

NONDESTRUCTIVE PREDICTION OF LOAD-DEFLECTION RELATIONS FOR LUMBER¹

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(Received June 1986)

ABSTRACT

Three machine-stress-rated grades of Douglas-fir lumber were pretested to the proportional limit (PL) under an accelerated deflection rate with a microcomputer-controlled testing machine. The same specimens were then tested to failure. Load, deflection, and acoustic emissions (AE) were monitored continuously throughout the testing. The observations from nondestructive testing were used as independent variables in regression models to predict the destructive parameters.

Computer-detected PL was highly correlated with PL determined from destructive testing ($r = 0.92$). The correlation of the computer-detected PL with modulus of elasticity was a good estimator of lumber strength ($r = 0.83$) but a poor predictor of ultimate deflection ($r = 0.54$). A combination of AE variables below the PL and physical properties was strongly correlated with PL ($r = 0.76$), strength ($r = 0.93$), and ultimate deflection ($r = 0.83$).

Keywords: Lumber strength, acoustic emissions, proportional limit, ultimate deflection.

INTRODUCTION

The lumber components in wood structures must safely withstand all anticipated service loads while deflecting no more than the limits specified by codes. Higher grades must be selected when structural analysis of the lumber shows that stresses and deflection of lower grades exceed the prescribed values. Thus, grades and grading procedures govern the structural safety, serviceability, and economical use of lumber and wood-based products. Lumber grades are determined most often by either visual grading or machine-stress-rating (MSR). While visual grading is not very precise and misgrading material is possible, machine grading is costly and may partially damage the lumber. Therefore, a reliable, inexpensive, and nondestructive grading procedure is highly desirable.

The main criterion for MSR is based on the correlation between modulus of elasticity (MOE) and modulus of rupture (MOR). However, lumber strength depends on the critical flaw in a member and not on MOE only. Therefore, visual observations, such as knot size and type, are included in grading. Because visual observations are time-consuming and entail human errors, alternative methods are desirable. One such method is measuring acoustic emissions (AE), which depend more on the critical flaw than does the MOE obtained from static bending tests.

Taking advantage of recently improved analysis procedures for wood building systems and of anticipated probability-based design methodology will require a method to predict accurately nonlinear lumber stiffness in bending between the

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TABLE 1. Correlation coefficients, r , between modulus of rupture (MOR) and nondestructively determined properties.

| Species ¹ | Nominal dimensions (in. × in.) | Sample size | r | Reference |
|----------------------|-----------------------------------|----------------|-----------|-------------------------------|
| <i>MOE</i> | | | | |
| CR | 2 × 4 | 125 | 0.68 | Schroeder and Atherton (1973) |
| DF | | 150 | 0.66 | Atherton (1980) |
| DF | 2 × 4 | 486 | 0.83–0.86 | Johnson (1965) |
| DF | 2 × 6 | 200 | 0.68 | Senft et al. (1962) |
| JP | 2 × 6 | 109 | 0.73 | Miller (1968) |
| RP | 2 × 6 | 199 | 0.81–0.84 | Miller and Tardif (1967) |
| SP | 2 × 4, 6, 8 | 88 | 0.78 | Walters and Westbrook (1970) |
| SP | 2 × 4, 6, 8 | 88 | 0.79 | Walters and Westbrook (1970) |
| SP | 2 × 4, 6, 8, 10 | 1,349 | 0.66 | Doyle and Markwardt (1966) |
| WH | 2 × 6 | 244 | 0.79–0.85 | Corder (1965) |
| WH | 2 × 6 | 244 | 0.83–0.84 | Corder (1965) |
| WS | 2 × 6 | 110 | 0.84 | Miller (1968) |
| <i>SPL</i> | | | | |
| DF | 2 × 4 | — | 0.82 | Adams (1969) |
| DF | 2 × 4 | 150 | 0.88 | Fernandez (1975) |
| CR | 2 × 4 | 125 | 0.90 | Atherton (1980) |
| DF and CR | 2 × 4 | 275 | 0.92 | Atherton (1980) |

¹ CR = California redwood, DF = Douglas-fir, JP = jack pine, RP = red pine, SP = southern pine, WH = western hemlock, WS = white spruce.

proportional limit (PL) and the ultimate load (UL). Existing design practices consider only MOE and MOR and neglect nonlinear stiffness. Such practices prevent accurate prediction of the strength of wood structures and evaluation of the probability of failure under service loads. Assuming linear behavior could result in wasteful use of lumber or unsafe construction.

Our overall objective was to improve existing methods for predicting the load-deflection curve of lumber under bending, in the region between the PL and UL. Our specific objectives were to develop a nondestructive testing procedure for detecting the PL, to use the test observations to characterize the nonlinear portion of the load-deflection curve, and to evaluate the effect of testing speed on MOE, MOR, and AE.

LITERATURE REVIEW

Values reported in the literature for the correlation coefficient, r , between MOR and MOE lie between 0.66 and 0.86; r values for the relation between stress at proportional limit (SPL) and MOR range from 0.82 to 0.92 (Table 1). Fernandez (1975) and Atherton (1980) observed that adding MOE to the MOR-SPL regression equations did not significantly improve the correlation.

Potential material damage during testing makes SPL difficult to evaluate. Atherton (1980) suggested using a microcomputer to detect SPL by constantly monitoring change in the slope of the load-deflection trace. At the first significant change, the load could be removed instantaneously, presumably with no damage to the lumber. Gerhards (1979) estimated that, if SPL is 70% of the ultimate load, about 99% of the residual lifetime remains, and the residual strength is hardly affected. He hypothesized that damage can be reduced further by testing at rates over 50 times faster than those specified by ASTM D198-76 (1977).

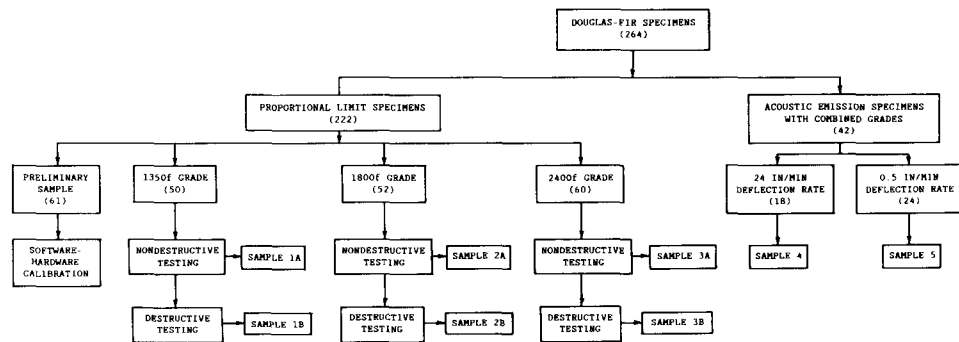


FIG.1. Experimental design for proportional limits and acoustic emissions testing (number in parentheses indicates sample size).

Acoustic emissions, which represent wave generation in stressed materials, are caused by the energy release initiating the acoustic impulse and by abrupt redistribution of internal stresses. Acoustic emissions are usually associated with crack growth and plastic deformation of stressed material. Joffé (1928) was the first to apply AE by relating noise levels in a structure to stresses, but Kaiser (1950) first explained the AE mechanism. He showed that materials such as wood not only exhibited AE under stress, but also ceased to emit AE at reloading to the original maximum stress level; this mechanism is now known as the Kaiser effect.

Miller (1963), using a contact microphone, found that beams from maple (*Acer* sp.) gave virtually no audible warning of failure, but most beams of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] emitted detectable sounds at loads equivalent to their long-term strength. Porter (1964) was the first to use transducers based on piezoelectric crystals to study wood AE in detail. He found a linear relationship between cumulative AE count and crack length in specimens of Alaska-cedar [*Chamaecyparis nootkatensis* (D. Don) Spach]. In the same study, Porter detected a weak relationship between the apparent PL and the number of AE in small Douglas-fir specimens. Porter et al. (1972) used AE to estimate the bending strength of Douglas-fir finger joints (2- by 6-in.); cumulative AE count was highly correlated with strength in the region around the PL. By loading the specimens to just beyond the SPL, they could estimate the fracture loads within 10% accuracy.

DeBaise et al. (1966) observed that AE resulted from unstable crack extensions in tension, bending, and cleavage in specimens of western white pine (*Pinus monticola* Dougl. ex D. Don). In bending tests, AE increased linearly with strain up to the PL and then decreased under increasing load. The rate of AE increased again just prior to specimen failure. This contrasts with the observation by Adams (1969) that the rate of AE increased rapidly upon reaching SPL. Adams also found that variables based on AE count-deflection traces were not significant predictors of MOR.

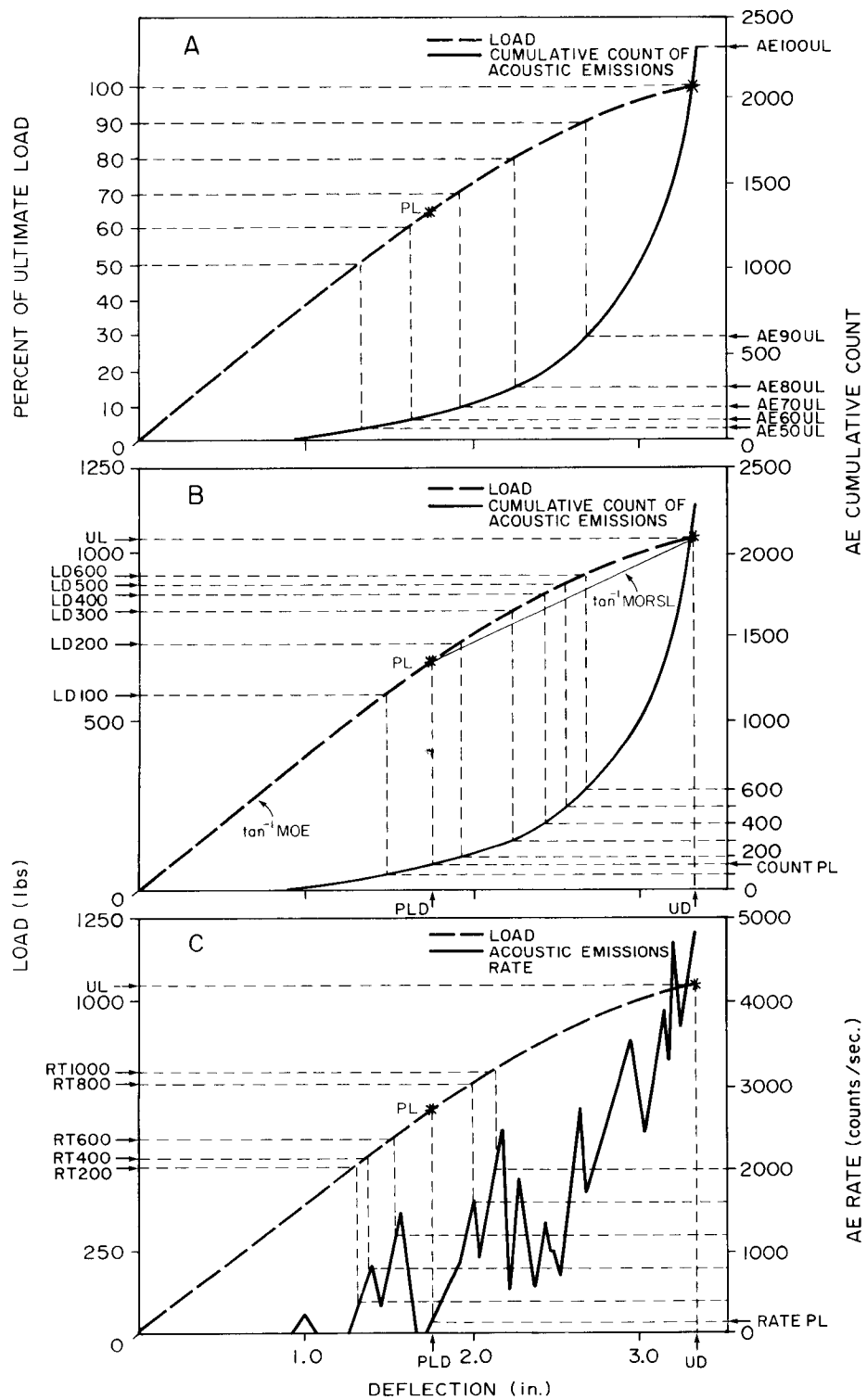
Testing clear specimens in tension, Ansell (1982a) found that AE count increased rapidly at low strain levels in summerwood, whereas in springwood AE counts increased gradually but were interspersed with rapid jumps. Ansell (1982b) also reported a marked effect of the proportion of springwood to summerwood

TABLE 2. Engineering properties of proportional limit specimens.

| Sample (n) | PL failures | Statistics ¹ | Properties ² | | | | | | | | |
|----------------|----------------|-------------------------|-------------------------|-------|---------------------------|-------|-----------|-------|-------------|--------------|----------------|
| | | | MC | SG | MOE (10 ⁶ psi) | | SPL (psi) | | UD (in.) | MOR (psi) | MORSL (ppi) |
| | | | | | Nondest. | Dest. | Nondest. | Dest. | | | |
| 1A and 1B (52) | 6 | Mean | 10.9 | 0.473 | 1.56 | 1.53 | 4,250 | 4,310 | 3.57 | 5,990 | 176 |
| | | SD | 0.7 | 0.031 | 0.16 | 0.16 | 990 | 1,040 | 1.02 | 1,680 | 40 |
| | | COV | 14.7 | 6.6 | 10.3 | 10.5 | 23.3 | 24.1 | 28.6 | 28.0 | 22.7 |
| 2A and 2B (50) | 5 | Mean | 11.3 | 0.502 | 1.78 | 1.58 | 4,610 | 4,290 | 3.49 | 6,600 | 177 |
| | | SD | 0.7 | 0.030 | 0.16 | 0.55 | 600 | 1,590 | 1.04 | 1,520 | 72 |
| | | COV | 16.9 | 6.0 | 9.0 | 34.8 | 13.0 | 37.1 | 29.8 | 23.0 | 40.7 |
| 3A and 3B (60) | 1 | Mean | 11.3 | 0.559 | 2.39 | 2.34 | 5,470 | 5,940 | 3.96 | 9,020 | 241 |
| | | SD | 0.6 | 0.041 | 0.21 | 0.21 | 830 | 1,170 | 1.31 | 2,180 | 74 |
| | | COV | 18.2 | 7.3 | 8.8 | 9.0 | 15.2 | 19.7 | 33.1 | 24.2 | 30.7 |
| Combined (162) | 12 | Mean | 11.2 | 0.515 | 1.94 | 1.85 | 4,830 | 4,920 | 3.69 | 7,340 | 201 |
| | | SD | 0.7 | 0.050 | 0.40 | 0.52 | 960 | 1,510 | 1.16 | 2,270 | 72 |
| | | COV | 16.0 | 9.7 | 20.6 | 28.1 | 19.9 | 30.7 | 31.4 | 30.9 | 35.8 |

¹ SD = standard deviation; COV = coefficient of variation (%).

² MC, moisture content; MOR, modulus of rupture; nondest., determined by nondestructive testing; dest., determined by destructive testing. See Fig. 2 for definitions of other properties.



on the shape of the traces relating AE count to strain. He also developed regression equations defining MOE, MOR, and work to fracture in terms of AE count.

Other researchers have characterized AE with regard to loading type and defect type. Sato et al. (1983) reported generation of burst-type AE during plastic deformation of specimens under static compression. Sato et al. (1984b) also determined that burst-type AE came from macrocracks propagating radially across annual rings. Sato et al. (1984a) postulated that slow rates of AE counts in tension specimens are caused by the opening of microcracks present before testing.

EXPERIMENTAL PROCEDURES

Material selection

Douglas-fir boards were selected from lumber cut from logs harvested from the east and west sides of the mid-Willamette Valley, Oregon. Nominal board size was 2- by 4-in. by 12 ft. long. The boards were dried to an average moisture content (MC) of 12% at the mill and included MSR grades of 1350f, 1800f, and 2400f. Of the 265 beams selected, 162 were used for PL testing and 42 for AE testing. The remaining 61 boards were used for software and hardware calibration (Fig. 1). Samples 4 and 5 each contained an approximately equal number of specimens from each of the grades evaluated; each of the other samples contained lumber of a single grade.

Static bending tests

Specimens were proof-loaded in third-point bending using a conventional testing machine with a span of 114 in.. Conditions were in accordance with ASTM D198-76 (1977), except that the loading rate was 24 in./min for nondestructive and 0.5 in./min for destructive tests. The rate of 24 in./min (48 times faster than the recommended ASTM rate of 0.5 in./min) was employed to emulate possible industrial applications, enhance research efficiency, and decrease specimen damage. Midspan deflection was monitored by a linear variable differential transformer and recorded as a function of load (monitored by a load cell). Specific gravity was based on specimen weight and volume, determined immediately before testing (MC approximately 12%).

During the tests, an HP-9825A microcomputer continuously evaluated the load : deflection ratio to detect the first deviation of the load-deflection trace from linearity. The slope of the linear regression equation for observations between 200–400 pounds provided the basic measure of linearity. PL was defined as the point at which the load : deflection ratio deviated from the basic linearity slope by more than 8 lbs. Load-deflection data pairs were evaluated and checked every

FIG. 2. Acoustic-emission (AE) variables typical of specimens in Samples 4 and 5. (A) Percent of ultimate load and cumulative AE traces describing AE_{iUL} , the cumulative AE count at $i\%$ of ultimate load ($i = 50, 60, 70, 80, 90, 100$). (B) Load and cumulative AE traces describing LD_j , the load when the cumulative AE count exceeds j counts ($j = 100, 200, 300, 400, 500, 600$). (C) Load and AE rate traces describing RT_k , the load when the AE rate exceeds k counts/sec ($k = 200, 400, 600, 800, 1,000$). *, point at which specimen fails; COUNTPL, cumulative AE count at the proportional limit (PL); MOE, modulus of elasticity; MORSL, slope of the line connecting the ultimate load (UL) and the PL; PLD, deflection at PL; RATEPL, AE rate at the PL; UD, ultimate deflection.

TABLE 3. Regression equations for predicting destructive variables by nondestructive variables.

| Sample | Dependent variable (Y) ¹ | Coefficients of regression equation: $\hat{Y} = a_0 + a_1x_1 + a_2x_2 + a_3x_3$ | | | | | | | r |
|----------|-------------------------------------|---|----------------|----------------|----------------|-----------------|----------------|----------------|------|
| | | a ₀ | a ₁ | x ₁ | a ₂ | x ₂ | a ₃ | x ₃ | |
| 1 | UD (in.) | 0.499 | 0.000723 | SPL | | | | | 0.70 |
| | MOR (psi) | -194 | 1.45 | SPL | | | | | 0.86 |
| | MORSL (ppi) | -603 | 462 | MOE | -0.15 | SPL | 280 | PLD | 0.51 |
| 2 | UD (in.) | 0.373 | 0.000677 | SPL | | | | | 0.39 |
| | MOR (psi) | -4,430 | 1.24 | SPL | 2,500 | MOE | | | 0.67 |
| | MORSL (ppi) | -355 | 1,120 | SG | | | | | 0.39 |
| 3 | UD (in.) | -0.206 | 0.000763 | SPL | | | | | 0.48 |
| | MOR (psi) | -541 | 1.75 | SPL | | | | | 0.66 |
| Combined | UD (in.) | 1.02 | 0.000736 | SPL | 0.00047 | FS ¹ | | | 0.54 |
| | MOR (psi) | -2,970 | 1.43 | SPL | 1,500 | MOE | | | 0.83 |
| | MORSL (ppi) | 55.5 | 79.0 | MOE | | | | | 0.44 |

¹ FS, fiber strength (1,350, 1,800, or 2,400 psi); MOR, modulus of rupture. See Fig. 2 for definitions of other variables.

TABLE 4. *Effect of testing speed on engineering properties of lumber.*

| Variable ¹ | Deflection rate | | | | Significantly different at $\alpha = 0.05$ |
|-----------------------|-----------------|-------|-------------|-------|---|
| | 24 in./min | | 0.5 in./min | | |
| | Mean | SD | Mean | SD | |
| COUNTPL (counts) | 459 | 449 | 439 | 474 | No |
| RATEPL (counts/sec) | 417 | 511 | 208 | 337 | Yes |
| LD100 (lb) | 725 | 364 | 494 | 274 | Yes |
| LD200 (lb) | 798 | 388 | 571 | 269 | Yes |
| LD300 (lb) | 866 | 402 | 627 | 259 | Yes |
| LD400 (lb) | 906 | 417 | 684 | 250 | Yes |
| LD500 (lb) | 947 | 434 | 731 | 254 | Yes |
| LD600 (lb) | 975 | 431 | 756 | 249 | Yes |
| RT200 (lb) | 677 | 359 | 394 | 180 | Yes |
| RT400 (lb) | 782 | 400 | 498 | 281 | Yes |
| RT600 (lb) | 895 | 444 | 616 | 329 | Yes |
| RT800 (lb) | 1,010 | 521 | 738 | 410 | No |
| RT1000 (lb) | 1,190 | 550 | 785 | 345 | Yes |
| SPL (psi) | 5,000 | 1,170 | 3,840 | 940 | Yes |
| PLD (in.) | 1.89 | 0.32 | 1.82 | 0.42 | No |
| UL (lb) | 1,340 | 450 | 933 | 287 | Yes |
| UD (in.) | 3.36 | 0.83 | 3.31 | 1.22 | No |
| MOR (psi) | 8,300 | 2,790 | 5,830 | 1,810 | Yes |
| MORSL (ppi) | 351 | 112 | 236 | 79 | Yes |

¹ SPL = stress at proportional limit; MOR = modulus of rupture. See Fig. 2 for definitions of other variables.

35 microseconds. Loading was terminated instantly when the PL was reached. Each test specimen was then examined visually for possible physical damage from testing. A few specimens failed as they reached PL (Table 2) and were discarded. Undamaged specimens were retested to failure using the recommended ASTM deflection rate. Individual specimens were double-tested to check SPL accuracy and to assess possible lumber damage caused by nondestructive testing.

Detection of acoustic emissions

To determine the effect of loading rate on AE, 18 specimens were tested under the 24 in./min deflection rate (Sample 4) and 24 specimens under the 0.5 in./min deflection rate (Sample 5). Acoustic emissions were detected with a 500-kHz piezoelectric transducer, clamped to the wide face of the board four feet from the midspan. Preliminary testing indicated that all AE below 0.5 kHz originated in the testing arrangement; these emissions therefore were filtered out. Since frequencies of AE from rupturing wood are considerably above 0.5 kHz (Adams 1969; Ansell 1982b), no useful data were lost. The filtered signal was processed by a digital counter, which identified and counted the critical peak amplitudes exceeding 0.13 volts. Preliminary testing established this threshold voltage to be twice the upper limit of AE from background noise. Data from the digital counter were transferred to magnetic tape for analysis.

Data analysis

Data were analyzed by a standard computer package, SPSS (Nie et al. 1975). The most significant linear multiple regression models were determined by the forward stepwise-selection procedure: the independent variables with the highest

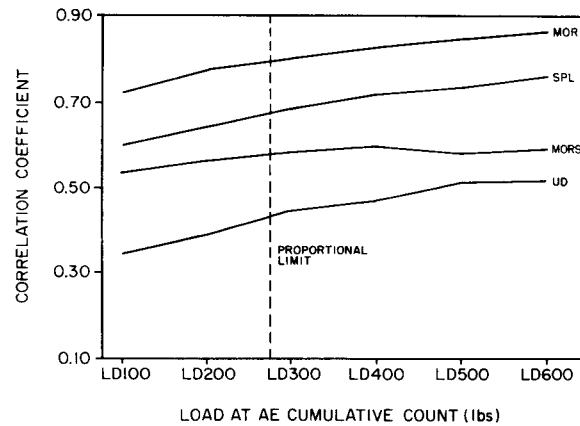


FIG. 3. Correlation coefficients for the relationship between AE cumulative count and lumber properties.

partial correlation to the dependent variable were gradually added to the previous significant model until their contribution became insignificant at the 5% level.

The dependent variables in regression models for data from PL tests were MOR, ultimate deflection (UD), and the slope (MORSL) of a theoretical line connecting load at PL and UL. Independent variables were MOE, SPL, deflection at proportional limit (PLD), and specific gravity (SG). Each sample was first analyzed individually; then all samples were combined and analyzed as one sample.

The data from the AE tests were described by the following variables: cumulative AE count at $i\%$ of ultimate load, AE_iUL ($i = 50, 60, 70, 80, 90$, and 100) (Fig. 2A); load when cumulative AE exceeded j counts, LD_j ($j = 100, 200, 300, 400, 500$, and 600) (Fig. 2B); load when AE rate exceeded k counts/sec, RT_k ($k = 200, 400, 600, 800$, and $1,000$) (Fig. 2C); cumulative AE count at PL, COUNTPL; and AE rate at PL, RATEPL. Two regression analyses were performed on these AE data. Dependent variables for both analyses were SPL, PLD, UD, MOR, and MORSL. Independent variables for the first regression analysis were SG, MOE, SPL, PLD, and AE variables at or below the PL. Independent variables for the second regression analysis included all AE variables exclusively. Data for the regression analyses were first grouped and analyzed by their deflection rate and MSR grade, and then were combined into one overall sample. The specimens at 24 in./min loading accumulated AE 48 times faster than those at 0.5 in./min. Thus, the AE rate of the latter was multiplied by 48 to make the rates equivalent.

RESULTS AND DISCUSSION

Evaluation of nondestructive tests

The basic properties derived for the PL samples are summarized in Table 2. Several specimens (six in the 1350f, five in the 1800f, and one in the 2400f grades) failed when tested nondestructively, because their PL and UL coincided; this often happens in lumber testing. Fernandez (1975) noted that fifteen of his 250 Engelman spruce studs failed within 5% of the PL and seven failed at the PL.

The coefficient of variation (COV) of 31% for the destructively evaluated PL

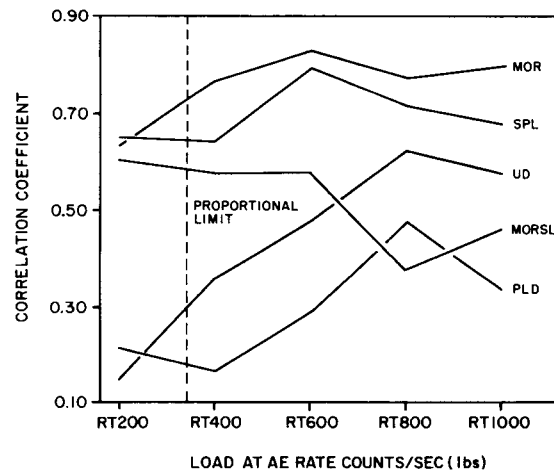


FIG. 4. Correlation coefficients for the relationship between AE rate and lumber properties.

(Table 2) was considerably lower than the 45% obtained by Fernandez (1975), suggesting that the lower variability in the nondestructively evaluated PL may have been inherent in this sample. However, reduction in variability could also be attributed to the fact that this study used MSR lumber, as opposed to the visually graded lumber used by Fernandez (1975). The MSR lumber grades are based on both the mechanical properties of the lumber and visual observations. An MSR lumber grade, in which boards are accepted on the basis of the actual MOE, has a narrower distribution of mechanical properties than does visually graded lumber, where 5% of the material may be off-grade.

Although the mean for the nondestructively evaluated MOE and SPL was generally the same as that for its destructively evaluated counterpart, the COV was significantly lower (Table 2). This suggests that visual evaluation of PL may introduce variability and so increase the standard deviation.

The multiple regression equations having a significance level (α) of 0.05 are shown in Table 3. To characterize grade effect, estimated fiber stress (FS), as defined by MSR grade, was added as an independent variable. This variable significantly improved the prediction of UD. For all samples combined, SPL was the best predictor of UD and MOR, and MOE was the best predictor of MORSL. Correlation coefficients between destructive and nondestructive variables were 0.51 to 0.86 for the 1350f grade and 0.39 to 0.67 for the 1800f and 2400f grades. The lowest grade has larger, more critical defects than the higher grades. The effects of such defects are easier to predict than those of the many small, less critical defects in the higher grades, so r 's are higher. This reasoning may also explain why the r 's obtained in this study were lower than those observed by Atherton (1980) and Fernandez (1975) for *Stud* grade lumber, which contains many critical defects.

In SPSS, the variable is accepted on the basis of the probability that its contribution is significant. However, the probability indicators are complex and difficult to interpret, while r is less powerful but easy to understand. Therefore, only r 's are shown in this paper.

TABLE 5. *Relations of nondestructive and AE variables to mechanical properties.*

| Sample no. (n) | Dependent variable (Y) ¹ | Regression equations: independent variables and coefficients | | | | | | | | | |
|-----------------------|--|--|---------|--------|---------|--------|--------|--------|--------|-------|--|
| | | Low stress: | | | | | | | | | |
| | | $Y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_5$ | | | | | | | | | |
| | | a_0 | a_1 | x_1 | a_2 | x_2 | a_3 | x_3 | a_4 | x_4 | |
| 4 (18) | SPL | 1,110 | 1,560 | MOE | | | | | | | |
| | UL | -39.9 | 0.904 | RT400 | 0.55 | AE50UL | 0.11 | SPL | | | |
| | UD | -0.299 | 0.00164 | RT400 | 0.00082 | AE60UL | 1.0 | PLD | | | |
| | MOR | -247 | 5.61 | RT400 | 3.4 | AE50UL | 0.68 | SPL | | | |
| | MORSL | -115 | 188 | MOE | | | | | | | |
| 5 (24) | SPL | 1,610 | 1,120 | MOE | | | | | | | |
| | PLD | 2.81 | 0.0012 | RT200 | 0.00079 | AE50UL | -3.2 | SG | | | |
| | UL | -13.2 | 0.130 | SPL | 0.59 | LD200 | 0.43 | AE50UL | | | |
| | UD | 0.702 | 0.00382 | AE50UL | 0.0029 | LD200 | | | | | |
| | MOR | -145 | 0.805 | SPL | 3.8 | LD200 | 2.8 | AE50UL | | | |
| | MORSL | 109 | -0.145 | AE60UL | 96 | MOE | | | | | |
| Com- bined (42) | SPL | 1,160 | 1,100 | MOE | 1.5 | RT200 | | | | | |
| | UL | -276 | 0.106 | SPL | 0.72 | LD200 | 0.47 | AE50UL | 150 | MOE | |
| | UD | 0.0711 | 1.63 | PLD | 0.00048 | COUNT | 0.0026 | AE50UL | 0.0023 | LD200 | |
| | MOR | -1,690 | 0.649 | SPL | 4.5 | LD200 | 2.9 | AE50UL | 940 | MOE | |
| | MORSL | -64.6 | 172 | MOE | -0.12 | AE50UL | | | | | |

¹ SPL = stress at proportional limit; MOR = modulus of rupture. See Fig. 2 for definitions of other variables.

TABLE 5. Continued.

| Regression equations: independent variables ¹ and coefficients | | | | | | | | | | |
|---|-------|------|---|---------|--------|---------|---------|-------|--------|------|
| Low stress: $Y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_5$ | | | Acoustic emissions: $Y = a_0 + a_1x_1 + a_2x_2 + a_3x_3$ | | | | | | | |
| a_5 | x_5 | r | a_0 | a_1 | x_1 | a_2 | x_2 | a_3 | x_3 | r |
| | | 0.71 | | | | | | | | |
| | | 0.96 | 332 | 0.981 | RT600 | 0.084 | AE80UL | | | 0.93 |
| | | 0.85 | 1.34 | 0.00133 | RT800 | 0.00017 | AE100UL | | | 0.89 |
| | | 0.96 | 2,060 | 6.09 | RT600 | 0.52 | AE80UL | | | 0.93 |
| | | 0.89 | 193 | 0.177 | RT600 | | | | | 0.70 |
| | | 0.47 | | | | | | | | |
| | | 0.63 | | | | | | | | |
| | | 0.85 | 321 | 0.779 | RT1000 | | | | | 0.94 |
| | | 0.78 | 0.817 | 0.00255 | RT1000 | 0.0019 | AE50UL | | | 0.88 |
| | | 0.86 | 1,970 | 4.91 | RT1000 | | | | | 0.94 |
| | | 0.86 | 303 | -0.157 | AE60UL | | | | | 0.72 |
| | | 0.76 | | | | | | | | |
| | | 0.93 | 57.2 | 0.923 | LD600 | 0.37 | AE50UL | 0.18 | RT1000 | 0.94 |
| 0.0004 | SPL | 0.83 | 1.70 | 0.00148 | RT800 | 0.0016 | AE50UL | | | 0.75 |
| | | 0.93 | 345 | 5.78 | LD600 | 2.4 | AE50UL | 1.1 | RT1000 | 0.94 |
| | | 0.86 | 226 | 0.197 | RT200 | 0.0086 | AE100UL | | | 0.70 |

Acoustic emissions

Figures 2B and 2C compare load-deflection traces for specimens typical of Samples 4 and 5 with the cumulative count or rate of AE. Traces of cumulative AE showed two general patterns. The first pattern, which appeared in approximately 90% of specimens, showed the AE peak counts beginning slightly below the PL, in an apparent exponential pattern. At approximately 75% of UL, AE cumulative-count traces were either linear or concavely curvilinear (Fig. 2A). In the second pattern (not shown), the peak counts were distributed linearly throughout the loading, with maximum count remaining below 1500 peaks. These patterns were compared to those of Adams (1969) for nominal 2- by 4-in. lumber. He found four patterns; these were not very distinctive and can be grouped into two patterns closely resembling those observed in this study.

Testing speed significantly affected RATEPL, LD100 to LD600, RT200 to RT600, RT1000, SPL, UL, MOR, and MORSL ($\alpha = 0.05$, two-tailed mean difference *t*-test), but had no effect on COUNT, AE50UL to AE100UL, RT800, PLD, and UD (Table 4). This is consistent with Madsen's observation (1978) that increasing the deflection loading rate increased the load at the same deflection. Thus the variables dependent upon UL are also affected by the rate; UL increased by about 25% for the loading rates used in this study.

Porter (1964) observed a linear correlation between extension of crack length during cleavage and cumulative AE peak count. Thus, AE indicate how much crack extension (that is, the amount of damage increase) occurs in a specimen during stress testing. Comparing COUNT with AE100UL shows that about 10% of cumulative AE occur below the PL. Gerhards (1979) demonstrated that these 10% of cumulative AE, and thus crack extensions, should not correspond to the same percent decrease in strength, since not all crack extensions are related to the overall strength of the specimen.

The *r*'s between AE variables and SPL were between 0.6 and 0.8, suggesting that AE may be useful in determining PL (Figs. 3 and 4). The AE-SPL correlations were significant at $\alpha = 0.05$, but PLD correlated poorly with AE variables. This outcome was expected, since material damage and AE depend directly on stress and indirectly on deflection. In predicting MOR, AE between loads of 300 lb (LD300) and 600 lb (LD600) had *r*'s between 0.83 and 0.89 (Fig. 3), a much stronger correlation than for other variables. These *r*'s exceeded the observed value of 0.81 for SPL-MOR, indicating that AE may be more useful in predicting lumber strength than the PL.

Acoustic emission variables were also included in the prediction of the load-deflection relation in the region between the PL and UL. The resulting correlations were moderately strong, with *r*'s of about 0.6 for relations between MORSL and AE variables below PL (Figs. 3 and 4). Although this significant correlation is not as strong as that between MOE and MORSL ($r = 0.81$), it is still useful in predicting specimen behavior above the PL.

Two regression analyses were carried out on the data, using the forward stepwise-selection technique. The first was based on AE at low stress levels and engineering variables, while the second included all AE variables but excluded engineering variables (Table 5). In the first analysis, loading rate affected the prediction of dependent variables (except PLD) at which specimens at the deflection rate of 24

in./min had higher r 's. (PLD was excluded from Table 5 for the 24 in./min and combined samples, since their r 's were below 0.4.) It is possible, however, that the increase in r 's could be attributed to sample size.

Loading rate based solely on AE, as well as 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 was weakened by the absence of MOE.

Combining all AE data at or below PL resulted in r 's of 0.76, 0.83, 0.93, and 0.86 for SPL, UD, MOR, and MORSL, respectively (Table 5). 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.

The results from Table 5 suggest a strong correlation between lumber strength and AE that corresponds to the physical nature of wood under stress: flaw type, size, and location affect both lumber strength and AE.

SUMMARY AND CONCLUSIONS

The PL can be determined by a nondestructive, microcomputer-controlled test, in which lumber is loaded at a fast rate and the load is reversed immediately when the load-deflection trace deviates from linearity. The PL obtained by this method showed a strong correlation with the PL determined from load-deflection traces obtained in destructive testing.

Nondestructive testing up to the PL showed that a combination of stress at PL and MOE was a good estimator of lumber MOR but a poor predictor of ultimate deflection. The correlation between MOR and engineering variables consistently improved as lumber quality decreased.

The peak count of acoustic emissions (AE) indicated that preloading to the PL might have caused partial structural damage, because about 10% of the total count occurred before the PL; but the preloading had a negligible effect on MOR. Rate and cumulative count of AE at various load levels appeared to be better predictors of MOR than either stress at PL or MOE. A combination of AE count at loads below the PL and physical properties was correlated to stress at PL; the same combination was also strongly correlated to strength and ultimate deflection. Finally, while a 48-fold increase in loading rate affected engineering properties such as PL and MOR, it did not affect the rate of cumulative count of AE.

The application of the results of this investigation are to be viewed with caution; they are valid for the type of materials tested only. Further research is needed if similar equations are desired for other types of lumber.

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