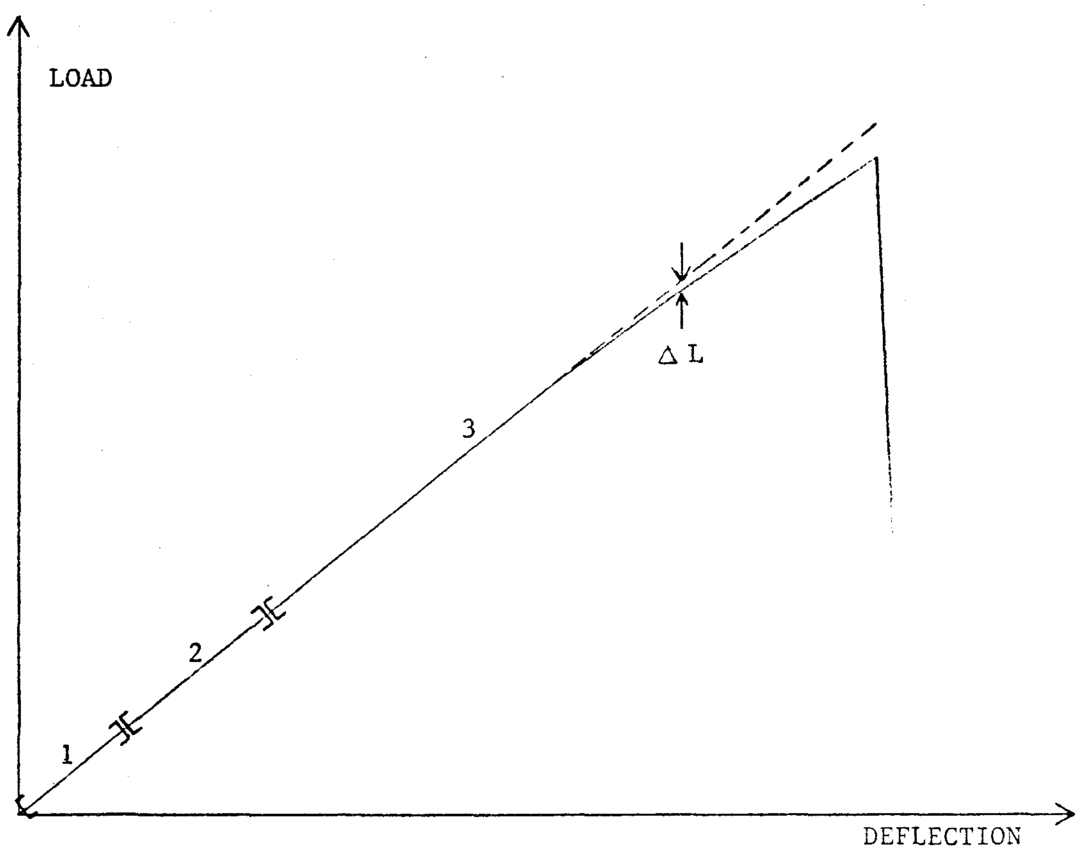

Figure 3.3. Technique used to determine proportional limit from

load-deflection data (1 = data ignored, 2 = slope determination, and 3 = proportional limit detection region).

After being loaded to the apparent PL, each test specimen was visually examined to detect possible damage. Failed specimens were discarded. Test specimens that did not fail were subsequently retested in bending to failure using the recommended ASTM deflection rate. The double testing of each specimen was aimed at determining standard mechanical properties using accelerated PL test variables and to provide data for checking the accuracy of the PL evaluation by the nondestructive tests.

3.2.2 ACOUSTIC EMISSIONS

AE were monitored on 42 specimes tested to failure in flexure (Figure 3.1); 18 specimens under the 24-ipm deflection rate (Sample 4) and 24 specimens under the 0.5-ipm deflection rate (Sample 5).

Figure 3.4 shows the schematic diagram of the apparatus for gathering AE. The AE were monitored by a 500-kHz piezoelectric transducer which was attached to specimens by a clamp (Figure 3.5). A 60-dB amplifier boosted the signal from the transducer 1000 fold. Preliminary testing indicated that all emissions below 0.5 kHz were artifacts of the loading system and were thus eliminated by passing the signal through a band-pass filter. This conditioned signal was then sent to a digital counter where the critical peak amplitudes exceeding 0.13 volts were counted. The threshold voltage level of 0.13 volts, which was determined during preliminary testing, was

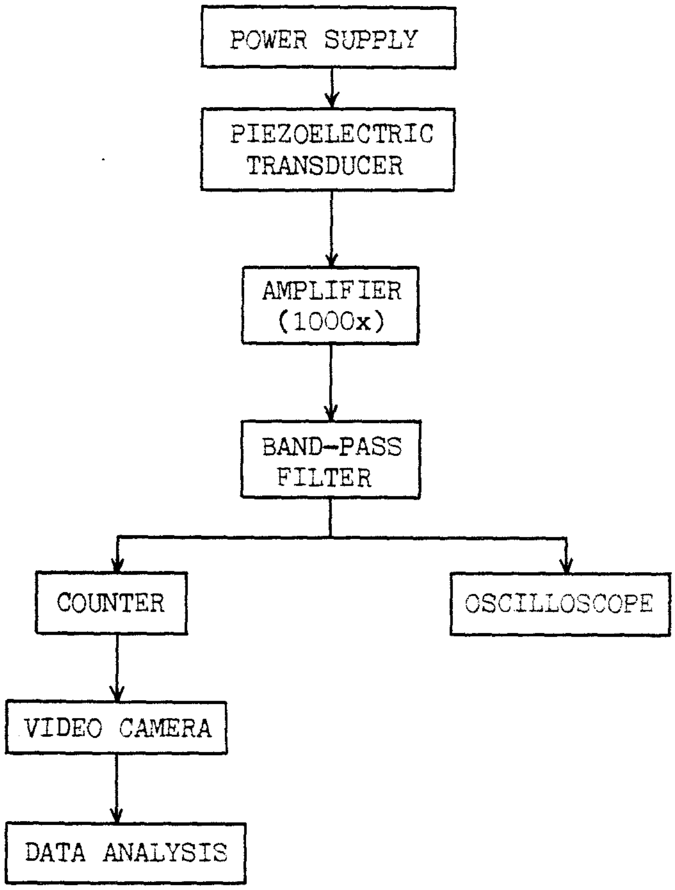

Figure 3.4. Schematics for gathering of acoustic emissions data.

selected to minimize background noise and maximize specimen noise.

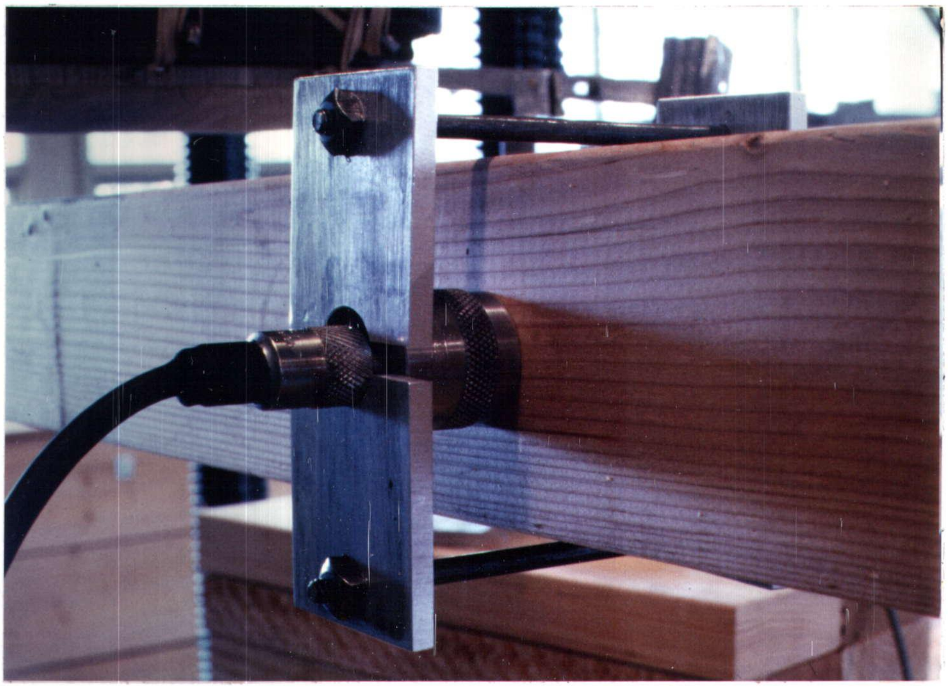

Figure 3.5. Attachment of piezoelectric transducer to acoustic emission test specimen.

The rate of AE counts was obtained with the aid of a video camera, since no signal output was available from the digital counter. The camera recorded the peak counts from the digital counter and time from the digital stopwatch. To obtain the corresponding load, a load voltmeter was referenced to initiate the time when load was first applied to the specimen (Figure 3.6). The video tape was played back to manually read the AE peak count and time from the individual picture frames. This information was transferred to magnetic tape for analysis.

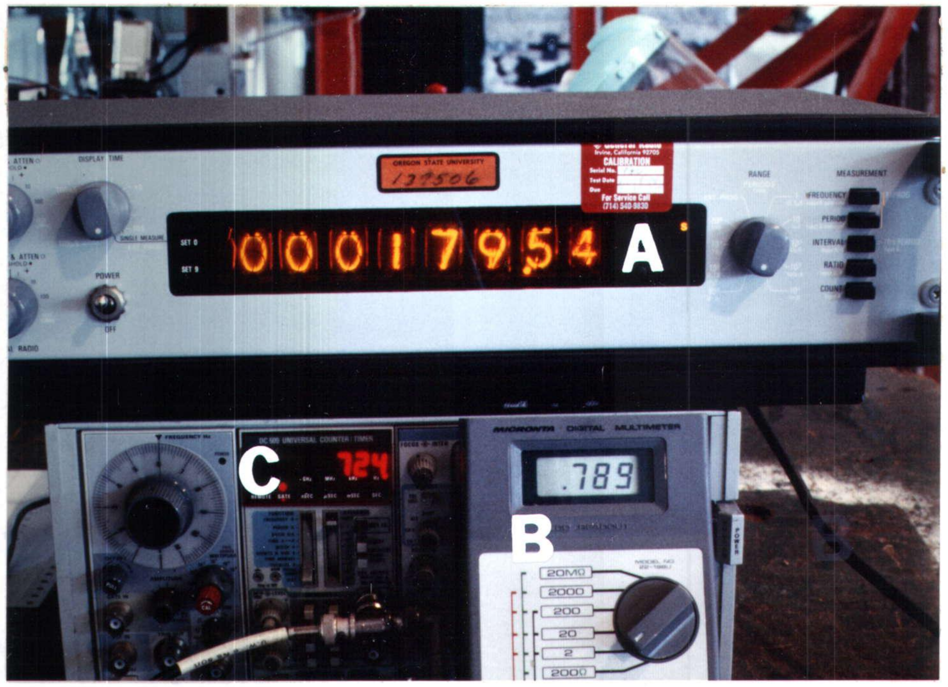

Figure 3.6. Arrangement for video monitoring of acoustic emissions rate: A = digital stopclock, B = load voltmeter, and C = digital counter.

3.3 DATA ANALYSIS

The analysis included, first, evaluation of engineering properties, such as MOE and MOR, and, second, statistical testing and interpretation.

3.3.1 DATA REDUCTION

Conventional relations from the strength of materials were applied in calculating engineering properties from the load-deflection traces:

$$MOR = (UL)(L) / b h^2$$

$$MOE = (PLL)(L)^3 / 4.7 b h^3 (PLD)$$

$$MORSL = (UL - PLL) / (UD - PLD)$$

where UL = maximum load,
PLL = load at proportional limit,
b = specimen width,
h = specimen depth,
L = span,
UD = deflection at maximum load,
PLD = deflection at proportional limit,
MOR = modulus of rupture,
MOE = modulus of elasticity, and
MORSL = slope approximating inelastic MOE.

3.3.2 STATISTICAL ANALYSIS

Raw and reduced data were analyzed by the computer package "Statistical Package for the Social Sciences" (27). The most significant linear multiple regression models were determined by the forward selection procedure, in which the independent variables with the highest partial correlation to the dependent variable were gradually added to the current model until their contribution becames insignificant at the 5 percent level.

Regression models for bending tests contained MOR, UD, and MORSL as dependent variables, and MOE, SPL, PLD, and SG as independent variables. Each sample was first analyzed individually and then all samples were combined and analyzed as one sample.

Table 3.1 summarizes the symbols used for AE independent variables. There were three different types of regression analysis performed on the AE data. The first regressed SPL and PLD on SG, MOE, and low stress level AE. These low stress level AE variables, which were generally at or below the PL, consisted of AE50UL, AE60UL, LD100, LD200, RT4, RT8, RT200, RT400, COUNT, and AERATE. The second had UL, UD, MOR, and MORSL as the dependent variables and low stress level AE, SG, MOE, SPL, and PLD as the independent variables. The third had UL, UD, MOR, and MORSL as the dependent variables and all AE variables as independent predictors. The data were first grouped and analyzed by their deflection rate and MSR grade, and then were combined into one grand sample.

Table 3.1. Acoustic emissions (AE) independent variables used in regression analysis.

AEiUL	=	Cumulative AE peak count at i percent of ultimate load. (i = 50, 60, 70, 80, 90, 100)
LDi	=	Load when cumulative AE reaches i peak counts. (i = 100, 200, 300, 400, 500, 600)
RTi	=	Load when AE rate reaches i counts/sec (lbs). (i = 4, 8, 12, 16, 20, 200, 400, 600, 800, 1000)
COUNT	=	Cumulative AE peak count at proportional limit.
AERATE	=	AE rate at proportional limit (counts/sec).

IV. RESULTS AND DISCUSSION

This chapter summarizes mechanical properties, presents reduced data, and discusses regression results obtained from samples described in Chapter III.

4.1 PROPORTIONAL LIMIT AS DEPENDENT VARIABLE

This section discusses overall lumber properties for test types 1, 2, and 3 and the correlation of some of these properties to destructive parameters, as well as the correlation between nondestructively and destructively determined PL.

4.1.1. OVERALL LUMBER PROPERTIES

A summary of material and static-bending properties of test types 1, 2, and 3 is shown in Table 4.1. The results show that six, five, and one specimens in the 1350f, 1800f, and 2400f grades, respectively, failed when tested nondestructively. However, it is not uncommon for lumber tested to failure to fail at the PL. Fernandez (13) found that 15 of his 250 Englemann spruce studs failed within five percent of the PL, with 7 failing at the PL.

4.1.2 EVALUATION OF PROPORTIONAL LIMIT

The coefficient of variation (COV) of 19.9 percent for the nondestructively evaluated SPL and PLD in this study is approximately

Table 4.1. Summary of engineering properties for proportional limit samples.

SAMPLE NO.	SAMPLE SIZE	NUMBER OF PL FAILURES	STATISTICS	PROPERTIES							
				SG	MOE (10^6 psi)	SPL (psi)	PLD (in)	UL (lbs)	UD (in)	MOR (psi)	MORSL (ppi)
1	52	6	MEAN	0.473	1.56	4250	2.16	959	3.57	5990	176
			S. D.[1]	0.031	0.16	990	0.37	268	1.02	1680	40
			COV[2]	6.5	10.3	23.3	16.9	27.9	28.6	28.0	22.5
2	50	5	MEAN	0.502	1.78	4610	2.06	1059	3.49	6600	177
			S. D.	0.030	0.16	600	0.26	244	1.04	1520	72
			COV	5.9	8.9	12.9	12.4	23.0	29.8	23.0	40.7
3	60	1	MEAN	0.559	2.39	5470	1.85	1438	3.96	9020	241
			S. D.	0.041	0.21	830	0.30	348	1.31	2180	74
			COV	7.4	9.0	15.1	16.4	24.2	33.1	24.2	30.7
combined	162	12	MEAN	0.515	1.94	4830	2.01	1173	3.69	7340	201
			S. D.	0.050	0.40	960	0.34	361	1.16	2270	72
			COV	9.7	20.7	19.9	16.7	30.8	31.4	30.9	35.7

[1] S.D. = Standard deviation

[2] COV = Coefficient of variation

half of that reported by Fernandez (13) and Atherton (6) for destructively evaluated PL, as well as lower than the 31.7 percent for the destructively evaluated PL in this study. A possible explanation for the reduced COV is the elimination of the human error when selecting the PL from destructive data. By eliminating the judgement a researcher must make as to the location of the PL, precision is increased which in turn reduces statistical variability. However, while the nondestructive MOE evaluated obtained in this study had approximately the same COV as that found by Fernandez (13), the MOR variation of 30.9 percent for this study was considerably lower than the 45 percent obtained by Fernandez. Thus, some of this reduction in variability may have been natural to this sample.

Figure 4.1 shows the scatter diagram for the nondestructive PL evaluated under the 24-ipm deflection rate and the destructive PL evaluated during the 0.5-ipm deflection rate. The r of 0.92 between these two variables illustrates a strong relationship between the two methods for evaluating PL even when using different deflection rates. Thus the nondestructive evaluation method of PL is preferred because of reduced variability and the strong relationship between the two methods for evaluating PL.

4.1.3. REGRESSION EQUATIONS

Table 4.2 summarizes the multiple regression equations with significance level, α, equal to 0.05 and r´s for each MSR grade and for all grades combined. An independent variable, estimated fiber stress (FS), was added to the combined equation to characterize grade.

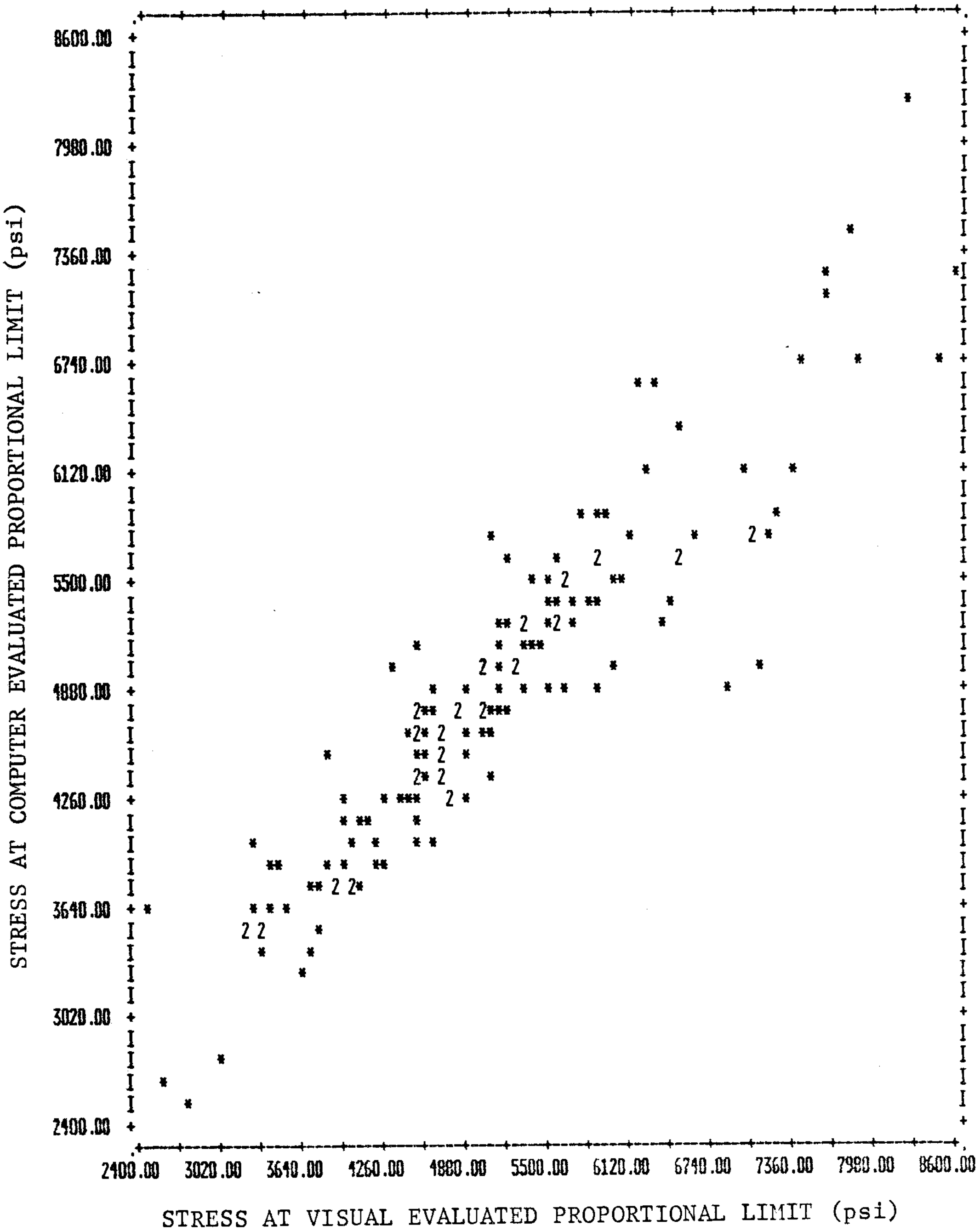

Figure 4.1. Relationship between nondestructively and destructively evaluated proportional limit.

Table 4.2. Regression models of destructive properties using nondestructive variables

SAMPLE NO.	DEPENDENT VARIABLE (Y)		COEFFICIENTS OF REGRESSION EQUATION: $Y = a_0 + a_1x_1 + a_2x_2 + a_3x_3$ [1]							r
	SYMBOL	UNITS	a_0	a_1	x_1	a_2	x_2	a_3	x_3	
1	UL	lbs	-33.3	0.234	SPL					0.860
	UD	in	0.499	.000723	SPL					0.702
	MOR	psi	-194	1.45	SPL					0.858
	MORSL	ppi	-603	462	MOE	-0.15	SPL	280	PLD	0.505
2	UL	lbs	-680	0.200	SPL	390	MOE			0.662
	UD	in	0.373	.000677	SPL					0.388
	MOR	psi	-4430	1.24	SPL	2500	MOE			0.669
	MORSL	ppi	-355	1120	SG					0.393
3	UL	lbs	-96.7	0.281	SPL					0.667
	UD	in	-0.206	.000763	SPL					0.479
	MOR	psi	-541	1.75	SPL					0.663
combined	UL	lbs	-459	0.230	SPL	230	MOE			0.830
	UD	in	1.02	.000736	SPL	.00047	FS [2]			0.540
	MOR	psi	-2970	1.43	SPL	1500	MOE			0.832
	MORSL	ppi	55.5	79.0	MOE					0.443

[1] Units for independent variables in Appendix A.

[2] FS = 1350 psi, 1800 psi, or 2400 psi.

effect.

For all samples combined, SPL was the best predictor of UL, UD, and MOR, which was followed by MOE for predicting MOR and UL (Table 4.2). Addition of FS to the combined group was significant in the prediction of only UD.

The analysis shows that the correlations between destructive and nondestructive variables were higher for the 1350f grade than for the 1800f or 2400f grades (Table 4.2). The lower grade has larger and more critical defects than the higher grades. The affect of these defects are easier to predict than a series of many small and less critical defects in the higher grades, which results in higher r´s. This reasoning may also explain the lower r´s in this study than those of an earlier work; Atherton (6) and Fernandez (13) used stud grade lumber, which generally contains large and critical defects, which resulted in r´s of 0.88 to 0.92 which are close to the r of 0.86 of this study.

4.2 ACOUSTIC EMISSIONS INDEPENDENT VARIABLES

4.2.1 DATA DESCRIPTION

Figure 4.2 compares a load-deflection trace with the peak count and rate of AE for a typical specimen of Sample 4 and 5. AE independent variables were estimated from such traces and then included in the regression analysis.

Traces of cumulative AE showed two general patterns. The first pattern appeared in approximately 90 percent of specimens. They show

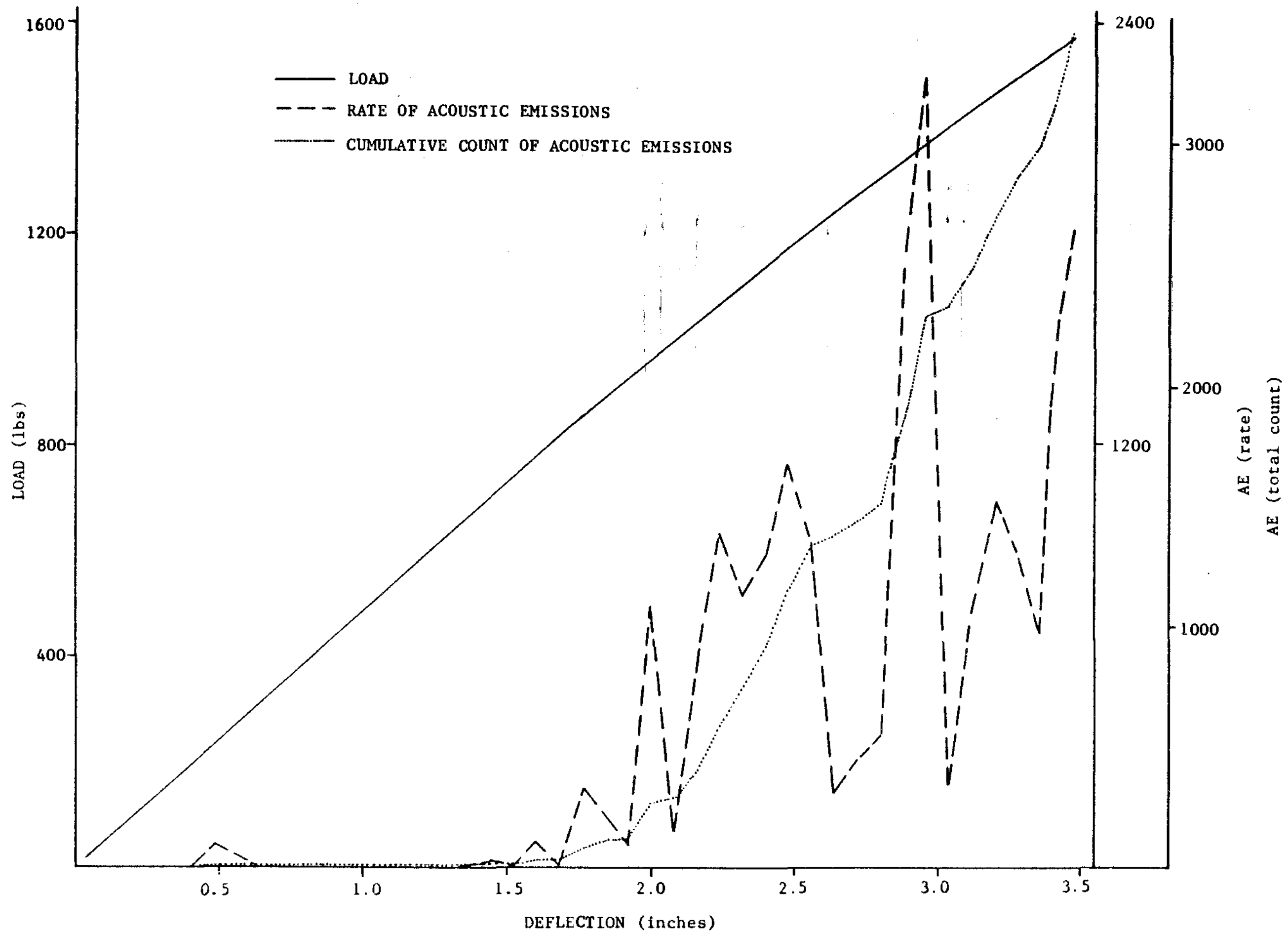

Figure 4.2. Comparison between load-deflection and acoustic emissions-deflection traces for a typical specimen of Samples 4 and 5.

the AE peak counts beginning slightly below the PL in an apparent exponential pattern. At approximately 75 percent of UL, AE trace became either linear or concavely curvilinear and remaining as such till failure (Figure 4.2). The second pattern had the peak counts beginning linearly to failure after the PL, with maximum count remaining below 1500 peaks. Adams (1) also investigated nominal 2- by 4-inch specimens and found four patterns, but he noted that the distinctions between his categories were small and somewhat arbitrary. The distinctions between the Adams´s patterns are so small that they can be grouped into two patterns that closely resemble the patterns observed in this study.

If a specimen is stressed and then the stress is removed, no AE will occur upon restressing until the previous stress is reached. The results of this study demonstrate this effect. Figures 4.3a and 4.3b show, respectively, the loading and AE history of a typical specimen which was repeatedly loaded, until failure occured during the sixth loading. The first loading produced a cumulative AE count of slightly more than 5000 peaks (trace 1), with the next three loadings producing few AE counts. The fifth loading was increased to the original load with a slight increase in AE peak counts, but far less than 5000 counts of the first cycle. The sixth loading cycle, carried out to failure, had no AE occurring until just before failure, at which point there was a marked increase in AE rate. Thus, the Kaiser effect seems to be rather well defined in wood also. Because the Kaiser effect is applicable to wood, AE equipment can be calibrated to insure that the specimen and not the testing apparatus is producing AE.

Table 4.3 contains a summary of the AE data. Deflection rates

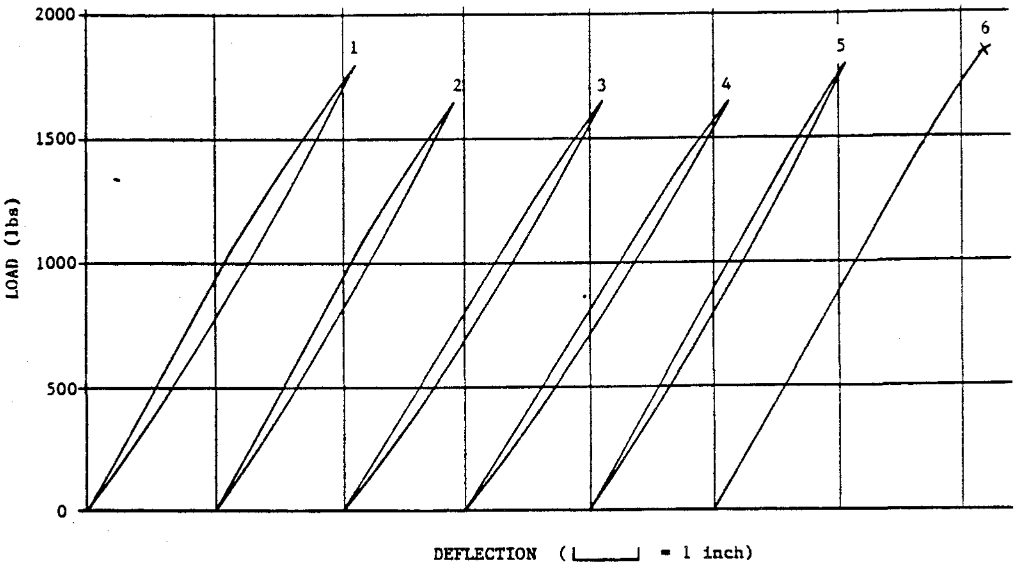

Figure 4.3a. Load-deflection diagram of each cycle in a Kaiser test.

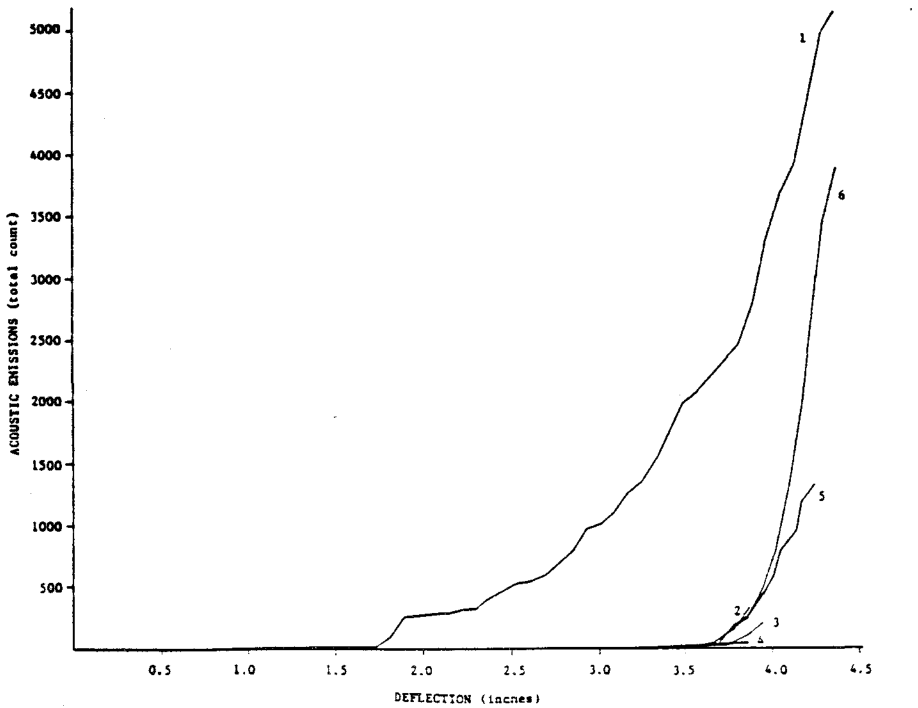

Figure 4.3b. Cumulative acoustic emissions of each loading displaying Kaiser effect.

Table 4.3. Mean, standard deviation, and t-statistics comparing 0.5 in/min deflection rate to 24 in/min deflection rate.

VARIABLE		MEAN AT DEFLECTION RATE, ipm		STANDARD DEVIATION AT DEFLECTION RATE, ipm		*t-statistics
SYMBOL	UNITS	24	0.5	24	0.5	
COUNT	peak counts	459	439	449	474	0.14
RATEPL	cps	417	4	511	7	3.97
AE50UL	peak counts	216	256	335	244	-0.45
AE60UL	peak counts	492	431	672	365	0.38
AE70UL	peak counts	867	897	987	997	-0.10
AE80UL	peak counts	1520	1510	1460	1520	0.01
AE90UL	peak counts	2500	3020	2150	3380	-0.57
AE100UL	peak counts	3920	5700	2780	5460	-1.26
LD100	lbs	725	494	364	274	2.36
LD200	lbs	798	571	388	269	2.24
LD300	lbs	866	627	402	259	2.33
LD400	lbs	906	684	417	250	2.15
LD500	lbs	947	731	434	254	2.02
LD600	lbs	975	756	431	249	2.07
RT200,RT4	lbs	677	394	359	180	3.36
RT400,RT8	lbs	782	498	400	281	2.70
RT600,RT12	lbs	895	616	444	329	2.35
RT800,RT16	lbs	1010	738	521	410	1.90
RT1000,RT20	lbs	1190	785	550	345	2.93
SPL	psi	5000	3840	1170	940	3.56
PLD	in	1.89	1.82	0.32	0.42	0.62
UL	lbs	1340	933	450	287	3.56
UD	in	3.36	3.31	0.83	1.22	0.16
MOR	psi	8300	5830	2790	1810	3.28
MORSL	ppi	351	236	112	79	3.74

*for; = 0.01, t = 2.704
= 0.05, t = 2.021
= 0.10, t = 1.684

were separated and compared with the help of t-statistics to identify variables that are significantly affected by testing speed. If the tabulated t-statistics exceeds those associated with α at the bottom of Table 4.3, then the corresponding variable is affected significantly. The variables that are different at $\alpha = 0.05$ are in italics.

Table 4.3 shows that the deflection rate affected the following variables: RATEPL, LD100, LD200, LD300, LD400, LD500, LD600, RT200, RT400, RT600, RT1000, SPL, UL, MOR, and MORSL, while it had no affect on COUNT, AE50UL, AE60UL, AE70UL, AE80UL, AE90UL, AE100UL, RT800, PLD, and UD. Because an increase in deflection loading rate increases the load at the same deflection (23), it is expected that the variables dependent upon UL are also affected by the rate. An increase for deflection rates of this study was about 25 percent. This increase may be partially due to the small sample size as well as the grade breakdown which was somewhat different in samples studying the two deflection rates (Appendix C).

Porter (33) demonstrated that there is a linear correlation between extension of crack length during cleavage and cumulative AE peak count. Therefore, an attribute of AE is its ability to indicate how much crack extension, that is the rate of damage increase, occurs in a specimen during stress testing. Comparing COUNT with AE100UL shows that about eight to twelve percent of cumulative AEs occur below the PL. Gerhards (16) demonstrated that this should not correspond to the same numerical decrease in strength, since the crack extensions are not related to the overall strength of the specimen. However, some damage does occur, because AE do indicate internal material damage.

4.2.2 RELATIONS AMONG VARIABLES

AE were used to accomplish several objectives, one of which was to predict the PL. Table 4.4 shows a summary of r´s for the AE data analyzed. The values for AE50UL to AE100UL were omitted from Table 4.4, because the absolute value of r´s were less than 0.30. Table 4.4 shows that correlation between AE variables and SPL are good. However, since only AE at small loads, such as LD100, LD200, RT200, and RT400, are below the PL, the corresponding r´s are approximately the same as those of MOE. While the AE-SPL correlations are significant at $\alpha = 0.05$, PLD correlates poorly with AE variables. However, because material damage and, thus, AE are dependent on stress, then it is expected that AE variables should show a stronger correlation with SPL than with PLD.

The r´s for relating AE to UL, UD, and MOR increase as AE levels increase. Again, this was expected, because the higher AE levels corresponded to higher deflections and loads. Table 4.4 shows that LD300 to LD600 and MOR, with r´s between 0.83 and 0.89, show stronger correlation than other variables. Because these r´s exceed 0.81 for SPL-MOR, AE may be more useful in predicting lumber strength than the PL. To show such a correlation, observations for LD600 were plotted with respect to MOR (Figure 4.4). The AE rate may also prove useful in predicting lumber strength. This is emphasized in Figure 4.5 which shows observations for RT1000 plotted with respect to MOR, with an r of 0.80.

AE variables were also included in the prediction of the

Table 4.4. Correlation coefficients for relations between strength and stiffness properties and acoustic emissions variables.

INDEPENDENT VARIABLES	DEPENDENT VARIABLES					
	SPL	PLD	UL	UD	MOR	MORSL
MOE	0.693	-0.220	0.754	0.099	0.754	0.810
SPL	-	0.533	0.807	0.378	0.806	0.629
PLD	0.533	-	0.231	0.445	0.230	-0.103
LD100	0.599	0.151	0.722	0.344	0.722	0.534
LD200	0.642	0.143	0.774	0.386	0.775	0.562
LD300	0.685	0.175	0.825	0.445	0.825	0.581
LD400	0.718	0.199	0.847	0.468	0.849	0.595
LD500	0.734	0.214	0.868	0.512	0.869	0.580
LD600	0.756	0.221	0.884	0.517	0.885	0.587
RT200,RT4	0.651	0.212	0.639	0.146	0.634	0.609
RT400,RT8	0.643	0.164	0.766	0.358	0.767	0.572
RT600,RT12	0.793	0.288	0.830	0.477	0.831	0.573
RT800,RT16	0.715	0.472	0.769	0.621	0.772	0.376
RT1000,RT20	0.679	0.332	0.800	0.578	0.797	0.458

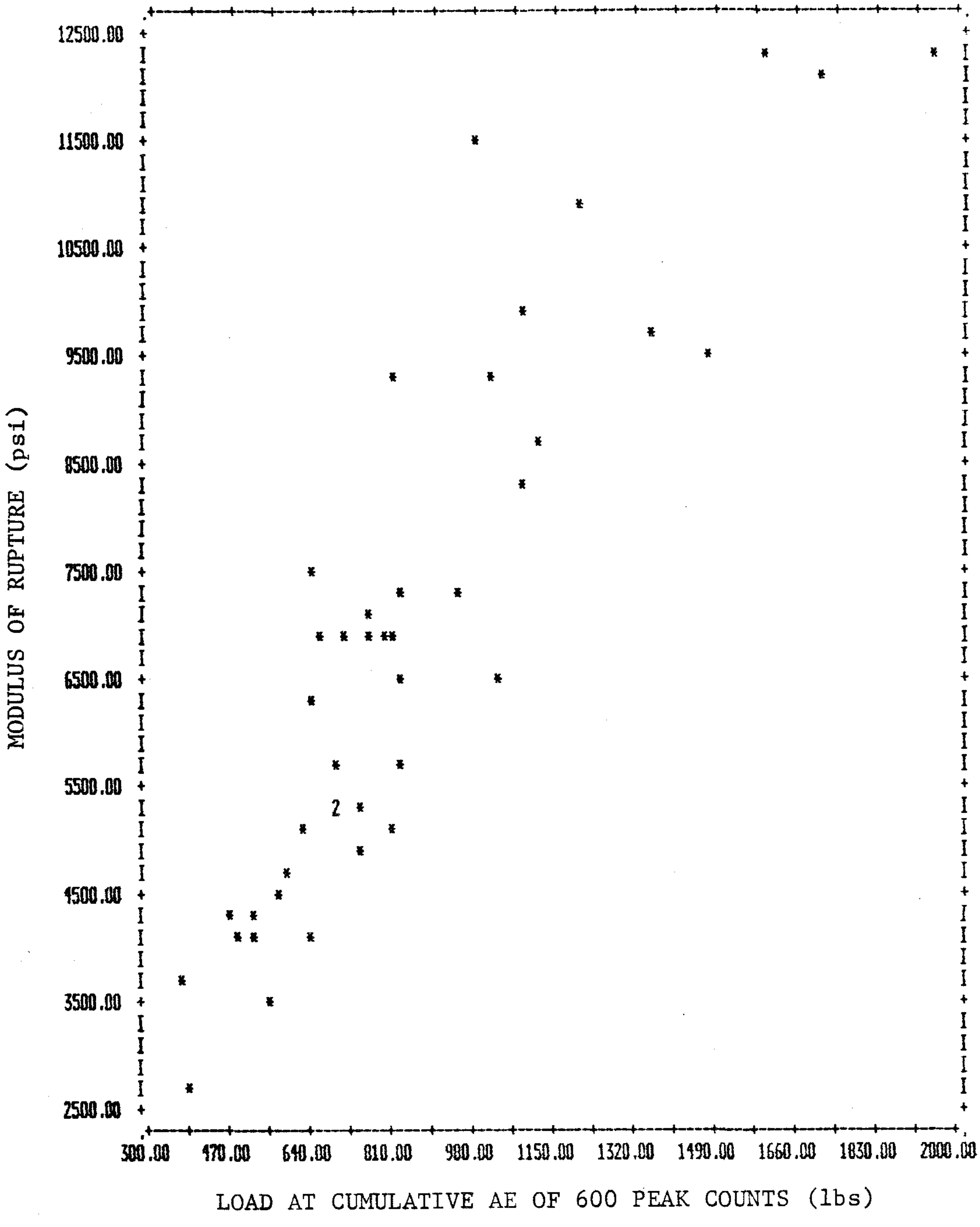

Figure 4.4. Relationship between modulus of rupture and cumulative acoustic emissions peak counts.

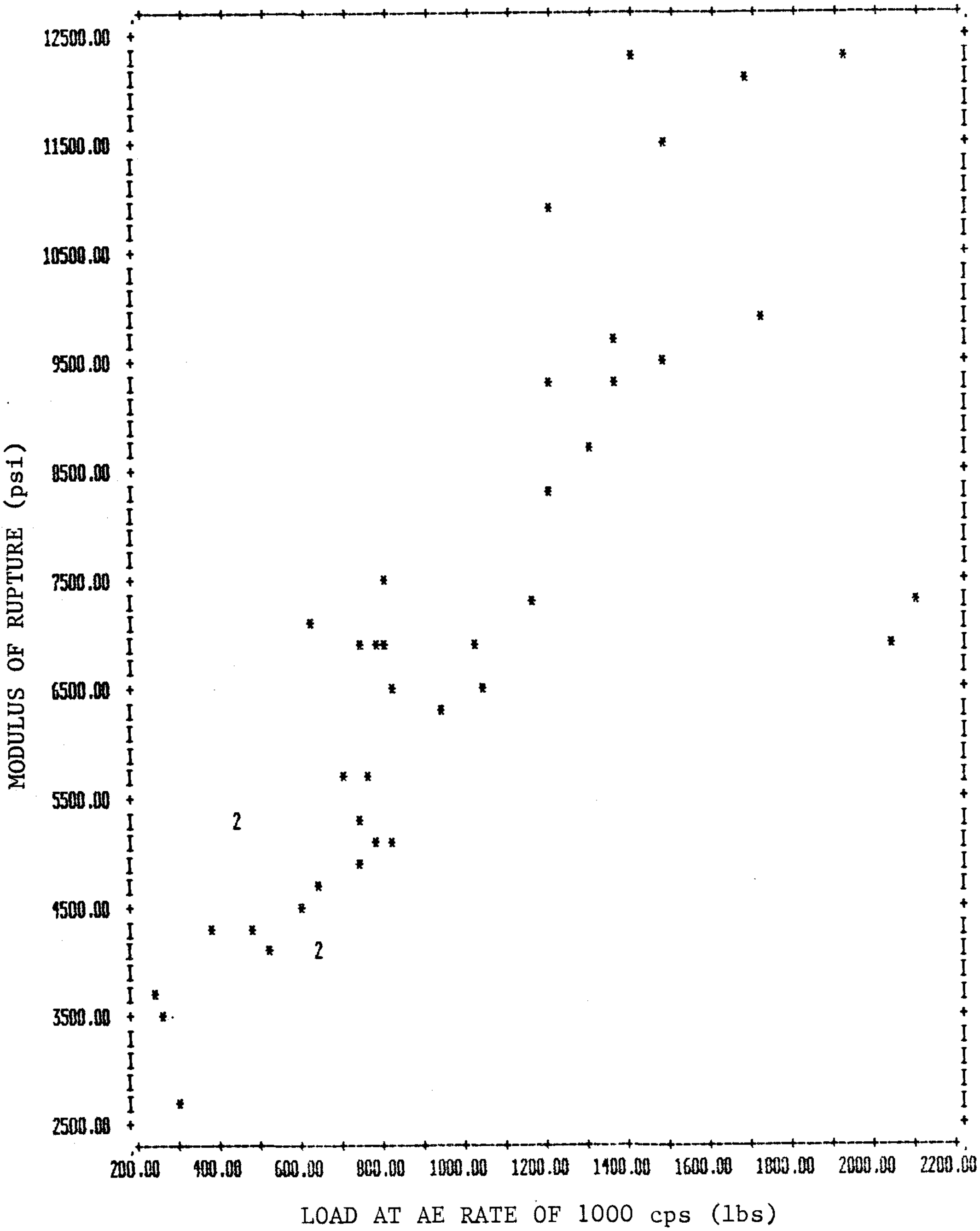

Figure 4.5. Relationship between modulus of rupture and acoustic emissions rate.

load-deflection relation in the region between the PL and UL. The results are promising, with r´s of about 0.6 for relations between MORSL and AE variables below PL (Table 4.4). Although this significant correlation is not as strong as that between MOE and MORSL, it is still useful in predicting specimen behavior above the PL.

To better explain mechanical properties using more than one variable, multiple regression was also performed on the AE data by the forward-selection technique (Table 4.5). The data were subdivided into two groups with respect to deflection rate; in addition, the data were analyzed as belonging to one group that included all the data. The variables summarized in Table 4.5 are those which are significant at $\alpha = 0.05$. Two separate regression analyses were carried out on the data; the first based on AE at low stress levels and physical properties, while the second included all AE variables but no physical properties.

Table 4.5 shows that the deflection loading rate did not affect the correlation studies, especially those based on AE. An affect was observed on the prediction of SPL for low load levels, at which specimens at the deflection rate of 24 ipm have higher r´s for all variables except PLD. It is possible, however, that the increase in r´s could be attributed to sample size.

Exclusion of physical properties and inclusion of AE data above the PL did not substantially alter r´s, with the exception of MORSL. The correlation of AE to MORSL gets reduced because of the absence of MOE which has traditionally been essential in predicting MORSL.

Combining all AE data below PL results in r´s of 0.76, 0.83,

Table 4.5. Relations between nondestructive and acoustic emission variables with mechanical properties.

SAMPLE NO.	SAMPLE SIZE	DEPENDENT VARIABLE (Y)		LOW STRESS LEVEL INDEPENDENT VARIABLES[1]												ACOUSTIC EMISSIONS INDEPENDENT VARIABLES[1]							
				COEFFICIENTS OF REGRESSION EQUATION: $Y=a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_5$												COEFFICIENTS OF: $Y = a_0 + a_1x_1 + a_2x_2 + a_3x_3$							
		SYMBOL	UNITS	a_0	a_1	x_1	a_2	x_2	a_3	x_3	a_4	x_4	a_5	x_5	r	a_0	a_1	x_1	a_2	x_2	a_3	x_3	r
4	18	SPL	psi	1110	1560	MOE									0.705								
		UL	lbs	-39.9	.904	RT400	.55	AE50UL	.11	SPL					0.958	332	.981	RT600	.084	AE80UL			0.933
		UD	in	-.299	.00164	RT400	.00082	AE60UL	1.0	PLD					0.849	1.34	.00133	RT800	.00017	AE100UL			0.885
		MOR	psi	-247	5.61	RT400	3.4	AE50UL	.68	SPL					0.958	2060	6.09	RT600	.52	AE80UL			0.933
		MORSL	ppi	-115	188	MOE									0.886	193	.177	RT600					0.704
5	24	SPL	psi	1610	1120	MOE									0.465								
		PLD	in	2.81	.0012	RT200	.00079	AE50UL	-3.2	SG					0.633								
		UL	lbs	-13.2	.130	SPL	.59	LD200	.43	AE50UL					0.853	321	.779	RT1000					0.938
		UD	in	.702	.00382	AE50UL	.0029	LD200							0.776	.817	.00255	RT1000	.0019	AE50UL			0.876
		MOR	psi	-145	.805	SPL	3.8	LD200	2.8	AE50UL					0.855	1970	4.91	RT1000					0.937
		MORSL	ppi	109	-.145	AE60UL	96	MOE							0.862	303	-.157	AE60UL					0.724
combined	42	SPL	psi	1160	1100	MOE	1.5	RT200							0.758								
		UL	lbs	-276	.106	SPL	.72	LD200	.47	AE50UL	150	MOE			0.932	57.2	.923	LD600	.37	AE50UL	.18	RT1000	0.941
		UD	in	.0711	1.63	PLD	.00048	COUNT	.0026	AE50UL	.0023	LD200	.0004	SPL	0.828	1.70	.00148	RT800	.0016	AE50UL			0.748
		MOR	psi	-1690	.649	SPL	4.5	LD200	2.9	AE50UL	940	MOE			0.933	345	5.78	LD600	2.4	AE50UL	1.1	RT1000	0.943
		MORSL	ppi	-64.6	172	MOE	-.12	AE50UL							0.862	226	.197	RT200	.0086	AE100UL			0.703

[1] Units for independent variables in Appendix A.

0.93, and 0.86 for SPL, UD, MOR, and MORSL, respectively. Excluding physical properties and including AE above PL resulted in r´s of 0.75, 0.94, and 0.70 for UD, MOR, and MORSL, respectively. These results suggest a strong correlation between lumber strength and AE, which corresponds to the physical nature of wood under stress: flaw type, size, and location affects lumber strength as well as AE.

V. CONCLUSIONS AND RECOMMENDATIONS

The most important conclusions reached on the basis of testing and data analysis performed in this investigation are:

1. The proportional limit (PL) can be determined in a microcomputer-controlled test by loading lumber at a fast rate and reversing the load immediately upon achieving the PL. The computer-detected PL is highly correlated with the PL determined from load-deflection traces obtained in destructive testing;
2. Although a combination of stress at PL and MOE is a good estimator of lumber MOR, it results in poor prediction of ultimate deflection;
3. The correlation between MOR and physical properties improves with a decrease in lumber quality;
4. Approximately ten percent of the total count of acoustic emissions (AE) occur before the PL, indicating that preloading to the PL may cause partial structural damage;
5. The rate and cumulative count of AE are better predictors of lumber strength than either stress at PL or MOE;
6. Not only is a combination of AE below the PL and physical properties strongly correlated to stress at PL, but the same combination is also strongly correlated to strength and ultimate deflection; and
7. A fifty-fold increase in strain rate during the testing did not affect the cumulative count of AE.

The testing results and literature study also provided several recommendations for future work, which should help to apply AE in industrial processes:

1. Fundamental research should be carried out correlating AE and the size and type of defects and its effect on the PL.

2. The use of a spectrum frequency analyzer in future studies would provide AE variables, such as frequency and acoustical energy, which could assist in categorizing defect types and sizes.

3. The effect of AE by load level, loading on flat and edge face, commercially important species and effect of moisture content should be investigated.

4. A study is needed to quantify structural damage from nondestructive loading up to PL on strength and stiffness of lumber.

5. Criterion should be found for stopping loading of lumber that behaves elastically up to ultimate load.

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APPENDICES

APPENDIX A

LIST OF SYMBOLS USED IN THIS STUDY

List of abbreviations

AE	= acoustic emissions
AERATE	= rate of AE at proportional limit (cps)
AE50UL	= cumulative AE peak counts at 50% of ultimate load
AE60UL	= cumulative AE peak counts at 60% of ultimate load
AE70UL	= cumulative AE peak counts at 70% of ultimate load
AE80UL	= cumulative AE peak counts at 80% of ultimate load
AE90UL	= cumulative AE peak counts at 90% of ultimate load
AE100UL	= cumulative AE peak counts at failure
ASTM	= American Society for Testing and Materials
b	= specimen width (in)
CLT-1	= Continuous Lumber Tester-1
COUNT	= cumulative AE peak counts at proportional limit
COV	= coefficient of variation (percent)
cps	= counts per second
E	= dynamic modulus of elasticity
FS	= rated fiber stress (psi)
h	= specimen depth (in)
ipm	= inch per minute
L	= load (lbs)
LD100	= load when cumulative AE reaches 100 counts (lbs)
LD200	= load when cumulative AE reaches 200 counts (lbs)
LD300	= load when cumulative AE reaches 300 counts (lbs)
LD400	= load when cumulative AE reaches 400 counts (lbs)
LD500	= load when cumulative AE reaches 500 counts (lbs)
LD600	= load when cumulative AE reaches 600 counts (lbs)
MC	= moisture content (percent)
MOE	= modulus of elasticity (10^6 psi)
MOR	= modulus of rupture (psi)
MORSL	= slope approximating inelastic MOE (ppi)
MSR	= machine-stress-rating
PL	= proportional limit
PLD	= proportional limit deflection (in)
PLL	= proportional limit load (lbs)
r	= correlation coefficient
RT4	= load when AE rate first reaches 4 cps, 0.5 ipm (lbs)
RT8	= load when AE rate first reaches 8 cps, 0.5 ipm (lbs)
RT12	= load when AE rate first reaches 12 cps, 0.5 ipm (lbs)
RT16	= load when AE rate first reaches 16 cps, 0.5 ipm (lbs)
RT20	= load when AE rate first reaches 20 cps, 0.5 ipm (lbs)
RT200	= load when AE rate first reaches 200 cps, 24 ipm (lbs)
RT400	= load when AE rate first reaches 400 cps, 24 ipm (lbs)
RT600	= load when AE rate first reaches 600 cps, 24 ipm (lbs)
RT800	= load when AE rate first reaches 800 cps, 24 ipm (lbs)
RT1000	= load when AE rate first reaches 1000 cps, 24 ipm (lbs)
SG	= specific gravity
SOM	= Stress-O-Matic
SPL	= stress at proportional limit (psi)
SR	= strength ratio
UD	= ultimate deflection (in)
UL	= ultimate load (lbs)

V_o = AE voltage threshold level
ΔL = difference between experimental and theoretical load (lbs)
ε_{pl} = strain at proportional limit
ε_{ud} = strain at failure
σ_{ul} = stress at failure
α = significance level

APPENDIX B

PROPORTIONAL LIMIT DATA

OF INDIVIDUAL SPECIMENS

Columns contain the following data:

COLUMN	DESCRIPTION
1	ID no., with the first four numbers representing the MSR rating
2	Specific gravity
3	Moisture content (%)
4	Slope of microcomputer regression line (lbs/in)
5	y-intercept of regression line (lbs)
6	Number of data pairs comprising regression line
7	Specimen width (in)
8	Specimen depth (in)
9	Computer PL load evaluated at 24 ipm deflection rate (lbs)
10	Visual PL load evaluated at 0.5 ipm deflection rate (lbs)
11	Computer PL deflection evaluated at 24 ipm rate (in)
12	Visual PL deflection evaluated at 0.5 ipm rate (in)
13	Premature failure indicator; 0 = no break, 1 = break
14	Ultimate load (lbs)
15	Ultimate deflection (in)

TABLE B1.

SAMPLE 1 DATA

C O L U M N S

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1350-04	.476	11.7	407.2	17.0	195	1.50	3.50	1325	1325	3.23	3.34	0	1746	6.38
1350-05	.465	10.2	306.4	11.0	113	1.50	3.50	575	609	1.87	2.01	0	806	2.79
1350-07	.448	9.7	283.5	29.0	104	1.50	3.46	527	521	1.80	1.80	0	1013	3.80
1350-08	.472	9.3				1.50	3.45	358	0	1.50	0	1	358	1.50
1350-10	.469	11.2	296.7	29.5	158	1.50	3.50	774	744	2.54	2.51	0	1166	4.56
1350-13	.488	11.8	287.6	24.5	105	1.50	3.49	514	580	1.73	2.00	0	812	3.80
1350-14	.447	9.5	347.9	2.3	110	1.50	3.50	615	661	1.78	1.92	0	691	2.04
1350-15	.504	12.0	265.3	21.3	138	1.49	3.48	615	624	2.25	2.36	0	644	2.49
1350-17	.459	11.2	287.4	18.0	121	1.50	3.49	574	568	1.97	1.98	0	675	2.45
1350-18	.411	11.4	370.1	-10.4	148	1.50	3.49	878	958	2.42	2.67	0	1432	5.17
1350-19	.496	10.8	331.8	-0.4	133	1.50	3.48	715	747	2.18	2.31	0	948	3.09
1350-20	.471	10.0	305.6	21.2	124	1.49	3.48	618	660	1.99	2.21	0	709	2.48
1350-21	.460	9.9				1.50	3.48	0	0	0	0	1	407	2.01
1350-22	.509	11.6	293.5	7.4	128	1.50	3.50	605	626	2.06	2.14	0	863	3.21
1350-23	.463	11.0	275.5	10.2	148	1.50	3.49	546	0	1.93	0	1	661	2.39
1350-24	.463	9.5	318.9	7.7	138	1.50	3.49	721	616	2.26	1.96	0	791	2.58
1350-25	.488	10.3	299.3	6.6	140	1.50	3.49	671	662	2.25	2.24	0	869	3.06
1350-26	.454	10.2	297.0	4.0	157	1.50	3.50	752	786	2.54	2.69	0	1105	4.21
1350-27	.474	10.6	281.5	4.6	97	1.49	3.46	429	470	1.54	1.69	0	660	2.56
1350-28	.481	10.7	280.2	12.5	123	1.50	3.49	565	517	2.00	1.84	0	789	4.00
1350-30	.477	10.1	330.1	-1.9	136	1.49	3.46	715	705	2.20	2.22	0	1138	4.20
1350-32	.528	11.1	355.7	6.6	181	1.49	3.47	1049	990	2.95	2.82	0	1573	5.47
1350-33	.494	10.0	347.4	4.1	122	1.50	3.50	683	704	1.98	2.05	0	785	2.31
1350-34	.480	10.5	307.6	5.7	149	1.49	3.47	739	799	2.41	2.65	0	1225	5.02
1350-35	.433	10.9	353.7	-2.6	160	1.50	3.49	900	942	2.58	2.72	0	1232	4.00
1350-36	.487	10.2	341.2	0.9	164	1.50	3.50	899	942	2.66	2.82	0	1479	5.18
1350-37	.455	10.7	309.8	6.5	112	1.50	3.49	564	531	1.82	1.77	0	916	4.15
1350-38	.469	12.1	318.1	-1.5	145	1.50	3.50	738	727	2.34	2.36	0	865	3.09
1350-39	.454	10.7	304.9	3.3	159	1.50	3.50	789	830	2.60	2.78	0	1209	4.66
1350-40	.494	10.8	288.2	6.1	157	1.50	3.50	740	817	2.57	2.94	0	1021	3.82
1350-41	.439	10.7	287.2	1.3	151	1.50	3.50	702	726	2.45	2.63	0	936	3.89
1350-42	.481	11.0	280.9	8.9	103	1.50	3.49	0	0	0	0	1	487	1.73
1350-43	.452	11.0	368.4	-0.5	122	1.50	3.50	741	756	2.03	2.15	0	994	3.36
1350-44	.485	10.9	330.4	5.9	109	1.50	3.50	582	546	1.77	1.69	0	789	2.76
1350-45	.504	12.1	314.4	3.9	128	1.49	3.48	647	646	2.07	2.08	0	886	2.97
1350-46	.499	12.1	310.8	2.0	95	1.50	3.49	0	0	0	0	1	471	1.52
1350-47	.520	11.6	297.3	6.7	117	1.50	3.50	560	516	1.89	1.77	0	746	2.76
1350-48	.473	10.9	321.2	6.8	144	1.49	3.49	749	796	2.34	2.51	0	1081	3.63
1350-49	.520	10.9	367.1	6.6	112	1.50	3.50	655	723	1.79	1.99	0	1142	3.94
1350-50	.498	12.0	299.6	3.9	126	1.50	3.50	613	645	2.06	2.20	0	714	2.79
1350-51	.499	10.9	293.9	7.2	140	1.50	3.49	670	636	2.28	2.20	0	807	2.94
1350-52	.450	11.0	310.2	2.5	113	1.50	3.50	554	596	1.81	1.96	0	789	3.64
1350-53	.432	11.0	230.6	12.1	114	1.50	3.50	427	420	1.83	1.85	0	543	2.48
1350-54	.396	10.7	243.8	6.0	159	1.50	3.50	624	553	2.57	2.29	0	773	3.69
1350-55	.403	10.3	306.6	-1.9	141	1.50	3.50	683	690	2.25	2.31	0	730	2.45
1350-56	.469	11.9	377.6	-1.0	125	1.50	3.50	763	824	2.05	2.22	0	1063	3.03
1350-57	.483	10.7	325.6	4.7	146	1.50	3.50	771	834	2.38	2.61	0	1329	5.37
1350-58	.505	11.8	345.5	4.5	117	1.50	3.50	658	728	1.91	2.14	0	1245	4.96
1350-59	.530	12.1	300.6	12.5	82	1.50	3.48	408	446	1.35	1.49	0	595	2.14
1350-60	.432	10.7	316.6	2.6	144	1.50	3.50	739	0	2.35	0	1	739	2.35
135019X	.486	11.5	292.3	6.7	131	1.50	3.48	631	523	2.16	1.82	0	864	3.22
135017X	.440	11.8	313.1	3.7	114	1.50	3.47	571	520	1.84	1.68	0	911	3.63

TABLE B2.

SAMPLE 2 DATA

COLUMNS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1800-11	.531	11.3	380.8	2.7	106	1.50	3.50	640	750	1.69	2.01	0	964	2.86
1800-12	.533	12.0	353.0	-8.5	142	1.50	3.49	792	747	2.29	2.21	0	888	2.67
1800-13	.509	11.4	362.1	6.6	147	1.51	3.50	850	836	2.35	2.33	0	1142	3.32
1800-14	.502	12.5	362.1	0.1	142	1.50	3.50	815	697	2.27	2.00	0	878	3.17
1800-15	.522	10.4	385.0	7.7	110	1.50	3.49	677	783	1.76	2.07	0	1121	3.22
1800-16	.501	11.9	377.7	1.4	134	1.50	3.48	807	951	2.15	2.59	0	1247	3.57
1800-17	.454	10.0	348.5	2.8	136	1.50	3.50	753	806	2.17	2.35	0	1089	4.12
1800-19	.454	11.8	384.1	-8.0	117	1.50	3.50	701	760	1.87	2.04	0	1082	3.86
1800-20	.465	11.5	357.3	3.0	152	1.50	3.50	867	0	2.44	0	1	867	2.44
1800-21	.560	11.8	343.3	-2.7	148	1.50	3.48	820	859	2.42	2.59	0	1224	4.16
1800-22	.488	12.0	369.8	-2.8	134	1.50	3.49	798	806	2.19	2.25	0	1030	2.95
1800-23	.461	11.8	385.2	-1.2	125	1.50	3.50	778	951	2.04	2.70	0	1326	4.75
1800-24	.491	11.8	350.6	4.4	113	1.50	3.50	633	691	1.82	2.02	0	921	3.15
1800-25	.516	10.3	346.4	4.0	137	1.50	3.48	771	892	2.24	2.62	0	1110	3.44
1800-26	.516	11.0	497.0	-0.1	101	1.50	3.48	798	801	1.62	1.67	0	1474	3.83
1800-27	.542	11.5	351.0	6.0	114	1.50	3.50	651	651	1.86	1.86	0	872	2.82
1800-28	.476	9.7	328.8	1.1	165	1.50	3.50	877	908	2.69	2.84	0	1421	5.41
1800-29	.522	10.6	399.8	0.4	115	1.50	3.49	736	753	1.86	1.93	0	1050	3.19
1800-30	.490	10.9	328.4	-0.4	153	1.50	3.48	808	723	2.49	2.23	0	1123	3.90
1800-31	.494	10.8	350.3	6.4	121	1.50	3.50	691	724	1.98	2.14	0	1035	3.91
1800-32	.549	11.0	389.8	4.4	115	1.50	3.50	726	737	1.87	2.02	0	1434	4.57
1800-33	.502	11.4	326.3	4.9	119	1.50	3.47	625	0	1.92	0	1	625	1.92
1800-34	.522	12.2	351.1	2.9	122	1.50	3.46	686	722	1.97	2.11	0	764	2.37
1800-35	.483	11.8	384.5	0.4	130	1.50	3.50	800	846	2.10	2.26	0	1046	3.50
1800-36	.469	12.0	364.1	3.7	119	1.50	3.50	710	753	1.96	2.10	0	1119	3.79
1800-37	.505	10.4	340.3	4.1	140	1.50	3.50	763	730	2.26	2.19	0	941	2.94
1800-39	.516	10.8	354.3	7.6	108	1.50	3.50	624	620	1.76	1.77	0	1168	5.10
1800-40	.560	11.5	377.2	5.7	141	1.50	3.50	863	921	2.29	2.48	0	1836	7.69
1800-41	.527	11.5	401.9	-0.2	111	1.50	3.50	732	786	1.84	2.02	0	1076	3.38
1800-42	.498	10.8	323.9	3.3	130	1.50	3.50	680	641	2.11	2.02	0	892	2.92
1800-43	.487	12.0	343.6	4.3	102	1.50	3.50	573	538	1.68	1.59	0	727	2.32
1800-45	.470	11.9	341.7	0.6	141	1.50	3.52	779	747	2.30	2.22	0	1066	3.41
1800-46	.487	12.0	368.1	10.3	124	1.50	3.50	738	0	2.00	0	1	738	2.00
1800-47	.562	11.2	361.2	7.5	126	1.50	3.49	737	730	2.04	2.06	0	961	2.82
1800-48	.433	10.7	320.9	6.2	106	1.50	3.50	542	0	1.68	0	1	542	1.68
1800-49	.498	11.0	395.5	-1.6	165	1.50	3.50	1058	1000	2.70	2.66	0	1319	3.78
1800-50	.500	11.5	402.9	-3.8	109	1.50	3.51	696	770	1.76	1.95	0	1082	3.45
1800-51	.498	11.5	334.0	0.6	113	1.50	3.50	609	611	1.84	1.86	0	921	3.51
1800-52	.518	10.7	341.7	0.4	140	1.50	3.49	773	786	2.29	2.35	0	997	3.57
1800-53	.459	11.7	334.7	4.1	138	1.50	3.49	740	726	2.22	2.19	0	1023	3.84
1800-54	.505	12.1	335.6	10.7	120	1.50	3.50	663	0	1.96	0	1	663	1.96
1800-55	.538	10.7	350.9	5.8	126	1.50	3.50	708	725	2.02	2.11	0	902	2.69
1800-56	.536	12.5	357.9	3.0	130	1.50	3.49	755	806	2.13	2.32	0	1043	3.07
1800-57	.507	10.4	393.1	1.4	133	1.50	3.49	847	836	2.17	2.16	0	1540	5.01
1800-58	.503	10.5	345.1	8.8	105	1.49	3.49	583	388	1.69	1.12	0	786	2.72
1800-59	.465	11.0	310.6	7.0	133	1.50	3.50	677	770	2.18	2.57	0	1188	4.94
1800-60	.465	10.2	328.9	3.4	116	1.50	3.50	615	642	1.88	2.00	0	1007	3.57
180007X	.506	10.6	386.5	0.1	128	1.50	3.47	798	808	2.08	2.22	0	1260	4.38
180018X	.493	10.9	420.6	-1.9	122	1.49	3.40	827	839	1.99	2.04	0	1347	4.01
180017X	.527	11.2	397.8	5.9	129	1.49	3.48	834	875	2.10	2.25	0	1079	3.06

TABLE B3.

SAMPLE 3 DATA

C O L U M N S

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2400-01	.528	11.9	464.9	-2.6	111	1.50	3.47	828	878	1.80	1.95	0	1740	6.28
2400-02	.508	11.6	408.5	10.2	94	1.50	3.48	618	536	1.51	1.32	0	665	1.69
2400-03	.505	11.0	430.9	1.3	125	1.50	3.50	859	938	2.01	2.22	0	1670	4.61
2400-04	.613	11.2	561.6	-3.9	87	1.50	3.47	799	1122	1.44	2.08	0	1823	4.74
2400-05	.535	10.8	442.4	6.6	122	1.50	3.50	879	868	1.99	2.01	0	1372	3.80
2400-06	.662	11.5	520.1	-2.0	90	1.49	3.45	754	1063	1.47	2.21	0	1520	4.58
2400-07	.575	12.3	533.4	1.8	105	1.50	3.48	913	1119	1.72	2.15	0	1198	2.35
2400-08	.494	12.3	431.2	5.5	86	1.50	3.48	603	622	1.41	1.48	0	826	2.18
2400-09	.557	12.2	438.1	7.2	119	1.50	3.50	847	852	1.94	2.01	0	913	2.19
2400-10	.549	12.3	457.4	0.6	97	1.50	3.50	710	813	1.57	1.83	0	1671	4.82
2400-11	.552	11.2	455.2	1.7	121	1.50	3.48	891	829	1.97	1.86	0	1244	2.98
2400-12	.517	12.0	508.3	0.2	130	1.50	3.47	1061	1346	2.10	2.74	0	1984	7.30
2400-13	.617	11.6	506.6	10.4	73	1.50	3.47	605	582	1.19	1.16	0	926	3.35
2400-14	.542	12.1	488.3	10.1	106	1.50	3.50	840	1023	1.72	2.14	0	1346	2.89
2400-15	.519	12.2	456.2	10.4	86	1.50	3.48	641	671	1.40	1.50	0	753	2.16
2400-16	.578	11.8	525.5	12.1	104	1.50	3.48	911	1058	1.73	2.06	0	1875	4.68
2400-18	.511	12.0	474.8	8.8	145	1.50	3.49	1133	1217	2.38	2.59	0	1425	3.17
2400-19	.545	11.7	433.3	21.2	94	1.50	3.48	686	704	1.55	1.60	0	763	2.43
2400-20	.608	12.1	530.5	7.8	92	1.50	3.48	800	832	1.51	1.60	0	1819	5.79
2400-21	.528	11.9	517.4	4.8	136	1.50	3.48	1161	1217	2.25	2.38	0	1954	5.75
2400-22	.564	11.0	463.4	1.5	114	1.49	3.48	855	931	1.86	2.06	0	1540	3.86
2400-23	.600	11.3	489.8	3.9	145	1.50	3.46	1171	1227	2.40	2.57	0	1872	5.50
2400-24	.545	11.1	459.1	-2.1	124	1.50	3.48	916	1122	2.02	2.52	0	1619	4.40
2400-25	.575	11.5	465.3	-1.8	119	1.50	3.48	901	885	1.96	1.99	0	1638	4.99
2400-26	.533	12.3	453.5	4.1	103	1.50	3.46	751	763	1.66	1.79	0	869	2.24
2400-27	.558	12.6	399.4	6.0	137	1.50	3.47	859	0	2.25	0	1	859	2.25
2400-28	.516	10.9	449.0	5.7	129	1.50	3.50	942	951	2.10	2.18	0	1194	2.86
2400-29	.569	12.1	442.2	6.0	103	1.50	3.49	748	717	1.70	1.67	0	984	2.45
2400-30	.582	11.5	215.4	-6.5	105	1.50	3.48	876	1013	1.74	2.02	0	1372	4.34
2400-31	.634	10.6	461.0	0.7	130	1.49	3.46	984	1191	2.15	2.67	0	1895	4.88
2400-32	.546	11.7	477.5	3.0	93	1.50	3.50	733	707	1.55	1.51	0	1550	4.05
2400-33	.569	10.9	454.8	4.1	121	1.50	3.47	894	1043	1.97	2.35	0	1490	4.04
2400-34	.488	11.0	434.2	1.0	122	1.50	3.49	854	859	2.00	2.02	0	1138	2.89
2400-35	.603	10.3	557.6	2.6	82	1.50	3.44	748	756	1.35	1.39	0	923	1.73
2400-36	.533	10.4	417.6	1.0	139	1.50	3.46	942	925	2.27	2.29	0	1515	4.77
2400-37	.547	10.6	440.6	0.5	116	1.50	3.49	815	869	1.87	2.03	0	1443	3.82
2400-38	.560	10.5	524.5	-0.2	121	1.50	3.48	1033	1043	1.99	2.06	0	1671	3.77
2400-39	.542	11.8	490.6	2.2	122	1.50	3.50	967	987	1.98	2.06	0	1908	5.23
2400-40	.611	11.9	518.9	-3.0	111	1.50	3.46	933	989	1.82	1.97	0	1510	3.44
2400-41	.557	10.8	543.8	0.5	132	1.50	3.50	1173	1382	2.17	2.62	0	1786	4.00
2400-42	.498	11.1	407.8	5.1	122	1.50	3.50	817	823	2.01	2.06	0	1504	4.34
2400-43	.525	10.6	438.0	2.5	119	1.50	3.49	827	898	1.91	2.10	0	1410	4.22
2400-44	.561	11.1	512.8	1.0	105	1.50	3.47	865	955	1.70	1.90	0	1212	2.65
2400-45	.556	10.9	478.1	5.8	140	1.50	3.46	1084	1191	2.72	2.56	0	1918	6.12
2400-46	.507	11.3	445.4	-2.8	108	1.50	3.49	780	852	1.78	1.96	0	1293	3.44
2400-47	.535	10.3	458.3	15.4	109	1.50	3.50	840	892	1.82	1.95	0	1632	4.88
2400-48	.610	10.7	539.8	-0.2	97	1.50	3.49	863	895	1.61	1.69	0	1135	2.29
2400-49	.525	11.4	500.4	0.1	113	1.50	3.49	921	1148	1.88	2.33	0	1701	4.28
2400-50	.523	11.6	461.4	7.5	126	1.50	3.48	941	1155	2.04	2.57	0	1471	3.78
2400-51	.593	10.4	453.2	-0.6	118	1.50	3.48	876	888	1.95	2.03	0	1744	7.20
2400-52	.624	10.8	539.0	-2.5	108	1.50	3.47	947	947	1.78	1.84	0	1711	5.14
2400-53	.564	11.2	513.4	-10.8	106	1.50	3.50	866	1026	1.72	2.09	0	1484	3.50
2400-54	.649	10.8	543.7	0.9	77	1.49	3.50	708	734	1.31	1.39	0	1132	3.25
2400-55	.550	11.0	439.2	5.8	127	1.49	3.47	906	799	2.07	1.86	0	1684	5.91
2400-56	.595	10.3	512.4	-5.9	131	1.50	3.47	1083	1253	2.14	2.51	0	1844	4.32
2400-58	.512	10.5	442.2	-3.8	122	1.50	3.48	876	888	2.01	2.07	0	1332	4.17
2400-59	.535	11.3	460.9	1.2	132	1.50	3.50	988	1122	2.16	2.53	0	1424	4.35
2400-60	.671	11.4	588.7	0.8	83	1.50	3.49	810	842	1.39	1.47	0	1564	3.09
240018X	.615	11.1	495.8	-1.2	99	1.50	3.48	777	869	1.58	1.83	0	1359	3.20
240019X	.576	10.8	492.3	0.7	118	1.50	3.47	939	977	1.92	2.02	0	1046	2.19

APPENDIX C

ACOUSTIC EMISSIONS DATA

OF INDIVIDUAL SPECIMENS

Columns contain the following data:

COLUMN	DESCRIPTION
1	ID no., with the first four numbers representing the MSR rating
2	Specific gravity
3	Moisture content (%)
4	Computer PL load (lbs)
5	Visual PL load (lbs)
6	Computer PL deflection (in)
7	Visual PL deflection (in)
8	Comparison of computer PL with ultimate load (%)
9	Comparison of visual PL with ultimate load (%)
10	Deflection rate (ipm)
11	Cumulative AE at computer PL (peak counts)
12	Cumulative AE at visual PL (peak counts)
13	AE rate at computer PL (cps)
14	AE rate at visual PL (cps)
15	Specimen width (in)
16	Specimen depth (in)
17	Cumulative AE at 50% of ultimate load (peak counts)
18	Cumulative AE at 60% of ultimate load (peak counts)
19	Cumulative AE at 70% of ultimate load (peak counts)
20	Cumulative AE at 80% of ultimate load (peak counts)
21	Cumulative AE at 90% of ultimate load (peak counts)
22	Cumulative AE at failure (peak counts)
23	Load when cumulative AE reached 100 peak counts (lbs)
24	Load when cumulative AE reached 200 peak counts (lbs)
25	Load when cumulative AE reached 300 peak counts (lbs)
26	Load when cumulative AE reached 400 peak counts (lbs)
27	Load when cumulative AE reached 500 peak counts (lbs)
28	Load when cumulative AE reached 600 peak counts (lbs)
29	Load when cumulative AE rate reached 200 cps at 24 ipm deflect rate or 4 cps at 0.5 ipm deflect rate (lbs)
30	Load when cumulative AE rate reached 400 cps at 24 ipm deflect rate or 8 cps at 0.5 ipm deflect rate (lbs)
31	Load when cumulative AE rate reached 600 cps at 24 ipm deflect rate or 12 cps at 0.5 ipm deflect rate (lbs)
32	Load when cumulative AE rate reached 800 cps at 24 ipm deflect rate or 16 cps at 0.5 ipm deflect rate (lbs)
33	Load when cumulative AE rate reached 1000 cps at 24 ipm deflect rate or 20 cps at 0.5 ipm deflect rate (lbs)
34	Ultimate load (lbs)
35	Ultimate deflection (in)

TABLE C1. SAMPLES 4 AND 5 DATA

COLUMNS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
180014.	.486	12.7	1385	1681	2.55	3.09	70.2	84.6	24	117	281	487	11	1.50	3.50	12	31	117	273	416	1268	1372	1534	1634	1791	1926	1941	1371	1379	1916	1920	1923	1988	3.71
180005.	.492	12.9	778	996	1.96	2.54	74.8	95.0	24	59	2320	133	3130	1.50	3.50	0	0	24	706	1413	2787	784	804	816	819	821	828	783	788	794	801	813	1040	2.68
180006.	.477	12.2	719	757	1.65	1.74	65.1	68.5	24	673	804	328	570	1.50	3.50	376	601	900	1579	2273	3222	382	550	571	592	626	655	363	388	567	579	2047	1105	2.68
180016.	.501	13.1	790	813	1.65	1.70	72.0	74.1	24	427	584	669	1001	1.50	3.50	208	222	394	839	1172	1470	498	554	745	780	794	811	512	546	778	786	797	1097	2.33
180000.	.490	11.9	854	822	2.00	1.92	48.5	46.7	24	76	75	0	0	1.50	3.50	90	363	902	1651	2938	5544	1030	1074	1112	1176	1195	1204	503	1179	1186	1194	1202	1760	4.57
180010.	.507	12.6	838	869	1.85	1.93	53.9	55.8	24	0	0	0	0	1.50	3.50	2	325	460	1569	3064	6169	1043	1103	1143	1182	1320	1359	1016	1106	1123	1358	1363	1556	4.01
180020.	.465	12.9	876	832	1.58	1.50	47.6	45.2	24	382	332	284	182	1.50	3.50	1000	1323	1758	3081	4919	6952	578	629	818	856	937	973	574	599	949	1063	1488	1842	3.95
180019.	.471	12.2	605	605	1.60	1.60	50.5	50.5	24	582	582	210	210	1.50	3.50	1068	2885	4461	6784	10137	13115	464	500	516	531	594	635	373	496	503	512	809	1198	4.23
135014.	.452	11.9	612	612	2.06	2.06	94.7	94.7	24	1426	1426	1874	1874	1.50	3.50	79	197	697	1052	2460	4440	407	442	482	495	504	517	417	442	486	492	512	646	2.50
135004.	.461	12.6	544	544	1.70	1.70	77.8	77.8	24	1156	1156	1246	1246	1.50	3.50	37	413	874	1442	2231	2840	366	377	383	427	451	469	362	366	370	375	379	699	2.27
135016.	.455	12.3	746	746	2.38	2.38	67.0	67.0	24	555	555	959	959	1.50	3.50	97	359	717	759	1400	2324	600	628	707	721	738	755	598	603	609	729	748	1113	3.78
135007.	.472	12.3	734	710	2.53	2.47	62.3	61.0	24	192	188	0	0	1.50	3.50	17	255	255	703	1426	2055	660	730	889	913	927	944	656	662	669	2081	2093	1178	4.40
135020.	.447	11.3	605	626	1.83	1.91	90.6	93.7	24	1108	1302	652	902	1.50	3.50	109	362	590	884	1298	2115	349	370	399	438	472	491	341	348	355	361	640	668	2.08
240007.	.537	12.9	877	839	1.66	1.59	45.1	43.2	24	0	0	0	0	1.50	3.50	5	57	130	209	1130	2623	1333	1580	1672	1678	1695	1710	1236	1661	1666	1671	1676	1943	3.85
240014.	.562	13.2	910	946	1.66	1.73	46.0	47.8	24	0	0	0	0	1.50	3.50	0	0	601	1630	2254	3398	1377	1391	1471	1520	1571	1598	1399	1399	1399	1399	1399	1979	4.18
240008.	.544	12.3	798	760	1.65	1.57	50.3	47.9	24	17	8	29	27	1.50	3.50	63	328	1118	1533	2638	3413	874	943	1002	1030	1051	1074	841	942	949	1053	1724	1505	3.52
240009.	.571	13.4	1004	1062	2.14	2.26	66.4	70.2	24	857	911	443	155	1.50	3.50	608	662	865	1365	1794	2350	345	526	584	657	703	818	273	579	1186	1190	1193	1513	3.38
240016.	.529	12.5	820	802	1.63	1.59	70.8	69.2	24	632	626	198	300	1.50	3.50	110	477	738	1181	2045	4484	591	612	639	691	722	759	574	593	607	619	630	1159	2.39
135001.	.476	13.8	374	374	1.49	1.49	85.8	85.8	.5	780	780	12	12	1.50	3.50	711	1070	3999	5180	7480	13764	212	277	308	349	375	378	201	206	211	281	308	436	2.66
135002.	.554	12.5	916	916	2.89	2.89	70.2	70.2	.5	155	155	5	5	1.50	3.47	550	1001	2582	4395	5109	6333	890	924	991	1009	1047	1089	871	996	1009	1999	1207	1304	4.92
135003.	.501	12.2	433	433	1.64	1.64	74.7	74.7	.5	859	859	15	15	1.50	3.48	414	671	1056	1974	3303	4401	245	247	249	252	342	367	242	243	245	247	248	580	2.38
135004.	.423	12.4	528	528	1.95	1.95	76.7	76.7	.5	71	71	0	0	1.51	3.52	21	21	71	410	942	1683	535	543	574	587	640	640	472	537	541	545	640	688	2.75
135005.	.477	13.0	616	616	2.10	2.10	55.6	55.6	.5	560	560	0	0	1.50	3.47	600	655	699	1138	1434	2401	286	342	411	525	691	707	212	341	1010	1012	1014	1108	5.48
135006.	.458	12.1	603	603	2.07	2.07	85.5	85.5	.5	2096	2096	26	26	1.50	3.50	71	432	489	1630	5079	13911	463	469	476	482	524	529	464	466	468	471	474	705	2.53
135007.	.487	13.2	690	690	2.43	2.43	85.7	85.7	.5	478	478	2	2	1.50	3.50	5	11	173	345	850	3452	557	573	611	660	702	736	558	560	734	737	740	805	2.86
135008.	.441	14.2	462	462	1.69	1.69	64.7	64.7	.5	348	348	7	7	1.50	3.49	190	334	464	928	1417	4927	286	444	453	506	543	570	279	282	285	598	605	714	2.83
180001.	.478	11.8	557	557	1.72	1.72	67.5	67.5	.5	94	94	1	1	1.50	3.51	1	89	95	96	464	984	700	710	736	746	764	806	494	498	710	714	817	825	2.61
180002.	.465	13.1	688	688	2.13	2.13	73.7	73.7	.5	511	511	13	13	1.50	3.50	74	193	475	646	1939	3986	519	647	658	683	688	694	370	527	658	662	691	934	3.00
180003.	.492	12.0	744	744	2.40	2.40	63.7	63.7	.5	390	390	1	1	1.50	3.49	373	442	720	942	1054	2192	330	354	486	777	811	820	174	351	354	357	1161	1168	4.29
180004.	.516	14.1	547	547	1.48	1.48	63.9	63.9	.5	3	3	0	0	1.50	3.50	3	3	8	139	1997	3040	698	736	739	742	745	748	646	648	731	734	736	856	2.47
180005.	.476	12.6	819	819	2.45	2.45	54.2	54.2	.5	287	287	0	0	1.50	3.50	652	882	1169	1742	4528	7612	476	640	898	919	1001	1015	474	476	1015	1160	1352	1510	6.54
180006.	.536	15.0	449	449	1.47	1.47	55.4	55.4	.5	356	356	0	0	1.50	3.49	356	553	576	859	996	2718	105	281	394	505	514	617	103	105	107	515	775	810	2.90
180007.	.502	14.3	416	416	1.28	1.28	55.0	55.0	.5	8	8	2	2	1.50	3.50	61	177	684	1820	2231	4670	479	539	550	563	588	594	481	492	551	594	634	757	2.78
180008.	.551	12.0	482	482	1.57	1.57	87.3	87.3	.5	332	332	0	0	1.49	3.49	221	294	294	332	332	785	249	256	423	558	558	551	248	250	252	254	256	552	1.82
240001.	.547	13.0	675	675	1.67	1.67	48.5	48.5	.5	300	300	1	1	1.49	3.49	402	462	933	1080	1953	3370	333	552	624	807	1078	1120	328	332	337	1171	1308	1391	4.61
240002.	.557	15.0	629	629	1.57	1.57	74.2	74.2	.5	531	531	5	5	1.50	3.50	131	207	538	716	1958	4791	439	581	586	583	620	698	434	439	441	443	446	848	2.39
240003.	.549	14.6	662	662	1.67	1.67	72.8	72.8	.5	62	62	0	0	1.49	3.48	1	55	62	271	794	1549	738	751	759	767	816	829	542	752	754	757	759	909	2.48
240004.	.573	13.6	652	852	1.60	2.15	43.7	57.1	.5	74	74	0	0	1.50	3.47	77	77	81	81	185	1032	1432	1472	1473	1475	1475	1476	194	1427	1459	1471	1473	1491	5.18
240005.	.584	13.2	465	465	1.00	1.00	54.1	54.1	.5	248	248	4	4	1.49	3.49	282	642	2095	3695	9770	14039	439	444	597	608	690	691	436	439	441	443	446	859	2.88
240006.	.589	15.8	855	855	1.65	1.65	82.1	82.1	.5	317	317	8	8	1.50	3.48	46	118	158	316	364	965	615	769	850	977	1035	1037	604	774	1040	1040	1040	1042	2.05
240007.	.557	15.0	839	839	2.08	2.08	83.6	83.6	.5	1408	1408	2	2	1.50	3.50	711	1246	1631	3957	14185	21492	310	377	436	485	520	637	304	308	651	726	932	1003	3.27
240008.	.575	15.9	652	652	1.64	1.64	59.9	59.9	.5	189	189	0	0	1.50	3.48	193	720	2487	3630	4221	12690	502	772	775	778	781	785	314	508	771	774	777	1008	3.95