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Gripped-End Effect in Tension Proof Testing of Dimension Lumber

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Abstract

The objectives of this study were (1) to predict falldown of gripped-end lumber using a computer-simulated tension strength-length effect model and (2) to measure the effectiveness of tension proof testing of lumber in the light of a gripped-end effect. In the initial tension proof test, the middle portion of each lumber specimen (nominal 2- by 6-in. No. 2 KD15 Southern Pine) was tested as if the pieces were only 10 ft long. In the subsequent falldown test, the grips of the testing machine were moved out so that the entire middle 10-ft section of each specimen-including the portions that had been gripped during the initial proof test-was fully stressed.

Some specimens, referred to as falldown, were broken in the second test at a load level below the proof load. The results confirm that gripping lumber ends in the tension proof test prevents failure of some pieces of lumber with tension strength below the proof load level. This general problem is referred to as the gripped-end effect. Although the computer model predicted falldown at a low proof load level, it failed to predict the behavior of lumber at a higher, more practical load level.

Keywords: Gripped-end effect, tensile strength, proof testing, lumber

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Gripped-End Effect in Tension Proof Testing of Dimension Lumber

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Introduction

Proof testing is a means of reducing strength variability and ensuring some minimum strength of a sample of lumber. This is accomplished by applying a load to the lumber. Any specimen weaker than the applied load will be broken. If some pieces are broken, the left tail of the strength distribution will be truncated at the proof load level, and the variance of the strength of the proof test survivors will be less than that of the original sample.

Tension proof testing has been used as a quality control procedure. For example, in some manufacturing plants for machine stress rated (MSR) lumber, randomly chosen samples of lumber are tested to determine how well they meet the strength requirements for the grade. Moreover, interest is increasing in using a tension proof test as a means of rating lumber. This trend is motivated by the fact that tension is the dominant stress mode of parts of engineered components. For example, both the flange of an I-joist and the lamination of a glued-laminated beam are stressed in almost pure tension. Additionally, tension constitutes much of the stress in the lower chords of trusses.

In tension proof testing of dimension lumber, the ratio of compression perpendicular-to-the-grain strength to tension parallel-to-the-grain strength in lumber is approximately 1 to 20. This low crushing strength requires that a significant portion of each end of the lumber be gripped during testing. As a result, the gripped portions of the lumber do not uniformly experience the proof stress. The fact that the ends are not fully proof tested is viewed as a technical problem that could provide an obstacle to evaluating the tension proof test.

The objectives of this research were (1) to predict falldown of gripped-end lumber using the tension strength-length effect model developed by Showalter and others (1987) and (2) to measure the effectiveness of tension proof testing, given that the gripped ends of the lumber do not fully experience the proof stress.

Literature Review

The development of the model for the tension strength-length effect (Showalter and others 1987) was preceded by much research on the variability of lumber strength with member length. We present a brief review of the theories and models that have been used to explain the effect of volume on lumber strength.

In the past two decades, several researchers reported on the variation of wood tensile strength with member size. Studies by Kunesh and Johnson (1974) and Buchanan (1983) showed a trend of decreasing tension strength with increasing member size. The weakest link theory was used in many applications to explain size effects on lumber strength, mainly in the form of the Weibull distribution. Buchanan (1983) related the strength of clear, dry, straight-grained Douglas-fir in bending to its strength in axial tension. He concluded that Weibull's (1939) statistical theory for materials could be used for modeling wood in tension parallel to grain if the theory were modified to include the effects of material variability with length and cross section.

The effect of member length on tension strength parallel to grain was also examined by Poutanen (1984), who theorized that an increase in beam length results in a decrease in tension strength. Bender and others (1985) reported that in statistically modeling the laminations of glued-laminated beams, laminate tension strengths needed to be adjusted for the effect of length. These authors interpreted Weibull's weakest link theory through reliability theory by equating a long piece of lumber to a simple series system of shorter lumber lengths.

Bechtel (1988) examined the effect of lumber length on axial tension strength. He assumed all elements along the material to be under the same stress and considered each cross section as an element. Bechtel showed that the statistical independence assumption of the Weibull theory (1939) leads to conclusions that are inconsistent with experimental evidence. Introducing the concept of coherence length, he developed a model of the tension strength of a wood member that relaxes the assumption of statistical independence among the elements of the material. The model, which has not been experimentally tested, relates exponentially the tension strength distributions at different test lengths. The model allows a different exponent in the exponential relationship at each load level, and procedures are developed to determine this relationship from test data at different lengths (Bechtel 1988).

Likewise, Madsen (1986) developed a modified weakest link theory to explain size effects in timber. Formulas were developed to describe the effects of length, load configuration, depth, stress distribution, breadth, and length for members in series.

Showalter and others (1987) conducted a study to investigate and model the effect of length on tension strength parallel to grain in lumber. The test included two sizes (nominal 2 by 4 and 2 by 8 in.) and two grades (2250F-1.9E MSR, No. 2 KD15) of Southern Pine lumber with test span lengths of 30, 90, and 120 in. The measured tension strengths were significantly lower in the longer specimens, demonstrating that tension strength is affected by length. Tension strength and modulus of elasticity data from the 30-in. treatment groups were used to develop length-effect models of tension strength for each of the four grade and size groups.

The modulus of elasticity (E) variability model used was developed by Kline and others (1986) from E measurements made on the same lumber used in the study by Showalter and others (1987). On each specimen designated for the 30-in. tension test, a flat-wise static E was determined on four adjacent 30-in.-long segments. The lag-2 serial correlation r_2, which is the correlation between an outcome from the model at one interval length and outcomes from the model at two previous intervals, was preserved by fitting a second-order autoregressive model to the E data:

$$x_{i+1} = B_1\, x_i + B_2\, x_{i-1} + e_{i+1} \qquad [1]$$

where the x_i values represent the observed E data values from the model and the B values are multiple regression coefficients, which are functions of the lag-l and lag-2 serial correlations between lumber segments.

The tension strength-length effect model developed by Showalter and others (1987) incorporates this E variability model. The relationship between E and tension strength is modeled using the logarithmic transformation of the tension strength in a weighted least squares regression model developed by Woeste and others (1979):

$$\ln(Y) = C_1 X + C_0 + \epsilon \qquad [2]$$

where

Y is measured tensile strength,

X the independent variable E, and

ε the residual, which is assumed to be normally distributed with zero mean and variance KX.

In this equation, C_0, C_1, and K are estimated by maximizing a likelihood function; inputs X and Y are measured E and corresponding measured tension strength, respectively, for the 30-in. segments. The estimates are $\widehat{C}_0, \widehat{C}_1$, and $\widehat{K}$ for C_0, C_1, and K, respectively.

Additionally, the correlation between tensile strength residuals of neighboring segments is modeled by assuming that the residuals in the log space follow a first-order stochastic normal process. The first-order stochastic model generates a series of values from a normal distribution while preserving the first-order, or lag-l, serial correlation, but it also generates serial correlations of any lag k by the theoretical model (Haan 1977)

$$\rho_k = \rho_1^k \qquad [3]$$

The lag-3 serial correlation estimate r_3 for ρ_3 was obtained from the residuals ε_1 and ε_4 for the first and fourth 30-in. segments using the following form of Equation [2]:

$$\epsilon_i = \ln(Y_i) - b_0 - b_i X_i \qquad [4]$$

where

Y_i is measured tension strength parallel to grain and

X_i is measured E.

For each of the four size and grade groups, $r_1 = r_3^{1/3}$ according to Equation [3] was used in the model as an estimate of r_1.

This serial correlation is used in modeling the tension strength residuals of neighboring segments. The residual ε_i is assumed to be from a normal distribution, $N(0, K \times E)$, and to have first-order serial correlation r_1; ε_i may be generated by the following equation:

$$\epsilon_{i+1} = \frac{r_1[K \times E_{i+1}]^{1/2}\epsilon_i}{[K \times E_i]^{1/2}} + t_{i+1}[K \times E_{i+1}]^{1/2}(1 - r_1^2)^{1/2} \quad [5]$$

where

ε_i is the value of ε at segment i,

r_1 the estimated first-order serial correlation, and

t_{i+1} the standard normal deviate, N (0,1).

In summary, the following procedure is used to generate lengthwise stiffness and tension strength properties for a piece of lumber according to the model of Showalter and others (1987). Serially correlated E values from 30-in. segments are generated using the E variability model of Kline and others (1986). The variability along the length is modeled by a second-order autoregressive process (Eq. [1]). A parallel first-order stochastic process generates segment tension strength residuals in the log space such that the tension strength residuals of the 30-in. segments in the log space have variance $K \times E$ and first-order serial correlation r_1 (Eq. [5]). Segment tension strength values are generated from the segment residuals and E values according to Equation [4]. Using the weakest link concept, the tension strength of each specimen is the minimum segment tension strength.

Computer Simulations

Simulation Constraints

Discrete grip positions along the length of the tension test machine facilitated tension proof tests of 10-, 12-, 14-, 16-, 18-, and 20-ft lumber lengths. To explore a possible length effect, minimum and maximum testable lumber lengths were simulated in a preliminary study. The minimum standard length of lumber that could be proof tested was 10 ft, but a 14-ft length was required to perform the falldown test because of the 21 in. required on each lumber segment end for gripping. The maximum testable lumber length was 20 ft, leaving a 16-ft length for the initial proof test.

We used nominal 2- by 6-in. No. 2 KD15 Southern Pine for the experiment. Because Showalter and others (1987) did not use this type of lumber in their simulation program, all four types of lumber used by Showalter and others were simulated and analyzed to obtain a range of possible outcomes (Table 1).

Table 1 – Proof load levels for Southern Pine lumber simulated in the model[a]

Lumber size	Lumber grade	Proof load level (SF) Lower	Proof load level (SF) Upper
2 by 4	2250F–1.9E MSR	1.15	1.6
	No. 2 KD15	1.15	1.8
2 by 10	2250F–1.9E MSR	1.15	1.6
	No. 2 KD15	1.15	2.0

[a] Proof load level is defined as $SF \times F_t \times 2.1$.

Proof load level was defined as $SF \times F_t \times 2.1$ where SF represents an anticipated stress increase, F_t is the allowable tension stress value, and 2.1 is the adjustment factor for load duration and safety used in the visual stress grading system. Two proof load levels were used to simulate tests on each of the four types of lumber (Table 1). The lower SF value (1.15) represents a likely, economically feasible minimum value. The upper value, which varied with lumber type, was chosen to prevent excessive breakage of specimens.

Simulation Procedure

Lengthwise tension strength properties of 5,000 pieces of each length, size, and grade of lumber were simulated by a computer model. The initial proof test and subsequent falldown test were then simulated by "discarding" all specimens with tensile strength below the chosen proof load level.

Interpolation Rules for Simulation of Lumber Strength and Initial Proof Test

The computer simulation program used generates strength properties for lumber with length that is an integer multiple of 30 in., the test length used by Showalter and others (1987). Because the lumber and grip lengths are not even multiples of 30 in., a linear interpolation was performed to determine lumber strength during the proof and falldown tests. In the 14- to 10-ft-length case (Fig. l), only 126 in. were fully loaded in the falldown test. This length must be simulated by a rule since 126 is not an even multiple of 30. Thus, four- and five-segment specimens were used to interpolate the correct length.

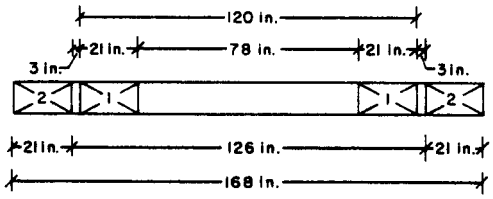

Figure 1—Tension proof test grip positions for 14- to 10-ft length case in simulated tension proof test.

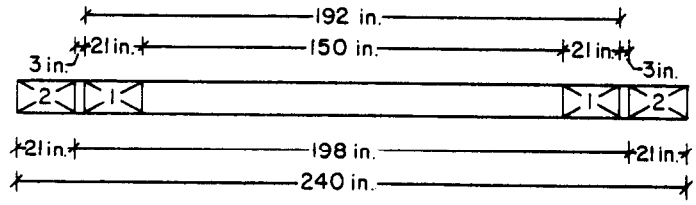

Figure 2—Tension proof test grip positions for 20- to 16-ft length case in simulated tension proof test.

The number of five-segment specimens was determined by the rule

$$\frac{R}{30} \times \text{total number of specimens}$$

Thus, 1,000 five-segment specimens (6/30 × 5,000) were used.

The number of four-segment specimens was determined by the rule

$$\frac{30 - R}{30} \times \text{total number of specimens}$$

Thus, 4,000 four-segment specimens (24/30 × 5,000) were used.

The final step in the interpolation was to add the 1,000 five-segment specimens to the 4,000 four-segment specimens to form a simulated sample size of 5.000 boards.

A second interpolation was required to simulate the tension strength of the lumber part being fully loaded in the initial proof test. For example, when performing the initial proof test on the 14- to 10-ft lumber, 78 in. of lumber between the grips was fully tested. Thus, 24 in. of lumber was assumed to be untested from each end of the 126-in. length. The tension strength of the tested part of the specimens was computed by similar interpolation, as reported by Terry (1988). The initial proof test was then simulated by "discarding" all specimens with strength lower than the desired proof load level. For each case, that level is given in Table 1.

Simulation of Falldown Test

The falldown test was simulated by removing all survivors of the initial proof test that had a 126-in. length strength less than the proof load level. The survivors of the initial proof test eliminated in the falldown test represent the specimens of low strength that we want to destroy in a tensile proof test but which are not destroyed because their strength-determining defects are held in the grips. For the 20- to 16-ft case (Fig. 2), interpolation rules similar to those for the 14- to 10-ft case were developed, and the proof and falldown tests were simulated.

The results of the preliminary study are shown in Table 2. As expected, the results showed that more falldown occurred at higher proof load levels. To determine whether or not falldown was affected by lumber length, linear regression techniques were used to relate percent breakage to percent falldown for the 20- to 16-ft and 14- to 10-ft data separately. Data from all four types of lumber were grouped together.

Because the dependent variable, falldown, was expressed as a percentage, all the data points used in the regression analysis do not have equal variances; the lower percentages have less variance than the higher percentages. These unequal variances were accounted for in a weighted least squares regression analysis. In this type of analysis, each weight value is proportional to the reciprocal of the observation variance. The resulting weighted least squares estimators are best linear unbiased estimators (SAS Institute, Inc. 1985). The weights are implemented in minimizing the following weighted residual sum of squares:

$$\sum w_i (y_i - \hat{y})^2 \qquad [6]$$

where w_i is proportional to the reciprocal of the variance of y_i.

The weight used for each observation in this analysis is simply the reciprocal of the variance of the observation. Each observation of percent falldown is a binomial random variable having the variance

$$\sigma_p^2 = p\frac{1-p}{n} \qquad [7]$$

where p is the proportion of n survivors broken in the falldown test. For the two observations for which no falldown occurred, a value of 1 falldown was assumed for the purpose of obtaining a value slightly greater than zero for the variance. In this way, when the weights were formed as $1/\sigma_p^2$, those weights corresponding to zero falldown were reasonable and comparable to the other weights. The resulting weighted least squares 1inear regressions were as follows:

Table 2—Computer simulation results using tension strength-length model

Lumber size	Lumber grade	Proof load level[a] (*SF*)	Board length[b] (ft)	Board total[c] (no.)	Breakage[d] (no.)	Breakage[d] (percent)	Falldown[e] (no.)	Falldown[e] (percent)
2 by 4	2250F-1.9E MSR	1.15	20–16	5,000	52	1.04	19	0.38
		1.15	14–10	4,996	41	0.82	11	0.22
		1.6	20–16	5,000	945	18.90	196	4.83
		1.6	14–10	4,996	640	12.81	201	4.61
2 by 4	No. 2 KD15	1.15	20–16	4,996	313	6.27	68	1.45
		1.15	14–10	4,985	218	4.37	58	1.22
		1.8	20–16	4,996	1,825	36.53	227	7.16
		1.8	14–10	4,985	1,509	30.03	250	7.19
2 by 10	2250F-1.9E MSR	1.15	20–16	5,000	63	1.26	27	0.55
		1.15	14–10	4,991	52	1.04	19	0.38
		1.6	20–16	5,000	1,015	20.30	239	6.00
		1.6	14–10	4,991	639	12.80	234	5.38
2 by 10	No. 2KD15	1.15	20–16	5,000	2	0..04	0	0
		1.15	14–10	4,999	4	0.08	0	0
		2.0	20–16	5,000	485	9.70	121	2.68
		2.0	14–10	4,999	319	6.38	134	2.86

[a] Proof load level was calculated as $SF \times F_t \times 2.1$; a 0.6-width adjustment factor was also included for 2 by 10 No. 2 KD15.
[b] Values indicate simulated and actual board lengths. For example, 20-16 denotes a 20-ft board used to simulate an actual 16-ft board.
[c] Total number of boards simulated.
[d] Specimens broken with grips in position 1 (Fig. 5) in initial tension proof test. Percentage is number of broken specimens divided by total number of boards simulated.
[e] Specimens broken with grips in position 2 (Fig. 5) in falldown test. Percentage is number of falldown specimens divided by number of survivors,

Percent falldown = 0.008 + 0.241 × percent breakage, for 14- to 10-ft length specimens

Percent falldown = -0.015 + 0.309 × percent breakage, for 20- to 16-ft length specimens

For each of the two regressions, the intercept was tested for a significant difference from zero. Both intercepts were found to be nonsignificant. The intercept was therefore dropped from the linear model, and the model

$$Y = \beta_1 X + \epsilon \qquad [8]$$

was used to fit the data. The resulting weighted least squares regression lines were as follows:

Percent falldown = 0.307 × percent breakage, for 14- to 10-ft length specimens

Percent falldown = 0.242 × percent breakage, for 20- to 16-ft length specimens

These regression lines are plotted in Figures 3 and 4. Analysis of variance indicated that both regressions were significant at the 0.0001 level.

Experimental Proof Testing of Lumber

Experimental Design

The procedure for the tension proof test required increasing the test specimen length by two grip lengths (Fig. 5). The sample of lumber consisted of specimens that were the same grade within length A. The parts covered by the grips (C) were regraded individually; this grade was recorded for future research that will explore the use of special end-grading rules for tension proof testing.

When the grips were in position 1 (Fig. 5), the tension proof test was similar to a production proof test for rating pieces of lumber of length A. However, because

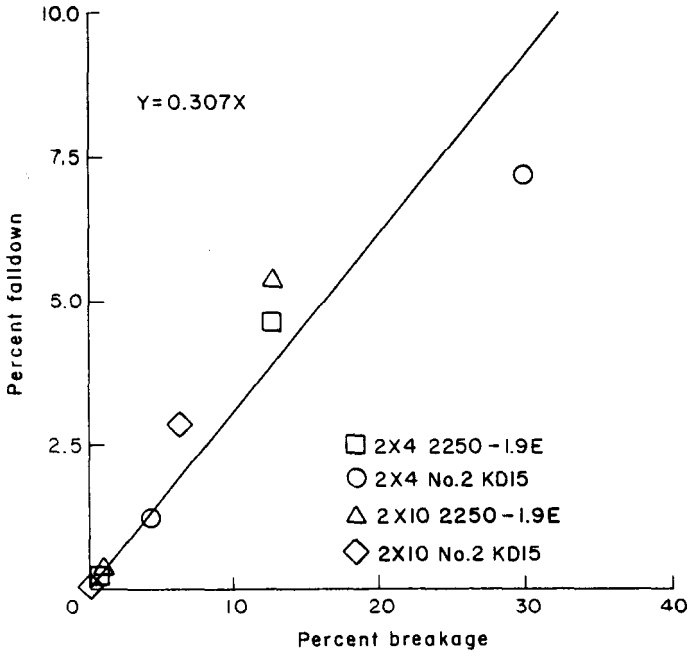

Figure 3—Relationship of percent breakage to percent falldown for 14- to 10-ft length specimens.

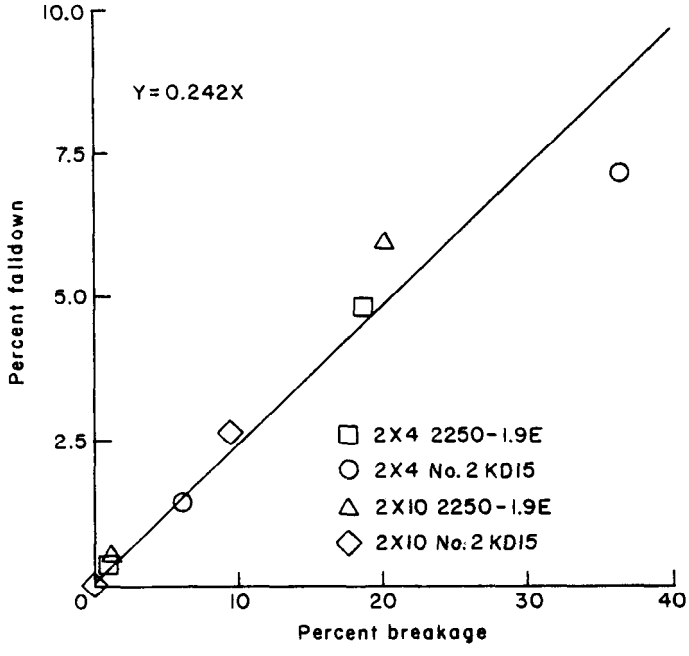

Figure 4—Relationship of percent breakage to percent falldown for 20- to 16-ft length specimens.

parts C were held in the grips, only length B was fully tension proof tested, even though testing the entire length A was desired. Lumber specimens not broken in this initial proof test are referred to as survivors. The percentage of pieces failing this test is referred to as percent breakage.

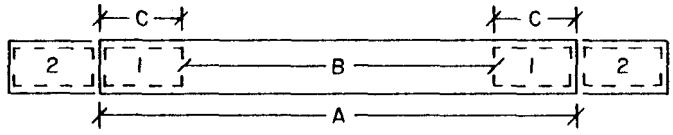

Figure 5—Schematic representation of specimen for tension proof test. (1) Grip positions for initial proof test; (2) grip positions for falldown test. Length A was the same grade in all specimens; length C was regraded for each specimen. Only length B was fully tension proof-tested.

When the grips were moved to position 2, the survivors were tension proof tested to the same load level used in the initial test. This procedure revealed survivors that had full-length tension strength below the proof load level but were not broken in the initial proof test because of the grips-the strength-limiting defects of these specimens were in the gripped segments. Note that failure of survivors may occur because of a defect in the original grip area, indiscernible grip or tension stress damage during the initial proof test, or a combination thereof. However, this is the result desired because in reality proof-loaded lumber is gripped and tension stressed. We refer to this second tension proof test as the falldown test, and to the specimens broken in this test as falldown. Percent falldown refers to the number of falldowns as a percentage of the number of survivors of the initial proof test.

The experimental analysis was aimed at validating the model of Showalter and others (1987) in a specialized use through tests of 2 by 6 No. 2 KD15 Southern Pine lumber. Validation of the model as applied to this problem could lead to size- and grade-specific recommendations for proof-load levels that yield acceptable levels of falldown.

Specimen Length Determination

The numerical difference in slopes of the regression lines in Figures 3 and 4 shows the simulated percent falldown to be higher for the shorter lumber than for the longer lumber at equal levels of percent breakage. This result was expected since the ratio of lumber untested (gripped) to the length tested in the computer simulation is larger for the shorter lumber. A hypothesis test for the equality of slopes was not conducted because of the strong physical basis for a difference of slopes. The specimens used to test the worse falldown case were 14 ft long.

Sample Preparation

Sample Size Determination

The results of the 14- to 10-ft-length 2 by 4 No. 2 KD15 Southern Pine simulation were used initially to determine sample sizes for the experiment because this lumber type incurred the greatest amount of simulated breakage and falldown. Additionally, the 2 by 4 No. 2 KD15 Southern Pine is the closest in size and allowable tension strength to 2 by 6 specimens of this lumber grade. By using the following equation, the sample size that would yield approximately 200 survivors was determined for the high and low proof load levels:

$$N = \frac{(200 \text{ survivors})}{(1 - \text{breakage})} \qquad [9]$$

These two sample sizes, as well as percent falldown as predicted by the regression equation, and the 90-percent confidence intervals on percent falldown are summarized in Table 3. The confidence intervals were computed using the normal approximation of the binomial distribution, without the continuity correction at this stage (Snedecor and Cochran 1980).

Table 3 also includes an intermediate proof load value (1.49). Just as current allowable lumber design strength values are based on 5th-percentile strength characteristics, the intermediate proof load level was selected to correspond to a 5-percent falldown rate. Using the regression equation, this falldown rate corresponds to 16.28 percent breakage. Rerunning the simulation program for 14- to 10-ft-length 2 by 4 No. 2 KD15 Southern Pine (total of 4,985 specimens), a proof load level of 1.49 × F_t yielded 16.43 percent breakage.

Note that a linear interpolation between proof load level and percent falldown (Table 2) predicts a proof load level of 1.56 for a corresponding 5-percent falldown rate. This proof load level is nearly equal to the 1.49 proof load level determined from the regression equation and simulation model.

Three-Step Experimental Design

We designed a three-step experiment to change (after preliminary test results) the three sample sizes so that the confidence intervals on percent falldown would have comparable widths. Table 3 indicates that with increasing predicted percent falldown, the confidence intervals widen. However, there is more interest in narrowing the confidence intervals at the two higher levels because improved accuracy at these two levels is more valuable; end grading may be necessary for tension proof tests that produce levels of falldown above 5 percent. Because increasing the sample size for a fixed falldown rate decreases the width of the confidence interval, the optimum design has the smallest sample size at the low proof level, a larger size at the intermediate level, and the largest size at the high level.

Table 3—Sample sizes for experimental proof load studies and 90-percent confidence interval bounds for percent falldown

Proof load level (SF)	Sample size	Predicted percent falldown	90-percent confidence intervals for percent falldown: Lower bound	Upper bound
1.15	209	1.34	0	2.7
1.49	239	5.00	2.5	7.5
1.80	286	9.22	5.9	12.6

In Step 1, two samples of approximately 100 pieces of lumber each were formed from a total of approximately 750 pieces of 2 by 6 No. 2 KD15 Southern Pine. These two samples were proof- and falldown-tested-one sample at the low proof load level (SF = 1.15), and the other at the high level (SF = 1.80). For the falldown test, the lumber was tested to failure to establish the general quality of the sample. However, only the specimens that broke at a load level at or lower than the proof load level were tallied as falldown. From these tests, a linear interpolation could be performed to estimate a third proof load level corresponding to a 5-percent falldown rate. This method could result in a better estimate of the needed third proof load level than that obtained previously from simulation (Table 4) because the quality of the 750 sample boards may have differed from the quality of the/lumber used to build the simulation model.

In Step 2, a sample of approximately 100 pieces of lumber (formed like the lumber in Step 1) was proof- and falldown-tested at the intermediate (5-percent) falldown rate from Table 3. The amount of breakage and falldown in this test and in the Step 1 tests aided in the allocation of 465 remaining pieces to the three proof load levels used in Step 3.

In Step 3, the 465 remaining pieces of lumber were distributed among the different proof load levels. The final sample sizes were chosen to yield optimal estimates of falldown in accordance with the application of the research.

The details of the proof load levels and sample sizes chosen are described by Terry (1988). The three-step procedure was modified slightly when severe amounts of breakage and falldown occurred in Step 1

Table 4—Adjusted proof load levels for Steps 2 and 3 of experimental design

Assumed base stress[a] (lb/in^2)	ASTM test strength[b]	Rate adjustment[c]	FAST proof load level (lb/in^2)
675	1.62	1.064	1,160
497	1.62	1.050	845

[a] An assumed base stress was needed. In this case, the base stress was much too low for commercially viable proof tests.
[b] Conversion from "normal duration" to ASTM 10-min test duration.
[c] Adjustment from McLain and Woeste (1986), a conversion from ASTM test duration of 10 min to 20 s.

High breakage and falldown levels indicated that the quality of the test sample lumber was much lower than that used to build the simulation model of Showalter and others (1986). Moreover, the quality of the test sample lumber was much lower than that implied by the tension strength allowable value for No. 2 KD15 Southern Pine published by the National Forest Products Association (1988). Therefore, lower and different proof load levels were chosen for Steps 2 and 3 of the experiment, as described by Terry (1988). In summary, the safety factor of 1.3 was removed from the calculation of proof load level, and a base stress value, lower than the present book value of F_t, had to be assumed because of the poor quality of the lumber sample. The adjusted proof load levels for Steps 2 and 3 are listed in Table 4.

Selection and Preparation of Test Lumber

In the Southern Pine structural lumber market, material grade-stamped No. 2 most commonly includes material No. 2 and better in quality. However, the actual mixture of grades differs from mill to mill and from time to time. Theoretically, a sample of lumber grade-stamped No. 2 could contain strictly No. 2 material. To test this worst possible scenario, "strictly No. 2" lumber was selected for this study.

The lumber sample (778 pieces of 14-ft 2 by 6 No. 2 KD15 Southern Pine) was selected by a licensed grader and regional manager of the Southern Pine Inspection Bureau (SPIB) to ensure that the middle 126 in. of all specimens was strictly No. 2 grade and that the remaining 21-in. lengths on each end were No. 2 grade or better. The term strictly No. 2 is used because all the provisions of the No. 2 grade were met, both structural and nonstructural. Additionally, the 24 in. adjacent to each end of the middle 78 in. of each piece of lumber were regraded, and the grade of each of the two 24-in. sections was recorded. These two sections were the parts of the lumber that were not fully tension stressed in the initial proof load test but fully stressed in the subsequent falldown test.

The lumber was stickered and left in a temperature-controlled building for approximately 4 weeks, until all specimens reached a stable moisture content. A resistance moisture meter was used to monitor the conditioning process. Considerable drying took place between the time when lumber was brought into the laboratory and when modulus of elasticity was measured. This drying reduced the mean moisture content from approximately 10 percent to approximately 8 percent. The range of moisture content was reduced significantly from an initial 7.0-15.5 percent to 7.0-11.5 percent when modulus of elasticity was measured.

Full-span modulus of elasticity of each specimen was measured in a flatwise static test using a 10-ft span. Modulus of elasticity (E) measurements established the general quality of the lumber and provided a means for dividing the lumber into groups for the experimental design. The overall mean E for the entire sample of 778 pieces of lumber was 1.37×10^6 lb/in^2. This value is significantly lower than the average value of 1.6×10^6 lb/in^2 published for No. 2 KD15 Southern Pine. The lumber was assigned to 15 groups of approximately 50 specimens, to ensure that the distribution of tensile strengths in the groups was as similar as possible. The mean and coefficient of variations were calculated for each group. This process was computed several times using a separate (and independent) stream of random numbers. We selected the one set of 15 groups that yielded the smallest range in group average E. (With this selection, the coefficients of variation of E of each group ranged from 0.194 to 0.223, a satisfactory range for the sample sizes involved.)

Tension Proof Test

A computer-controlled lumber tension proof testing machine developed by the Lumbermate Company[1] (St. Louis, MO), Frank Lumber Company (Mill City, OR), and Washington State University (Pullman, WA) was used to perform the experiment. This machine loads lumber at a constant rate to a predetermined target level or to a maximum capacity of 40,000 lb.

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

The grips of the proof testing machine are balanced and free to rotate about their pinned connection to the arms connecting them to the tension rod. These rotating grips reduce eccentric loading of slightly crooked pieces and transmit a nearly pure axial tension force to the test lumber. The 21-in.-long gripping surfaces are polyurethane.

Before testing, the load cell calibration within the tension proof testing machine was verified. A calibrated reference standard load cell was loaded in tension by the system as would be experienced by a proof-tested piece of lumber. This was accomplished by mechanically connecting the reference standard load cell to two pieces of 2 by 6 lumber held in the grips during the verification. The output of the system load cell was traced against the reference standard load cell output as load was applied. A lo-percent bias was discovered in the system load cell, and the controller was then programmed to account for this bias in its output to the personal computer.

Prior to testing, moisture content of each specimen was measured with a resistance moisture meter calibrated daily using the oven-drying method. Additionally, the presence or absence of pith in each piece of lumber was recorded. For the final nine groups of lumber tested, the growth rate on one end was measured for each piece of lumber. This measurement did not represent the average growth rate of the entire cross section, but rather the fastest growth rate, measured within 1 in., along a radial line.

The grips of the tension proof testing machine were set to test a 10-ft board, and the initial proof test was performed in 20 s on the middle 78 in. of each 14-ft specimen. Specimens were proof tested to the target FAST proof load levels listed in Table 4. The FAST load rate was 6,000 lb/in^2/min. Failures near or associated with the grips were recorded. The load at failure and the size and position of visible defects were recorded for failed lumber.

For the survivors, the grips were then moved to the falldown test position so that the middle 126-in. length of lumber was fully stressed. In the falldown test, each survivor of the initial proof test was loaded to failure at the same rate of loading as used in the initial proof test. All failures were recorded in the manner described for the initial proof test. Results are summarized in Table 5.

Predictive Abilities of Simulation Model

The percentage of falldown during experimental testing was greater than that predicted by the weighted least squares regression model from the preliminary study (Fig. 3). For the 2.4-percent breakage at the lower proof load level (845 lb/in^2), 1.5 percent falldown occurred, but only 0.7 percent falldown was predicted by the regression model. For the 11.4-percent breakage at the higher proof load level (1,160 lb/in^2), 11.4 percent falldown occurred; only 3.5 percent falldown was predicted by the regression model.

The predictive ability of the tension strength-length effect model (Showalter and others 1987) in this application can be evaluated based on comparison of the weighted least squares regression model estimate to the interval estimates of percent falldown formed from the point estimates obtained experimentally. Interval estimates of percent falldown were formed using a normal approximation to the binomial probability distribution with a continuity correction (Snedecor and Cochran 1980). The calculation of confidence limits using the normal approximation procedure with continuity correction is as follows:

$$p - \left[Z_{a/2}\sqrt{\frac{pq}{n}} + \frac{1}{2n}\right] < P < p + \left[Z_{a/2}\sqrt{\frac{pq}{n}} + \frac{1}{2n}\right] \quad [10]$$

where

$Z_{a/2}$ is the coordinate of the normal curve with area $(1 - a/2)$ beyond it,

p the estimated proportion of falldowns (or percent falldown expressed in fractional or decimal form),

P the true proportion of falldowns (unknown),

n the sample size of those specimens tested in the falldown test or the number of survivors of the initial tension proof test, and

$$q = 1 - p$$

Interval Estimate of Percent Falldown at Low Proof Load Level

For the falldown resulting from the 845-lb/in^2 FAST proof load level, 3 of 202 specimens failed. The resulting 95-percent confidence interval is

$$0 < P < 0.03395$$

Thus, for the case in which 2.4 percent breakage occurs for a proof-tested sample of lumber, it may be stated with 95 percent certainty that the interval 0 to 3.4 will

Table 5—Experimental results from Step 3

Proof load level (lb/in^2)	Group number	Sample size (no.)	Breakage (no.)	Breakage (percent)	Survivors (no.)	Falldown (no.)	Falldown (percent)
845	6	52	1	1.9	51	0	0.0
	7	51	1	2.0	50	0	0.0
	8	52	1	1.9	51	1	2.0
	9	52	2	3.9	50	2	4.0
(Overall)		207	5	2.4	202	3	1.5
1,160	5	50	5	10.0	45	5	11.1
	10	51	5	9.8	46	8	17.4
	11	52	2	3.9	50	8	16.0
	12	52	8	15.4	44	5	11.4
	13	51	9	17.7	42	3	7.1
	14	52	4	7.7	48	4	8.3
	15	51	8	15.7	43	5	11.6
(Overall)		359	41	11.4	318	38	11.9

contain the true percentage of falldown. This interval estimate of percent falldown at 2.4 percent breakage is valid for 2 by 6 No. 2 KD15 Southern Pine lumber tested with the rotating-grip machine used in this study.

As illustrated graphically in Figure 6, the regression model falls within the 95-percent confidence interval for the estimated falldown percentage. This indicates the model was able to predict subsequent falldown for the lumber sample with 2.4 percent breakage. This implies that the interval estimate of percent falldown (0 to 3.4 percent) corresponding to 2.4 percent breakage is also valid in a predictive sense for the sizes and grades of Southern Pine lumber with which the Showalter and others (1987) model was originally validated (2 by 4 and 2 by 10 2250F-1.9E MSR and No. 2 KD15).

For production proof tests of the types of Southern Pine lumber used in this study and in the study by Showalter and others (1987), if 2.4 percent or less of the specimens are broken, <3.4 percent of the survivors should have tensile strength below the proof load level (95 percent confidence). Note that this result is applicable for the sizes and grades of Southern Pine lumber described here when proof tested in the rotating-grip machine used in this study. These results may have limited value because breakage amounts in excess of 2.4 percent may be necessary in production proof testing.

Interval Estimate of Percent Falldown at High Proof Load Level

For the falldown resulting from the 1,160-lb/in^2 FAST proof load level, 38 of 318 specimens failed. The resulting 95-percent confidence interval is

$$0.0822 < P < 0.1568$$

Thus, for the case in which 11.4 percent breakage occurs for a proof-tested sample of 2 by 6 No. 2 KD15 Southern Pine lumber, it may be stated with 95 percent certainty that subsequent falldown will be between 8.2 and 15.7 percent.

In this case, the regression model failed to predict lumber behavior. Therefore, no conclusions may be drawn concerning the validity of the 95-percent confidence interval estimate of percent falldown at 11.4 percent breakage for any sizes or grades of Southern Pine lumber other than the 2 by 6 No. 2 KD15 tested.

The inability of the model to predict percent falldown at the higher level of breakage may be explained by three reasons.

First, the inability of the model to predict falldown at the high breakage level may stem from the interpolation methods used to adapt the model to this specialized problem. Perhaps the model is inapplicable to this specialized use. If the model is applicable, perhaps the interpolation methods used to adapt the model to this problem were inappropriate.

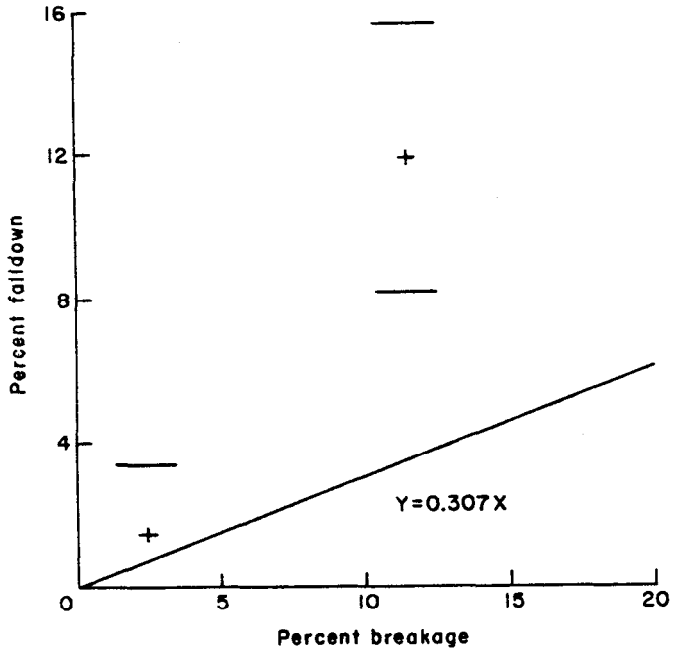

Figure 6—Graphical comparison of experimental results and preliminary computer simulation prediction. The horizontal lines above and below the two experimental data points (+) represent upper and lower limits for 95-percent confidence intervals for estimated percent falldown. The line $Y = 0.307\ X$ is the weighted least squares regression model resulting from the preliminary study in which the Showalter and others (1987) model was adapted to this specialized application.

Second, the discrepancy between predicted and experimental falldown at 11.4 percent breakage could be due to damage caused by the grip pressure or the axial tension stress during the proof test. Of the 38 falldown specimens at the higher proof load level, eight specimens failed in the middle 78 in., which is the entire length of lumber that was between the grips in the initial proof test (Fig. 1). This result implies that the lumber was either damaged by the tension stress during the initial proof test or, just as likely, that regripping each specimen at a longer span during the falldown test produced a different stress condition throughout the member from that experienced in the proof test. This theory is supported by the fact that much of the lumber was severely warped; the warpage could have caused amplified bending and torsional forces when the lumber was gripped at a longer span and could have contributed to a more severe stress condition in the lumber during the falldown test. The remaining 30 falldown specimens failed in one or the other graded 24-in. sections adjacent to each end of the middle 78-in. section. These failures may have been caused by a defect, indiscernible grip damage, or a combination thereof.

At the higher proof load level, damage is a more likely cause of falldown because the stresses throughout the lumber and gripping pressure are much higher. This could explain why the model was better able to predict falldown for lumber tested at the lower proof load level. The modeled lumber mechanical properties remain constant for a simulated piece of lumber throughout the proof and falldown tests. However, the experimental proof test damage at relatively high stress levels could downgrade the mechanical lumber properties and cause more falldown than predicted through the simulation model used.

Third, the inability of the model to predict lumber behavior at the higher proof load level may be due to the difference between the quality of the test sample lumber used in this study compared to that of the lumber used in the study by Showalter and others (1987). Undoubtedly, the strength properties of the 2 by 4 and 2 by 10 2250F-1.9E MSR lumber in the latter study were superior to the strength properties of the 2 by 6 No. 2 KD15 lumber used in our study. The allowable tension stress value (F_t) for the 2250F-1.9E MSR lumber is 1,750 lb/in^2, compared to an F_t of 675 lb.in^2 for 2 by 6 No. 2 KD15 Southern Pine (National Forest Products Association 1988).

Recall that the 2 by 6 No. 2 lumber was graded for use in this study and included purely nondense No. 2 material. The 2 by 4 and 2 by 10 No. 2 KD15 Southern Pine material used to validate the Showalter and others (1987) model was more representative of lumber available in the Southern Pine structural lumber market because it included material graded No. 2 and better. A quality supervisor from the Northern Hardwood and Pine Manufacturing Association visually regraded the No. 2 KD15 material used in the Showalter and others (1987) study. The result of that regrade, the F_t values for the individual grades, and the number of specimens in each grade are shown in Table 6.

A comparison of lumber grades and allowable tension stress values indicates that most of the lumber used by Showalter and others (1987) was of better quality or higher grade than the lumber used in our study. The quality differences are amplified by the fact that the published allowable tension stress value for the grade had to be abandoned as a basis for choosing proof load levels. Clearly, the quality of this particular sample of 2 by 6 No. 2 KD15 Southern Pine lumber was far inferior to the quality implied by the National Forest Products Association (1988) F_t value.

The difference between the two study samples is even more apparent in a comparison of mean tension strength values. The mean tension strength of the

Table 6—Regraded No. 2 lumber grades, allowable tension stress values, and quantities[a]

Lumber grade	2 by 4 F_t (lb/in^2)	2 by 4 Specimens (no.)	2 by 10 F_t (lb/in^2)	2 by 10 Specimens (no.)
SSD	1,500	35	1,160	31
SS	1,250	4	960	5
No. 1 D	1,250	77	750	61
No. 1	1,050	11	630	42
No. 2 D	1,050	79	480	58
No. 2	900	38	405	59

[a] From Showalter and others (1987).

Table 7—Mean tension strength of 10-ft Southern Pine lumber tested by Showalter and others (1987)

Lumber grade	Mean tension strength (lb/in^2) 2 by 4	2 by 10
2250F-1.9E MSR	8,100	7,976
SSD	8,186	6,596
SS and No. 1 D	4,472	4,119
No. 1 and No. 2 D	3,946	3,412
No. 2	3,197	2,084

2 by 6 No. 2 KD15 lumber for the nine groups (465 pieces) of lumber tested in Step 3 of our study was 1,780 lb/in^2. Converting this FAST test rate value to an ASTM test rate strength (tension tests in the Showalter and others (1987) study were performed at a test rate complying to ASTM standard D198), the comparable mean tension strength of the 2 by 6 No. 2 KD15 Southern Pine sample is

$$\text{Mean tensile strength (ASTM)} = \frac{\text{FAST rate mean}}{\text{Rate adjustment}}$$

$$= \frac{1,780 \text{ lb/in}^2}{1.10} = 1,620 \text{ lb/in}^2$$

where the rate adjustment is the ratio of the 2 by 6 No. 2 KD15 Southern Pine strength at FAST proof test level to ASTM rate strength at equal percentile levels (McLain and Woeste 1986).

Mean tension strength values for the 120-in. lumber tested in the Showalter and others study (1987) are shown in Table 7. These tabulated mean tension strength values, when compared to the mean tension strength of 1,620 lb/in^2 used in our study, indicate the higher quality of the lumber used in the study by Showalter and others. The model used by Showalter and others simulates the properties of the lumber sample with which it was validated. The fact that the quality of that lumber was better than that of the lumber in our study may be one reason that the model was not able to accurately predict falldown at the higher level of breakage.

Concluding Remarks

This study was designed to measure the effectiveness of tension proof testing. The occurrence of falldown demonstrates that tension proof testing does not fail certain pieces of lumber with strength below the proof load level. A significant portion of this lumber is within the grips and does not experience the full proof stress.

The experimental design and analysis were aimed at validating the tension strength-length effect model of Showalter and others (1987). The model was modified so that it could be used to predict falldown for several grades and sizes of Southern Pine lumber. Although this modified model predicted lumber behavior at a very low proof load level, in which only 2.4 percent of the lumber broke, it failed to predict the behavior of lumber tested at a higher, more practical load level, in which 11.4 percent of the lumber broke.

The 2 by 6 No. 2 KD15 Southern Pine lumber tested was not representative of commercially available lumber because it contained material that was strictly No. 2 grade. In addition, the lumber may have been overdried and may have contained excessive amounts of juvenile wood. All these factors may have contributed to the finding that the strength and stiffness qualities of the test sample were inferior to that implied by the National Forest Products Association (1988) allowable design properties.

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