DETERMINATION OF YLINEN'S PARAMETER FOR PARALLEL-STRAND LUMBER

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ABSTRACT: This study investigates the performance of 38 by 89 mm (1.5 by 3.5 in.) parallel-strand lumber columns. Currently, the 1991 national design specification of the American Forest and Paper Association for columns includes a *c* factor that describes the interaction of columns between the pure crushing and stability failure modes. For wood material, *c* is a combination of member straightness, material inhomogeneity, and stress-strain plasticity. The objective of our study is to determine an appropriate *c* value for parallel-strand lumber. Columns of several lengths are axially loaded to failure. Baaed on the nonlinear least-squares fit of column results, adjusted to a common moisture content, the most probable value of *c* for parallel-strand lumber is 0.86. This increased *c* value is attributed to the greater homogeneity and straightness of the manufactured columns.

INTRODUCTION

Parallel-strand lumber has entered the marketplace as a substitute for solid-sawn lumber. Its coefficient of variation is approximately 7 to 8% for stiffness and 10% for strength. Strands are made of peeled veneer 3 mm (1/8 in.) thick that has been cut into pieces about 16 mm (5/8 in.) wide and 1.52 m (5 ft) to 2.44 m (8 ft) long. The strands are glued and compressed into sizes comparable to structural lumber (Fig. 1). For use of parallel-strand lumber as compression members a value of $c = 0.8$ is commonly used in Ylinen's column interaction formula This value is the same as a value currently used for solid-sawn lumber *(National design specification* 1991). The recently adopted Load and Resistance Factor Design (LRFD) for engineered wood construction allows a value of $c = 0.9$ for parallel-strand lumber ("Standard" 1996). It is believed that the increased material homogeneity and member straightness should warrant a higher *c* value.

In 1991 American Forest and Paper Association *(National design specification)* adopted the Ylinen (1956) column design formula, replacing the fourth-power parabola that had been in use until then. Ylinen's column formula is a failure model that contains three parameters: zero-length column strength, F_0; buckling strength, F_E; and an interaction parameter, *c*. If $c = 1.0$, there is no interaction, and the formula reduces to pure crushing and pure buckling, but such an idealization does not apply to any real materials. For all real materials, $c < 1$. The formula has been adopted for use in design by assigning design values F_c and F_{cE} in place of F_0 and F_E, respectively. Because *c* measures interaction, it is not reduced by any safety factor. It is the same in both the failure model and the design model, and it can be measured only by fitting the failure model to mean failure data.

If this *c* parameter were adjusted to fit the timber column data of Newlin and Gahagan (1930), it would be 0.97; if fitted to modem lumber column data, *c* would be 0.8 (Zahn 1991). Zahn and Rammer (1995) experimentally determined *c* for Douglas fir and southern pine glued-laminated columns as 0.76 and 0.83, respectively. For design, they advocate the use of $c = 0.8$ for lumber and glued-laminated columns. A higher *c* value is attributed largely to the lack of dithering (vibration of support to break restraining static friction) in the tests of Newlin and Gahagan (1930). Zahn and Rammer (1995) used the same supports and found that dithering was needed to eliminate false datum points. Additionally, the focus of the column studies has changed over time. Newlin and Gahagan's work focused on first-growth timbers, whereas current studies focus on second-growth dimensional lumber.

The objective of this study was to determine a value of *c* for use in design of parallel-strand lumber compression members. Only standard 38 by 89 mm (nominal 2 by 4 in.) Douglas fir specimens were tested because material homogeneity should be independent of size by virtue of the manufacturing process for parallel-strand lumber.

NEW COLUMN DESIGN CRITERION

In the current specifications of the American Forest and Paper Association *(National design specification* 1991), a prime is used to denote that the tabulated design value, F_c, has been multiplied by all applicable modification factors, such as load duration, moisture content, and temperature. The resulting quantity is called the allowable design value. The effect of slenderness is accounted for by one of the modification factors, namely the "column stability factor," C_p. The slenderness ratio, l_e/d, is limited to a maximum value of 50, in which l_e, is

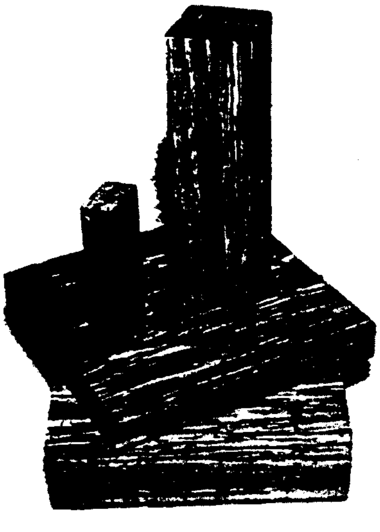

FIG. 1. Example of Various Sizes of Parallel-strand Lumber

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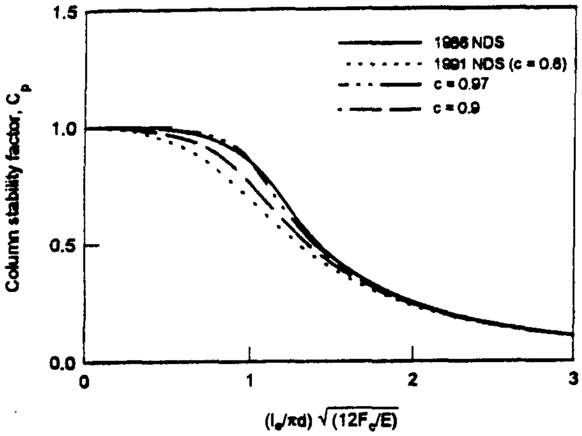

FIG. 2. Comparison of 1986 and 1991 National Design Specification Column Formulas

the effective length and d is the corresponding depth of cross section in the direction of buckling.

The column stability factor is calculated from Ylinen's formula:

$$C_p = \frac{1 + (F_{cE}/F_c^*)}{2c} - \sqrt{\left[\frac{1 + (F_{cE}/F_c^*)}{2c}\right]^2 - \frac{F_{cE}/F_c^*}{c}} \qquad (1)$$

in which F_c^* = the tabulated compression design value multiplied by all applicable modification factors except C_p; $F_{cE} = KcE'/(le/d)^2$; K_{cE} = 0.3 for visually graded lumber K_{cE} = 0.384 for machine-evaluated lumber; and K_{cE} = 0.418 for products with $COV_E \leq 0.11$. (COV_E = coefficient of variation of modulus of elasticity.)

Fig. 2 compares the 1986 and 1991 column design formulas of the American Forest and Paper Association with several c values. Note that the c value of 0.97 nearly matches the fourth-power parabola of the 1986 formula whereas the value of 0.8, which was adopted for solid-sawn lumber, is considerably more conservative.

The physical meaning of Ylinen's c factor as it applies to wood and wood-based products was presented by Zahn (1991). In Ylinen's original derivation, the c parameter characterized the nonlinearity of the stress-strain curve for a homogeneous, isotropic material. When Ylinen's theory is applied to wood, the physical meaning for c must be expanded because wood and wood products are neither isotropic nor homogeneous. Wood contains grain deviations, knots, varying density, and warp; therefore, c is not directly related to the stress-strain curve. Instead it is a combination of the following three factors: (1) crook or warp of the original member, (2) inhomogeneity of material properties, and (3) plasticity of the stress-strain curve. All three conditions affect interaction to produce the final c values for wood and wood products. For parallel-strand lumber, it is thought that increased uniformity and straightness of the manufactured columns would lead to a higher c value than the value of 0.8 given to solid-sawn lumber.

EXPERIMENTAL METHODS

Materials

All material was donated by a commercial manufacturer of parallel-strand lumber and manufactured according to their specifications. Originally, 60 standard orientation, grade 2.OE, Douglas fir parallel-strand lumber members arrived at the Forest Products Laboratory in 7.31 m (24 ft) lengths. This stock was cut into a total of 258 specimens of various lengths and sample sizes (Table 1). All member material had standard 38 by 89 mm (nominal 2 by 4 in.) cross-sectional dimensions.

TABLE 1. Experimental Design

Width, b mm (in.) (1)	Depth, d mm (in.) (2)	Length, l m (ft) (3)	l/d (4)	Sample size (5)
38 (1.50)	90 (3.50)	0.30 (1)	~0ᵃ	47
		0.91 (3)	10.3	48
		1.22 (4)	13.7	48
		1.52 (5)	17.1	48
		1.83 (6)	20.6	48
		2.41 (7.9)	27.1	66

ᵃThese specimens were used to measure "zero-length" column strength, F_0.

We did not consider it necessary to test different species or variations of parallel-strand lumber because small differences in c are extremely difficult to discriminate with any degree of statistical certainty (Zahn and Rammer 1995). Furthermore, effects on strength and stiffness (including their variability) are addressed by other parameters in the column equation.

Preliminary Tests

The Ylinen formula (1) reduces to F_c (compressive strength) at zero length (zero-length column strength is called F_0 here). The 0.30 m (1 ft) members (Table 1) were tested in compression parallel to grain to obtain the zero-length column strength of the material. Rigid platens were used as end supports and the head speed was 1.0 mm/s (0.0392 in/s). Note, all tests were conducted prior to the adoption of ASTM D5456 ("Standard Specification for Evaluation" 1995), which outlines procedures for testing and evacuating structural characteristics of composite lumber. This standard states that a compression perpendicular-to-grain specimen has an l/r ratio between 15 and 17, but for this test program the l/r value was slightly smaller than 15 and therefore has little effect on zero-length compressive strength.

The flexural modulus of elasticity, E, of each column was obtained by correlating the nondestructive stress wave elastic modulus, E_{sw}, with a static bending modulus for the longer specimens. The stress wave elastic modulus is determined by measuring the time required for a compression wave to travel in the member. Knowing the member length and density and the speed of the compression wave, E_{sw} is calculated by the following expression:

$$E_{sw} = C^2\rho \qquad (2)$$

where C is the compression wave speed and ρ is the material density (Ross and Pellerin 1994). This stress wave modulus was correlated with the static bending elastic modulus.

Flexural elastic modulus values were determined on a single span with loads applied at the third points on the 2.41 m (7.9 ft) and 1.83 m (6 ft) specimens. Bending stresses were kept less than 3.5 MPa (500 lb/sq in.), and loading was in the strong axis direction, with the other direction supported to prevent lateral buckling. Head speed was sufficient to reach the desired maximum stress in approximately 5 min.

Column Tests

Column tests were postponed until the results of all preliminary material tests were available. Knowledge of E and F_c^* allowed the column length to be selected so that the theoretical Euler stress was approximately equal to the crushing strength. This ensured that the results of the column tests would fall in the range where Ylinen's formula is most sensitive to c (Fig. 3). Column lengths shown in Table 1 were deemed suitable for determining c.

All members were laterally supported at the third points to

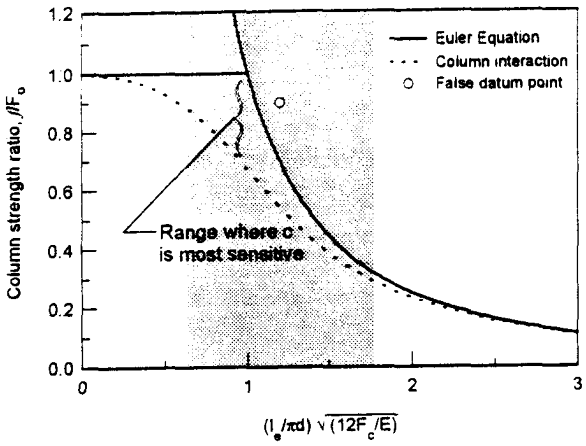

FIG. 3. Location of Critical Column Slenderness and Typical False Datum Obtained When End Supports Lock Up, with Shaded Area Denoting the Range of Slenderness Values Tested

prevent buckling in the weak direction with a roller system and had end supports equivalent to a pinned end condition [Fig. 4(a)]. Head speed was equal to the length of the specimen divided by 1,000 s, in which s = time in s.

For simply supported columns, the Euler load is always an upper bound on the real column capacity. Prior tests of glued-laminated columns (Zahn and Rammer 1995) revealed that dithering was necessary to avoid false data points, i.e., values greatly in excess of the Euler load. Dithers are vibrators that supply the energy needed to break static friction. Under heavy axial load, the end supports would sometimes lock up if the member was centered very accurately and its cross section had good material symmetry. Enough friction could develop to make the test behave like one of square ends on rigid platens rather than one of simple support. Friction between the specimen and lateral supports could also have been a factor in preventing buckling [Fig. 4(b)]. Therefore, a vibrator was attached to the bottom support to prevent the end supports from locking up. This gentle vibration was also sufficient to break static friction at points of lateral support. Dithering eliminated all occurrences of loads in excess of the Euler load.

After testing, a small block was cut to determine the specific gravity and moisture content of each specimen according to ASTM D2395 (“Standard Test Methods for Specific” 1994) and ASTM D4442 (“Standard Test Methods of Direct” 1994).

RESULTS

Compressive Strength Tests

A mean published zero-length column strength (F_{0p}) was inferred from the report by the National Evaluation Service (“PARALLAM” 1993) for parallel-strand lumber. According to ASTM D5456 (‘‘Standard Specification for Evaluation” 1995) standard, multiplying the published design stress by 1.9 should give the fifth-percentile strength. Assuming a normal distribution, the mean can be inferred from the fifth percentile by the following relation:

$$\text{Mean} = \frac{\text{fifth-percentile}}{1 - 1.645\ \text{COV}} \qquad (3)$$

From the 0.3 m (1 ft) column results and ASTM D5456 (1995), the COV of the compressive strength is approximately 0.12. A design compression strength value for Douglas fir parallel-strand lumber is 20.0 MPa (2.9 × 10^3 lb/sq in.). Therefore, (3) gives the estimated mean compressive strength for parallel-strand lumber as

$$F_{0p} = \frac{20.0(1.9)}{1 - 1.645(0.12)} = 47.3\ \text{MPa}\ (6{,}866\ \text{lb/sq in.}) \qquad (4)$$

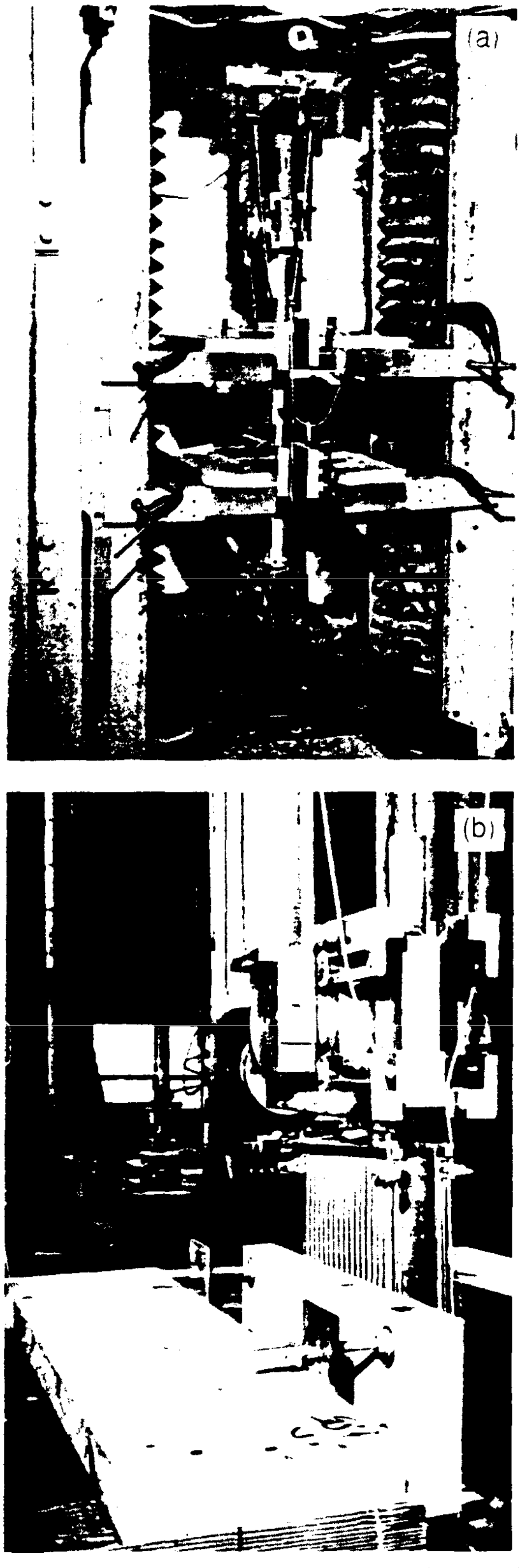

FIG. 4. Experimental Test Setup: (a) Testing of 2.41 m (7.9 ft) Column; (b) End Support Used to Obtain Condition of Simple Support and Lateral Stability Rollers

From tests, the mean value of F_0 equals 53.7 MPa (7.79 × 10^3 lb/sq in.) at a moisture content of 8.3%. Currently, there are no published moisture adjustment procedures for parallel-strand lumber. Therefore, procedures applied to solid-sawn and glued-laminated material are applied to adjust the F_0 value. Adjusting the test data to an equivalent moisture content that results from conditioning in a 12% (20°C–65% relative humidity) moisture content room according to ASTM D2915 (“Standard Practice for Evaluating” 1994) gave a mean F_0

value of 46.9 MPa (6.81×10^3 lb/sq in.), which is very close to the estimated mean published value of 47.3 MPa (6.87×10^3 lb/sq in.).

Modulus of Elasticity Tests

Measured bending modulus of elasticity values for the 2.41 m (7.9 ft) and 1.83 m (6 ft) columns and the correlated bending elasticity values of all tested columns are listed in Table 2. Differences in the flexural elastic modulus between the 2.41 m (7.9 ft) and 1.83 m (6 ft) columns are statistically significant at a 0.01 level of confidence. This difference is partially attributed to the effect of shear deformation on the two specimen lengths.

Linear regression analysis was used to relate the stress wave elastic modulus to the flexural modulus of elasticity for each size of specimen and the combined set. Fig. 5 shows the stress wave elastic modulus and the flexural modulus of elasticity along with best fit lines for each specimen size and the combined set. As this figure shows, the 2.41 m (7.9 ft) elastic values and best fit line tend to be above that of the 1.83 m (6 ft) values and line. This regression difference is also attributed to the presence of larger shear deformations in the shorter specimens. For the determination of the bending elastic modulus for column analysis, the correlation based on the fiexural and stress wave values of the 2.41 m (7.9 ft) specimens is used because the influence of shear deformations is smaller at greater shear span-to-depth ratios. The relationship is

$$E = 0.133 + 0.89E_{sw} \tag{5}$$

where E_{sw} is the stress wave elastic modulus, in GPa. Regression analysis determined a coefficient of determination of 0.89 and root mean square error of 69,432 for (5). Using this equation, the average elastic modulus of each size of specimen was determined at a moisture content of 8.3% (Table 2). Adjusting the test data to an equivalent moisture content that results from conditioning at 12% moisture content (20°C–65% relative humidity) according to ASTM D2915 ("Standard Practice for Evaluating" 1994) gave mean E values between 13.8 GPa (2.00×10^6 lb/sq in.) and 14.9 GPa (2.15×10^6 lb/sq in.), which encloses the mean published value of 13.8 GPa (2.00×10^6 lb/sq. in.) (National Evaluation Service 1993).

Column Tests

Width b, depth d, length l, and failure load P were recorded for each column. From these measurements, the column strength, f, and Euler stress, F_E, were calculated:

$$f = \frac{P}{bd} \tag{6}$$

$$F_E = \frac{\pi^2 E d^2}{12 l^2} \tag{7}$$

Average compression failure loads and coefficient of variation values for each column size are listed in Table 3.

All data for parallel-strand-lumber were plotted on a single figure of f/F_0 versus $\sqrt{F_0/F_E}$ [that is, $(l_e/\pi d)\sqrt{12F_0/E}$] (Fig. 6). The scatter on such a figure shows the variability in f, but it does not reflect the variability in F_0 and F_E. Fig. 6 also shows the best-fitting Ylinen formula for comparison, with $c = 0.90$ obtained by nonlinear least squares using a Markquart-Lewnberg algorithm (Marquardt 1963) with a coefficient of determination (r^2) of 0.91 and a root mean square error of 0.075.

Table 3 summarizes the material characteristics of the parallel-strand lumber tested. This table reveals that between the time the preliminary tests were completed and the column tests were conducted, the moisture content of the specimens decreased by approximately 1%. For completeness, F_0 and E were adjusted to a mean moisture content of 7.3% of the col-

TABLE 2. Elastic Modulus Values of Tested Parallel-Strand Lumber

Width, b mm (in.) (1)	Depth, d mm (in.) (2)	Length, l m (ft) (3)	Flexural elastic modulus, E GPa ($\times 10^6$ lb/sq in.) (4)	Correlated elastic modulus, E GPa ($\times 10^6$ lb/sq in.) (5)	Elastic modulus at 12% MC[a] GPa ($\times 10^6$ lb/sq in.) (6)
38 (1.50)	90 (3.50)	0.91 (3)	—	15.3 (2.22)	14.6 (2.11)
		1.22 (4)	—	14.5 (2.11)	13.8 (2.00)
		1.52 (5)	—	15.6 (2.26)	14.9 (2.15)
		1.83 (6)	13.9 (2.01)	15.5 (2.25)	14.8 (2.14)
		2.41 (7.9)	15.5 (2.25)	15.5 (2.25)	14.8 (2.14)

[a] MC: moisture content.

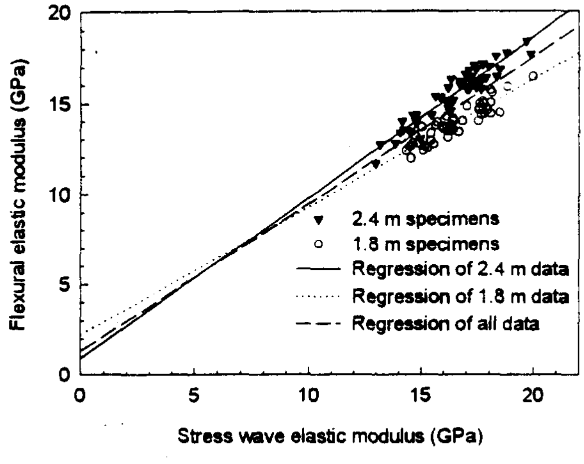

FIG. 5. Stress Wave Elastic Modulus versus Flexural Elastic Modulus and Best Fit Lines

TABLE 3. Specific Gravity, Average Column Strength, and Moisture Content of Parallel-Strand Lumber

Width, b mm (in.) (1)	Depth, d mm (in.) (2)	Length, l m (ft) (3)	Column Failure Load		Specific gravity (6)	Moisture content (%) (7)
			Average (N) (4)	COV (%) (5)		
38 (1.50)	90 (3.50)	0.30 (1)	182,000	9.0	0.57	8.3
		0.91 (3)	173,100	8.7	0.58	7.3
		1.22 (4)	144,800	10.9	0.56	7.4
		1.52 (5)	120,500	13.9	0.58	7.1
		1.83 (6)	96,600	20.5	0.58	7.4
		2.41 (7.9)	53,600	12.6	0.57	7.1

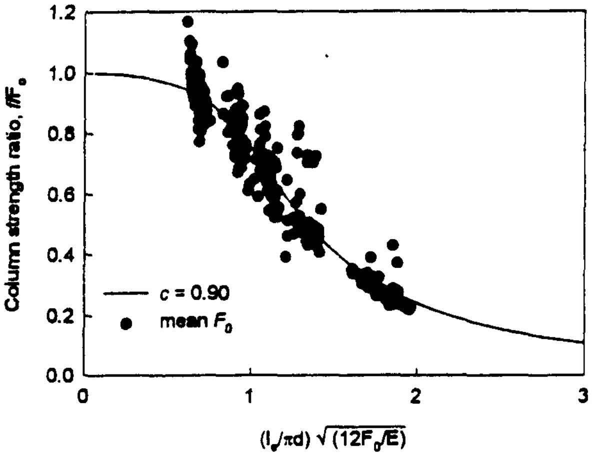

FIG. 6. Results of 258 Parallel-Strand Lumber Column Tests Unadjusted for Moisture, with F_c Assumed to Be 53.7 MPa

umn specimens, and the *c* parameter was reevaluated. This moisture content is approximately equivalent to conditioning the parallel-strand lumber in a 9% (26°C–65% relative humidity) moisture content room.

Moisture adjustments to F_0 and *E* were made according to ASTM D2915 ("Standard Practice for Evaluating" 1994). Again the data were plotted on a single figure of f/F_0 versus $\sqrt{F_0/F_E}$. Fig. 7 shows the adjusted data and the best-fitting Ylinen formula, $c = 0.86$, with a coefficient of determination of 0.91 and a root mean square error of 0.071.

To show the influence of F_0 on *c*, a nonlinear least-squares fit was conducted assuming F_0 values of plus and minus one standard deviation from the mean (Fig. 8). Both F_0 and *E* values were adjusted to 7.3% moisture content prior to analysis. In Fig. 8, solid symbols represent mean values and open symbols represent a one-standard-deviation shift of F_0. Note that a smaller value of F_0 increases the fitted value of *c* and vice versa. For parallel-strand lumber, the probable *c* values lie within a range of 0.79-0.92. A similar figure (Fig. 9) indicates the influence of modulus of elasticity on *c; c* values lie within a range of 0.80-0.90. Again, *c* was fitted by nonlinear least squares and *E* was varied by plus or minus one standard deviation. Note that the variability in F_0 and *E* has approximately the same effect on *c*.

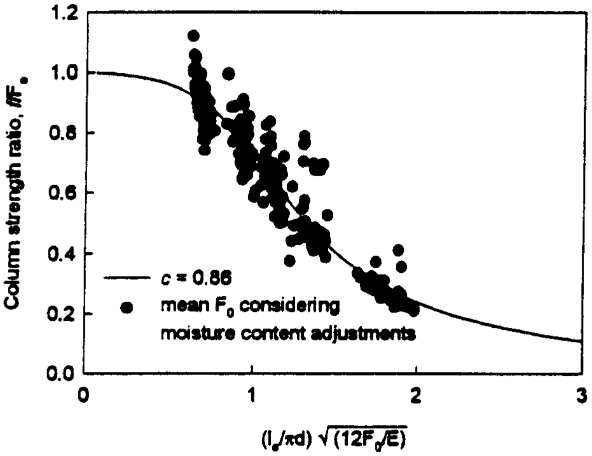

FIG. 7. Results of 258 Parallel-Strand Lumber Column Tests Adjusted for Moisture, with F_c Assumed to Be 45.7 MPa

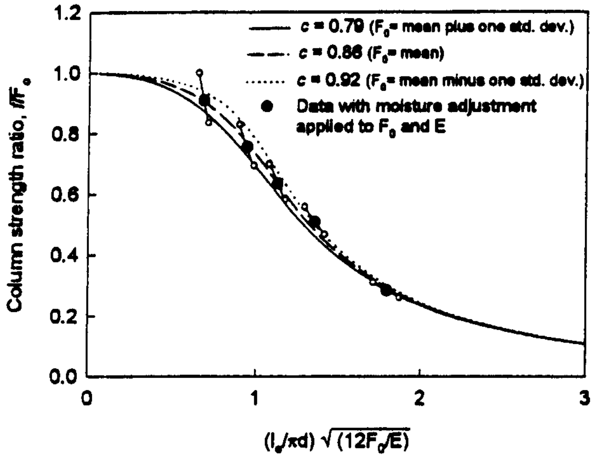

FIG. 8. Effect of Variability in F_0 on Fitted *c* Value

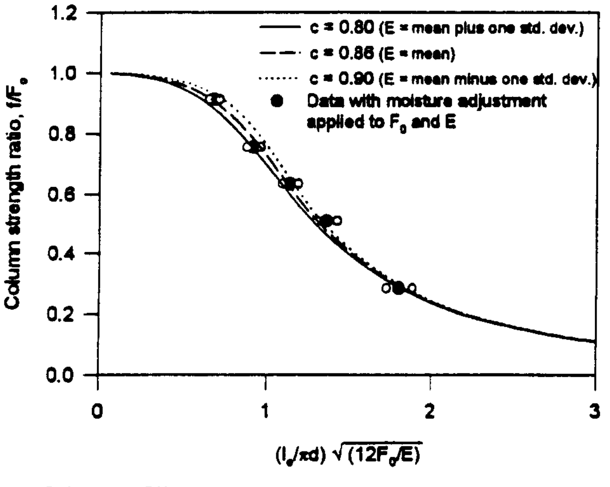

FIG. 9. Effect of Variability in *E* on Fitted *c* Value

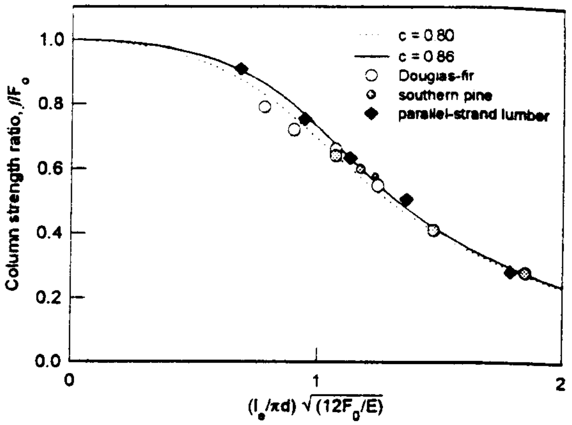

FIG. 10. Comparison of Glued-Laminated and Parallel-Strand Lumber Column Tests

Implications for Column Design

Because *c* measured interaction, it is the same in both the model and the design space, and it is determined by best fitting the failure model to the failure data. The best fit $c = 0.86$ value obtained for parallel-strand lumber is slightly greater than the 0.8 value adopted for solid sawn in the current specifications of the American Forest and Paper Association *(National design specification* 1991) and slightly lower than the 0.90 for structural composite lumber in the LRFD Wood Standard ("Standard" 1996). At the most sensitive location, namely the slenderness at which the Euler stress equals the compressive strength, this 0.06 difference translates to a 5.3% increase in the allowable column load. We conclude that higher *c* values of parallel-strand lumber are attributed to its greater homogeneity and straighter columns.

This conclusion is evident in Fig. 10, in which the sample averages of both the glued-laminated (Zahn and Rammer 1995) and parallel-strand lumber are plotted with Ylinen's formula (1956) at *c* values of 0.8 and 0.86. In this figure, the relative size of the samples is indicated by the relative size of the symbols; circles represent glued-laminated average results, and diamonds represent parallel-strand lumber average results. [In Fig. 10, the dashed line represents the current failure model for lumber in the specifications of the American Forest and Paper Association (199l).] At all slenderness ratios near the inelastic buckling region, parallel-strand lumber averages are greater than glued-laminated averages.

CONCLUSION

This study tested 258 Douglas fir parallel-strand lumber columns and 47 0.31 m (1 ft) compression blocks. The columns ranged from 2.4 to 0.9 m (3 to 8 ft) in length and were 38 by 89 mm (nominally 2 by 4 in.) in cross section. Based on a nonlinear least-squares fit of column results. adjusted to a common moisture content, the most probable value of **c** for parallel-strand lumber is 0.86. This higher *c* value, as compared in sawn lumber and glued-laminated timber values, is attributed to improved homogeneity and straightness of parallel-strand lumber columns. The parallel-strand lumber manufacturing processes produce a straighter and more uniform column compared with sawn lumber and glued-laminated timber but with more stress-strain plasticity, because stress levels at failure are generally higher for parallel-strand lumber. Straightness and uniformity increase the c factor, while the increased plasticity decreases it.

ACKNOWLEDGMENTS

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APPENDIX II. NOTATION

The following symbols are used in this paper:

b = width of cross section;
C_F, C_P = modification factors in 1991 national design specification;
c = Ylinen parameter;
d = depth of cross section;
E = modulus of elasticity;
E_{sw} = stress wave modulus of elasticity;
F_c = compressive strength;
F_E = Euler stress;
F_0 = zero-length column strength;
F_{cE} = allowable buckling stress in 1991 national design specification;
f = column strength;
K_{cE} = reduction factor on E in 1991 national design specification;
l, l_e = length of simply supported column, or equivalent length;
P = column capacity; and
r = radius of gyration.

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