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Evolution of Tensile Design Stresses For Lumber

Abstract

Until approximately 1965, allowable design stresses for lumber in tension were taken as equal to those assigned for bending. As interest in tensile properties increased, testing machines were designed specifically to stress lumber in tension. Research results that accumulated on tensile tests of full-size lumber suggested lower design stresses for tension than for bending for both machine stress rated and visually graded lumber. The latest change for visual grades, based on a review of research data available up to 1977, was a reduction in design tensile stresses that varied by size and grade.

KEYWORDS: tension, tensile strength, allowable design stresses, visual grading, machine grading, lumber

Evolution of Tensile Design Stresses[1] for -

By
WILLIAM L. GALLIGAN, Engineer
C. C. GERHARDS, Engineer
R. L. ETHINGTON, Forest Products Technologist [2]

Forest Products Laboratory,[3] *Forest Service*
U.S. Department of Agriculture

Introduction

An accumulation of research studies on tensile properties of full-size lumber led to review in 1976 by the National Forest Products Association (NFPA) and the American Lumber Standard Rules-writing agencies of the tensile design properties assigned to lumber by ASTM procedures. The review suggested reductions which were instituted in the spring of 1977 by all agencies writing lumber grading rules under the Voluntary Product Standard 20-70 (27).[4]

The reduction in allowable stress had a profound effect on design, particularly in long-span industrial and farm-type structures using metal-plate trusses. Span reductions of over 20 percent were often required with 2 by 8 bottom cords; designers and fabricators searched for alternative designs to meet market needs (6).

Research results, such as those reviewed by NFPA, constantly flow into the marketplace; many, however, may influence only a small segment of the market or appear to be of an evolutionary nature. It is less common for an accumulation of research knowledge to lead to a massive change in the description of a product. Such a change is very noticeable, however, where, as in the case of the tension stresses for lumber, the product affected is a nationally recognized commodity item.

The purpose of this paper is to outline the historical development of tensile stresses for lumber, with particular emphasis on both current research and background for recent changes.

Historical Overview

Throughout the world, the tensile stress assigned to lumber for design purposes until about 1965 was taken as equal to the assigned bending stress. This procedure was usually thought to be conservative because strength of small, clear, straight-grained pieces of wood in tension was invariably shown to be greater than for clear wood in flexure (26). Research emphasis was placed on evaluation of tensile characteristics of wood during World War II, coincident with use of wood in aircraft (28). This, however, also dealt principally with clear, straight-grained wood, often of relatively small sections, for which the acknowledged relationship between bending and tension of clear wood was a reasonable premise for evaluation. Perhaps the earliest attempt to relate tensile strength of lumber to the measured tensile strength of small, clear, straight-grained specimens was by Ylinen (30). Others have more recently made similar attempts (4,22). It has become evident, however, that full-size lumber must be evaluated to estimate the efficiency of grading systems such as machine grading and to relate to evolving engineering design concepts.

Tension Testing Methods for Lumber

Testing of lumber in tension was a challenge because it is difficult to grip specimens having a ratio of compression perpendicular strength to tensile strength of roughly 1 to 20; the low

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[1] Presented at the 1978 Summer Meeting of the American Society of Agricultural Engineers, Utah State University, Logan, Utah.

[2] Currently Director, Forest Products and Engineering Research Staff, Forest Service, Washington, D.C.

[3] Maintained at Madison, Wis., in cooperation with the University of Wisconsin

[4] Underlined numbers in parentheses refer to literature cited at end of this report.

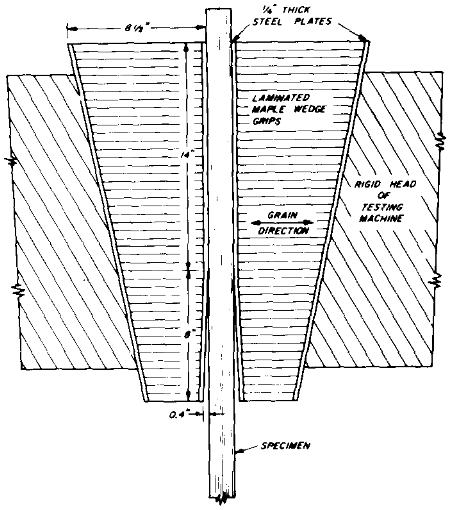

Figure 1. — An illustration of tensile grips designed by Bohannan (5) to reduce crushing perpendicular to grain, especially at the leading edge.
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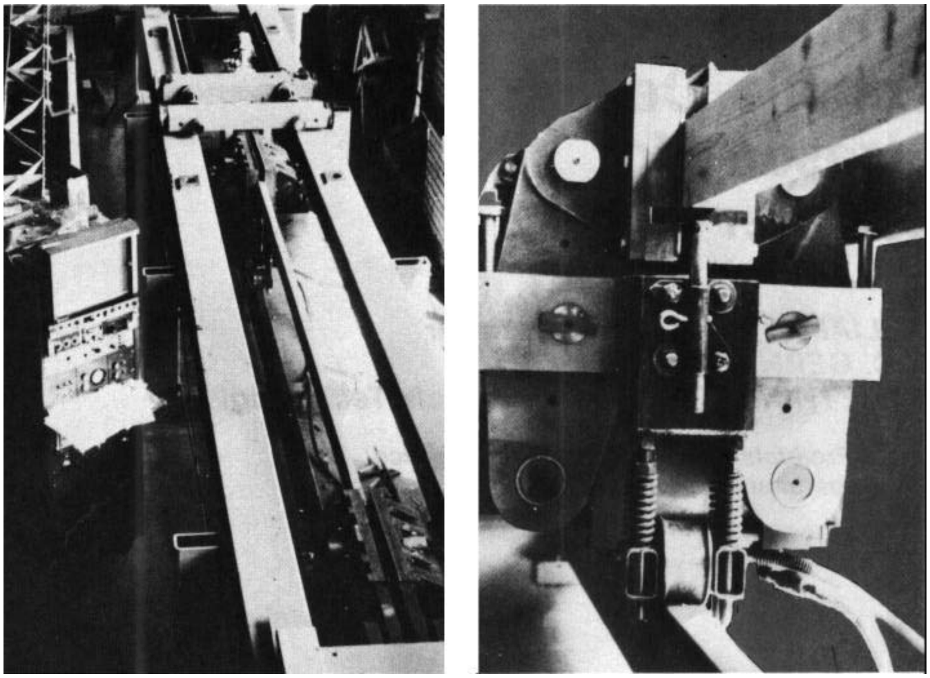

Figure 2. — Overview of Washington State University tension testing machine (left), with polyurethane grip faces engaging a 2 x 6 specimen (right).
M 147 153-3 M 747 153-2

crushing strength of wood across the grain requires gripping a very large area of specimen (11), adding wood to the ends of the specimen by gluing (30), or removing wood from between the gripped ends of the specimen by machining (24). Failure to grip properly often resulted in the ends of the specimen being crushed until it slipped out of the grips or until a tension failure occurred that was obviously affected by the crushed fibers at the leading edge of the grips. Gripping a large area leaves little of the specimen free to be tested. Gluing on additional wood or machining off some of the wood increases the cost of specimen preparation. Much early tensile testing of structural-size lumber was done in universal type testing machines; wedgegrips (20,30) and bolted-on grips (11) were used.

In one of the earliest efforts, Bohannan (5) developed grips with the leading edge relieved (fig. 1). This arrangement reduced the stress-riser at the leading edge. This was found satisfactory for most grades of lumber of nominal 1- or 2-inch thickness; yet, very high quality lumber sometimes failed at the grips due to excessive crushing. McGowan (16) developed a different gripping method where wedge grips were not permitted to tighten indefinitely. A similar version of a wedge-type grip was developed at Oregon State University (11). A modification introduced by the Weyerhaeuser Company employed multiple hydraulic cylinders to vary pressure within the grip area. A more recent development by Pellerin at Washington State University uses a polyurethane grip face with a high coefficient of friction (13), permitting a somewhat simpler grip design and resulting in very few compression failures (fig. 2).

Most testing laboratories do not have universal testing machines that will handle lumber more than a few feet long. Furthermore, universal testing machines almost always require that lumber be tested in a vertical orientation which is inconvenient for axial loading. Consequently, many laboratories that make tension tests of lumber have built special horizontal machines that are easily accessible. At least eight laboratories in North America are now equipped to do tensile testing of structural lumber. A standard ASTM test method has been published (1). Nevertheless, few of the existing machines operate with the same mechanical arrangements for grip fixity or support. Bohannan (5) noted the concern for induced bending moment in a tensile test through knots or local cross grain. Orosz (21) later illustrated the possible effect of different grip fixity on apparent tensile strength as related to this induced bending moment (fig. 3).

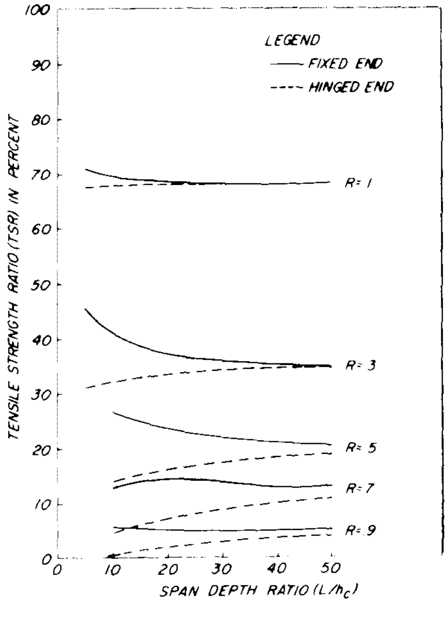

Figure 3. — Relationship between predicted tensile strength ratio TSR and span-depth ratio for various edge knot sizes expressed as a fraction R of the width (depth of the piece (21). The edge knot is placed at one-fifth the distance between the grips.
M 141 247

Tensile Strength of Visually Graded Lumber

The onset of full-size lumber tests began to clarify differences between small, clear-wood, tensile properties and full-size lumber graded for commercial use. Yet progress was slow because of the general lack of machines and the reluctance to make changes in accepted properties with incomplete data. Major early studies included Doyle and Markwardt (8) with southern pine, McGowan (17) with Douglas-fir, Nemeth with Douglas-fir and white fir (20), and Schniewind and Lyon (22,23) with redwood. These studies provided evidence that the tensile allowable stress for visual grading should be less than the allowable stress in bending. As a consequence, the ASTM Subcommittee on Lumber established a reduction factor of 0.55 to relate tensile allowable stress to bending allowable stress in the 1968 version of ASTM D 245 (2) with the implication that further data would be forthcoming. Because there was a well-established size effect in bending but not in tension, the 0.55 factor was to be applied to bending stresses before any adjustment for size was made.

No size effect in tension was assumed in the early development of the ASTM treatment of allowable stresses. The literature permitted only a crude comparison. There was no careful matching of quality of specimens from one size to another in any of the studies cited. It was assumed that if there were a size effect, it was masked by the within-grade variation that occurred in the samples. Yet the Doyle and Markwardt study (8) suggests a 12 percent reduction from 2 by 4 to 2 by 8 at the No. 1 grade level. The limited data by Foslie and Moen illustrated a 16 to 20 percent lower tensile strength for 3 by 8 than for 2 by 4 (9). The Schniewind and Lyon data of 1971 (22,23) suggested a 16 percent reduction on the average from 2 by 6 to 2 by 10. Clearly more research was needed.

By the mid-1970's, size and grade effect data were accumulating. Kunesh and Johnson suggested in 1974 that tensile strength decreased with size, based on comparisons of 2- by 4-, 6-, and 8-inch Douglas-fir and Hem-fir using their new horizontal tension machine with wedge grips (12). This lumber was clear and some of the size effect trends were not statistically significant. The same investigators reported in 1975 on the tensile strength of special Douglas-fir and Hem-fir 2-inch dimension selected with specific knot sizes. in center and edge locations (10). This research was based on a comprehensive sample set, thus clarifying the earlier observations on the existence of size effect for lumber. Lumber of greater width and with larger knots demonstrated significantly lower tensile strength (fig. 4 and 5).

McGowan et al. (18) compared the tensile strength of western hemlock and Pacific silver fir of grades Select Structural, No. 1 and No. 2, and western spruce and lodgepole pine of Select Structural, No. 1, No. 2, and No. 3. Both 2 by 4 and 2 by 8 were examined. Trends of decreasing average strength with grade were evident for 2 by 4 (fig. 6) and less so for 2 by 8. In view of the variability within a grade, trends shown by mean value may not be the same as these exhibited by near-minimum values. Cumulative frequency

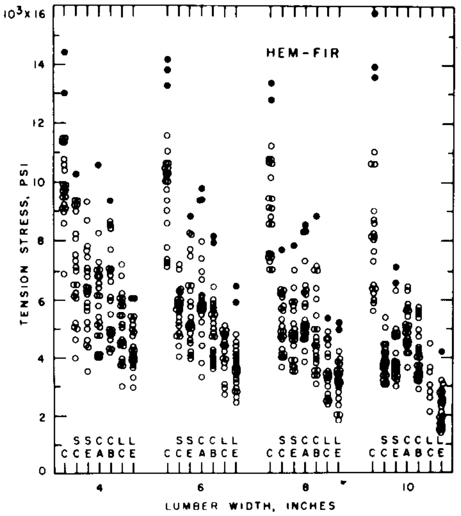

Figure 4. — Distributions of tension stress obtained from tests of nominal 2- by 4-, 6-, 8-, and 10-inch Hem-fir dimension lumber at 10 percent moisture content. Code for samples: C, clears; SC, small center; SE, small edge; CA and CB, knot combinations A and B; LC, large center; and LE, large edge knots. (10). (M 148 041)

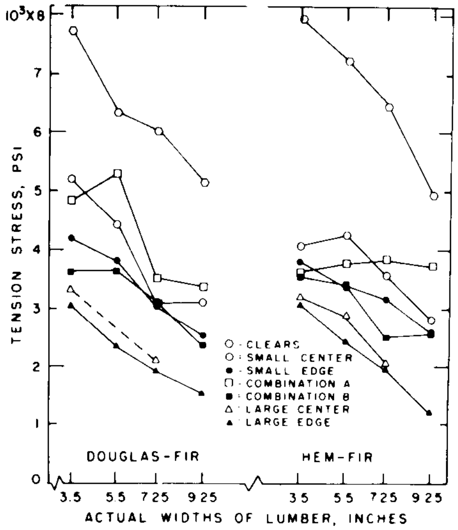

Figure 5. — Tension stress values at the lower 5 percent exclusion limit for the categories of knots for Douglas-fir and Hem-fir 2-inch dimension lumber. Plotted points were calculated from adjusted distributions in which some of the greater test values were not included. (10). (M 148 042)

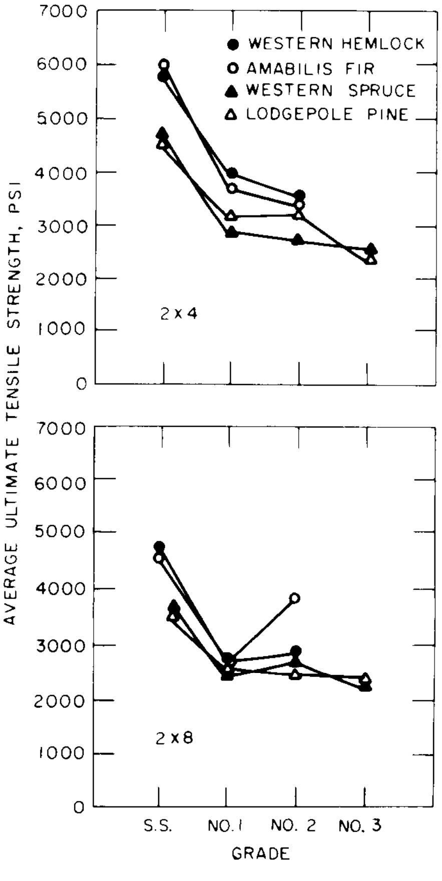

Figure 6. — Average ultimate tensile strength in relation to species and grade for nominal 2- x 4-inch and 2- x 8-inch lumber (18). (M 148 044)

distributions were used to illustrate the difficulty of generalizing (fig. 7). Examination of the data summaries suggests that within grade level these differences may be directly influenced by differences in knot size distribution between species. This study illustrates that even as we learn more of the science of tensile strength and influencing factors, translating this information to practical grading procedures and design factors is not easy, especially across many combinations of size, grade, and species.

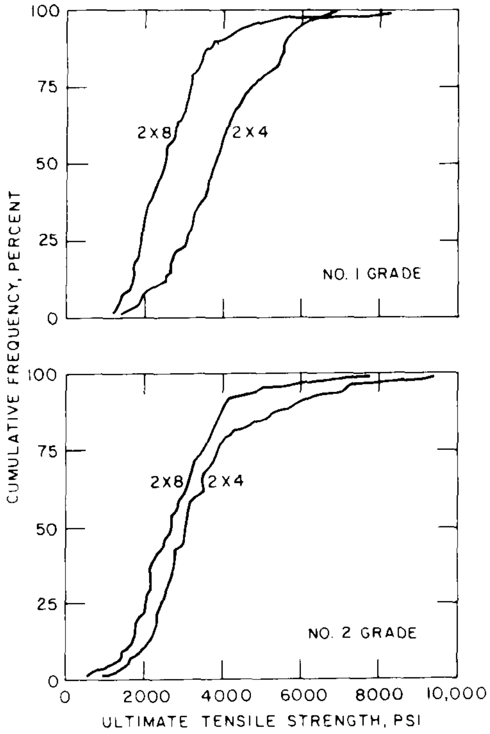

Figure 7. — *Cumulative distribution of ultimate tensile strength for No. 1 and No. 2 grades of 2- x 4- and 2- x 8-inch western hemlock (18).*
(M 148 045)

Tensile Strength of Machine Graded Lumber

McKean and Hoyle at the Potlatch Corporation (19) reported in 1964 on tests of the early machine grades of lumber, resulting in the recommendation that the allowable stress in tension for machine grades be set at 80 percent of the bending stress. The McKean and Hoyle recommendation was supplemented by a series of tests reported by Littleford in 1967 and 1969 (14,15). The latter illustrate the effect of visual restrictions added to grade rules — visual edge knot restrictions added to the E criteria increased exclusion level stresses an average of 28 percent in simulated E grades. Subsequently, tension stresses for MSR were linked to allowable bending properties on a sliding scale (29). The relationship used today under the American Lumber Standard (27) for machine graded lumber is shown in table 1.

Table 1. — Tensile ratios for MSR lumber from 1969 to present

Allowable stress in bending, f_b	Allowable stress in tension, f_t
	Pct of f_b
900	39
1,200	50
1,500	60
1,800	65
2,100	75
2,400	80
2,700	80
3,000	80
3,300	80

The practical concerns of experimental procedures and analysis methods is illustrated by a 1977 study reported by Curry and Fewell (7). They investigated the effect of size on tensile strength for lumber graded according to British practice and sorted by E classes. Although their samples were limited, they concluded that there was no significant effect of size on tensile strength between 38- by 100-millimeter, 38- by 150-millimeter, and 38- by 200-millimeter specimens, based on observations of mean tensile strength and significance tests on regressions rather than on trends of near minimum values.

Effect of Size and Grade on Tensile Properties of Lumber

Against the diverse research background outlined above, the NFPA in 1976 was asked by its Technical Advisory Committee to review specific knowledge on tensile strength of existing visual lumber grades. The committee consisted of representatives of the major U.S. lumber rules-writing agencies and other wood product associations. Of the studies available, few were suited to address this question directly or independently. Those selected by NFPA were based on samples of full-size lumber of stress grades covering several sizes: Schniewind and Lyon on redwood (22). Doyle and Markwardt on southern pine (8). Johnson and Kunesh on Douglas-fir and Hem-fir (10), and McGowan et al. on four species (18).

These four studies were conducted at different dates and for differing research objectives. As a consequence, the specimens differed in species, size, grade, and quantity. The following briefly summarizes the original studies and points up specific analysis steps taken by NFPA to relate the differing data sources.

Johnson and Kunesh (10)

In 1975, Johnson and Kunesh (10) carried out tension tests on 593 pieces of Hem-fir and 563 pieces of Douglas-fir divided approximately equally between 2 by 4, 2 by 6, 2 by 8, and 2 by 10. The lumber was selected to represent specific knot size and placement combinations: clear (no knots), single small edge knot, single small center knot, single large edge knot, single large center knot, and multiple small knots in two categories. Slope of grain was limited to not more than 1 in 16. Since this lumber was not stress graded, a strength ratio (SR) based on ASTM D 245 was assigned by NFPA based on the maximum size limit permitted for the knot category. The resulting values ranged from 0.56 to 1.0 by knot size class. The lumber, grouped by this knot SR, thus did not display the usual range in SR expected in a grade of lumber with a more normal variation in quality. As the Hem-fir test material was reported more than 85 percent western hemlock, all of the Hem-fir sample was considered to be this species. The Douglas-fir was classified as coast type.

Johnson and Kunesh reported the lowest and next lowest tensile strength test values as well as a 5 percent exclusion value assuming normality for each knot class. The test data were positively skewed; thus, the normal assumption was judged too conservative and a revised 5 percent exclusion value was obtained by adjusting the distributions to eliminate the heavy skewness. The revised estimates of the fifth percentiles from the adjusted distributions were used for the NFPA analysis.

The estimate of fifth percentile tensile strength (termed observation)

Table 2. — Regressions of ratio of observed to expected 5 percent exclusion value of tensile *strength* on bending strength ratio

Species	Data source	Regression coefficients							
		2x4		2x6		2x8		2 x 10	
		Slope	intercept	Slope	Intercept	Slope	Intercept	Slope	Intercept
United States									
Western hemlock	(10)	+1.5873	+0.2424	+1.9843	-0.1465	+2.0673	-0.3958	+1.7735	-0.3560
Douglas-fir	(10)	+1.3902	+.3450	+1.3039	+.3037	+1.4950	-.1204	+1.1944	-.1240
Southern pine	(8)	+.8727	+.5386	Text	Text	+.5165	+.5822	—	—
Redwood	(22)	—	—	+1.6154	-.3777	—	—	+1.7071	-.5680
Canadian									
Western hemlock	(18)	+1.5500	+.0965	—	—	+1.1162	+.0945	—	—
Pacific silver fir	(18)	+1.2500	+.4108	—	—	+.9317	+.4119	—	—
Lodgepole pine	(18)	+2.4500	-.2632	—	—	+.5941	+.5220	—	—
White spruce	(18)	+1.9500	+.0118	—	—	+.9225	+.3637	—	—

then was divided by the anticipated or expected fifth percentile value for the appropriate strength ratio as predicted by ASTM Standard D 245, based on a 12 percent moisture content assumption. The resulting quotient, termed the “ratio,” was used to characterize the lumber at that strength ratio level. A ratio of 1 or above signified data supporting or exceeding the assigned design value.

This “ratio” process was followed with each of the other three data sets selected for scrutiny; the ratio served as a common basis for combining the data sets.

Schniewind and Lyon (22)

Schniewind and Lyon (22) tested 525 pieces of redwood of five dimension lumber grade/size combinations. Only 350 pieces tested met visual stress grade requirements and thus were used in the NFPA analysis. The assigned minimum strength ratios for the grades were 0.85 for Clear Heart Structural; 0.76 for Select Heart Structural; and 0.63 for Construction Heart Structural. These samples were taken from production; thus, the average SR was higher than the minimum of the grade. The minimum SR’s were used to develop the expected fifth percentiles of tensile strength as described previously. The NFPA observed values were taken on a nonparametric basis from the data by count and extrapolation.

Doyle and Markwardt (7)

Doyle and Markwardt (7) tested parallel-to-grain tensile properties of southern pine dimension lumber in 1967. Three grades each of 2 by 4 and 2 by 8 No. 1 KD, No. 2 KD, and No. 3 MG KD were used for the NFPA analysis, comprising a sample of 446 specimens. The SR’s for the grades according to 1963 Southern Pine Inspection Bureau Rules (25) were used to establish the expected fifth percentile value of tensile strength, but the clearwood base used for calculation was that of ASTM D 2555-76 (3). The NFPA observed values were reported to be based on estimating the fifth percentile by count and interpolation.

McGowan, Rovner, and Littleford (18)

In 1977, McGowan et al. (18) studied parallel-to-grain tensile properties of dimension lumber. This analysis used data from tensile tests of 2 by 4 and 2 by 8 of four species — western hemlock, Pacific silver fir, lodgepole pine, and white spruce — all collected in British Columbia. All species/size combinations were represented by Select Structural, No. 1, and No. 2 grades of lumber. In addition, lodgepole pine and white spruce included No. 3 grade. Pieces were classified by the SR associated with the maximum knot permitted in the grade. Specimens per category (20 categories) ranged from 60 to 83. The estimate of the observed fifth percentile tensile strength for each species was reported by NFPA to be by count and interpolation.

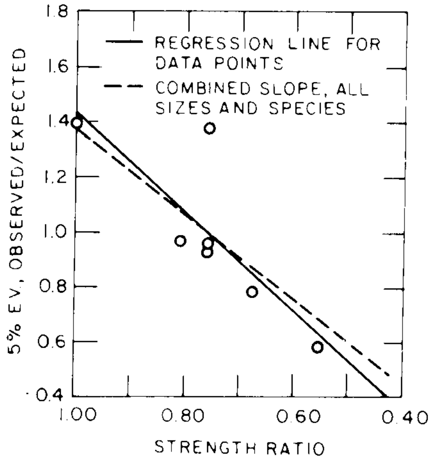

Figure 8. — Relationship between ratio of observed to expected 5 percent exclusion value and bending strength ratio for western hemlock 2 x 10 in NFPA analysis.
(M 148 043)

NFPA Analysis

Ratios of observed to expected fifth percentile values of tensile strength versus SR by size for each species is illustrated by the graph of 2 by 10 Hem-fir (fig. 8). Where the ratio exceeds 1, D 245 is indicated to be conservative;

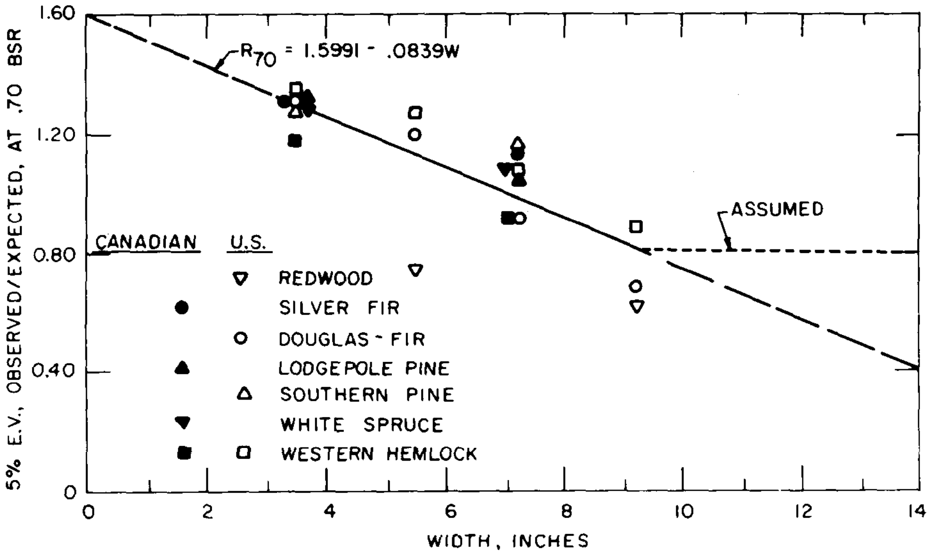

Figure 9. — Effect of size on ratio of observed to expected 5 percent exclusion value at-bending strength ratio *of 0.70.*
(M 148 046)

ratios of less than 1 indicate an overestimation of the fifth percentile by current practice.

Review of the ratios illustrated that the present procedures appeared adequate or conservative for higher grades and narrower widths of lumber; however, it was necessary to devise a procedure for establishing trends that could be suggested for general application. One aspect, for example, was that the decreasing ratio was not apparent in the lower grades (No. 3), but the data were limited. NFPA observed that many pieces at the No. 3 level are in that category for reasons other than strength-reducing defects (i.e., for wane, skip, warp), concluding that this may be more prevalent at the No. 3 and lower levels than at the higher grades. They noted that assigning the minimum SR to the grade could decidedly underestimate the strength of these lower grade pieces.

To examine the average trends of "ratio" versus SR for all the data, regressions were fitted to the data for each species and grade; the solid line in figure 8 illustrates one regression. Lodgepole pine and white spruce No. 3 grade (SR = 0.27) were excluded from the analysis. Table 2 records the regressions.

The regression coefficients for each species-size category were examined for significant difference; NFPA found no significant difference and a combined slope for all sizes and species was calculated. The small number of data points (points represent the ratio for each size/grade/species data set) was a disadvantage in these comparisons The combined slope was 1.504 — a change of 0.15 in the ratio of the observed to the expected fifth percentile for a 0.10 change in bending SR. The dashed line in figure 8 is the combined slope fitted through the mean of the ratio and the SR for that size/grade combination. This was done for all species/size combinations. By observation, it was judged to provide a satisfactory description of the grade effect on tensile strength for all data sets.

This average effect of change of ratio of observed to expected with change of grade (SR) then was used to establish a general effect of size on the ratio by adjusting the average ratio for each of the size/species combinations to the same SR. This resulted in 20 data points on a graph of ratio versus width, thus compensating for the lack of data sets for direct comparison of ratio versus width. A regression of these 20 data sets at an SR = 0.70 is shown in figure 9; the regression line has a slope of -0.08 (for each l-inch increase in width the ratio decreased by 0.08). This procedure results in regression lines with the same slope for other SR levels.

This size relationship, if extrapolated, would predict zero tensile strengths for a piece over 14 inches in width of No. 2 grade. Because of the implausibility of this result and the fact that conclusions for widths over 10 inches would have to be extrapolated from these data, a position was taken by NFPA that the relationship be regarded as asymtotic beginning with a 10-inch width. The results for 10-inch lumber were therefore applied to widths of 12 inches and greater. It was assumed also that (1) adjustments for No. 2 grade level would apply to lower grades; (2) no adjustments upward would be taken although the data for narrow widths suggested this to be a possibility; (3) the 4-inch results would be applied to narrower widths; and (4) the results would apply only to dimension lumber (nominal 2- to 4-in.-thick lumber). The combined adjustment can be stated in formula form:

$$\frac{\text{Observed}}{(\text{Expected})}\ \text{SR}_i = [\ 1.5991 - 0.0839\ W] - 1.504\ [0.70 - \text{SR}_i]$$

where
Observed = 5 percent exclusion value or estimate of the fifth percentile from the data
Expected = 5 percent exclusion value calculated from ASTM D 2555 and D 245
W = nominal piece width (in.)
SR = bending strength ratio.

The application of the combined adjustment procedure to existing dimension lumber resulted in NFPA recommendations for adjustments for tensile design values by grade and size (table 3). The rules-writing agencies employed the adjustments shown for all dimension lumber graded under PS 20-70 in grading rule revisions adopted in 1977.

Conclusion

The transition from tensile stresses based solely on observations made on small, clear wood specimens to adjustments based on tests of full-size lumber has been an evolutionary process in the research community. Research input to design, however, has come at more sporadic intervals, the latest causing significant and sudden changes in the truss industry. Evaluation of full-size members provides a direct evaluation of the product; we expect this trend to continue. Research and industry are making an overt effort to coordinate research on properties and design with engineering practice to make the changes of the future more evolutionary and more predictable.

Table 3. — 1977 adjustments to derive tensile stress from bending stress.

Nominal width	Grade	Bending strength ratio	Calculated adjustment	Adjustment to D 245 tensile stress 1/	Adjustment employed 2/	Adjustment, percent of BSR 3/
In.						
≤4	Select Structural	0.67	1.26	1.00	1.00	0.55
	No. 1	.57	1.11	1.00	1.00	.55
	No. 2 and lower	≤.47	.96	.96	1.00	.55
6	Select Structural	.67	1.09	1.00	1.00	.55
	No. 1	.57	.94	.94	1.00	.55
	No. 2	≤.47	.79	.79	.80	.44
8	Select Structural	.67	.93	.93	.90	.50
	No. 1	.57	.78	.78	.80	.44
	No. 2	≤.47	.64	.64	.64	.35
10	Select Structural	.67	.76	.76	.80	.44
	No. 1	.57	.61	.61	.60	.33
	No. 2	≤.47	.45	.45	.48	.26

1/ These adjustments constitute the NFPA changes recommended to the ALS rules-writing agencies based on the data analysts

2/ These rounded adjustments were uniformly adopted by the ALS rules-writing agencies to be applied to D 245-derived tensile values.

3/ These adjustments are those which combine the D 245 adjustment for tension (0.55 of BSR) and those of footnote 2. To derive a tensile stress, this adjustment is applied to the bending stress before any adjustment for the size effect in bending is made.

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