NONDESTRUCTIVE PREDICTION OF LOAD-DEFLECTION RELATIONS FOR LUMBER[1]

Leslie Groom and *Anton Polensek*
Graduate Research Assistant and Professor
Department of Forest Products, Oregon State University
Corvallis, OR 97331

(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

---

[1] This is Paper 2099 of the Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Mention of a commercial product or trade name does not constitute endorsement by Oregon State University.

Wood and Fiber Science, 19(3), 1987, pp. 298–312

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

Species[1]	Nominal dimensions (in. × in.)	Sample size	*r*	Reference
		MOE		
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)
		SPL		
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).

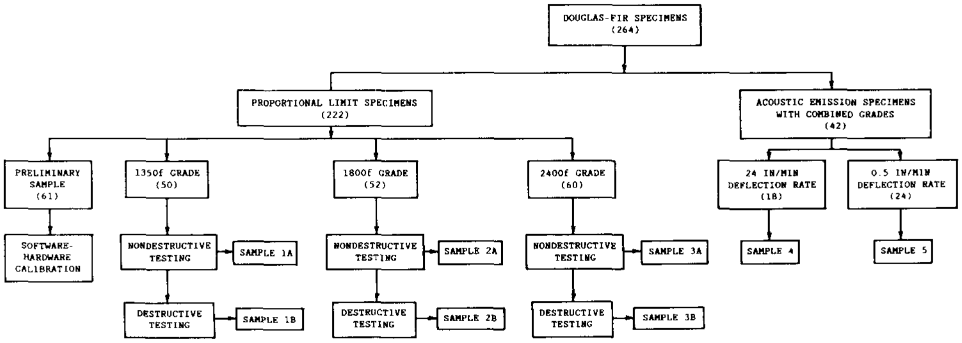


FIG. 1. Experimental design for proportional limits and acoustic emissions testing (number in parentheses indicates sample size).

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.

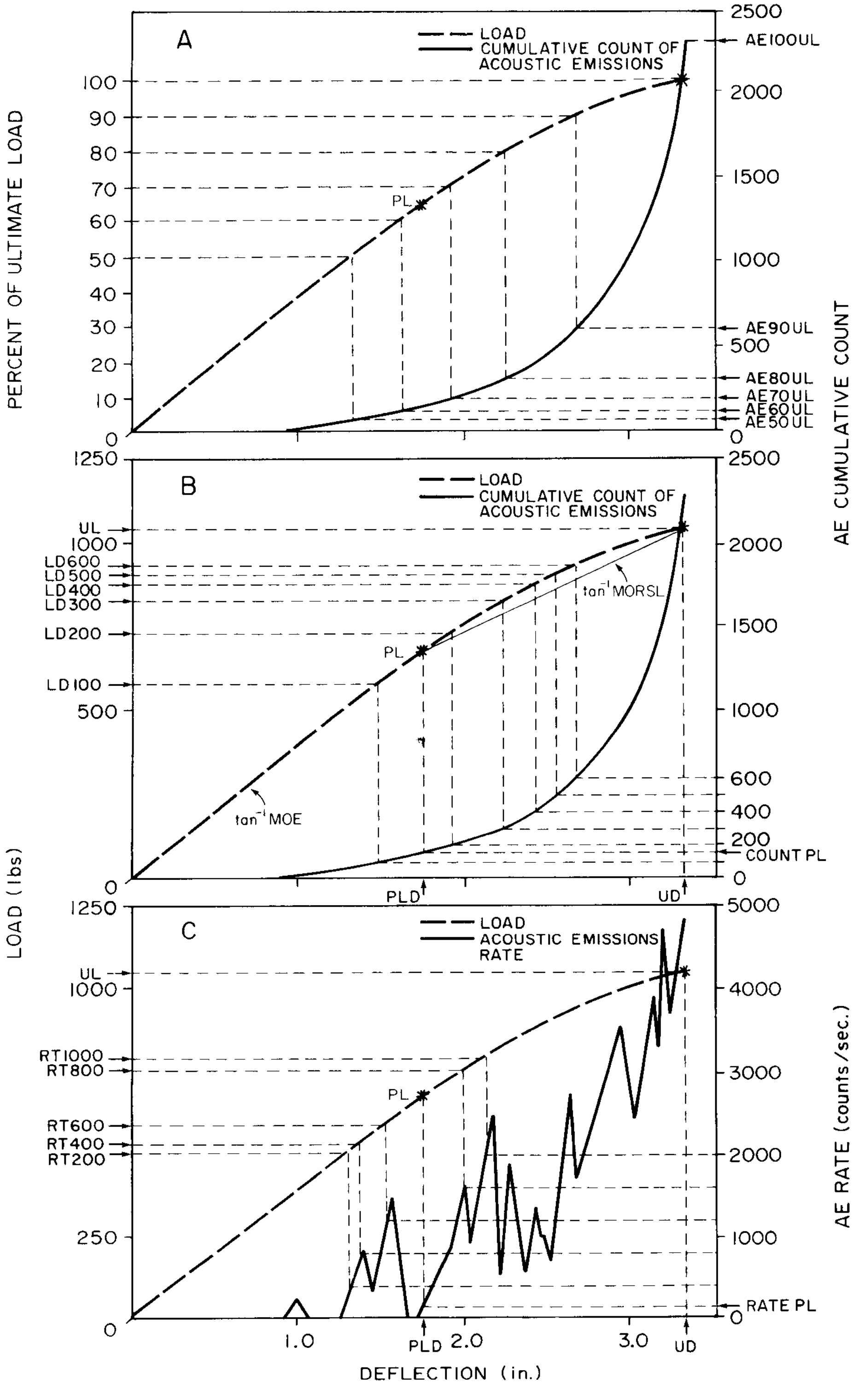
Testing clear specimens in tension, Ansell (1982a) found that AE count increased rapidly at low strain levels in summerwood, whereas in springwood AE counts increased gradually but were interspersed with rapid jumps. Ansell (1982b) also reported a marked effect of the proportion of springwood to summerwood

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.


A
LOAD
CUMULATIVE COUNT OF ACOUSTIC EMISSIONS
PERCENT OF ULTIMATE LOAD
0
10
20
30
40
50
60
70
80
90
100
PL
AE100UL
AE90UL
AE80UL
AE70UL
AE60UL
AE50UL
0
500
1000
1500
2000
2500
B
LOAD
CUMULATIVE COUNT OF ACOUSTIC EMISSIONS
UL
LD600
LD500
LD400
LD300
LD200
LD100
0
500
1000
1250
PL
tan⁻¹MOE
tan⁻¹MORSL
PLD
UD
COUNT PL
0
200
400
600
1000
1500
2000
2500
AE CUMULATIVE COUNT
LOAD (lbs)
C
LOAD
ACOUSTIC EMISSIONS RATE
UL
RT1000
RT800
RT600
RT400
RT200
0
250
1000
1250
PL
RATE PL
0
1000
2000
3000
4000
5000
AE RATE (counts/sec.)
1.0
PLD
2.0
3.0
UD
DEFLECTION (in.)

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: $Y = a_0 + a_1x_1 + a_2x_2 + a_3x_3$							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.*

	Deflection rate				
	24 in./min		0.5 in./min		Significantly different at $\alpha = 0.05$
Variable[1]	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

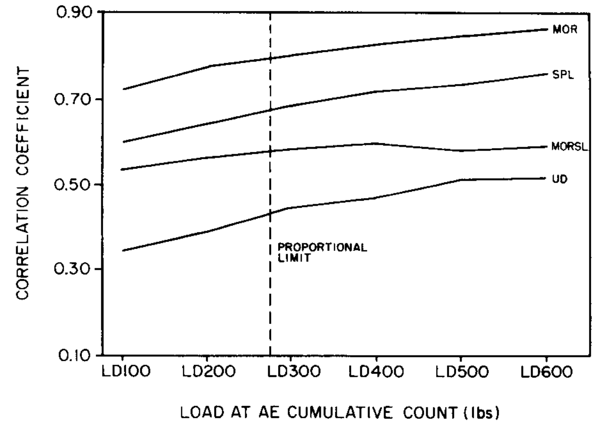


FIG. 3. Correlation coefficients for the relationship between AE cumulative count and lumber properties.

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 analzyed 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 Engelmann 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