PROOF LOADING TO ASSURE LUMBER STRENGTH

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ABSTRACT

The control of within-mill variations in the strength distribution of a given structural grade of lumber is of growing concern to the wood industry. Recent studies have proposed the use of on-line proof loading procedures to maintain quality through the elimination of weak pieces.

An experiment was conducted on one thousand two hundred pieces of 2 × 4 No. 2 Dense KD Southern pine to determine the effect of both single and reverse bending proof loads on the strength of lumber tested in both bending and tension parallel-to-grain. The specimens were separated into six groups, each containing two hundred pieces. A pair of control groups, single proof load groups, and reverse proof load groups were tested. One group in each pair was failed in bending, the other was in tension. During the testing, no damage due to the proof loading was detected.

Probabilistic analysis of the data indicates that the bending strength of the single proof loaded specimens could be reduced by 12% and still remain as reliable as the control. Reverse proof loaded specimens could tolerate a reduction of 33%. The tensile strength for each single proof loaded member could tolerate a reduction of 13%, while reverse proof loaded specimens could face a decrease of 18% and maintain a level of safety equal to the related control. When using a bending proof load to assure lumber strength, it is necessary to use a higher proof load to assure tensile strength than would be needed just to assure bending strength.

Keywords: Proof loading, proof test, lumber, strength, tension, bending, reliability.

INTRODUCTION

The majority of structural lumber is visually graded at the sawmill where it is produced. The occurrence of natural irregularities, such as knots and varying grain slope, greatly affect its mechanical properties. The visual stress rating (VSR) procedure considers these factors when assigning grades to the lumber. However,

because of the inability to accurately assess these factors and because of the speed at which the grading is conducted, coupled with unseen variations within the boards, grading errors occur. Other factors can also influence the process, such as accuracy of grading models, various levels of grader expertise, and inconsistency of grading between lumber mills. No matter what causes the grading error, the result of inaccurate assessment is an increase in the probability of an individual member failing under service conditions. Some way to minimize the final effect of grading inaccuracies is necessary to insure product reliability and safety. The objective of this study is to investigate the use of bending proof loads to assure lumber strength assignments.

Published studies have proposed that the best way to control within-mill variation is through the use of on-line proof loading procedures (Marin and Woeste 1981; Madsen 1976; Pellerin 1978; Strickler and Pellerin 1974; Strickler et al. 1970; Bechtel 1983). However, many questions concerning the optimum orientation and level of the proof load still exist. Nevertheless, the ultimate goal of any proof loading procedure is to remove those pieces of lumber that have strengths below the assigned strength for the grade without damaging the survivors. With proof loading in mind, it might be possible for the VSR performance variables to fluctuate significantly while maintaining the overall quality of the product.

In this study we determined the effect of edgewise bending proof loads on the tensile and bending strength of dimension lumber. Both single and reverse proof load situations are investigated. The single proof loaded specimens are subjected to a bending proof load on a randomly selected edge. The reverse proof loaded pieces have loads applied to each of the beam edges in sequence, prior to their destruction in either a bending or tension mode. The percent of material breakage and possible damage resulting from the proof loading procedure are considered.

LITERATURE

Proof loading, a test procedure in which members are subjected to a load up to a specified level, is not a new concept. Freas (1949) reported on a study of the use of "proof loading" on ladders. He applied loads equal to or greater than those which the ladder was expected to carry. Freas warned against compression failures resulting from such tests and recommended that such tests for ladders be discontinued because of the lack of proper testing skills. Rossnagel (1950) saw it as a way of possibly detecting defective scaffold planks.

More recently, Strickler et al. (1970) studied the phenomenon of applying a bending proof load to insure the strength of structural end joints. Experiments were conducted to determine if significant damage occurred in the joints and to consider the ability of a bending proof load to screen tensile members. Results from the study revealed no reduction in lumber strength due to the applied proof load. It was also found that a bending proof load would indeed assure the tensile quality of structural end-jointed lumber. Additional proof loading studies were conducted on individual Douglas-fir lamina by Strickler and Pellerin (1974) and on finger joints by Pellerin (1978). In these studies it was concluded breakage from proof load could be minimized by presorting the material to be proof loaded.

Madsen (1976) conducted a bending proof load study as part of a larger research program. He tested four proof load and failure load arrangements based upon the

TABLE 1. *Moisture content, specific gravity, and modulus of elasticity for specimen groups are nearly identical.*

Group number	Sample size	Moisture content (%)		Specific gravity		MOE ($\times 10^6$ psi)	
		Mean	COV	Mean	COV	Mean	COV
1	193	9.2	0.08	0.55	0.11	2.108	0.205
2	197	8.9	0.09	0.55	0.12	2.099	0.206
3	197	9.1	0.08	0.54	0.12	2.102	0.205
4	196	9.5	0.07	0.54	0.12	2.105	0.203
5	198	8.7	0.06	0.55	0.12	2.093	0.209
6	198	8.9	0.07	0.54	0.12	2.097	0.208

apparent weak side orientation relative to the direction of loading. Madsen found that in cases where the proof load and final load were of the same orientation, no proof load damage was observed. In cases where the proof load and failure load were of opposite orientation, proof load damage was apparent. However, because some initially weak pieces had been removed from the population, he concluded that the lumber returned to the mill after proof loading did not reduce the strength distribution of the end products.

Marin and Woeste (1981) studied the effect of a bending reverse proof load on the lumber strength distribution of 2 × 4 No. 2 Dense KD Southern pine. The research was designed to test a hypothetical mill process in which every piece of lumber would be subjected to the reverse proof load during production, thus eliminating the weak pieces. The investigation was intended to indicate what mill variations in lumber quality could be tolerated using hypothetical proof loading to maintain the design strength of the lumber. In their study, two hundred pieces comprised a control group. The lumber was tested in third-point loading using a random edge orientation. A 3-parameter Weibull distribution best approximated the probability function, and a 5th percentile bending strength was estimated for subsequent use as a proof load level. Another two hundred pieces were subjected to reverse proof loads in bending with a random edge orientation. If the piece survived the first proof load, it was turned and the proof load was applied to the opposite edge. Eight percent of the samples failed during the reverse proof load sequence. The remaining pieces were then failed in bending. With the survivors of the reverse proof load, one piece failed at a stress level 6.2% below the proof load level. There were no other indications of damage resulting from the proof loading. Comparison of the reliability of the control sample to that of the reverse proof loaded sample showed that the proof loading procedure could protect the allowable design stress in light of a hypothetical decrease of up to 27% in the modulus of rupture (MOR) distribution of the lumber being produced.

A similar study was conducted by Woeste et al. (1984) in an attempt to assess the effect of a bending proof load on parallel-to-grain compression strength. Again, the tests were performed using 2 × 4 No. 2 Dense KD Southern pine lumber. A control sample and a proof loaded sample, both originally consisting of two hundred specimens, were formed by serial selection. In this process, one piece from the lumber bundle was placed in one group, the next piece in the second group, the next in the first group, and so forth, until both samples were complete. This procedure was necessary because of the suspected serial correlation of bending

TABLE 2. *Group number and treatment types for subsequent discussion.*

Group	Treatment
1	Bending control (CNTL-B)
2	Single proof load, failed in bending (SPL-B)
3	Reverse proof load, failed in bending (RPL-B)
4	Tension control (CNTL-T)
5	Single proof load, failed in tension (SPL-T)
6	Reverse proof load, failed in tension (RPL-T)

strength in lumber bundles (Marin 1979). Using a test machine designed to subject the member to pure compression parallel-to-grain, each piece in the control sample was stressed to failure. The specimens in the treatment group were then reverse proof loaded in bending as described by Marin and Woeste (1981). The surviving pieces were subsequently failed in compression. Subsequent probabilistic analysis of the results found that the application of a bending reverse proof load did not reduce the parallel-to-grain compressive strength of the surviving lumber.

EXPERIMENTAL PROCEDURES

Sampling

The lumber tested in this study consisted of one thousand two hundred pieces of "as-graded" 2 × 4 No. 2 Dense KD Southern pine, 12 feet in length, obtained from an Alabama mill. The specimens were conditioned to an equilibrium moisture content of approximately 9% (74 F and 50% relative humidity) prior to separation into six treatment groups. In an attempt to maintain uniformity between the strength distributions of the groups, the stiffness of each piece was obtained over its entire length using an E-computer and the strength ratio in the middle 80 inches of span estimated. The pieces were then ranked by MOE and separated into E-classes. The material within each E-class was then ranked by the estimated strength ratio using the maximum strength-reducing defect within the middle 80 inches of the span. To assign lumber to the treatment groups, the six pieces with the smallest strength ratio within a specific E-class were randomly assigned to one of the six treatment groups. This procedure was repeated until all of the specimens had been assigned to a test group. Table 1 shows the consistency between groups for moisture content, specific gravity, and MOE.

Edge orientation for testing

Three of the six groups were arbitrarily chosen as bending groups. One of these three, a control sample, was tested to failure in bending using random edge placement. The second, a single proof load sample, was subjected to a bending proof load on a randomly selected edge, and then the survivors were tested to failure on the opposite edge. The third, a reverse proof load sample, was failed in bending after a proof load had been applied to each edge of the beam. The destructive loading was applied to alternate edges of the beams; i.e., after proof loading, the first beam was loaded on the edge used for the first proof load and the next beam on the edge used for the reverse proof load. The three remaining groups were tension groups subjected to similar conditions as those for the bending tests, except that destructive testing was in tension rather than bending. Table 2 contains both
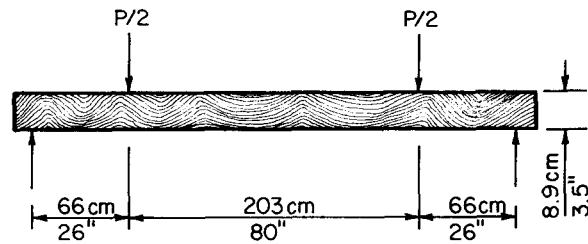
FIG. 1.   A schematic of the testing arrangement for the application of bending proof loads. The center 80 inches were subjected to constant moment as a result of symmetrical loading. This section was then failed in either bending or tension parallel-to-grain.

the group numbers and subsequent treatments for both the tension and the bending samples.

Loading conditions

The bending loads were applied at two points located a distance of L/5 from each span end. An 11-foot span was tested with an L/d ratio of 37.7. The loading blocks were positioned 26 inches from the reactions. This arrangement yielded a maximum moment area having a length of 80 inches, the same section subjected to the tensile tests. The L/d ratio for the tension tests was 22.8. Figure 1 illustrates the test configuration for bending. It is the same loading procedure used by Woeste et al. (1984).

For the purposes of this study, a proof load was selected so that the expected breakage would be about 5% of the pieces. Using the bending control, BC, group as a guide, the proof load was 700 lb, or about 3,070 psi. It is noted, however, that in actual use it is only necessary to use a proof load level that is sufficiently high to maintain the claimed reliability of the end products.

EXPERIMENTAL RESULTS

Damage due to proof loading

Although possible damage due to proof loading is difficult to quantify, it was not detectable in this study. The group subjected to reverse bending proof loads and the survivors failed in bending showed no failures at or below the proof load level. However, the group subjected to a single bending proof load and loaded to failure on the opposite edge had 7 of 197 specimens fail at a load lower than the applied proof load. It cannot be assumed that the bending strength for one edge orientation will be identical to that for the opposite orientation. This is because knot distributions are not identical on the two edges. This disparity in strength distribution due to edge orientation has been noted in previous investigations (Johnson 1965; Madsen 1976). Since damage was not evident with reverse proof loading at the estimated 5th percentile, it would not be a problem in proof loading at lower, more economical levels relative to mill production schemes.

Because of the potential differences in knot distribution on the two beam edges noted above, the percent breakage may differ significantly from the target value of 5%, especially for the reverse proof load case. This phenomenon was present in this study and is summarized in Table 3. For the two reverse proof load cases, 9.1 and 11.1% of the pieces were broken instead of 5%.

TABLE 3. *Breakage due to proof loading by number and percent.*

Treatment	Sample size	No. of proof load failures	% breakage
CNTL-B	193	—	—
SPL-B	197	15	7.6
RPL-B	197	18	9.1
CNTL-T	196	—	—
SPL-T	198	14	7.1
RPL-T	198	22	11.1

Selection of distributional forms

Distribution analyses were performed for each treatment, and both the lognormal and 3-parameter Weibull distributions were tested using Chi-square goodness-of-fit criteria (Ang and Tang 1975) and visual appraisal. Parameters for the 3-parameter Weibull distributions were calculated using a computer program developed by Simon and Woeste (1980). Given a relatively large Type I error of 0.20, only 2 of the 12 distribution assumptions were rejected using the goodness-of-fit tests. Therefore, in most cases both the lognormal and the 3-parameter Weibull distributions were statistically adequate representations of the same treatment.

To determine which curve most accurately followed the data, the distributions were overlaid on the observed relative frequency histogram and a visual assessment of the fit between theoretical and observed frequencies was made. Each of the bending groups were best fit by a 3-parameter Weibull distribution (Fig. 2). The tension groups were found to follow lognormal distributions (Fig. 3).

RELIABILITY ANALYSIS

To calculate degree of within-mill variability that can be controlled through proof loading, it is necessary to compare the reliability of proof loaded lumber to that of general mill output. However, it will first be necessary to define the calculation procedure.

Probability of failure

The probability of failure, denoted by P_f, is a quantity associated with the inherent risk of a structure, member, or material under loaded conditions. For this analysis, failure is considered to occur when the strength, R, of a structure member is exceeded by the applied load, S. A mathematical representation can be written as

$$P_f = Pr(R < S) \tag{1}$$

Given that the resistance and load have continuous probability density functions $f_R(r)$ and $f_S(s)$, respectively, the above definition can be used to yield the integral expression (Suddarth et al. 1978).

$$P_f = \int_0^\infty \left[\int_0^s f_R(x) \, dx \right] f_S(x) \, dx \tag{2}$$

where $f_S(x) \, dx$ is the probability of the load occurring in the interval $(x, x + dx)$ and $\int f_R(x) \, dx$ is the probability that the resistance is less than x. A numerical solution to Eq. (2) was used in this study (Marin and Woeste 1981).
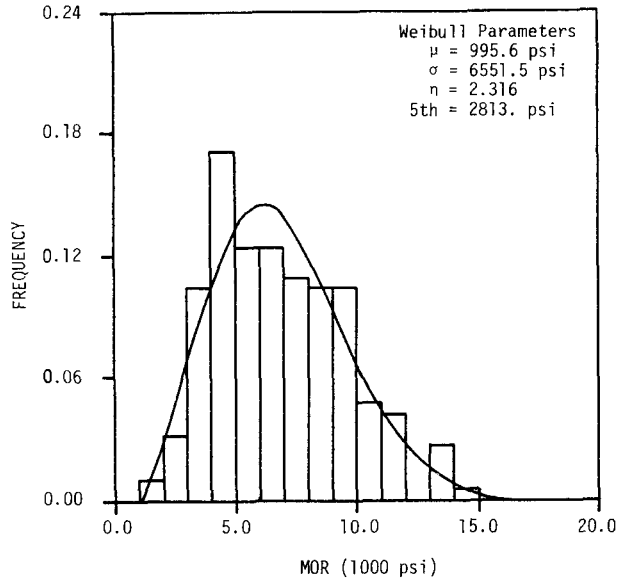
Fig. 2a. The MOR's of the control specimens are represented by the histogram. A 3-parameter Weibull probability distribution was found to be the best approximation.

Load distributions

Recent work by Thurmond et al. (1984) on loading conditions for low slope roof trusses centered around the determination of statistics for dead loads and snow loads. In conventional design situations, the design load is assumed to be
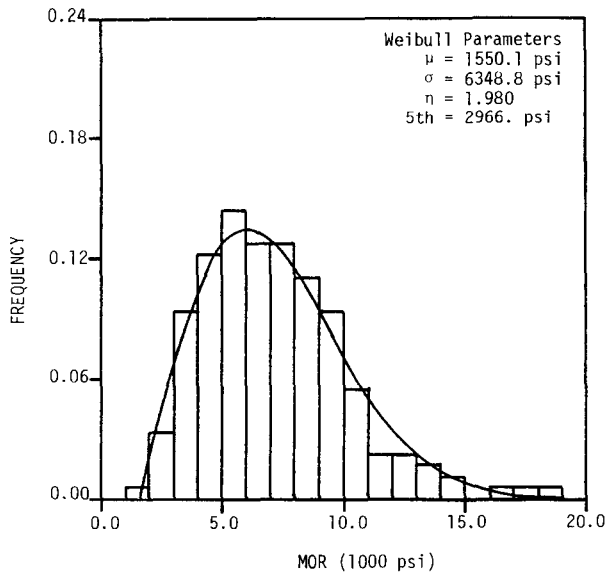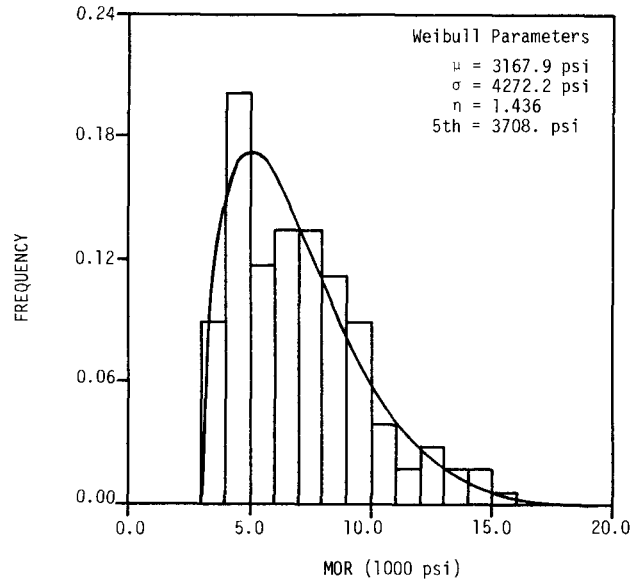

Fig. 2b. The MOR's of the single proof loaded specimens are represented by the histogram. A 3-parameter Weibull probability distribution was found to be the best approximation.

FIG. 2c.   The MOR's of the reverse proof loaded specimens are represented by the histogram. A 3-parameter Weibull probability distribution was found to be the best approximation.

equal to the design resistance. In a reliability analysis, the normalized mean ratio, $\bar{X}/X_n$, is used to relate the mean of the load distribution ($\bar{X}$) to the nominal load (X_n). The nominal design load must have the same units as the resistance variable. The load distribution is then shifted by the value $\bar{X}/X_n$ because the mean value is more representative of the actual load than is the nominal value.

In the case of dead loads, the normalized mean of the distribution ($\bar{D}/D_n$) was found to be 0.57 for a rafter design (2 × 8 No. 2 Douglas fir rafters, 16 inches on center) with ½-inch plywood sheathing and asbestos shingles. The actual dead load was 5.7 psf. The coefficient of variation of the dead load (Ω_D), defined as the mean dead load divided by the standard deviation, was assumed to be 0.10. Similarly, Thurmond et al. (1984) calculated the normalized mean of the maximum lifetime roof snow load distribution ($\bar{S}/S_n$) to be 0.69 with a coefficient of variation (Ω_s) equal to 0.44. The total load, being a combination of the dead and the snow loads, has the following parameters:

$$\mu_T = D_n/T_n(\bar{D}/D_n)F_b + S_n/T_n(\bar{S}/S_n)F_b \tag{3}$$

$$\Omega_T = [(\mu_D\Omega_D)^2 + (\mu_S\Omega_S)^2]^{\frac{1}{2}}/\mu_T \tag{4}$$

where

μ_T = the mean total lifetime load (psi)
Ω_T = the coefficient of variation of the total lifetime load
T_n = the total nominal load, $D_n + S_n$ (psf)
F_b = the adjusted allowable bending design value (psi).

The allowable bending design strength, F_b, is calculated by taking the 5th percentile from the reference data, dividing it by the appropriate adjustment factor
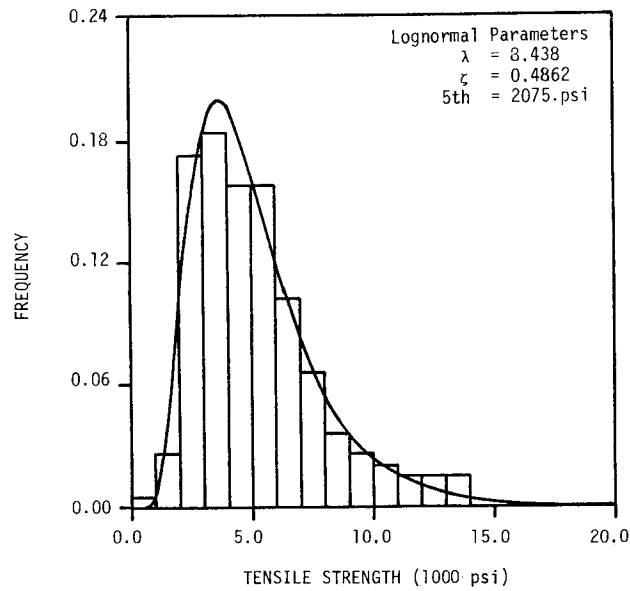
Fig. 3a. The ultimate tensile strengths parallel-to-grain of the control specimens are represented by the histogram. A lognormal probability distribution was found to be the best approximation.

(2.1 for both bending and tension), and multiplying it by 1.15, the duration of load factor for snow loads.

To preserve some consistency between design examples, this study assumes that the loads on both bending and tension members were due entirely to snow.
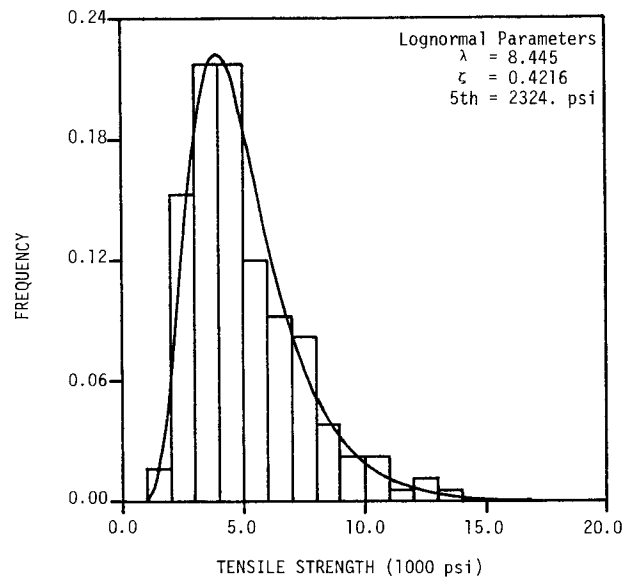

Fig. 3b. The ultimate tensile strengths parallel-to-grain of the single proof loaded specimens are represented by the histogram. A lognormal probability distribution was found to be the best approximation.
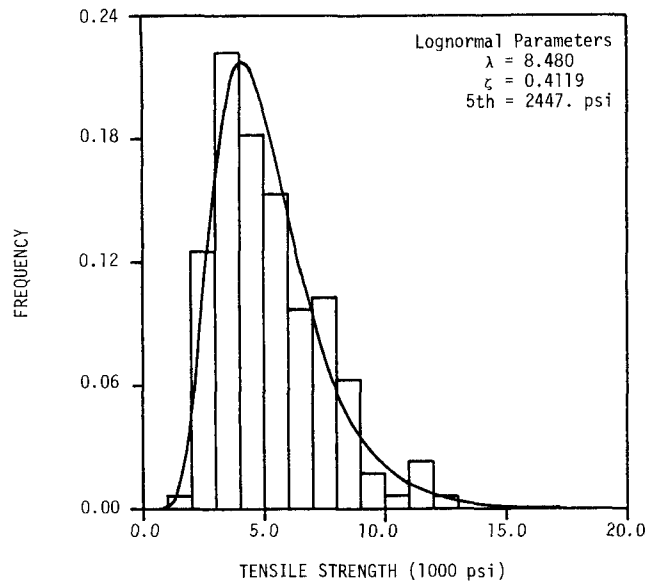
Fig. 3c.   The ultimate tensile strengths parallel-to-grain of the reverse proof loaded specimens are represented by the histogram. A lognormal probability distribution was found to be the best approximation.

Hence, the following load parameters are computed:

For bending: $\mu_T = 0.69(1.15/2.1)2{,}817 = 1{,}064$ psi
$\Omega_T = 0.44$

For tension: $\mu_T = 0.69(1.15/2.1)2{,}075 = 784$ psi
$\Omega_T = 0.44$.

Using the above parameters, it was possible to calculate probabilities of failure associated with each treatment sample. Figure 4 shows the load and resistance curves used in calculating P_f for the bending control group.

k-factors

Another concept used by Thurmond et al. (1984) in relating different treatments to some control group was that of k-factors. By definition, the k-factor is a number which each value of one property distribution is multiplied by to produce the same probability of failure as some specified benchmark property distribution. Thus, the k-factor is a shift factor that shows how far one property distribution must be shifted to give safety equal to that obtained with a reference property distribution. In this case, the benchmark P_f was obtained from the strength distributions of the control groups. Table 4 contains the probability of failure and k-factor results for the bending and tension samples. The single proof loaded sample yielded a k-factor of 0.88 if only a snow load is considered. Therefore, every value of the single proof load resistance distribution can be reduced by 12% and still yield a probability of failure that will not be higher than that obtained with the bending control sample.

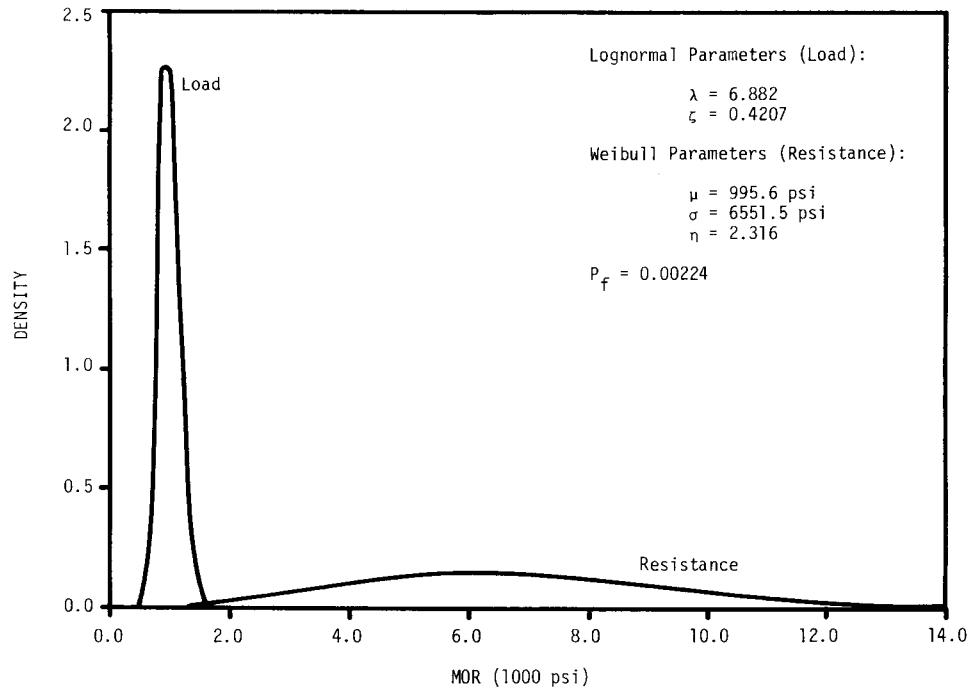To depict a more realistic loading condition, both dead load and live load were

FIG. 4. The load function and resistance function for the bending control lumber are illustrated. The distribution types and parameters are listed as well as the related probability of failure.

considered in another analysis of the bending groups. Such load combination applies to the top chord of a truss. Since the roof design would employ trusses instead of rafters, the $\bar{D}/D_n$ ratio computed by Thurmond et al. (1984) is not applicable. Assuming that the trusses are made of 2×4 No. 2 Dense KD Southern pine top chords and are spaced 2 feet on center with $\frac{1}{2}$-inch plywood sheathing and asbestos shingles, the dead load is 4.2 psf (Hoyle 1978).

TABLE 4. *Results of probabilistic analysis.*

Load type considered	Type	Member treatment	Probability of failure $(\times 10^{-3})$	k-factor	5th percentile ratio[1]
Snow	Bending[2]	CNTL-B	2.240	1.00	1.000
		SPL-B	1.110	0.88	0.948
		RPL-B	0.118	0.67	0.759
	Tension[3]	CNTL-T	1.890	1.00	1.000
		SPL-T	0.853	0.87	0.893
		RPL-T	0.610	0.82	0.848
Snow + dead	Bending[4]	CNTL-B	5.300	1.00	1.000
		SPL-B	1.230	0.83	0.948
		RPL-B	0.0114	0.58	0.759

[1] $\bar{X}_{0.05}$ control $\div$ $\bar{X}_{0.05}$ proof loaded.
[2] Load assumed lognormal with $\mu = 1,064$ psi and $\Omega = 0.44$.
[3] Load assumed lognormal with $\mu = 784.1$ psi and $\Omega = 0.44$.
[4] Load assumed lognormal with $\mu = 925.6$ psi and $\Omega = 0.34$.
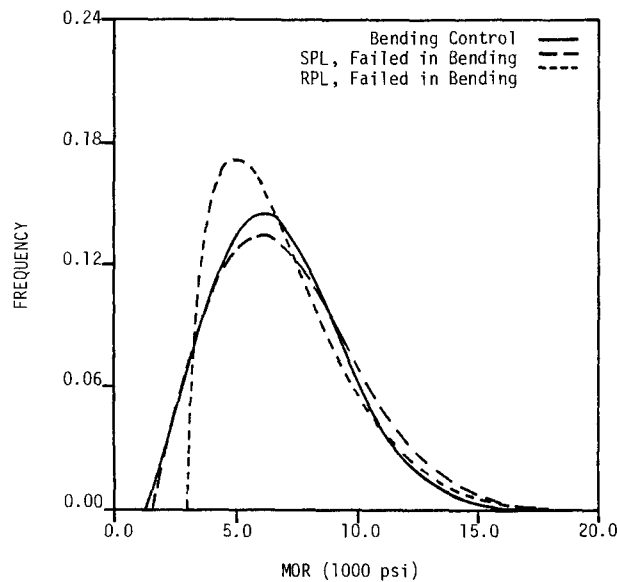
FIG. 5. The 3-parameter Weibull curves representing the MOR values for the bending control, single proof loaded, and reverse proof loaded specimens are seen to differ primarily in the lower tail. Differences in the average MOR for the treatments are noted.

Therefore, for the top chord of a truss with a 20 psf nominal snow load, the parameters for the load distribution are calculated using Eqs. (3) and (4), which results in a mean lifetime load of 926 psi and a coefficient of variation of 0.34. Since the normalized mean dead load was less than the normalized mean snow load (0.42 vs. 0.69), both parameters for the load distribution decreased. Hence, the resulting probabilities of failure for the bending groups were reduced (Table 4).

DISCUSSION OF RESULTS

The findings of this study support the idea that the application of bending proof loads to lumber, in this case 2 × 4 specimens, increases product quality of the survivors by eliminating weak pieces in the population. A single proof load had only a slight effect on the shape of the bending frequency distribution (Fig. 5). However, the lower tail of the reverse proof load curve is shifted noticeably to the right of the bending control curve. Also its dispersion is less than that of the control. The advantage of using a reverse proof load is further emphasized by comparing 5th percentile estimates for the three bending groups. The 5th percentile estimate of the single proof loaded group is only 5% higher than that of the control, but the 5th percentile of the reverse proof loaded lumber is 24% higher than that of the control group (Table 4).

Results for the application of a bending proof load to insure tensile strength given in Fig. 6 are less pronounced than was found for bending strength. Application of a single-proof load increased the 5th percentile tensile strength of the survivors about 10% (Table 4). Use of a reverse bending proof load increased the 5th percentile of the survivors about 15%.
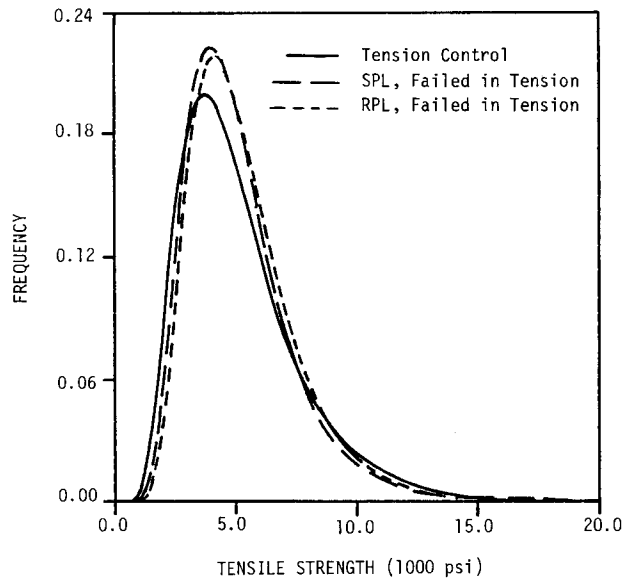
Fig. 6.   The lognormal curves representing the tensile strengths parallel-to-grain for the tension control, single proof loaded, and reverse proof loaded specimens are similar. A shift in the lower tails of the distributions is apparent.

Results for the reliability analysis of the bending members further emphasized the advantages of the reverse proof load over the single direction proof load. As previously noted, the application of only a live (snow) load provides consistency between the bending and tension resistances. For this loading situation, probability of failure was decreased by a factor of 2 using a single proof load but was decreased by a factor of about 20 if a reverse proof load was used (Table 4).

For tensile strength, the single proof load decreased P_f by a factor of 2 while a reverse proof load decreased P_f by a factor of about 3 (Table 4). Application of the more realistic snow plus dead load indicates that the probability of failure in bending is reduced by a factor of 4 for a single proof load, while the reverse proof load reduced P_f by a factor of over 400.

Fluctuations in strength of the lumber produced by a mill are a common occurrence and may be caused by a number of factors. For example, fluctuations in strength could result from variations in log quality, erroneous decisions during log breakdown, problems with the drying operation, or errors in the grading operation. Thus the practical implications of the reliability analysis are significant. Examination of the k-factors in Table 4 suggests that a mill using a reverse proof load to insure bending strength could suffer a 33% reduction in bending strength of every piece of lumber produced and still supply material having safety equal to that of non-proof loaded lumber. Inclusion of the dead load in the probability of failure calculation indicates that up to a 42% reduction in strength could be tolerated. These results are similar to those of Marin and Woeste (1981) who found that a reverse bending proof yielded a bending strength distribution with a probability of failure equal to that of the control sample even after a 27% reduction in strength of each piece.

A bending proof load also affects the reliability of tensile strength. Reliability analysis of tension members subjected to a reverse bending proof load shows that tensile values could suffer a 15% reduction and still maintain the same reliability as the control pieces.

It is sometimes argued that lumber should be proof loaded to the estimated 5th percentile of the population (2.1 times the design value for the particular grade-size combination). Comparison of the 5th percentile ratios given in Table 4 with the k-factors suggests that proof loading to the 5th percentile of the bending strength is overly conservative with respect to the reliability of the bending data. In all cases the k-factor for the bending data is much smaller than the 5th percentile ratio. Thus use of the 5th percentile as a guide to setting proof loads will cause more lumber to be broken in bending than is justified solely on the basis of reliability.

Note, however, that using the 5th percentile of the bending data to set proof load levels is not as conservative with respect to tensile strength as it is for bending strength. Here the difference between the k-factors and the 5th percentile ratios are much less than they were for bending (Table 4). If a bending proof load is to be used to insure tensile strength, it would appear necessary to use a higher proof load level than would be justified solely for the purpose of assuring bending strength. Similar results were obtained by Strickler et al. (1970) in their investigations of the use of proof loading to assure the quality of end-jointed lumber. They concluded that to obtain accurate assurance of design load "a proof load should . . . stress a member in the same mode in which it would be used in service."

CONCLUSIONS

From the results of this study we conclude:

1. Bending proof loads could be used in lumber grading to offset within-mill variations in lumber strength in tension parallel to the grain as well as in bending.
2. The use of a reverse bending proof load provides better assurance of product quality than does a single direction bending proof load.
3. No damage due to proof loading is apparent in surviving specimens failed in either bending or tension parallel to the grain.
4. When using a bending proof load to assure the tensile strength of lumber it is necessary to use a higher proof level than would be necessary to assure bending strength.

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