Reliability of Wood and Composite Distribution Poles

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Abstract

The structural reliability of wood and composite distribution poles is investigated on the basis of bending strengths determined from full-scale tests. Two types of wood (Western Red Cedar and Southern Yellow Pine) and two types of composites (modular and pultruded) were considered. All analyses referred to 13.7m (45 ft.) tangent poles with standard embedment. Applied loads referred to a distribution pole with four conductors subject to 193 kmph (120 mph) wind. Numerical values of reliabilities for the poles were computed and compared. The study showed that composite poles offer more than four times the structural reliability of wood poles and are ideally suited for meeting the resiliency and replacement demands in hurricane-prone areas.

Index Terms **- composite, distribution, poles, pultruded, reliability, wind, wood.**

I. INTRODUCTION

Climactic events such as hurricanes, tornadoes, and ice storms cause substantial damage to overhead utility lines every year. One common aftermath of these events is the need for emergency system restoration and rebuilding. The main component of this utility system rebuilding process is the *hardening* of the electrical power infrastructure to prevent future damage and reduce or eliminate outages due to structural failures. This storm-hardening can be performed in various way, including utilizing only engineered pole materials to provide a reliable structural capacity and/or upgrading existing pole designs to achieve better structural resilience.

Wood, tubular steel, lattice towers, concrete, laminated wood and composite (fiber-reinforced polymer or FRP) are the pole materials currently used in transmission and distribution structures. Wood is the most predominant and is reportedly used in nearly 95% of distribution lines [1]. It is estimated that about 150 million *wood* utility poles are in service across North America. Some studies [2] indicate that about 3.6 to 3.7 million wood poles are replaced each year in addition to installation of 1.9 million new poles.

Composite poles are becoming increasingly popular in the utility industry at both transmission and distribution levels. Some of the biggest advantages of composite poles are their proven engineered performance, light weight, excellent flexural strength, easy installation, immunity to weather-related effects, require little or negligible maintenance, excellent fire resistance, impervious to woodpeckers and finally an estimated service life of 80 years.

A significant amount of research has been performed on wood and composite utility poles. However, there is no specific study aimed at comparing the relative structural reliabilities of wood and composite poles using strengths from full-scale tests. This study is a small step in that direction and is focused on poles of two species of round wood (Western Red Cedar and Southern Yellow Pine) and two types of composites (filament-wound, modular and pultruded) in a hurricane loading environment. Only distribution–level poles (voltage below 46kV) of length 13.7 m (45 ft.) are considered.

II. POLE MATERIALS

Wood poles used on distribution lines are generally of Western Red Cedar (WRC) or Southern Yellow Pine (SYP) species with designated fiber bending strength (or Modulus of Rupture, MOR) ranging from 41.4 MPa (6,000 psi) to 55.2 MPa (8,000 psi). Most tangent poles are directly embedded into the ground to a given depth, usually equal to 10% of pole length plus 0.6 m (2 ft.). Design is governed by bending at the ground line and embedment depth needed to resist lateral overturning forces. Note that the MOR values are *mean* values with a coefficient of variation (COV) ranging from 0.17 to 0.20 per ANSI Standard O5.1 [3] for poles smaller than 15.2 m (50 ft.). Wood is a bio-degradable material, and therefore from a structural perspective, strength reduction factors are normally specified in wood design to account for the statistical variation, decay and decrease of wood strength with time [4], [5].

Composite materials are generally non-isotropic with elastic properties varying with the direction and orientation of the constituent fibers relative to the applied loads. They also depend

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on the type of resin bonding materials used in construction, which transfers stresses to the fibers in the laminate. To facilitate easier analysis, engineers often use "bulk" material properties that represent the global response of the structure to a given loading. These properties are determined through full-scale bend testing and theoretical calculations.

RS Technologies Inc.'s [6], [7] filament-wound, *tapered*, modular composite poles – which are used in this study along with pultruded poles – are rated for a designated fiber (bending) stress ranging from 125 MPa (18,170 psi) to 288 MPa (41,870 psi) depending on the module diameter and wall thickness. RS Technologies' *constant- diameter* pultruded poles [8] are generally known to sustain stresses up to 372 MPa (54,000 psi). Like wood, tangent composite poles are embedded into the ground to a depth of 10% pole length plus 0.6 m (2 ft.). Design is governed by strength – flexural capacity or bending stress at the ground line.

III. RELIABILITY BASED DESIGN OF UTILITY STRUCTURES

Utility structures in the United States [9] and Canada [10] are designed on the basis of Load and Resistance Factor Design (LRFD) [11] where the statistical variability of applied loads is matched with that of the resistance to reduce the potential for failure. This method is also called Reliability-Based Analysis and Design (RBAD) since it provides a specified level of design reliability based on the occurrence of climactic events such as hurricanes and ice storms. Table 1 shows a typical relationship between Reliability Index β and Probability of Failure P_f. Engineers often use a target value of β = 3.0 as a reasonable design goal to achieve.

TABLE I. TYPICAL VARIATION OF P_f WITH BETA

Reliability Index Beta β	**Probability of Failure P_f**
0	0.500
1	0.159
2	0.0228
2.33	0.0099
3.00	*0.00136*
3.09	0.001
3.54	0.0002
4.75	0.000001

For more understanding of the various loading criteria and structural element resistance related to an RBAD, the reader is referred to the abundant literature available on the topic [12], [13]. The standards of reliable performance of utility pole structures are discussed in ASCE Manual of Practice 111 [14]. Guidelines governing the performance of FRP composite utility pole structures are outlined in the ASCE Manual of Practice 104, Second Edition [15].

Some basic features of RBAD, as used in this study, are as follows:

A. Reliability-Based Analysis

The definition of a Reliability Index for a *normally distributed variable* is:

$$\beta = M_R - M_W \,/\, sqrt(\sigma_R^2 + \sigma_W^2) \qquad \text{(A-1)}$$

where:

M_R = Mean value of Resistance as determined from testing

$$= (P_R) * (L_{AG} - 0.6) \qquad \text{(A-2)}$$

M_W = Mean Value of Applied Load Effects

$$= (P_A) * (L_{AG} - 0.6) \qquad \text{(A-3)}$$

P_R = Maximum Test Load Rating
P_A = See Section B below
L_{AG} = Pole Height above Ground
σ_R = Standard Deviation of Resistance = (COV_R) * (M_R)
σ_W = Standard Deviation of Load Effect = (COV_W) * (M_W)
COV_R = Coefficient of Variation of Resistance
COV_W = Coefficient of Variation of Load Effect

Load Effect $\mathbf{M_W}$ is the *applied* bending moment at the ground line (GL) due to a lateral load P_A applied 60 cm from the top.

Resistance $\mathbf{M_R}$ is the bending moment *capacity* at the ground line (GL) based on test load P_R.

The following values of COV's are used in the study:
WRC Wood COV_R = **0.204** applied to the maximum bending stress or MOR [3]
SYP Wood COV_R = **0.169** applied to the maximum bending stress or MOR [3]
Modular Pole COV_R = **0.05** (nominal) [15]
Pultruded Pole COV_R = **0.07 [**8]
All Load Effects COV_W= **0.09** applied to the wind load [18], [19].

B. Calculation of Applied Loads P_A

Effective span = 300 ft. (91.4 m)
Number of conductors = 4 (3 phase, 1 Neutral)
Diameter of the conductor = 1.0" (25 mm)
Wind speed V = 120 mph (193 kmph)
Wind pressure w = 0.00256 V^2 = (0.00256)(120)(120) = 36.9 psf (1767 Pa)
Wind force acting on pole P_A = (4)(300)(1/12)(36.9) = 3690 lbs. (16.42 kN)
Moment M_W due to Applied Load P_A is calculated using Equation A-3.

IV. RELIABILITY ASSESSMENT OF SELECTED POLES

The basic principles of structural reliability, loads, resistances and associated equations are explained in the previous section. These concepts are now applied to a select set of wood and composite poles and their performance is assessed in terms of probabilistic resistances (obtained from tests) and applied wind loads. For strength rating purposes, the ANSI Standard classifies poles in terms of a single lateral (cantilever) load applied 0.6 m (2 ft.) below the top of the pole as shown in Figure 1.

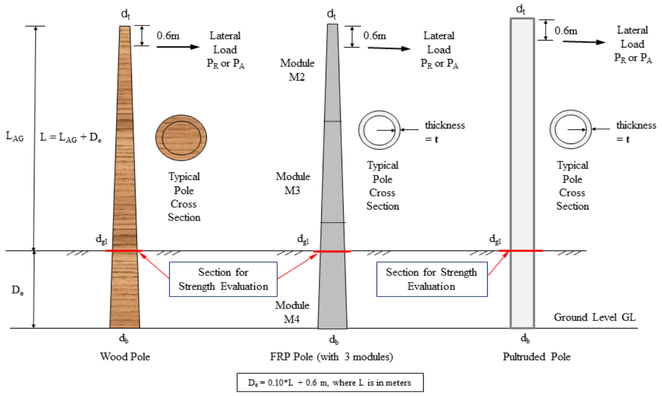

Figure Not to Scale. For simplicity, actual slip joints in FRP are not shown.

Figure 1. Wood and Composite Poles: Geometric Configuration

For simplicity, it is assumed that all load and resistance variables are normally distributed.

The selected groups of poles are shown in Table 2 (wood) and Table 3 (composite). All wood poles are ANSI Class 1. *The resistance ratings shown in the tables are the* ***average*** *of measured values at or near ground line from full-scale tests [16]-[18].* Since the resistances P_R are actual *measured* values, no strength reduction factors are applied to them. It is noticed that the average P_R values of WRC and SYP are somewhat higher than ANSI Class 1 value (20 kN or 4,500 lbs.), but falls within the range of variation given in the ANSI Standard [3]. All associated coefficients of variation (COV), given in section III above, also refer to the test data.

To maintain consistency in comparison, all load effects due to applied loads correspond to a typical 4-wire distribution pole as seen in Figure 2 and subject to 120 mph (193 kmph) wind. The related calculations are shown in section III-B. The associated coefficient of variation (COV) for wind velocity is taken as 0.09, consistent with values reported in literature [18], [19]. Wind loads are generally known to follow Weibull or Extreme Value Distributions; but for the sake of simplicity, a normal distribution is assumed. This load is applied as a point load consistent with the ANSI cantilever definition. Only wind on wires is considered and wind on pole is excluded.

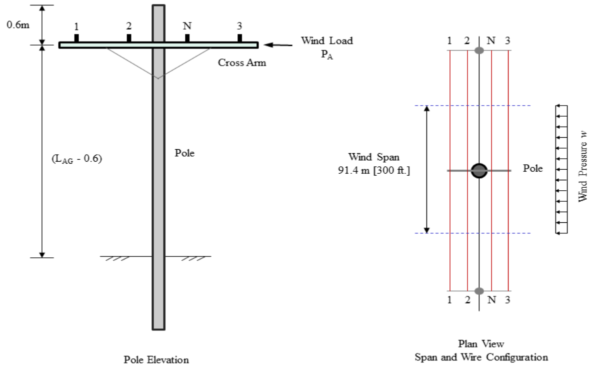

Figure 2. Scheme for Calculation of Wind Load on Poles

Tables 4 and 5 show the geometric data of the selected poles, along with the moment capacity (resistance) based on test loads (see Appendix for related equations). Table 6 and Table 7 show the reliability calculations for wood and composite poles, respectively. Composite poles consistently showed larger reliability indices. The average reliability index β for composite poles is 7.597 whereas that for the wood poles is 1.680. That is, composite poles are more than 4.5 times safer than wood poles at the wind load imposed.

In terms of probabilities of failure, this translates to the following inferred values (see Table I):

Composite: Probability of Failure P_f for $\beta = 7.597$ is less than 0.000001
Wood: Probability of Failure P_f for $\beta = 1.680$ is 0.0664

Numerically, this means for every 1000 poles considered in a high wind loading situation, wood poles would experience about 66 failures whereas composite poles would experience virtually no failures at all.

V. CONCLUSIONS

In this study, we investigated the structural reliability of composite poles (modular and pultruded) in comparison with two species of wood poles. All poles are 13.7 m (45 ft.) long. Ground line resistances of all poles are based on failure loads from full-scale bending tests. Applied loads correspond to a distribution pole supporting four (4) conductors in a 120 mph (193 kmph) high wind situation. Main inferences from the reliability analyses of the poles of this study are:

1. Composite poles consistently showed higher structural reliability than wood poles;
2. The average reliability index of composite poles (7.597) is more than four and half times that of wood poles (1.680) for the same level of wind loading;
3. From a weight versus reliability perspective, composite poles are 60% lighter than wood but four times more reliable; and,
4. With almost zero probability of failure, composite poles are better suited for regions exposed to high winds events (including hurricanes, tornadoes and straight-line winds) for strategic as well as one-on-one replacement for wood poles.

This study considered Western Red Cedar (WRC) and Southern Yellow Pine (SYP) wood poles, but the results can also be considered applicable to other types of wood. The wood pole used here is Class 1 but lower classes (2, 3, and below), along with other pole lengths, may be examined in a future study. Reliabilities at other climactic loads, such as ice and combined ice and wind, may also be considered in the future. Though this study focused on just two pole materials, namely wood and composite, the concepts can be extended to poles of other materials. Further studies are needed before the observations made herein can be generalized.

ACKNOWLEDGEMENT

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CONVERSION FACTORS

1 m = 3.28 ft. 1 kg = 2.204 lbs. 1 kN = 4.45 kips 1 kN-m = 0.737 kip-ft.

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TABLE II. SELECTED WOOD POLES: CLASSES, LOAD RATINGS AND WEIGHTS

Wood Pole Group	Pole Length L (m)	ANSI Class	No. of Tests *	Average Test Load Rating * P_R (kN)	Pole Weight (kg)
WRC	13.7	1	3	19.2	605
SYP	13.7	1	3	28.3	975

* pole failure at or near the ground line only

TABLE III. SELECTED COMPOSITE POLES: CODES, LOAD RATINGS AND WEIGHTS

Pole Group Type	**Pole Length L (m)**	**RS Pole Modules**	**RS Pole Code**	**No. of Tests ***	**Average Load Rating * P_R (kN)**	**Pole Weight (kg)**
Modular	13.7	M2 M3 M4	PP-0450-F-0204-C	4	41.5	301
Pultruded	13.7	N/A	UU-450-F-D4-X1-000	5	29.4	314

* pole failure at or near the ground line only

TABLE IV. WOOD POLE GEOMETRIC AND STRENGTH DATA

Wood Pole Group	**Pole Length L (m)**	**Embed D_e (m)**	**Height Above Ground L_{AG} (m)**	**Average Test Load Rating P_R (kN)**	**Moment Capacity M_R (kN-m)**
WRC *	13.7	2.0	11.7	19.2	213.9
SYP *	13.7	2.0	11.7	28.3	315.3

* For pole cross section dimensions, refer to [3]

TABLE V. COMPOSITE POLE GEOMETRIC AND STRENGTH DATA

Pole Group Type	**RS Pole Modules**	**RS Pole Code**	**Pole Length L (m)**	**Embed D_e (m)**	**Height Above Ground L_{AG} (m)**	**Average Test Load Rating P_R (kN)**	**Moment Capacity M_R (kN-m)**
Modular	M2 M3 M4	PP-0450-F-0204-C *	13.7	2.0	11.7	41.5	462.3
Pultruded	N/A	UU-450-F-D4-X1-000 *	13.7	2.0	11.7	29.4	327.5

* For pole/module dimensions, refer to [7] and [8]

TABLE VI. RELIABILITY ANALYSIS OF WOOD POLES

Wood Pole Group	**Moment Capacity M_R (kN-m)**	**Applied Moment M_W (kN-m)**	**Std. Dev. σ_R (kN-m)**	**Std. Dev. σ_W (kN-m)**	**Reliability Index β**
WRC	213.9	182.9	47.3	16.5	0.981
SYP	315.3	182.9	53.3	16.5	2.379
				Average	**1.680**

TABLE VII. RELIABILITY ANALYSIS OF COMPOSITE POLES

Pole Group Type	**Moment Capacity M_R (kN-m)**	**Applied Moment M_W (kN-m)**	**Std. Dev. σ_R (kN-m)**	**Std. Dev. σ_W (kN-m)**	**Reliability Index β**
Modular	462.3	182.9	23.1	16.5	9.859
Pultruded	327.5	182.9	22.9	16.5	5.334
				Average	**7.597**