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ALLOWABLE BENDING STRENGTH ENHANCEMENT OF 2 BY 4 LUMBER BY TENSION AND COMPRESSION PROOFLOADING

Edwin L. Heatwole

Graduate Research Assistant
Agricultural Engineering Department
Virginia Tech, Blacksburg, VA 24061

Frank E. Woeste

Professor
Agricultural Engineering Department
Virginia Tech, Blacksburg, VA 24061

and

David W. Green

Engineer
U.S. Forest Products Laboratory
Madison, WI 53705

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ABSTRACT

Simple 5th percentile and reliability analysis methods were used to evaluate increases in allowable bending strength from proofloading in tension and compression. The analysis included the use of realistic load data for residential roof and floor trusses, and combined stress present in truss chords was given consideration as part of the reliability analysis. Proofloading in tension or in compression both produced significant increases in allowable bending strength for 2 by 4 1650f-1.5E hem-fir. Proofloading in tension to a target 15% breakage level, or 2,838 psi, yielded for the survivors an increase of 72% in allowable bending strength. The allowable bending strength increased 60% because of compressive proofloading to a target 15% breakage level. Since relatively small sample sizes were used, the results are not definitive but provide justification for a comprehensive study.

Keywords: Lumber, proofloading, proof test, bending, tension, compression, hem-fir, southern pine.

INTRODUCTION

The objective of the research was to determine the increase in allowable bending strength of lumber when proof-tested at various levels in tension and compression. Proof-testing or proofloading is a process of applying a load to a specimen with the purpose of ensuring the strength of the survivors is greater than a desired level. Any specimen not of the pre-set strength level will be broken and therefore

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excluded from the sample. By excluding the weaker specimens, the strength distribution of the remaining specimens will be shifted to the right and have less variance than the strength distribution for the initial sample.

Using differential reliability and the appropriate mathematical and statistical methods, the probability of failure for the proofloaded and the control lumber samples can be found and compared. When calculating the probability of failure, the lower tail of the strength distribution is of major concern. The impact of the variability of lumber strength on the probability of failure makes it important to utilize the best statistical tools available for the analysis of lumber properties.

LITERATURE

Damage concerns

The concern of damage due to proofloading is a valid one. In a publication by Freas (1949), he discussed the use of high proofloads on specimens of ladder stock. His conclusions made many skeptical of proofloading and caused a long delay in the research on proofloading to ensure strength levels. More recent research experiments shed valuable insight into the theory of why and when damage occurs.

Gerhards (1979) proposed a linear cumulative damage theory that relates to proofloading. The theoretical relation indicates that loads that do not cause failure may have little effect on residual strength. According to his theory, a very small percentage of the proofloaded boards may be weakened, and the remaining pieces will have a residual strength equal to their original strength.

More recent research on modeling wood damage accumulation from stochastic loads was conducted by Corotis and Sheehan (1986). Little significant damage accumulation occurred when using realistic structural designs and load models. In research by Gerhards and Link (1987), a ramp bending load was applied to specimens of 2 by 4 Douglas-fir and was held constant for a duration of 4.65, 33.9, and 220 days. Surviving specimens were loaded to failure in bending. All failed at ramp loads higher than the constant load, except for one specimen having a long, moderate slope-of-grain split. The results suggest little or no duration-of-load influence—a weakening due to loading history.

In an experiment using reverse proofloading in bending of lumber by Marin and Woeste (1981), 2 by 4 No. 2 Dense KD southern pine did not show any significant damage due to proofloading at the approximate fifth percentile, or 3,366 psi. In another experiment by McLain and Woeste (1988), 2 by 6 Dense Select Structural, No. 1 Dense, and No. 2 Dense KD15 southern pine were proofloaded in tension at 1.6, 1.8, and 2.0 times an adjusted allowable tension for the grades, respectively. In each case the adjusted allowable tension was the published F_t for the grade multiplied by 2.1 and also a fast test speed factor from McLain and Woeste (1986). That research resulted in the conclusion that damage in surviving lumber due to the proofload used was nonexistent or at worst minimal. Woeste et al. (1987) conducted a research experiment with 2 by 4 No. 2 Dense KD southern pine using both single and reverse bending proofloads. No damage due to the proofloading was detected.

Only relatively low levels of proofloading are currently used for commercial applications of lumber rating. Based on published research it is valid to assume there is no appreciable damage to surviving lumber due to proofloading in tension or bending at these low load levels.

Correlations of lumber strength properties

The correlation of lumber strength properties is difficult to measure since the determination of one strength property requires the entire piece to be tested to failure. When a specimen is broken in bending, the tensile strength parallel-to-grain cannot be measured for that specimen. Johnson and Galligan (1983) used a basic approach which depends upon identifying the correlation between the residuals in two regressions used to predict two strength properties from the same nondestructive MOE measurement. This approach utilized information gained from proofloading. The correlation between the residuals of bending and tension can be thought of as a conditional correlation between bending and tension. Because bending and tension cannot be observed on a single specimen, samples of 2 by 4 1650f-1.5E MSR hem-fir and No. 2 KD southern pine lumber were randomly subdivided so they could be tested in various failure modes and proof-load levels. One set each was tested exclusively in bending, tension and compression and the remaining sets were proofloaded in tension or compression with survivors failed in bending. Target proofload levels were set at 5 and 15% of the bending failure level.

EXPERIMENTAL

The study reported herein uses data from a report by Galligan et al. (1986) that characterizes the properties of 2-inch softwood dimension lumber with regressions and probability distributions. In that study, a machine stress rated (MSR) grade of 2 by 4 1650f-1.5E hem-fir and a visual grade of 2 by 4 No. 2 KD southern pine were chosen because they are common in house trusses. The hem-fir was collected at a production mill in the Cascade range of Washington and the southern pine in Oklahoma. The testing was done at Washington State University after moisture content stabilized to 12%, plus or minus 2%. For each species, selection was made at random to make uniform groups for predetermined testing. For each species, groups of 80 pieces were broken in bending, tension, and compression. Two groups of 120 pieces each for both species were proofloaded in tension with target breakages of 5 and 15%. Likewise, two groups of 120 pieces each for both species were proofloaded in compression with target breakages of 5 and 15%. The groups of 120 pieces were failed in bending after proofloading to estimate the correlation of lumber strength properties.

The same ten groups of lumber as described for the Galligan et al. studies (1986) were used as part of our bending strength enhancement study. The 80 piece lots from each species were broken in bending, and used to establish the bending strength distributions of the controls. These control groups and the four proof-loaded groups of each species were used to determine the effect of tension and compression proofloading on bending strength.

The data files were identified as follows:

CNBH—The control bending hem-fir.
T5H—Proofloading in tension at the target 5% breakage hem-fir.
T15H—Proofloading in tension at the target 15% breakage hem-fir.
C5H—Proofloading in compression at the target 5% breakage hem-fir.
C15H—Proofloading in compression at the target 15% breakage hem-fir.

TABLE 1. *Summary of the lumber groups used in the analyses listing the sample size, number and percent broken by proofloading and the number of remaining pieces broken in bending.*

	2 by 4 1650f-1.5E hem-fir				
	T5H	T15H	C5H	C15H	CNBH*
Sample size	120	120	120	120	80
Pieces broken in proofloading	9	16	10	29	—
Percent broken in proofloading	7.5	13.3	8.3	24.2	—
Remaining pieces broken in bending	111	104	110	91	—
	2 by 4 No. 2 KD southern pine				
	T5S	T15S	C5S	C15S	CNBS*
Sample size	120	120	120	120	80
Pieces broken in proofloading	8	18	6	16	—
Percent broken in proofloading	6.7	15.0	5.0	13.3	—
Remaining pieces broken in bending	112	102	114	104	—

* The bending controls were not proof tested.

CNBS—The control bending southern pine.
T5S—Proofloading in tension at the target 5% breakage southern pine.
T15S—Proofloading in tension at the target 15% breakage southern pine.
C5S—Proofloading in compression at the target 5% breakage southern pine.
C15S—Proofloading in compression at the target 15% breakage southern pine.

Table 1 is a summary of the lumber groups used in the analyses showing the total pieces in the group, the number and percent broken by proofloading, and the number of remaining pieces broken in bending.

ANALYTICAL PROCEDURE

Distribution selection

Lognormal and 3-parameter Weibull distributions were fitted to each data set to determine which distribution best describes the bending strength for each of the 10 groups of lumber. GDA, an automated goodness-of-fit package by Worley et al. (1990), was used to determine the adequacy of the fit for each data set. Since the time of our distributional analyses, improved goodness-of-fit methods for the 2- and 3-parameter Weibull have been reported by Evans et al. (1989). The distribution chosen as best describing the data was the 3-parameter Weibull distribution for each of the hem-fir groups and the lognormal distribution for each of the southern pine groups. Tables 2 and 3 give the parameters of the selected distributions.

Fifth percentile analysis

The fifth percentile value for each group of lumber was calculated from the distribution best representing the data. The following formulas yield the fifth percentile value for the 3-parameter Weibull and lognormal distributions:

3-parameter Weibull:

$$x_{0.05} = \mu + \sigma(\ln 0.05)^{1/\eta} \qquad (1)$$

TABLE 2. *Sample sizes of the hem-fir data from tension or compression proofloading. In each case the 3-parameter Weibull was selected over the lognormal.*

	2 by 4 1650f-1.5E hem-fir				
	T5H	T15H	C5H	C15H	CNBH
Sample size	111	104	110	91	80
Distribution selected	Weibull	Weibull	Weibull	Weibull	Weibull
Parameters					
Location, μ (ksi)	2.539	3.660	2.207	2.285	0.375
Scale, σ (ksi)	4.282	3.640	4.851	5.050	6.388
Shape, η	2.590	1.975	2.421	3.114	3.284

where:

μ = location parameter
σ = scale parameter
η = shape parameter.

Lognormal:

$$x_{0.05} = \exp[\lambda - 1.645\zeta] \tag{2}$$

where:

λ = scale parameter
ζ = shape parameter.

Loads

To determine probability of failure, appropriate load distributions must be calculated to be used with the resistance or strength distributions. Because the data base is from 2 by 4 lumber, which is routinely used in residential truss fabrication, residential housing loads were selected to use with roof and floor truss analyses.

Thurmond et al. (1986) recommended using three load cases. The following equations were used to determine the parameters of the distributions for the recommended load cases.

$$\mu_T = \frac{D_n}{T_n}(\bar{D}/D_n)F_b(LDF) + \frac{L_n}{T_n}(\bar{L}/L_n)F_b(LDF) \tag{3}$$

$$\Omega_T = \frac{\sqrt{(\mu_D\Omega_D)^2 + (\mu_L\Omega_L)^2}}{\mu_T} \tag{4}$$

TABLE 3. *Sample sizes of the southern pine data from either tension or compression proofloading. In each case the lognormal distribution was selected over the 3-parameter Weibull.*

	2 by 4 No. 2 KD southern pine				
	T5S	T15S	C5S	C15S	CNBS
Sample size	112	102	114	104	80
Distribution selected	LN	LN	LN	LN	LN
Parameters					
Scale, λ (ksi)	1.233	1.392	1.459	1.412	1.353
Shape, ζ	0.394	0.323	0.345	0.339	0.379

where:

μ_T = mean total lifetime load, psf
Ω_T = coefficient of variation of the total lifetime load
D_n = nominal dead load, psf, design value
L_n = nominal live load, psf, design value
T_n = total nominal load ($D_n + L_n$), psf
$\bar{D}/D_n$ = normalized mean of the dead load distribution
$\bar{L}/L_n$ = normalized mean of the maximum lifetime live load distribution
μ_D = mean dead load
Ω_D = coefficient of variation of the dead load
μ_L = mean maximum lifetime live load
Ω_L = coefficient of variation of the live load
F_b = allowable normal duration bending stress
LDF = load duration factor.

To derive F_b, the fifth percentile of the data from the ten-minute tests were divided by 1.6 to convert to a ten-year normal duration and 1.3 to provide for safety. The product of these adjustments is the more familiar 2.1 adjustment factor that can be found in ASTM D245-88 (ASTM 1989).

Recommended ratios of mean to nominal values of snow load and floor live loads from Thurmond et al. (1986) were used in this research and are reported in Table 4. Two floor live load cases are needed due to uncertainty in the load information. In addition to these load ratios, the ratio of mean dead load to nominal dead load must be determined for each application. The coefficient of variation of the dead load was assumed to be 0.10 as suggested by Thurmond et al. (1986).

The total lifetime load is equal to the sum of two random variables, live plus dead. For reliability comparisons, Thurmond et al. (1984) found the resulting distribution to be approximated by the lognormal distribution due to the lognormal snow load having a large coefficient of variation and the assumed lognormal dead load having a relatively small coefficient of variation. Likewise, for Extreme Value Type I live loads and lognormal dead loads, the resulting distribution was found to be approximated by the Extreme Value Type I distribution.

For these analyses, the mean dead loads are calculated using a "typical" residential construction. The results are shown in Table 5, where the mean dead load for the top and bottom chords is calculated as ½ the total truss weight. The pad and carpet weight was calculated for a 12-oz pad and a carpet with total weight of 45 oz per square yard. Lumbermate (1983) and Lumbermate (1986) along with the American Institute of Timber Construction (1985) were used for most weight estimates.

Timber Truss Housing Systems, Inc. of Roanoke, Virginia, provided seven single-story residential floor plans ranging from 950 to 2,600 square feet for use in determination of the dead weight due to interior walls. The average of the seven residences contained 96 linear feet of wall per 1,000 square feet of space. For interior walls with 24" o.c. studs weighing 1.3 psf, plus gypsum board weighing 2.0 psf on each side, the total wall weight is calculated at 5.3 psf of wall area. Translating the 5.3 psf to floor area, an average value of 4.1 psf was calculated for "typical" residential housing.

TABLE 4. *Recommended snow and floor live load distributions for the reliability analyses of lumber properties data from Thurmond et al. (1986).*

Load	Distribution	$\bar{x}/x_n$	Ω_x
Snow	Lognormal	0.69	0.44
Load A	Extreme Value Type I	0.94	0.21
Load D	Extreme Value Type I	0.73	0.19

Load calculation demonstration

The control fifth percentile for hem-fir and a 20-10-10 loading on a 4/12 W-truss were used to determine total lifetime load parameters. The following values were used in Eqs. 3 and 4 for calculating μ_T and Ω_T for the roof truss top chord.

$$F_b = 2.96/2.1 = 1.41 \text{ ksi}$$
$$D_n = 10 \text{ psf}, \quad S_n = 20 \text{ psf}, \quad T_n = 30 \text{ psf}$$
$$\bar{D}/D_n = 5.3/10 = 0.53 \text{ from Table 5}$$
$$\bar{L}/L_n = 0.69 \text{ from Table 4 for snow loads}$$
$$LDF = 1.15 \text{ for snow loads.}$$

The appropriate load for the roof truss top chord was lognormal with parameters μ_T equal to 1.033 ksi and Ω_T equal to 0.319. The values for southern pine were computed in the same way as those for hem-fir; only the fifth percentile value was 2.07 ksi and thus F_b equals 0.986 ksi. These load distributions were used with the control bending strength distributions to determine a benchmark probability of failure for each species. The proofloaded bending strength distributions were then used with the same load distributions to compare with the benchmark probability of failure.

TABLE 5. *The dead loads calculated for a residential roof and floor system.*

Roof truss top chord		
2 × 4 top chord	1.3 psf	
½ inch plywood	1.5 psf	
235# asbestos shingles	2.5 psf	
Total	5.3 psf	Nominal = 10 psf
Roof truss bottom chord		
2 × 4 bottom chord	1.3 psf	
½ inch gypsum board	2.0 psf	
6 inch glass wool insulation	1.8 psf	
Total	5.1 psf	Nominal = 10 psf
Floor truss top chord		
2 × 4 top chord	1.3 psf	
¾ inch T&G plywood	2.3 psf	
Pad and carpet	0.4 psf	
Interior walls	4.1 psf	
Total	8.1 psf	Nominal = 10 psf
Floor truss bottom chord		
2 × 4 bottom chord	1.3 psf	
½ inch gypsum board	2.0 psf	
Total	3.3 psf	Nominal = 5.0 psf

Reliability method

The probability of failure can be defined mathematically by a double integral when the load and strength distributions are continuous and mutually independent as

$$p_f = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{s} f_R(r)\, dr \right] f_s(s)\, ds \quad (5)$$

where:

$f_R(r)$ = the probability density function of the resistance distribution
$f_s(s)$ = the probability density function of the load distribution.

When the double integral of $f_R(r)$ and $f_S(s)$ cannot be solved using standard integration methods Eq. 5 can be evaluated using numerical techniques. After finding the probability of failure for the control with a predetermined load, the parameters of the proofloaded groups were adjusted by a K factor until a similar probability of failure was found. This procedure was named *differential reliability* by Suddarth et al. (1978). Computer programs used to solve for the K factors were from Thurmond (1982). This K value is then used as a measure of the possible increase in design value to maintain the same reliability.

Impact of combined stress in truss chords

When analyzing a truss chord, a combination of stresses will be present. For example, bending and tension stresses are present in the lower chord of a roof or floor truss under gravity loads. The issue is how the combined stresses will affect reliability analyses of lumber properties.

The bending stress contribution to the combined stress index (CSI) in the chords of a floor truss can be found using research from Suddarth et al. (1981). A "typical" parallel floor truss, shown in Suddarth et al. (1981), was used to determine the percent of the CSI value attributed by bending stress. Under a 40-10-5 psf loading, the floor truss 2 by 4 top chord analyzed had a bending stress contribution of 0.133 or 15.0% of the CSI value for the top chord. Likewise, under 40-10-5 psf loading, the floor truss bottom chord had a bending stress contribution of 0.074 or 7.0% of the CSI value.

In a typical 4/12 W-truss under 20-10-10 psf loading, 55% of the stress interaction, CSI, will be contributed by bending stress for the top chord (Heatwole 1988). For the bottom chord of the same truss and loading, 50% of stress interaction was contributed by bending stress.

The partial loads were used in the reliability analyses of the lumber data to determine an additional set of K factors. The K factors from the partial loads were expected to be smaller than those where full bending loads were used based on previous research experiences where lumber comparisons of this type were made (Suddarth et al. 1978). When evaluating the increase of bending strength due to proofloading, the largest K factor was selected to provide the most conservative bending stress increase.

RESULTS AND DISCUSSION

Among several methods available for evaluating the impact of proofloading on design values, we used the simple method of comparing fifth percentiles and a

TABLE 6. *Summary of the fifth percentile results for both hem-fir and southern pine. The ratio indicates the increase in 5th percentile over the control as a result of proofloading.*

	2 by 4 1650f-1.5E hem-fir				
	T5H	T15H	C5H	C15H	CNBH
Fifth percentile, ksi	3.90	4.47	3.63	4.23	2.96
Ratio of the fifth percentile to control	1.32	1.51	1.23	1.43	
	2 by 4 No. 2 KD southern pine				
	T5S	T15S	C5S	C15S	CNBS
Fifth percentile, ksi	1.79	2.36	2.43	2.35	2.07
Ratio of the fifth percentile to control	0.86	1.14	1.17	1.13	

more involved reliability-based method. Both methods are subject to sampling error. The fifth percentile method has the advantages of ease of computation and inherent credibility due to the historical precedent of stresses being derived from the fifth percentile point of the population. The reliability method is computationally more difficult, but it is likely to provide a more accurate evaluation of the proofloading impact.

Increase in the 5th percentile values by proofloading

The fifth percentile value for each proofloaded case was compared to the control fifth percentile value. Table 6 is a summary of the fifth percentile values for both hem-fir and southern pine grades. Since allowable bending stresses are based on the fifth percentile, these results imply that the NDS specified bending strength value for 1650f-1.5E hem-fir could be increased 32% provided the lumber was proof-tested to 2,611 psi in tension as was the T5H case. It should be noted the 32% increase is one estimate, subject to sampling error since it was found from the ratios of two fifth percentile estimates from small samples, sizes 80 and 111.

All proofloading cases for hem-fir showed an increase in bending strength over the control. As both tension and compression proofloading levels were increased, the fifth percentile of the bending strength also increased. The largest bending strength increase for hem-fir was a 51% increase due to tension proofloading for the T15H case. The smallest bending strength increase was a 23% increase due to compression proofloading for the C5H case.

The No. 2 KD southern pine results were not as consistent, in that increasing the proofload level in either tension or compression did not always increase the bending fifth percentile. For example, the control sample CNBS had a fifth percentile value greater than the fifth percentile value for the T5S case. Also, the C15S case had a fifth percentile value less than the fifth percentile value for the C5S case, the reverse of what would be expected.

The lack of a uniform trend between the proofloading and the resulting fifth percentile values could be due to the greater variability of southern pine population sampled interacting with small sample size. The bending strength coefficient of variation for the control No. 2 KD southern pine was 0.406 versus 0.310 for the 1650f-1.5E MSR hem-fir. For a given sample size, the sampling error of the fifth percentile estimate generally increases with increasing variance of the underlying

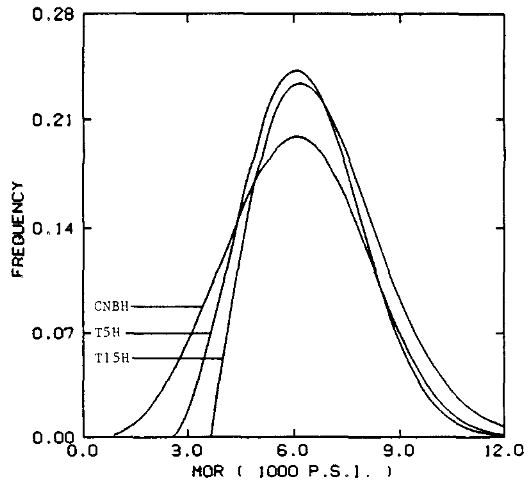

FIG. 1. Hem-fir bending strength distributions for control and tension proofloading at the 5 and 15% levels. CNBH = Control bending distribution; T5H = Bending distribution resulting from proofloading in tension to a 5% target breakage; T15H = Bending distribution resulting from proofloading in tension to a 15% target breakage.

population. Thus for the southern pine, the sampling error of the fifth percentile could have dominated over the proofloading effect on bending strength.

Increase in design strength by proofloading: reliability method

Hem-fir results.—The reliability method of analysis was used for each control and proofloaded case. Figure 1 compares graphically the distributions from the hem-fir data control and tension proofloading treatments. The left tails of the tension proofloaded cases were shifted to the right of the control, with the greatest shift being associated with the largest proofload level. Likewise, Fig. 2 shows the hem-fir distributions for the control and compression proofloading cases. The left tails of the compression proofloads were also shifted to the right of the control, in a way similar to the tension proofload cases. The results from the southern pine were mixed, again suggesting sampling error.

Probabilities of failure and K factors were found using a full bending stress load where the total loads were lognormal or Extreme Value Type I as given by column 1, Table 7. The bending strength data from the control and proofloaded samples were adjusted for load duration by dividing the test machine data by 1.6 to convert to a normal duration of 10 years. The K factor results are summarized in Table 7.

The benchmark probability of failure for the roof truss top chord was found using the lognormal load distribution having parameters μ equal 1.032 ksi and Ω equal 0.319. The resulting probability of failure was 0.501×10^{-2} for the roof truss top chord case, first row of Table 7. The roof truss top chord K factors were found using the same load distribution parameters as for the benchmark case. Simply stated, for the first entry of the table, by multiplying the bending strength values from the T5H proofloading treatment by 0.645 yielded a probability of failure equal 0.501×10^{-2} when using the same load as with the CNBH case.

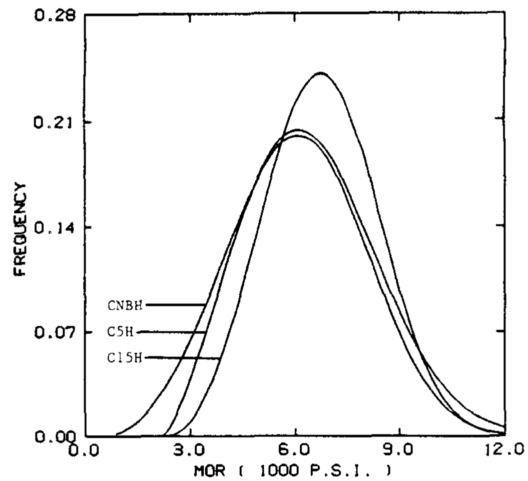

FIG. 2. Hem-fir bending strength distributions for control and compressive proofloading at the 5 and 15% levels. CNBH = Control bending distribution; C5H = Bending distribution resulting from proofloading in compression to a 5% target breakage; C15H = Bending distribution resulting from proofloading in compression to a 15% target breakage.

Each resulting distribution from proofloading is shifted on the x-axis by a K factor to yield a similar probability of failure.

The MSR 1650f-1.5E hem-fir results show that as proofloading levels were increased in tension or compression, the allowable bending strength also increased. For MSR hem-fir lumber as few as 80 specimens appeared adequate to estimate the increase in allowable bending strength due to tension or compression proofloading. However, 200 specimens would be a more appropriate sample size for allowable stress or fifth percentile determination.

The percentages of bending stress contribution to the CSI value for the top and bottom chords were used to calculate a percentage of the total load to be used with each proofload case. When using only a percentage of the total load, the K factors all decreased as anticipated. In each case a lower K factor, which represents a greater shift on the x-axis, was required to yield the same probability of failure as the control.

TABLE 7. *Differential reliability-based analysis of increases in design strength for hem-fir. Reference probability of failure for the control group and K factors for the proofloaded groups are listed for each loading case. 1/K is a measure of the increase in bending design strength by proofloading.*

	2 by 4 1650f-1.5E hem-fir				
	T5H	T15H	C5H	C15H	CNBH
Load case	K factor	K factor	K factor	K factor	p_f
Roof top chord LN(1.032, 0.319)*	0.645	0.560	0.695	0.600	0.501×10^{-2}
Roof bottom chord LN(0.827, 0.10)	0.435	0.345	0.495	0.430	0.106×10^{-2}
Floor load A EVTI(1.288, 0.174)**	0.670	0.580	0.725	0.625	0.148×10^{-1}
Floor load D EVTI(1.051, 0.15)	0.590	0.500	0.650	0.560	0.626×10^{-2}
Floor bottom chord LN(0.930, 0.10)	0.520	0.420	0.585	0.505	0.344×10^{-2}
Minimum 1/K value	1.49	1.72	1.38	1.60	

* LN(μ, Ω) specifies a lognormal distribution with mean, μ, and coefficient of variation, Ω.
** EVTI(μ, Ω) specifies an Extreme Value Type I distribution with mean, μ, and coefficient of variation, Ω.

TABLE 8. *Differential reliability-based analysis of increases in design strength for southern pine. Reference probability of failure for the control group and K factors for the proofloaded groups are listed for each loading case. 1/K is a measure of the increase in bending design strength by proofloading.*

	2 by 4 No. 2 KD southern pine				
	T5S	T15S	C5S	C15S	CNBS
Load case	K factor	K factor	K factor	K factor	p_f
Roof top chord LN(0.722, 0.319)*	1.165	0.855	0.835	0.865	0.219×10^{-2}
Roof bottom chord LN(0.578, 0.10)	1.195	0.775	0.790	0.805	0.289×10^{-4}
Floor load A EVTI(0.901, 0.174)**	1.170	0.860	0.840	0.870	0.822×10^{-2}
Floor load D EVTI(0.735, 0.15)	1.175	0.835	0.825	0.850	0.171×10^{-2}
Floor bottom chord LN(0.651, 0.10)	1.180	0.800	0.805	0.830	0.388×10^{-3}
Minimum l/K value	0.84	1.16	1.19	1.15	

* LN(μ, Ω) specifies a lognormal distribution with mean, μ, and coefficient of variation, Ω.
** EVTI(μ, Ω) specifies an Extreme Value Type I distribution with mean, μ, and coefficient of variation, Ω.

The structural design process requires a conservative choice for design values when more than one outcome is present. For purposes of defining a permissable increase in allowable bending stress due to a tension or compression proofloading treatment, the larger K factor from each proofloading case must be chosen since the reciprocal of K is the amount by which the F_b value can be increased for the proof tested lumber.

Southern pine results

Table 8 is a summary for 2 by 4 No. 2 KD southern pine showing the benchmark probability of failures for the control and the K factors for the proofloaded cases under roof and floor loads. The K factor for the T5S case is larger than 1.0 indicating the allowable bending strength for the T5S case was less than the control. The C15S case had a K factor greater than the C5S case. Thus, the increased compression proofloading level for the C15S case did not produce bending strength improvements above the C5S case. The lack of a trend between the proofloading level and K factors indicates that variability, coupled with small sample size, probably resulted in sampling error that dominated over the strength benefiting effect of proofloading in both tension and compression. Thus, based on the visual grade of 2 by 4 No. 2 KD southern pine, 80 specimens was clearly inadequate. A sample size of 200 may be adequate, however, there is no assurance of useful results even with 200.

SUMMARY AND CONCLUSIONS

The purpose of this study using the Galligan data was to identify an improvement in bending strength from tension or compression proofloading, due to the correlations that exist between tension and bending, and between compression and bending. Based on the concept of equal reliability, realistic dead loads for residential trusses, and load distributions from Thurmond et al. (1986), the bending strength distributions of tension and compression proofloaded lumber samples were compared to controls. The control strength distributions were established for each grade by testing samples to failure in bending, and the data were subsequently used to establish a benchmark probability of failure. Using a K factor adjustment, the bending strength distributions of the proofloaded samples were shifted on the x-axis until a probability of failure approximately equal to the benchmark probability of failure resulted. The K factor, therefore, became a direct indicator of a possible increase in the bending design value due to proofloading.

Both fifth percentile and reliability methods were used to analyze the data. The fifth percentile values were calculated for the controls and each proofloading case. The hem-fir fifth percentile values for the proofloading cases were greater than the control fifth percentile, and the difference between the proofloading cases and control increased as the proofloading levels increased. The southern pine fifth percentile analysis of bending strength improvement from tension proofloading and compression proofloading produced mixed results that indicated a sampling problem, probably a combination of small sample size and high variability.

The reliability method utilized the three load distributions recommended by Thurmond et al. (1986). The hem-fir grade showed a significant increase in allowable bending strength due to the proofloading in both tension and compression, with additional increases as the level of proofloading was increased. Using the most conservative loading case from an implementation standpoint, proofloading in tension at the target 5% level of breakage resulted in a 49% increase in allowable bending strength. At the target 15% breakage level, a 72% increase in allowable bending strength resulted. Compressive proofloading at the target 5% breakage level provided a 38% increase in allowable bending strength, and at the target 15% breakage level, a 60% increase in allowable bending strength was realized.

The reliability method gave mixed results for the southern pine data as did the fifth percentile analysis. Increasing the proofload level in either tension or compression did not always increase the allowable bending strength. It is believed that the sampling error for southern pine dominated over the effect of proofloading on the bending strength, causing the mixed results. Because of the mixed results with the visually graded southern pine, sample sizes of at least 200 are recommended for future research.

The increase in bending strength due to proofloading was not well defined by this study, but encouraging results provide justification for a comprehensive study. Also, profitable applications of proofloaded lumber should be explored.

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