DESIGN STRESS DERIVATION FOR ANSI POLES[1]

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ABSTRACT

Producers and users of wood poles actively participate in a consensus committee to maintain the American National Standards Institute's standard on specifications and dimensions of wood poles (ANSI O5). This activity provides a common basis of communication between buyers and sellers of products used in the construction of wood utility structures and serves as a basic material properties reference for derivation of their design load capacity. In maintaining this standard, the ANSI O5 committee must continually review and update its database and material classification procedures to assure that the wood structural elements are being evaluated to the same level of structural reliability as other materials. This paper discusses how changes in the knowledge of both wood pole properties and structural design methodology affect the ANSI pole classification and fiber stress derivations.

INTRODUCTION

In 1965, L.W. Wood and L.J. Markwardt of the USDA Forest Service, Forest Products Laboratory (FPL), in Madison, Wisconsin, published a report, often referred to as FPL 39 (13). That report summarized decisions made by the American National Standards Institute (ANSI) O5 committee in deriving the fiber stress values for commercial pole species listed in the ANSI O5.1 standard "Specifications and Dimensions for Wood Poles" (1). The committee decisions were based on a combination of full-sized pole test results from the American Society for Testing and Materials (ASTM) wood pole testing program, published small clear strength values, and performance history. The basis for some of the committee decisions is not well documented and therefore requires some interpretation and re-evaluation.

The purpose of this paper is to review the decisions summarized in FPL 39, provide some assessment of the applicability of these decisions today, and propose a similar procedure for deriving pole design stresses using the current full-scale pole test database, which is broader in scope than the one that was available in 1965. The current database not only includes more poles, it also includes tests of longer poles, used poles, and a range of preservative-treated poles. This database adds to the credibility of conclusions derived on the basis of fractile estimates of strength probability distribution functions. Thus, the recommendations include a more rigorous assessment and use of the strength distribution functions in the derivation of design values than was done in FPL 39.

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ADJUSTMENTS

Factors evaluated in FPL 39 as being significant influences on pole strength include form, moisture content, effects of pretreatment conditioning, and load sharing. Additional factors to consider include pole size, location with respect to height above ground, and deterioration with time. These adjustment factors are referred to as lambda (λ) factors in the Load and Resistance Factor and Design (LRFD) format. A factor to adjust for variability (φ) must also be considered in the derivation of a design nominal resistance. In the LRFD format, factors (γ) are also considered as adjustments on the load side to account for factor of safety and probability of occurrence. The design expression format is

$$\lambda \varphi R_n \infty \gamma_d D + \gamma_l L$$

where R_n is nominal resistance, D is dead load, and L is live load.

Form Factor

Wood and Markwardt make reference to a cross section form phenomenon noted by Trayer and Newlin in 1924 (5) to support a strength adjustment for round sections when bending strength is determined on the basis of the standard square small clear sample. When evaluating the strength of various structural shapes used to minimize weight in wood aircraft they noted that a round specimen that had the same cross-sectional area as the usual nominal 2- by 2-in. (standard 38- by 38-mm) small clear bending test sample exhibited a 15% greater bending stress. Despite the 18% greater section modulus of the square sample, the two samples had roughly the same bending moment capacity. They also noted that going from a small clear sample to a full-sized pole required some adjustment for size and defects. Rather than attempting to derive an adjustment on the basis of these three parameters, however, they chose to simply make a comparison of full-sized pole strengths with matched small clear specimens. They reference the ASTM program as being the source of pole-to-small-clear strength ratios, which they tabulated for six species. Similar tables are given in the ASTM pole report (12) and at least one interim report (11), but the values do not agree. Table 1 compares the ratio noted by Wood and Markwardt (13) to those presented in these other two publications (11,12).

Table 1. Ratios of full-sized pole strength to matched small clear samples by species.

Species	FPL 39 (13)	Interim report (11)	ASTM pole report (12)
Western redcedar	1.05	0.908	0.92
Douglas Fir	1.08	0.966	0.97
Western larch	1.04	0.953	0.95
Lodgepole pine	0.88	0.934	0.93
Longleaf and slash pine	1.07	1.00	1.05
Shortleaf and loblolly pine	1.19	1.02	1.03
All southern pines	1.13		

There did not appear to be any direct reference in FPL 39 and no supporting information in the ASTM pole data for the increase of 8% that was eventually adopted by the committee for going from small clear bending strength to full-sized pole strength.

Moisture Content Adjustment (C_m)

Wood and Markwardt (13) recommended a 10% increase on green modulus of rupture (MOR) for drying to 20% in service. Their recommendation was based on summaries of several studies related to pole moisture contents in service and pole strength. Work by Wilson and others (10) suggested that increases of 17% and 10% more than the green condition value were appropriate for tamarack and shortleaf pine poles, respectively, when dried to 20% moisture content. Surveys conducted by the Rural Electrification Administration indicated that more than 96% of all poles surveyed had moisture contents less than 20% at 4 ft (1.2 m) above ground. Of the nine species included in this survey, southern pine was the only one for which more than 4% of the in-service poles had moisture contents higher than 20% at 4 ft (1.2 m) above ground.

The ANSI committee modified the recommended moisture adjustment to give a 16% increase for drying on the premise that field moisture contents will rarely exceed 20% at 4 ft above ground and that is the most likely location of pole failure.

Available full-scale pole test data for poles tested at moisture contents under 30% are insufficient to characterize a relationship between strength and moisture content of round wood poles. It is commonly known, however, that the strength and modulus of elasticity (MOE) of wood increase and the dimensions of wood decrease as it dries below fiber saturation point. The Wood Handbook (6) provides relationships for estimating these effects in clear wood. For estimating the strength at any moisture content below fiber saturation point it gives the expression

$$P := P_{12} \times \left(\frac{P_{12}}{P_g}\right)^{\frac{(12-M)}{(M_p-12)}}$$

In this expression, P is the property at moisture content M(%), P_{12} is the same property at 12%, P_g is the property for green wood, and M_p is the moisture content at the intersection of a horizontal line representing the strength of green wood and an inclined line representing the logarithm of the strength moisture content relationship for dry wood. Table 2 shows two sets of MOR ratios (12%/green and 20%/green) for six species based on this relationship.

In addition to estimating property value effects of moisture, the Wood Handbook also gives a relationship for estimating the change in dimensions. Assuming that the shrinkage from fiber saturation point (FSP) to ovendry is a linear function of the moisture change, the reduction in log dimensions from FSP to 20% moisture content should be roughly 1/3 the green to ovendry value. In general, tangential shrinkage is roughly twice the radial shrinkage for most commercial softwood species. For this reason, the round timber develops drying checks as it dries to compensate for the greater reduction in circumference. If we assume that the effect of the drying check on section modulus is insignificant, the section modulus reduction can be determined as a cubic function of the

radial shrinkage ($❄_r$). Table 2 gives green–dry radial shrinkage values from the Wood Handbook along with the corresponding estimated ratio of section modulus at 20% to that at FSP (S_{20}/S_g).

The product of the strength increase and the section modulus reduction factors that correspond to drying to 20% provide an estimate of the expected change in moment capacity. This product is shown in the last column of Table 2. These values suggest that the strength change ranges from less than 1% for southern pine to 25% for western hemlock.

Table 2. Effect of moisture on moment capacity of small clear round wood.

Species	M_p	P_{12}/P_g	P_{20}/P_g	$❄_r$	S_{20}/S_g	M_{20}/M_g
Southern pine	21	1.71	1.06	0.048	0.95	1.01
Douglas-fir	24	1.6	1.17	0.048	0.95	1.12
Western hemlock	28	1.69	1.3	0.042	0.96	1.25
Western larch	28	1.69	1.3	0.045	0.96	1.25
Western redcedar	25	1.44	1.15	0.024	0.98	1.13
Lodgepole pine	25	1.71	1.23	0.043	0.96	1.18

The moisture adjustment recommended by Wood and Markwardt (C_m = 1.10) in 1965 appears to be more properly aligned with the available test data and in-service surveys than the value ultimately accepted by the ANSI committee. There remains some question, however, whether a constant material adjustment factor, applied independent of species or environment, is appropriate. The assumption that poles fail at or above 4 ft above ground is also not generally accepted as being a universal truth.

Pretreatment Conditioning (C_{PC})

There are a number of methods of conditioning poles prior to treatment. Those that involve high temperature, especially in the presence of steam, can have detrimental effects on wood strength. ANSI currently groups species into four treatment categories: air seasoning, Boulton drying, steam conditioning, and kiln drying. The ANSI committee recommended a 10% reduction in strength for Boultonizing (3,8) and low temperature kiln drying (<174°F (79°C)) (6) and a 15% reduction for steaming at 245°F (118°C) (4,9). There is no reduction for air drying.

Load Sharing

The premise behind load sharing is that when one pole deflects more than adjacent poles the cable connecting the poles will distribute load to the adjacent poles, enabling them to share the load. The fact that wood poles are more limber than concrete or steel makes them more likely to exhibit significant out-of-line deflections prior to failure and therefore more apt to redistribute load in this manner. The magnitude of load sharing, however, is dependent more on the line design than on material properties of the individual poles. Rule 261A2e of the National Electrical Safety Code (NESC) (7) permits recognition of load sharing for designated pole strength, spacing, and guying of

poles. Because this is not a material property and is considered by the designer, it should not be included in the derivation of fiber stresses for the ANSI O5.1 specification.

Wood and Markwardt (13) describe a method of accounting for load sharing as a factor in the reduction of strength variability, but they never actually apply it to the derivation of pole fiber stress. They refer to an analysis by Colley (3) in which a value estimated as one-half of a standard deviation below the mean strength of individual poles is assumed to approximate the 5% exclusion of the probability distribution function of groups of three poles. Wood and Markwardt accept this as valid justification for deriving fiber stress as one-half standard deviation below the mean.

The fiber stress values derived agreed more as a confidence limit on the mean than as a 5% exclusion value. The National Electrical Safety Code (7) adopted an overload factor of 4.0, which was, in essence, a 75% reduction in the fiber stress value reported by ANSI O5 for Grade B construction. Compared with conventional wood engineering, this would be considered overly conservative if applied to a lower 5% exclusion value but is a reasonable adjustment when applied to the mean. If normality exists, a 90% confidence band on the mean falls within the range bounded by 1.645 times the standard error either side of the mean. The standard error of the mean is, in most instances, much less than 0.3 times the standard deviation of individual pole strengths. Therefore, the lower 90% confidence bound on the mean strength is greater than the mean minus one-half a standard deviation as proposed by Wood and Markwardt and adopted by the ANSI committee. It is therefore advantageous for the pole industry to derive a fiber stress value as a 90% confidence on the mean rather than as 0.5 standard deviations below the mean.

Duration of Load (C_d)

Generally, a duration of load and factor of 1.6 is applied to adjust for the difference between test and service load conditions in wood structural components subject to bending. The test duration is normally less than 10 min. As the duration of a load is extended, the capacity of the wood is reduced. Because of the short duration of wind and ice loads on utility poles, the test duration is considered to be representative of service conditions and the duration of load adjustment has been omitted (C_d = 1.0).

Location

A number of studies have concluded that there is a significant reduction in strength with height in a pole. The reduction is generally attributed to increased proportion of juvenile wood near or within the active crown of a tree and the increased frequency of knots. The height effect cited in Appendix A of the ANSI O5.1 standard was based on surveys of the fiber stress at failure location for full-sized pole tests (2). Pole test data show a trend for failure stress to decrease with distance above ground. This relationship supports a 25% reduction in strength by mid-height in a pole with no further reduction beyond that. More recent evaluation of height effects suggests that the reduction is not this critical in the lower portion of the tree and that the reduction should be recognized as occurring across the full height of the pole. Appendix C of the ANSI standard shows height effects to vary with species but shows only an 18% reduction across the full length of the pole for southern pine and no reduction for Douglas-fir and western redcedar. This was based on work done as part of the Electric Power Research Institute (EPRI) sponsored pole testing program conducted in the mid 1980s (8).

The increased use of multi-pole structures makes this adjustment more important. The pole industry has adopted the convention of characterizing pole strength as the stress at the ground line at the time of failure. This failure stress will be greater than the actual failure stress. The lack of data on pole strength above mid height, however, limits the accuracy of any models proposed for deriving values for changing strength with height. This is a parameter that requires further study.

Pole Size

There are two size adjustments that have been discussed for poles. One of these has to do with the ANSI classification system and the other has to do with a reduction in strength with increase in pole circumference at the ground.

Classification (C_{cl}): The ANSI pole classification system was derived to give incremental changes in pole circumference from one class to the next. Pole tip circumferences vary by increments of 2 in. (51 mm), and pole circumferences 6 ft (1.8 m) from the butt vary by increments ranging from 2 to 4 in. (51 to 102 mm). When a pole is placed in a size class, it must fall between the minimums specified for two successive classes. Therefore, most poles in any one class are larger than the minimum specified. The over capacity of a pole stressed in bending is determined as the ratio of its actual section modulus to that assumed on the basis of its minimum dimension at the point of greatest stress. With the assumption that on average pole circumferences at 6 ft (1.8 m) from the butt (C) fall midway between the minimum specified for their class and the minimum specified for the next larger class, an over size factor would be derived as

$$C_{Cl} = [(C + 0.5I)/C]^3 = 1 + 1.5(i/C) + 0.75(i/C)^2 + 0.125(i/C)^3$$

As the pole circumference increases, the value of C_{Cl} decreases. This adjustment varies from a 19% increase for small poles to a 7% increase for the larger ones. One way of dealing with a variable factor such as this is to incorporate it into the analysis of pole strength. This requires classifying each test pole and estimating its ground line strength (adjusted ground line MOR or AMORGL) using the class minimum ground line circumference rather than its actual dimension. Another way to handle it is to simply give a 7% increase across the board as an adjustment for the classification effect. This approach gives more conservative designs for the smaller poles.

Circumference: The only method we have of evaluating the effect of size on strength is to review the test data on strength versus the timber size at the location of failure. To minimize effects of the change in strength with height, we evaluated available data for new untreated poles where the poles failed at or close to the ground line. These data show a trend for a reduction in ground line MOR with an increase in ground line circumference. The trends, however, are inconsistent across studies as well as across species. The majority of individual studies show a negative effect of ground line circumference on strength, but the correlation coefficients, which are a measure of the proportion of total variation around the mean (explained by a regression on this variable), are generally less than 0.35.

Figure 1 shows normalized strength compared with ground line circumference for three species: Douglas-fir, western redcedar, and southern pine. The circumference in this case is the ratio of measured MOR to the lower 90% confidence bound on the mean MOR for each species. Because of

the quantity of western redcedar test data included in the ANSI database, this plot and the accompanying regression line are strongly influenced by the cedar strength–size relationship.

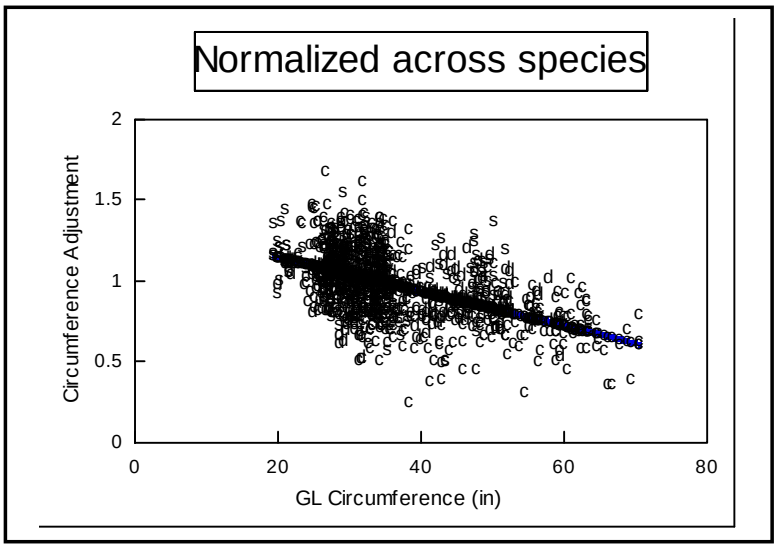

Figure 1. Normalized plot of strength versus ground line circumference. The circumference adjustment is the ratio.

If each of these species is evaluated separately, the reduction in strength with increasing circumference is lower than this composite regression would predict. Figures 2 to 4 suggest that strength versus circumference relationship varies with species. A log–log regression was used to fit the following continuous functions to the various species plots. The following functions, give some idea how the circumference effect varies with species included in the ANSI database.

Southern pine $16{,}887 \times C^{-0.194}$	$r^2 = 0.08$
Douglas-fir $16{,}939 \times C^{-0.238}$	$r^2 = 0.11$
Western redcedar $42{,}378 \times C^{-0.588}$	$r^2 = 0.32$

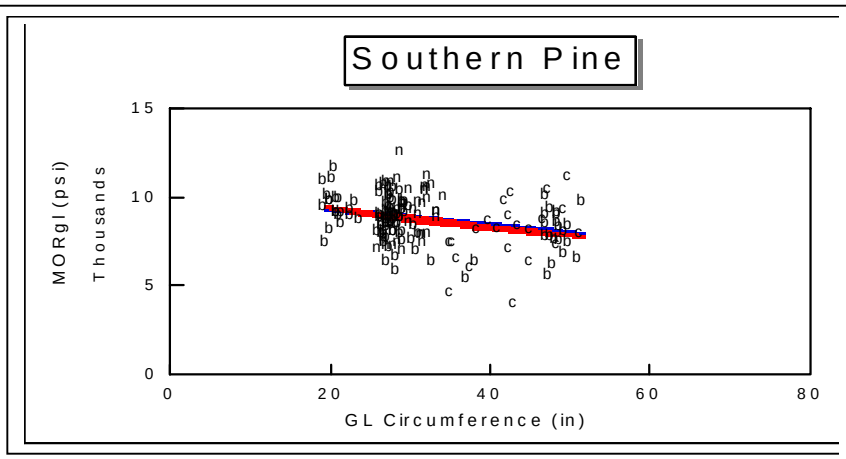

Figure 2. Relationship between ground line MOR and ground line circumference for southern pine.

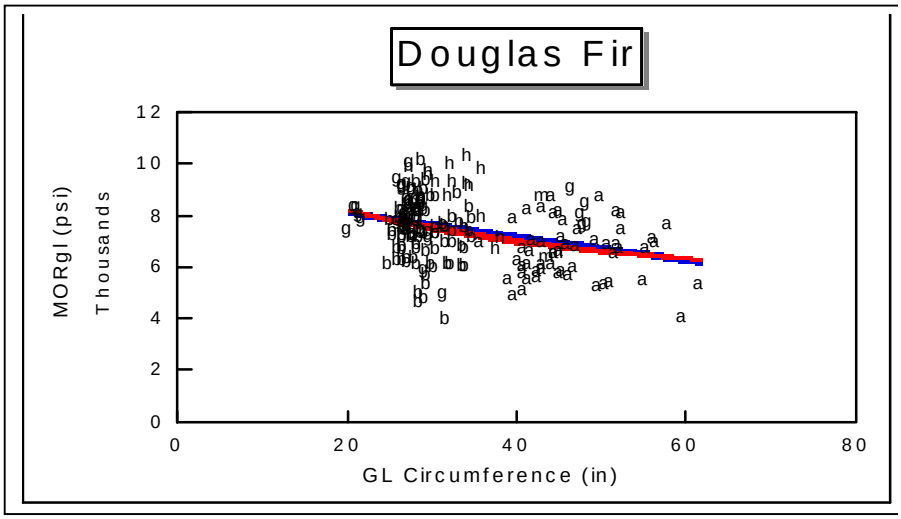

Figure 3. Relationship between ground line MOR and ground line circumference for Douglas-fir.

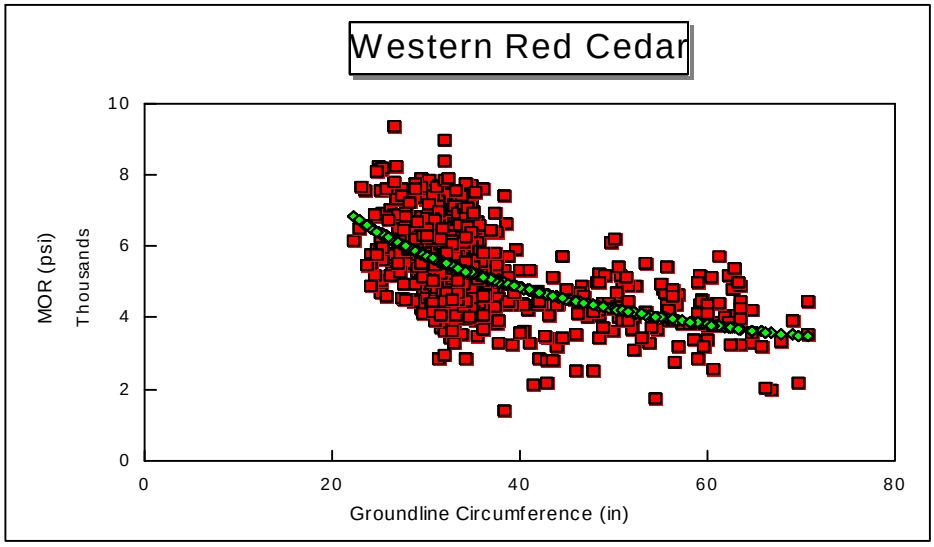

Figure 4. Relationship between ground line MOR and ground line circumference for western redcedar.

This evaluation supports the conclusion that there is a trend for reduction with increased circumference. For the Douglas-fir poles, the strongest correlation for an individual study (r^2 = 0.34) was obtained for data presented by Wilson in 1917 (12). That study included only 15- to 25-ft- (4.6- to 7.6-m-) long poles. For southern pine, the highest correlation (r^2 = 0.21) for poles that failed close to the ground came from the EPRI study and included only 22 poles. Other studies for Douglas-fir and southern pine had correlation coefficients under 0.15.

The fact that these regressions explain so little of the variation about the mean suggests that there may be other variables that should be considered in applying design adjustments. There seems to be a species effect in that western redcedar data exhibit a stronger trend for strength reduction with size. Other variables to consider include tree taper and properties of the wood such as growth rate, the occurrence of reaction wood or juvenile wood in the ground line region, and moisture gradient at the time of test.

Height effect is another variable to consider. Ground line distance from the butt increases with pole length and as shown in Figure 5, data taken from the pole database show that the failure location above the ground line increases with circumference at the ground line. If strength decreases with height as was discussed earlier, height effect may also play a role in the apparent trends in strength reduction with increased circumference.

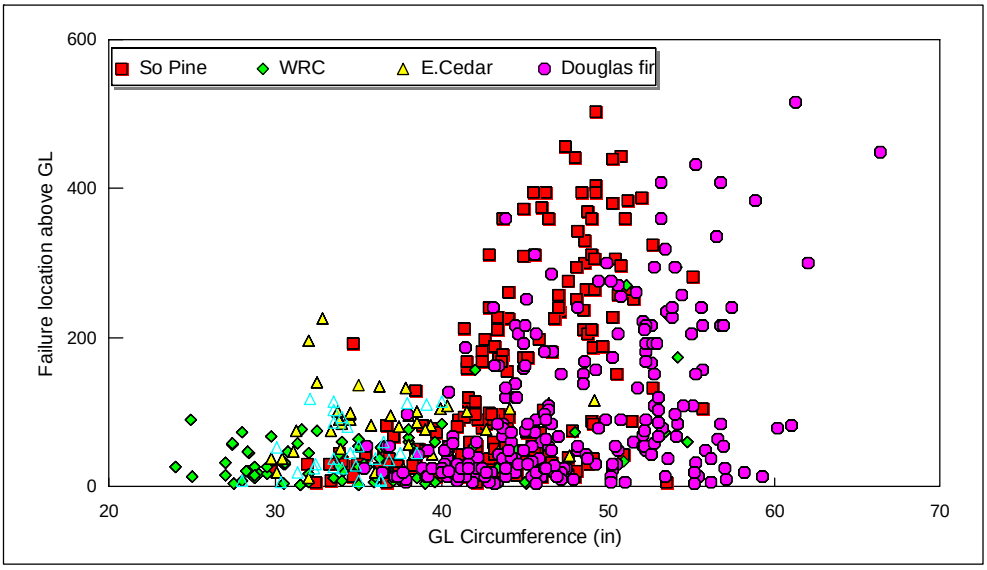

Figure 5. Variation in failure location above ground line with increasing ground line circumference.

Finally, these trends may also be attributed to differences in the test method; circumference as well as pole taper may influence the way in which stresses are distributed or the rate of strain at the ground line.

Adjusting pole strength for ground line circumference is a decision yet to be made by the ANSI committee. The assessment of size effect made by J. Bodig (1999 letter to the ANSI task group) should be reviewed in detail as a possible approach to dealing with size effect prior to making this decision.

Variability Adjustment (ϕ)

Design values for poles should be based on a lower exclusion limit (LEL). With the assumption that the coefficient of variation of 14%, adopted by the ANSI committee in 1965, is still valid and the

strength distribution function can be adequately modeled using a normal probability distribution function, a fiber stress adjustment to the 5% exclusion value would take the form

$$\Phi_B = (1 - 1.645*0.14)$$
$$= 0.77$$

For grade C construction, the committee may feel it appropriate to establish a design basis point that will exceed 15% of the poles used. In this case, the adjustment would be

$$\Phi_C = (1 - 1.035*0.14)$$
$$= 0.85$$

This is of course a simplification intended to facilitate the derivation of a variability adjustment factor (φ). Our current pole test database supports the assumed COV value, but new pole species, especially those coming from managed plantations, may exhibit lower variability. Thus, modification of the variability adjustment should remain an option. Table 3 compares the lower 5% and 15% exclusion values estimated using this approach with the current ANSI fiber stress values adjusted using NESC overload factors for grades B (0.65) and C (0.85) structures.

The ratios of the LEL and current NESC values vary with species because of the differences in the values reported in Table 4 between current ANSI fiber stress values and the adjusted mean confidence bound.

Table 3. Comparison of lower exclusion estimates and current NESC design values derived using adjustments to the current ANSI fiber stress values. The 5% LEL is R_n*0.77 and the 15%LEL is R_n*0.85. NESC grade B value is ANSI fiber stress *0.65 and for graded C, the value is ANSI fiber stress *0.85.

Species	5%LEL	NESC-B	Ratio	15%LEL	NESC-C	Ratio
Western redcedar	5,200	3,900	0.75	5,700	5,100	0.89
Douglas-fir - Boultonized	5,900	5,200	0.88	6,600	6,800	1.03
Jack pine - kiln dried	6,200	4,300	0.69	6,900	5,600	0.81
Red pine - air dried	4,100	4,300	1.05	4,500	5,600	1.24
Lodgepole pine- air dried	5,100	4,300	0.78	5,600	5,600	1.00
Western hemlock	6,500	4,800	0.74	7,200	6,300	0.87
Western larch	7,300	5,500	0.75	8,000	7,100	0.89
Southern pine - steamed	6,100	5,200	0.85	6,700	6,800	1.01
Engelmann spruce	3,600	1,700	0.47	4,000	2,200	0.55
Northern white and eastern cedar	3,100	2,600	0.84	3,500	3,400	0.97

Table 4. Recommended adjustments used to modify the 5% lower exclusion limit for effects of pretreatment conditioning (C_{PT}) moisture (C_M), duration of load effects (C_d), and size classification effects.

Species	Conditioning				C_M	C_d	C_{CL}	Net
	AD	KD	Steam	Boulton				
Recommended adjustments	1.0	0.9	0.85	0.9	1.1	1	1.07	
Western redcedar	1.0				1.13	1	1.07	1.21
Douglas-fir Boultonized				0.9	1.12	1	1.07	1.02
Jack pine - kiln dried		0.9			1.1	1	1.07	1.06
Red pine - air dried		0.9			1.1	1	1.07	1.06
Lodgepole pine- air dried		0.9			1.18	1	1.07	1.14
Western hemlock		0.9			1.25	1	1.07	1.20
Western larch				0.9	1.25	1	1.07	1.14
Southern pine - steamed			0.85		1.01	1	1.07	0.97
Engelmann spruce	1.0				1.1	1	1.07	1.18
Northern white and eastern cedar	1.0							1.18

Columns 4 and 5 have been revised from the published version. The steam entries were incorrectly listed as 0.9 and Boulton entries 0.85 in the published version.

RECOMMENDATIONS

ANSI should establish a pole design stress derivation method that will accommodate future modification as more data are collected. This derivation should focus on the evaluation of a strength probability distribution function based on full-sized pole tests whenever data are available.

A fiber stress value used to set pole size classes should be established as a conservative estimate of mean performance. This value, derived as the lower limit on a 90% confidence bound on the mean, adjusted for pretreatment conditioning effects, in-service moisture content, and ANSI class oversize would also be considered the nominal bending resistance of the pole species (R_n). The moisture adjustments given in Table 2 are used to derive a net adjustment for 10 principal species in Table 4. These adjustments are then applied in Table 5 to provide estimates of the mean and nominal resistance values and compare them to values recommended by Wood and Markwardt (13) and values currently reported in ANSI O5.1 table 1.

Table 5. Derivation of fiber stress values (lb/in^2) based on 90% confidence on mean strength of full-sized pole tests compared with values recommended by Wood and Markwardt (W&M) and with values published in the ANSI O5.1 Standard.

Species	90% Conf.	Adjusted by λ	W&M	ANSI
Western redcedar	5,550	6,720	5,490	6,000
Douglas-fir, Boultonized	7,560	7,710	7,530	8,000
Jack pine - kiln dried	7,640	8,100	…	6,600
Red pine - air dried	5,010	5,310	…	6,600
Lodgepole pine - air dried	5,850	6,610	4,920	6,600
Western hemlock	7,010	8,440	6,590	7,400
Western larch	8,280	9,440	7,900	8,400
Southern pine - steamed	8,120	7,880	7,330	8,000
Engelmann spruce	4,010	4,730	4,880	5,600
Northern white and eastern cedar	3,454	4,080	4,560	4,000

Designer Options

Load sharing increases should be applied at the discretion of the utility engineer. In some situations, adjacent poles may be able to pick up a significant portion of the load on a limber or partially failed pole. Load sharing contribution is dependent in part on the pole spacing, on connecting cable stiffness, and on the importance of the line.

Reduction in strength with height should also be considered when a multi-pole structure is being designed using cross bracing, which places critical moments well above the ground line. The reduction with height currently recommended in ANSI appendix A is

$$K_h = (1 - 0.25*x/L)$$

An alternative approach given in appendix C of the ANSI O5.1 standard gives an adjustment applicable only for southern pine in which mean strength is adjusted by

$$K_h = (1 - 0.176*x/L)$$

And the strength coefficient of variation is adjusted by

$$K_{hcov} = (1 + 2.072*x/L)$$

Research Needs

There are a number of controversial points that must be resolved by the ANSI committee at this point.

- Should the moisture adjustment be independent of species (C_m = 1.0 or 1.10)?
- Should the adjustment for ANSI class minimum circumference vary with pole class (C_{CL} ranging from 1.07 for large poles to 1.19 for small ones)?
- Should there be an adjustment for ground line circumference, reducing nominal ground line resistance as pole size increases?
- When pole strength is increased for oversize effect of the classification system, should pole strength be reduced for height effects when designing a cross braced H frame? Is the equation shown in Annex A of the ANSI O5.1 standard the one that should be used?

The evaluation of a size effect on strength of round timbers is inhibited by the lack of data collected specifically for this purpose. A study should be conducted at a single test facility with controls on physiological differences as well as extreme fiber strain rates. A range of pole circumferences should be tested for poles of a given length in major pole species. Tests of 5 poles in each of 5 sizes ranging from 25 to 80 in. (0.64 to 2 m) in circumference, each having a growth rate of 8 to 20 rings per inch, an average taper for their species, and a moisture content above fiber saturation point should be sufficient to identify and quantify a circumference effect.

Strength change with height also needs further investigation. In evaluating poles of equal length for the effect of pole circumference, the variable of height is removed. When a cross brace is connected at 1/3 the height, what strength reduction should be considered for stress at this point when calculating the design load on the structure? These questions should be answered and included in the ANSI O5.1 standard.

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