resistance distribution, there is limited value in attaining a precise fit. In such cases a normal PDF is the easiest of the established parametric functions to work with. For products subject to some level of quality control or quality assurance, there is generally some justification for assuming that the parent PDF will be skewed to the high side. Normal and log-normal PDFs give similar results with COVs under 20%. In this case, the normal PDF will give slightly more conservative 5% LTL values.

Documentation of the derivation of R_n should include discussion of the PDF and the process used for its selection. *ASTM Standard D 2915-99*, Section 4.5.7 (ASTM 1999a) suggests comparing a histogram or empirical cumulative distribution function to one or more overlaid parametric distribution functions as a means of justifying the PDF selection. Anderson (1952) discusses goodness-of-fit models and how they vary with distribution type.

Individual pole producers who maintain their own database on pole strength may select any PDF that can be supported by their data as a means of estimating a 5% LTL. The nonparametric PDF assumption is the most conservative and is best used with limited samples. If the sample size is large and pole strengths are supported by simple, conservative models that recognize basic material properties (from small clear tests, coupon tests, and cylinder tests) and permissible defects, the normal or log-normal assumptions are likely to give reasonably conservative estimates of a lower fractile of the PDF, as well.

Any organization interested in using a strictly empirical basis for the derivation of nominal resistance should maintain an up-to-date database for poles representative of those being used. Increasing the size of the database leads to greater confidence in the nominal resistance value. Increasing the sample size over time provides a basis for judging trends in materials and manufacturing that might affect the strength PDF. Larger samples also provide the opportunity for adopting a more rigorous approach to assessing the reliability of a utility line.

4.4.2.1.3 Empirical Analysis. Test data generally require some degree of interpretation. For example, ANSI wood pole dimensions are typically used in design, rather than the measured dimensions of the pole. If empirical strength values are derived using measured pole dimensions and applied using the ANSI size-class minimum dimensions, predicted GLM capacity will be less than the measured value. For this reason, values referred to by *ANSI O5.1-2002* (ANSI 2002), Annex C as "adjusted groundline modulus of rupture" are derived as the average failure moment at groundline, divided by the pole-class minimum groundline section modulus. Here the groundline section modulus was derived using the ANSI 6-ft-from-the-butt value adjusted to groundline using the ANSI-tabulated minimum dimensions to estimate taper. Pole modulus of elasticity estimates are also based on the class minimum dimensions at the butt and tip, assuming a linear taper and constant modulus of elasticity (MOE) value over the length of the pole. These values are therefore intended only for use with the ANSI-tabulated minimum dimensions

4.4.2.1.4 Confidence. A number of factors affect the confidence or assurance that an estimate based on a test sample provides a conservative representation of the target point of the parent distribution. The greater the sample size, the greater the probability that the sample mean and variance will closely approximate the parent population values. For a nonparametric distribution, confidence is characterized in terms of order statistics or the order of magnitude. The smallest value in a sample of 20 is the 5th percentile for that sample but only a 50% probability exists that it will be a conservative estimate of the parent population 5th percentile. The first-order statistic in a sample of 28, on the other hand, has a 75% probability of lying at or below the parent population 5th percentile. For a normal distribution, confidence/tolerance adjustment factors represent the distance from the mean of a sample to the point estimate in terms of the number of standard deviations. Basically, the confidence bound is set to provide some level of assurance that values derived on the basis of a small sample will encompass or provide a conservative estimate of the value for the parent population.

Table 4-1 provides a listing of order statistics used to estimate a lower 5% tolerance limit with a nonparametric distribution and adjustment factors representing the number of standard deviations from the mean to the 5% LTL of a normal PDF.

It is apparent from this discussion that an empirically derived value for R_n will vary, depending on the PDF assumed to represent the data. It is imperative for the pole supplier to provide documentation to support the assumptions made in the selection of a PDF and the derivation of the nominal resistance.

In Appendix B, the Method 1 section provides examples of the application of the empirical method to obtain the 5% LTL R_n.

4.4.2.2 Method 2: Mechanics-Based Models Used in Conjunction with Monte Carlo Simulation. Maintaining a database of full-sized pole tests can be prohibitively expensive. As an alternative, basic material properties can be used in conjunction with mechanics-based models to estimate mean pole strength. Strength variability, however, is a more complex issue. If there is no covariance between any of the independent variables, variance of a strictly linear model can be estimated as the sum of variances of the individual input parameters, eliminating the need for simulation. When using a nonlinear model with no covariance, variance may be influenced by parameter effects on any nonlinear function. Simulation provides a tool for characterizing this effect. However, models that rely on covariant input parameters are more complex because, for example, wood fiber strength and stiffness both vary with density, age, and moisture content, and the variability in weld strength may be larger with thicker steel plate. Application of Monte Carlo simulation in these cases requires establishment of an accurate covariance matrix and interaction equations to ensure realistic combinations of input parameters. Any influence that one input parameter has on another should be recognized in the development of the virtual structures being evaluated.

Computer simulation routines are designed to randomly generate physical and mechanical properties from defined PDFs assumed to represent the properties found in service, and are parameters of theoretical models used to predict performance. The advantage of Monte Carlo simulation is that statistical strength data are obtained using relatively inexpensive material coupon tests (small, clear samples for wood; cylinder tests for concrete) rather than testing a large population of full-size poles. Basically, the simulation routine compiles a large sample of computer-generated pole strength estimates. The resulting samples are then treated similarly to the empirical data, with the added adjustments for modeling error.

A few pitfalls to simulation must be considered. The most obvious is the question of mechanics-model accuracy. It is difficult to develop and verify a model that accounts for all variables that may influence strength and variability of the full-scale structure. When a model is used to predict performance of a complex system, it should be verified over the full range of input parameters for which it will be used.

Although the model being used may be accurate at predicting performance for any known combination of parameters, it may not accurately represent expected behavior in the tails of a distribution. For this reason, verification tests should be conducted to assess the prediction accuracy at the extremes of the influencing variables. A verification test should include accurate measurement of raw material mechanical properties as well as physical properties of the test poles. The more variable the material and the wider the range of structural configurations to be modeled, the larger the verification database should be. The model verification database should be well-documented and included along with simulation results as support for nominal resistance values to be used.

Nonlinear mechanics-based models employ iterative techniques to predict failure. These models account for change in material as well as geometric properties with increased strain levels. Verification tests are conducted to assess the prediction accuracy at the extremes of the influencing variables. Confidence in simulated data varies with the accuracy of the models as well as the input data. Model accuracy should be verified by comparing model predictions to full-scale pole test data using the actual material and geometric properties of the corresponding test specimen. The data used to establish input PDFs for mechanics-based models should be subject to the same assessment of confidence as the full-scale pole test data.

The number of simulations required to get a satisfactory confidence on estimates of distribution parameters will vary with the complexity of parameter interactions and symmetry of their assumed distribution functions. These topics are discussed in greater detail by Law and Kelton (2000), Hammersley and Handscomb (1964), and Balci and Sargenti (1984). It is often preferable to run a number of trials, each consisting of 200 to 500 simulations, to generate a distribution of point estimates rather than one run of 10,000 simulations. This provides a better indication of variability and confidence bounds. The number of simulations conducted needs to be large enough, however, to provide stable predictions of the 5th percentile.

The PDFs used to characterize the raw data input for simulation models should be based on large enough sample sizes to ensure a standard error (SE) no greater than 10% of the estimated 5th percentile. If normality is assumed, the tolerance limit is estimated using Eq. 4-4 (Natrella 1963). The SE of this statistic varies with sample size (N) and sample standard deviation(s) of the sample. It can be approximated using the equation:

$$SE = s\sqrt{\frac{1}{N} + \frac{k^2}{2(N-1)}} \quad \text{(Eq. 4-12)}$$

where

K = confidence level factor (Table 4-1).

In Appendix B, the Method 2 section provides examples on the application of Monte Carlo simulation along with mechanics-based models to obtain the 5% LTL R_n.

4.4.2.3 Method 3: Default Basis. The default basis is used if there are insufficient data to characterize the pole strength PDF empirically or if demonstrably reliable models have not been developed to provide accurate estimates of pole strength. The default method provides a conservative approach to assigning parameters for estimating R_n. The National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) proposed guidelines (Ellingwood 1980) for estimating strength variability as a function of so-called professional, material, and fabrication influences.

A simple approach is to obtain a best estimate of mean with some degree of confidence and establish a conservative estimate of variability until more data become available. Pole strength variability, expressed here as COV, is influenced by a number of factors that should be considered. These include inherent material variability (COV_M^2), which can be evaluated using standard material property tests. The geometric variability includes inherent or fabrication-related dimensional and thickness tolerances. Fabrication-induced variability (COV_{FA}^2) for steel, concrete, and FRP poles include manufacturing process effects on geometry and on material strength properties. Finally, the accuracy of the predictive model of pole strength is referred to as the professional factor or model accuracy (COV_P^2). In estimating the strength of a full-sized pole on the basis of raw material test data, confidence in the result is dependent on the accuracy of the model being used.

Finally, consider so-called other effects (COV_O^2) such as deterioration, design error, and environmental risk. Poles may be damaged due to mishandling during installation or they may experience deterioration from environmental exposure such as high temperatures, grass fires, ultraviolet radiation, decay, corrosion, cracking, and spalling. These effects are not generally included in a design model and they do not have the same effect on all poles in a line. Poles removed from a line after 30 years of service are likely to have neither the same strength nor the same strength variability they had when they were installed.

Combining these individual effects can provide an estimate of the pole strength COV_R:

$$COV_R^2 = COV_M^2 + COV_{FA}^2 + COV_O^2 + COV_P^2 \qquad \text{(Eq. 4-13)}$$

Further information is given in the American Iron and Steel Institute's (AISI) "Specification for the design of cold-formed steel structural members" (AISI 1996) and "Development of a probability-based load criterion for American National Standard A 58" by Ellingwood et al. (1980). These and other publications support overall default values for COV_R of steel and concrete poles of 0.15, and 0.20 for wood poles. A number of variables with fairly broad ranges affect the strength of FRP poles; therefore, useful default values cannot be established for these poles at this time.

4.5 PROOF LOADING

Proof loading to a design value provides some degree of quality assurance but, in the absence of pole failure, this procedure provides little useful information on the strength distribution. Even when the proof loading does result in occasional failures, such results can only provide a basis for assigning some level of confidence about the relative proximity of the proof load and some fractile of the strength distribution. The drawback of proof loading to a level that results in occasional failure is that it provides some risk of causing undetected damage to the pole.

If backed by research to correlate nondestructive evaluation (NDE) parameters to strength, proof loading methods might be developed to enable estimates of LELs of strength. In general, however, NDE parameters are not used to define strength since NDE parameters are poorly correlated with strength.

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Appendix A

DESIGN EXAMPLES

A.1 INTRODUCTION

The following examples are for unguyed tangent transmission and distribution (T/D) poles. They have been included to illustrate some of the concepts presented in this manual. The examples use force coefficients (drag coefficients, shape factors) that are based on the minimum recommendations of the 1991 edition of American Society of Civil Engineers (ASCE) *Manual 74* (ASCE 1991). For wind on poles, the force coefficient values were selected using *ASCE Manual 74*, Table 2-3 (ASCE draft). For wire loads, force coefficients of 1.0 are used for all wires, with or without ice. In the calculation of wind forces on both wires and poles, the selection of appropriate force coefficients is very important. Supplemental information on force coefficients can be found in Appendix H of *ASCE Manual 74* (ASCE draft) as well as in other specifications such as in Appendix B of ASCE 7-02 (ASCE 2002) and International Electrotechnical Commission (IEC) *Standard IEC 60826* (IEC 2002). Information in *ASCE Manual 74* (ASCE draft), Appendix H, for example, suggests that force coefficients greater than 1.0 may be appropriate for small-diameter (<~ ½-in.) wire, and *IEC 60826* recommends force coefficients between 1.0 and 1.4 for ice-covered wires.

The design parameters used for these examples do not represent all possible load conditions, structure types, or components but do provide insight into how to properly apply the reliability-based design (RBD) methodology discussed herein. These examples demonstrate how the loading requirements prescribed in the working draft of *ASCE Manual 74* can be used to determine the size of various pole types for different grades of construction. Examples are given for wood, steel, concrete, and fiber-reinforced polymer (FRP) poles based on pole bending (strength being the only design criterion). These examples do not consider other design criteria such as electrical clearances or seismic effects. In each example the pole size is initially established based on a calculated groundline moment (GLM), and then the pole strength is verified at other locations along the pole. As implemented, this GLM accounts for the deflected shape (P-Δ) effect.

The poles in each of the examples are sized for *National Electrical Safety Code* (*NESC*) (IEEE 2002) Grades B and C construction using the load factors given in Table 2-3 in Chapter 2 of this manual. As illustrated in the examples, weather-related loads on poles are independent of material type. Wind loading on the pole structure depends on the geometry of the pole (including the projected wind area of the pole above groundline), the height of the vertical centroid of the applied wind pressure, and the pole force coefficient (round, polygonal).

A.2 EXAMPLE LOAD REQUIREMENTS

In the following examples, two different pole configurations will be considered, each assumed to be governed by different loading conditions. A transmission pole will be designed for an extreme wind loading and a distribution pole will be designed for a combined ice and wind loading, both in accordance with the criteria set forth in the working draft of *ASCE Manual 74* (ASCE draft). (In practical applications, the controlling condition will often correspond to that of extreme wind loading, for both transmission and distribution poles.) For all examples, both pole configurations assume weight spans that are equal to the wind spans, although this is not often the case in actual practice. Note that the wind force formula used in the working draft of *ASCE Manual 74* (ASCE draft), Eq. 2.1-1, is the same as formula specified in the *National Electric Safety Code* (IEEE 2002) for extreme wind loading. This design process is an iterative one. Most methods require that an assumption be made regarding pole size. This pole size is then analyzed for the forces it must support. Based on this analysis, if a different pole size is required the analysis should be repeated to verify the adequacy of the pole.

Transmission Pole Design (Las Vegas, Nevada)

Consider a 75-ft-long pole (65.5-ft height above ground), of the configuration indicated, and subject to the following conditions and parameters (Fig. A-1):

- ASCE Extreme Wind: 90 mph, Exposure C
- Design for two grades of construction: *NESC* (IEEE 2002) Grade B and Grade C
- Wire Parameters:
  - Conductor: 795 aluminum conductor steel-reinforced (ACSR) (26/7) Dia. = 1.108 in., Wt = 1.091 lb/ft

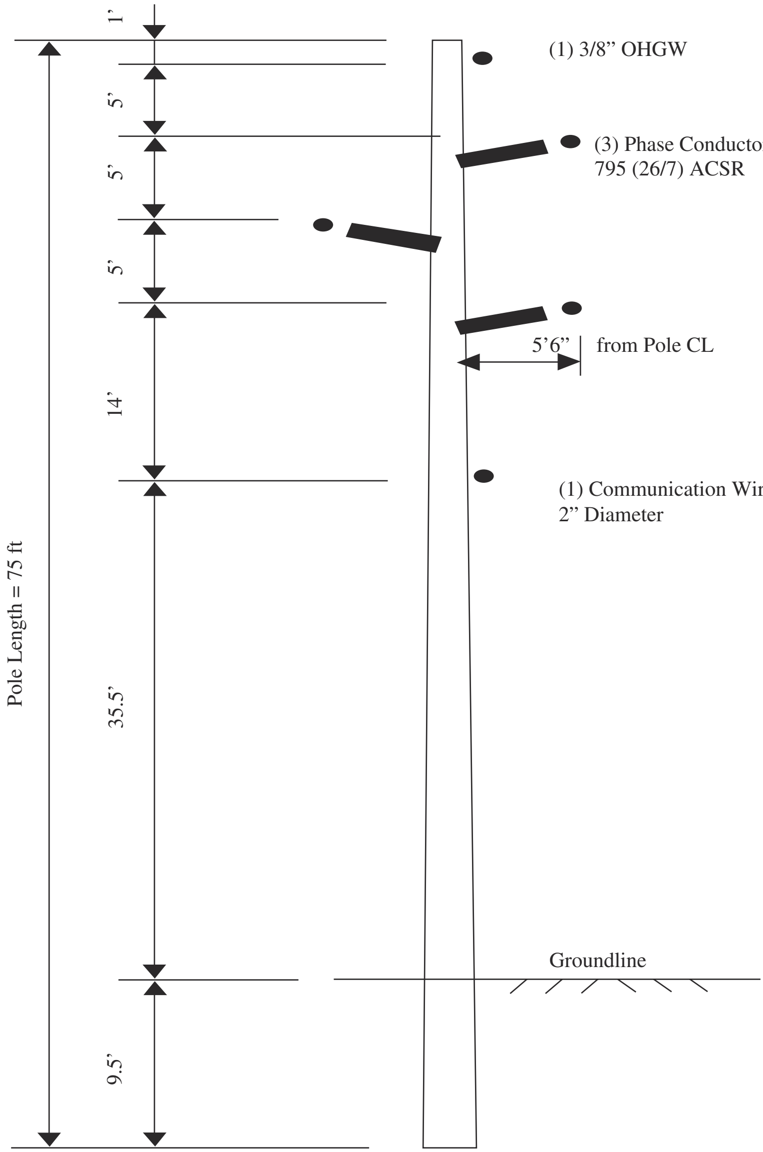

FIGURE A-1. Transmission Pole Design.

- Shield Wire: 3/8-in. high-speed steel (HSS)
  Dia. = 0.36 in., Wt = 0.273 lb/ft
- Communication Wire:
  Dia. = 2.0 in., Wt = 2.25 lb/ft

- Span Parameters:
  - Wind and Weight Spans = 500 ft