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STRUCTURAL RELIABILITY OF WOOD AND COMPOSITE POLES SUBJECT TO HURRICANE WINDS

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ABSTRACT

The structural reliability of wood and composite distribution poles in hurricane wind environments is investigated. Numerical values of reliabilities of ten (10) selected poles ranging from 10.7 m to 16.7 m (35 ft. to 55 ft.), with standard embedment, are computed and compared. Applied loads correspond to a typical, 4-wire distribution pole subject to 210 kmph (130 mph) wind. Though limited and preliminary, this study showed that composite poles offer a higher level of reliability than wood poles for the high-wind loading considered. Composite poles are ideal for pole replacement in hurricane-prone areas and to meet the additional demand for resilience and reliability.

Keywords: Composite, distribution, modular, poles, polymer, reliability, wood.

INTRODUCTION

Hurricanes, tornadoes, and ice storms cause substantial damage to overhead utility lines every year requiring emergency system restoration and rebuilding. This system rebuilding process is often aimed at *hardening* or strengthening of the electrical power infrastructure to prevent future damage and reduce or eliminate outages due to structural failures.

Wood, steel, lattice, concrete, laminated wood and composite (FRP or Fiber-Reinforced Polymer) currently comprise the materials used in transmission and distribution structural systems. Among these, wood is the dominant choice of material in nearly 95% of distribution lines (ANL, 2016). Each year at least 3.6 million damaged or failed wood poles are replaced while 1.9 million new poles are installed (Kalaga, 2013).

Composite poles are currently becoming increasingly popular in the utility industry at both transmission and distribution levels. The advantages they offer include established engineered performance, light weight, great flexural strength and ease of installation, safe against almost all weather-related effects, excellent fire resistance, and finally, an estimated maintenance-free service life of nearly 80 years.

A review of literature shows that most research on utility poles – both analytical and experimental – is focused on determining pole strength under various load conditions. Previous reliability studies (Kalaga, 2022) dealt with assessing probability of failure under standard or test loads. There is little information available on evaluating and comparing the actual structural reliabilities of wood and composite poles in a *hurricane or high-wind loading environment*. Such a quantitative assessment will be helpful to utility owners in planning for pole replacements after a climactic event. The present study is a small step towards that goal and is focused only on a nominal comparison of the mathematical reliabilities of WRC (Western Red Cedar) wood and filament-wound, modular composite poles when subject to extreme wind loads. Only tangent distribution–size poles (voltages under 46 kV) with pole lengths ranging from 10.7 m (35 ft.) to 16.7 m (55 ft.) are considered. All poles are directly embedded into the ground to a depth of 10% of pole length plus 0.6 m (2 ft.).

MATERIALS AND METHODS

POLE MATERIAL DATA

Western red cedar wood poles

1. Designated fiber bending strength (or Modulus of Rupture, MOR) of 41.4 MPa (6,000 psi).
2. Modulus of Elasticity (MOE) is 10.96 GPa (1,590 ksi)
3. Design is governed by bending at the ground line.

Note that the MOR is a *mean* value with an *average* coefficient of variation (COV) of 0.20 corresponding to ANSI data for all un-guyed poles (ANSI, 2017). Wood is

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also a bio-degradable material, and therefore from a structural perspective, strength reduction factors are specified for design to account for the statistical variation, decay and decrease of wood strength with time (RUS, 2015; USDA, 2001). For extreme wind loads, current guidelines (NESC, 2017) specify a strength reduction factor of 0.75 for all wood structures.

Modular composite poles

RS Technologies Inc.'s (RS Tech., 2012] filament-wound FRP poles are used in this study.

1. Fiber (bending) strengths range from 125 MPa (18.17 ksi) to 288.5 MPa (41.87 ksi) depending on the module and wall thickness.
2. Modulus of Elasticity (MOE) usually varies from 16.7 GPa (2,422 ksi) to 24 GPa (3,481 ksi) depending on module.
3. Design is governed by strength (flexural capacity or bending stress) at the ground line.

For extreme wind loads, current guidelines (NESC, 2017) specify a strength factor of 1.0 for all composite structures.

Reliability of utility structures

Design of transmission and distribution structures in North America is based on Load and Resistance Factor Design or LRFD approach (ASCE, 2019; NESC, 2017; RUS, 2015; CAS, 2015). This approach matches the statistical variability of imposed loads with the variability of structural resistance to help reduce the potential for failure. It is also known as Reliability-Based Analysis and Design (RBAD) as it provides a known level of design reliability based on the Return Period (RP) or Mean Recurrence Interval (MRI) of climactic events such as hurricanes and ice storms. The current default MRI is 100 years (ASCE, 2019), although larger periods of 200 years and above are often used in special circumstances.

Table 1 shows a typical relationship between Reliability Index β and Probability of Failure P_f. Engineers often choose a design target of β = 3.0 which translates to a failure probability of roughly 1.4 poles out of 1000 poles.

The basic principles of structural reliability, applied loads, resistances, and associated equations are given in Appendix 1.

The reader is referred to the literature available on the topic (Ang and Tang, 1984; Kharmanda, 2016) for more information on the various loading criteria and individual structural element resistance related to RBAD. ASCE Manual of Practice 111 (ASCE, 2006) gives the general requirements of reliability for utility pole structures. Guidelines governing the performance of composite utility pole structures are given in the ASCE Manual of Practice 104 (ASCE, 2019).

Reliability assessment of selected poles

The reliability concepts of Appendix 1 are applied to a selected set of five (5) wood and five (5) equivalent modular composite poles and their performance is assessed in terms of probabilistic resistance and applied loads. See Figure 1 for geometry of poles used in this study as well as ANSI definition of pole strength in terms of a single lateral (cantilever) load applied 0.6 m (2 ft.) below pole top.

For simplicity, resistance variables are assumed to be normally distributed. The following coefficients of variations (COV) are used:

Wood COV_R = **0.20** applied to the maximum bending stress or MOR (ANSI, 2017)

Composite COV_R = **0.05** applied to the maximum flexural stress in the material (ASCE, 2019)

Applied Load Effects COV_W= **0.09** applied to the wind load

Wind loads generally follow a Weibull or other Extreme Value distribution but for simplicity are assumed to be normally distributed for this paper. The COV for wind pressure (0.09) is taken from an average of those suggested in literature (Joffre and Laurila, 1988; NCHRP, 2003).

The selected sets of poles and their load ratings are shown in Table 2 (wood) and Table 3 (composite). The poles cover a length range of 10.7 m to 16.7 m (35 ft. to 55 ft.) common in distribution applications. The filament-wound composite poles correspond to the wood equivalents obtained from the Pole Selector algorithm of RS Poles (RS Tech., 2015).

Factored load ratings of wood poles of Table 2 include a strength reduction factor of 0.75 mandated by NESC for extreme wind (Rule 250-C) loads. The composite pole load ratings of Table 3 are based on RS Poles Technical Binder (RS Tech., 2012) and are calibrated on the basis of testing. The ground line moment capacity of composite poles is roughly based on these load ratings. The strength factor used for composite poles is 1.00, per NESC.

The applied lateral load P_A is the wind load on wires computed using the process shown in Appendix 2 and corresponding to the pole and 91.4 m (300 ft.) span wire configuration shown in Figure 2. Effect of wind on pole is excluded.

Table 1. Typical Variation of P_f with Beta.

Reliability Index Beta β	Probability of Failure P_f
0	0.5000
0.20	0.4215
0.25	0.4021
0.50	0.3092
1	0.1591
2	0.0228
2.33	0.0099
3.00	*0.00136*
3.09	0.001
3.54	0.0002
≥ 4.75	0.000001

Table 2. Selected Wood Poles: Lengths, Load Ratings and Weights.

Wood Pole No.*	Pole Length L (m)	Un-factored ANSI Load Rating [a] (kN)	Factored ANSI Load Rating [a, b] (kN)	Approximate Pole Weight (kg)
1	10.7	20.0	15.0	410
2	12.2	20.0	15.0	505
3	13.7	20.0	15.0	605
4	15.2	20.0	15.0	715
5	16.7	20.0	15.0	828

[a] Applied 0.6 m from the tip of the pole
[b] with 0.75 strength (reduction) factor
* All poles are ANSI Class 1

Table 3. Selected Composite Poles: Lengths, Load Ratings and Weights.

Composite Pole No.	Pole Length L (m)	RS Pole Modules	RS Pole Code**	RS Load Rating [a, b] (kN)	Pole Weight (kg)
1	10.7	M2 M3 M4	PP-0350-F-0204-C	30.9	257
2	12.2	M2 M3 M4	PP-0400-F-0204-C	26.3	280
3	13.7	M3 M4 M5	PP-0450-F-0305-C	33.0	380
4	15.2	M2 M3 M4 M5	PP-0500-F-0205-C	29.2	417
5	16.7	M2 M3 M4 M5	PP-0550-F-0205-C	25.8	440

[a] Applied 0.6 m from the tip of the pole [b] Based on RS Technologies Design Binder [RS Tech., 2012]
** based on RS Pole Selector [RS Tech., 2015]

Table 4. Wood Poles: Geometric and Strength Data *.

Wood Pole No.	Pole Length L (m)	Embed D_e (m)	Height Above Ground L_{AG} (m)	GL Diameter d_{gl} (mm)	Moment of Inertia I (x 10^8 mm^4)	Section Modulus S (x 10^6 mm^3)	Moment Capacity M_R (kN-m)
1	10.7	1.8	8.9	343.7	6.84	3.98	123.6
2	12.2	1.8	10.4	363.7	8.60	4.73	146.7
3	13.7	2.0	11.7	382.0	10.44	5.47	169.7
4	15.2	2.1	13.1	396.0	12.08	6.10	189.3
5	16.7	2.3	14.4	410.0	13.91	6.78	210.5

* All Poles are ANSI Class 1, Western Red Cedar (MOR = 41.4 MPa)

Table 5. Composite Poles Geometric and Strength Data.

Composite Pole No.	Pole Length L (m)	Embed D_e (m)	Length L_{AG} (m)	GL Diameter d_{gl} (mm)	GL Module Thickness 't' (mm)	Module Flexural Strength * f_m (MPa)	Moment of Inertia I (x10^8 mm^4)	Section Modulus S (x10^6 mm^3)	Moment Capacity M_R (kN-m)
1	10.7	1.8	8.8	427	9.7	205.2	2.96	1.385	284
2	12.2	1.8	10.4	427	9.7	205.2	2.96	1.385	284
3	13.7	2.0	11.7	500	9.7	199.3	4.74	1.896	378
4	15.2	2.1	13.1	497	10.3	199.3	4.96	1.999	399
5	16.7	2.3	14.4	494	10.3	199.3	4.87	1.974	394

* based on module at Ground Line GL

Table 6. Reliability Analysis of Wood Poles.

Wood Pole No.	Pole Height Above Ground L_{AG} (m)	Moment Capacity M_R (kN-m)	Wind Load P_A (kN)	Applied Moment M_W (kN-m)	Std. Dev. σ_R (kN-m)	Std. Dev. σ_W (kN-m)	Reliability Index β
1	8.8	123.6	19.3	159	24.7	14.2	0.220
2	10.4	146.7	19.3	188	29.3	17.0	0.228
3	11.7	169.7	19.3	214	33.9	19.3	0.306
4	13.1	189.3	19.3	241	37.9	21.7	0.267
5	14.4	210.5	19.3	267	42.1	24.0	0.277
						Average	0.260

Table 7. Reliability Analysis of Composite Poles.

Composite Pole No.	Pole Height Above Ground L_{AG} (m)	Moment Capacity M_R (kN-m)	Wind Load P_A (kN)	Applied Moment M_W (kN-m)	Std. Dev. σ_R (kN-m)	Std. Dev. σ_W (kN-m)	Reliability Index β
1	8.8	284	19.3	159	14.2	14.2	6.247
2	10.4	284	19.3	188	14.2	17.0	4.367
3	11.7	378	19.3	214	18.8	19.3	6.063
4	13.1	399	19.3	241	19.9	21.7	5.362
5	14.4	394	19.3	267	19.7	24.0	4.073
						Average	**5.222**

Tables 4 and Table 5 show the calculated geometric data of the selected poles, along with the moment capacity (resistance) based on elastic material properties. All geometric properties refer to the Ground Line (GL). The wood data refers to ANSI and those of composite poles refer to the datasheets in the RS Poles Technical Binder. Section properties for modular poles are computed using tubular, thin-walled cross section equations available in literature (ASCE, 2012).

RESULTS AND DISCUSSION

Tables 6 and Table 7 show the reliability calculations for wood and composite poles, respectively. Composite poles consistently showed larger reliability indices. The low reliability of wood poles is attributed to the reduced (factored) resistance large COV for wood properties (0.20) coupled with a high COV of wind loads (0.09). In comparison, the composite poles have no strength reduction and little variation in elastic parameters. The average reliability index β for composite poles is 5.222 whereas that for the wood poles is 0.260. In terms of probabilities of failure, this translates to the following values (see Table 1):

Composite: Probability of Failure P_f for β = 5.222 is less than 0.000001
Wood: Probability of Failure P_f for β = 0.260 is 0.398

Numerically, this means that for every 1000 poles subject to 210 kmph (130 mph) wind loads, wood poles would experience nearly 400 failures whereas composite poles would experience no failures at all.

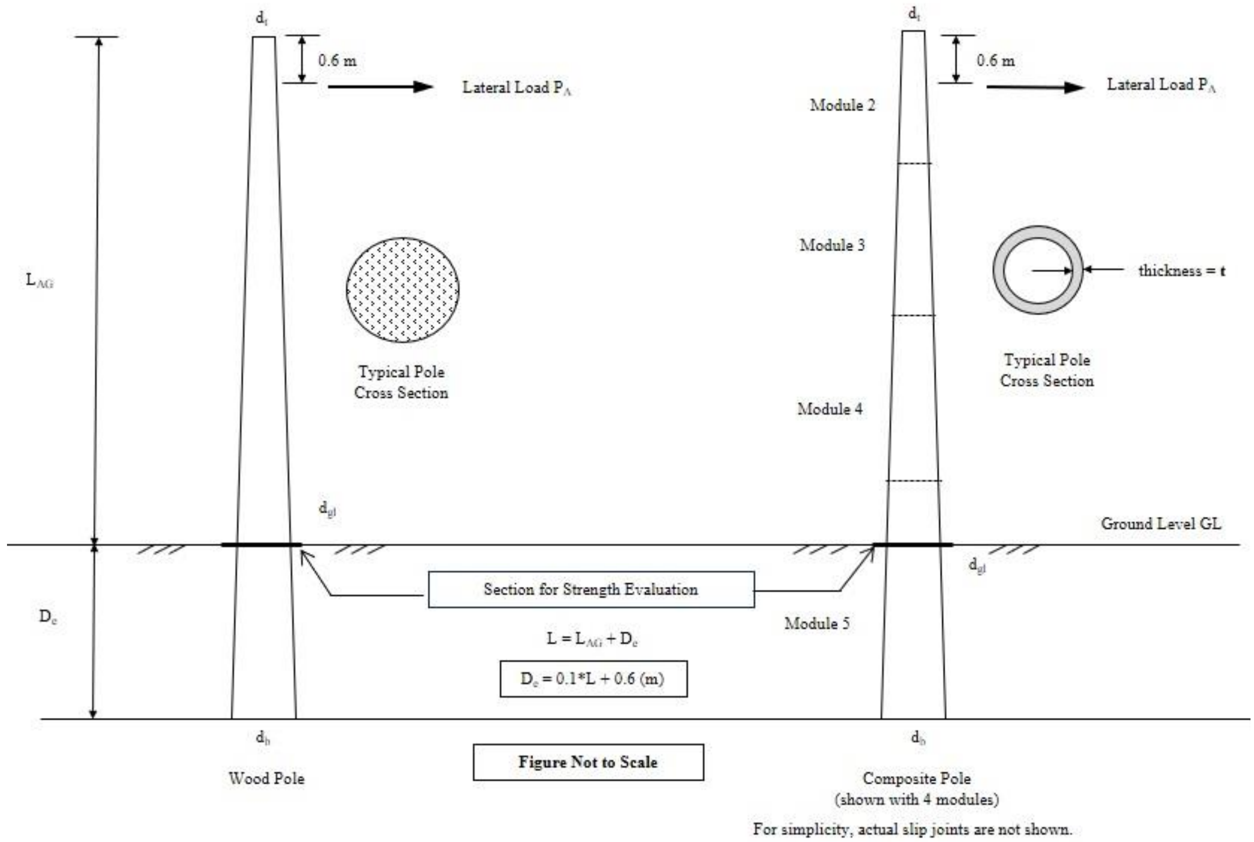

Fig. 1. Wood and Composite Poles: Geometrical Configuration.

If one were to reverse-calculate the wood pole class required to sustain the imposed hurricane wind loads, using Equation (A-1) for computing M_R for a β of 3.0, it can be seen that Class H5 is needed for 13.7 m (45 ft.) and 15.2 m (50 ft.) poles. (Class H5 is not available for lengths lower than 13.7 m). Class H5 wood poles would also mean 60% heavier poles compared to composites.

CONCLUSIONS

In this study, we investigated the mathematical structural reliability of modular, Fiber-Reinforced Polymer (FRP) composite poles in comparison with Western Red Cedar wood poles. Pole lengths ranged from 10.7 m to 16.7 m (35 ft. to 55 ft.). All wood poles are of Class 1. Applied loads corresponded to a typical distribution pole with 4-wires (3 phases and 1 neutral) with a wind span of 91.4 m (300 ft.). Wind pressure corresponded to 210 kmph (130 mph) wind velocity.

Inferences from reliability analyses of the small, limited set of 10 (ten) poles studied here include:

1. Composite poles showed significantly higher structural reliability than wood poles.
2. The computed average reliability index of composite poles is 5.222 while the corresponding value for wood poles is 0.260.
3. From a weight-versus-reliability perspective, composite poles are 60% lighter than wood which translates to lower shipping and transportation costs.
4. Given the low probabilities of failure, composite poles are ideally suited for hurricane-prone areas as a one-on-one replacement for wood poles or as a strategic alternative to wood poles.

This investigation used Western Red Cedar (WRC) wood poles, but the results are also applicable to other types of wood. To complement this study, reliabilities at other climactic loads involving ice and wind (such as NESC District Loads 250-B and 250-D), can be studied in the future. Deflections of poles are not considered here, but if proper definitions of service loads and/or deflection limits are available, future editions of this study may assess reliabilities subject to such limits. Additional work is also needed where the exact wind speed probability distributions are utilized in modeling. Further studies are needed before the findings here can be generalized in any shape or form.

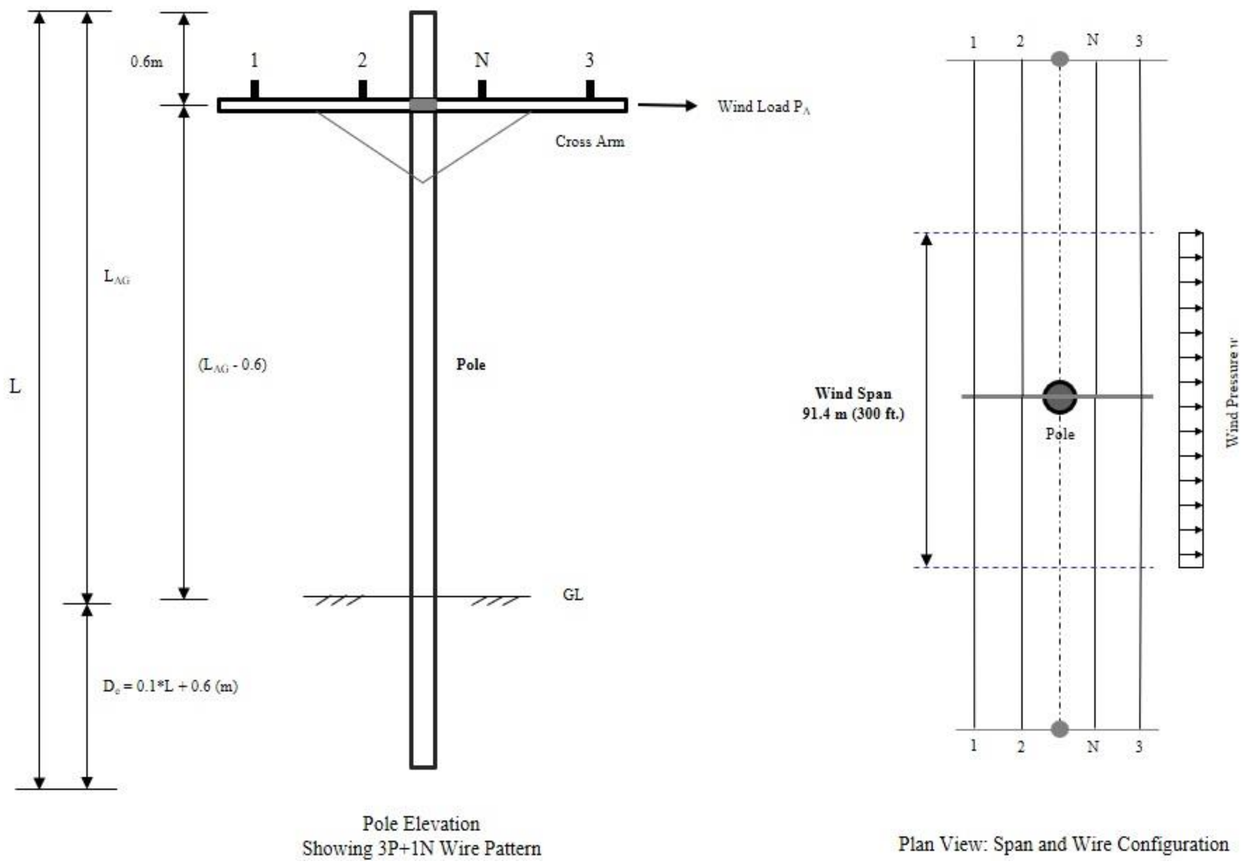

Fig. 2. Scheme for Calculation of Wind Load on Poles.

Additional note

The intent of this small study is to evaluate numerical reliability of a selected set of poles of the same class, height, embedment and loading. It is a pure scientific enquiry and implies no bias of any kind.

Appendix 1 Reliability principles

The traditional 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 at GL determined from A-2 or A-3

M_W = Mean Value of Applied Load Effects at GL = $(P_A) * (L_{AG} - 0.6)$

P_A = See Appendix 2 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

For circular wood cross sections:
$$M_R = (S) * (MOR) = (\pi * d_{gl}^3/32) * (MOR) \quad \text{(A-2)}$$

S = Section Modulus

d_{gl}= Pole Diameter at GL

MOR = Modulus of Rupture or Wood Fiber Strength

For tubular composite (FRP) cross sections:
$$M_R = (S) * (f_m) = (0.786 * d_{gl}^2 * t) * (f_m) \quad \text{(A-3)}$$

S = Section Modulus

d_{gl} = Pole Diameter at GL

t = pole module thickness at GL

f_m = Flexural Strength of the pole module at the GL

Appendix 2 Calculation of applied wind loads P_A

Effective span = 91.44 m (300 ft.)

Number of conductors = 4 (3 phase, 1 Neutral)

Diameter of the conductor = 25 mm (1")

Wind speed V = 210 kmph (130 mph)

Wind pressure w = 0.00256 V^2 = (0.00256)(130)(130) = 43.3 psf (2.07 kPa)

Wind force acting on pole P_A = (4)(300)(1/12)(43.3) = 4330 lbs. (19.3 kN)

Moment M_W due to Applied Load P_A is calculated using Equation A-3

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