Reliability Assessment of Transmission Poles

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***Abstract* — The structural reliability of round wood and fiber-reinforced polymer (FRP) composite transmission poles is investigated. Numerical reliabilities at ultimate loads for 20 poles are computed and compared. The main inference from this limited study is that FRP poles showed higher structural reliability than wood poles; the average reliability index of FRP poles is more than three times that of wood. It is suggested that composite poles offer better long-term performance, resilience and reliability when used in hurricane-prone and other high-load areas.**

***Keywords* — Composite, Distribution, Modular, Poles, Polymer, Reliability, Transmission, Wood.**

I. Introduction

In North America, extreme weather events such as major hurricanes, tornadoes, and ice storms cause substantial damage to the overhead transmission and distribution lines every year. The end effect of these events is the demand for emergency system restoration and rebuilding, where the costs of which are eventually borne by electric utilities' customers. A detailed discussion of the occurrences, statistics, after-effects, and losses due to weather-related disasters in North America is available in the literature [7], [10].

Integral to a utility system rebuilding process is the idea of *hardening* the power infrastructure to prevent future storm damage and reduce or eliminate power outages due to structural failures. This storm-hardening can be performed on the basis of various considerations:

a) Utilizing only engineered pole materials provides a reliable structural capacity

b) Upgrading existing pole designs to achieve better structural resilience and reliability

A wide range of materials are employed worldwide in the design, construction and restoration of transmission and distribution structures. Round wood, tubular steel, latticed steel, pre-stressed concrete, laminated wood and FRP (fiber-reinforced polymer) composites are the materials currently used in electric utility structures. Wood is the most predominant material and is reportedly used in nearly 95% of distribution lines and low-voltage transmission lines [7]. It is estimated that there are about 130 million *wood* utility poles in service across North America. Some studies [12] indicate that about 3.6 million wood poles are replaced each year in addition to the installation of 1.9 million new poles.

FRP 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 known engineered performance, lightweight, excellent flexural strength, easy installation, structural resiliency, immunity to most weather-related effects, little or no required maintenance, good fire resistance, impervious to pests including woodpeckers and an estimated service life range of 70 to 80 years.

During the past few decades, 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 at ultimate load levels. The present study is a small, preliminary step in that direction.

This study is focused on just two pole materials: **wood and composite** and is limited to round wood and filament-wound, modular FRP composite poles. Only transmission–size poles with total pole lengths ranging from 16.8 m [55 ft.] to 30.5 m [100 ft.] are considered.

II. Pole Materials

A. Round Wood

Wood poles used for distribution or transmission purposes are generally of Western Red Cedar, Douglas Fir or Southern Yellow Pine species with designated fiber bending strength (or Modulus of Rupture, MOR) ranging from 35.9 MPa [5,200 psi] to 58.1 MPa [8,400 psi]. Tangent poles are directly embedded into the ground to a specified depth. For single, free-standing poles, design is governed by bending at the ground line and setting depth needed to resist lateral overturning forces. Modulus of Elasticity (MOE) usually varies from 10.96 GPa [1,590 ksi] for Western Red Cedar to 18.2 GPa [2,640 ksi] for Douglas Fir. Note that these MOR and MOE values are *mean* values with a coefficient of variation (COV) ranging from 0.14 to 0.23.

The ANSI Standard O5.1 [8] categorizes wood poles into various classes in terms of a single lateral (cantilever) load applied 0.6m [2 ft.] below the top of the pole (see Fig. 1). Wood is also 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 [19], [20].

B. FRP Composites

Fiber-reinforced Polymer (FRP) composite materials are generally non-isotropic, and their elastic properties vary based on the direction and orientation of the constituent fibers with reference to applied loads. They are also dependent on the type of resin bonding materials used in construction, which transfers the stress to the fibers in the laminate. To facilitate easier analysis, engineers often use "bulk" material properties that represent the global response of the structure

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to a given loading. These properties are determined through vertical full-scale physical bend testing and theoretical calculations.

RS Technologies Inc.'s [18] filament-wound modular composite poles – which are used in this study – are rated for a designated fiber (bending) stress ranging from 125 MPa [18,170 psi] to 288.5 MPa [41,870 psi] depending on the module diameter and wall thickness. Tangent poles are directly embedded into the ground to a specified depth. In single, free-standing poles, design is governed by strength (flexural capacity or bending stress at the ground line) as well as stiffness (deflection). Modulus of Elasticity (MOE) usually varies from 16.7 GPa [2.42 ksi] to 24 GPa [3.48 ksi].

III. Reliability Of Utility Structures

Transmission and distribution structures in the United States and Canada are designed on the basis of Load and Resistance Factor Design (LRFD) where the statistical variability of applied loads is matched with that of the resistance to reduce the possibility of failure. This approach is also called Reliability-Based Analysis and Design (RBAD) since it provides a specified level of design reliability based on the Return Period (RP) or Means Recurrence Interval (MRI) of climactic events such as high winds and ice storms. The default MRI per Manual 74 [3] is 100 years, although larger periods are often used in special circumstances. Table I shows a typical relationship between Reliability Index β and Probability of Failure P_f. Engineers often consider $\beta = 3.0$ as a reasonable reliability target to achieve in design.

All electric utility overhead design in the United States is governed by the IEEE's National Electrical Safety Code [16] which is basically a "safety" code. Agencies such as RUS also provide guidelines for *rural* transmission and distribution line design, including structures and foundations [19]. However, structural design guidelines for poles, frames, and towers are stipulated by ASCE [2]-[4]. The NESC also draws heavily from ASCE Standards [1]. In Canada, all overhead electric utility line designs are governed by CSA [9] which requires a different approach to design (limit states).

For a detailed 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 [5], [6], [13]-[15].

The standards of reliable performance of utility pole structures are discussed in Manual of Practice 111 [5]. Guidelines governing the performance of FRP composite utility pole structures are outlined in the Manual of Practice 104, Second Edition [4].

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

IV. Structural Reliability Assessment

The basic principles of structural reliability are explained in Appendix. The concepts are applied to a selected set of wood and modular composite poles and their performance is assessed in terms of probabilistic resistance and applied loads. It is assumed that all resistance variables are normally distributed. Loading is the cantilever-type load per ANSI (Fig. 1).

A. Selected Poles

Twenty (20) poles, consisting of ten (10) each of wood and composite, are chosen to evaluate structural reliability at ultimate load levels. The selected sets of poles are shown in Table II (FRP) and Table III (wood). The poles cover a range of lengths, 16.8 m to 30.5 m [55 ft. to 100 ft.] used in transmission applications. All wood poles are of Western Red Cedar and vary from ANSI Class 1 to Class H2, with mean MOR taken as 41.3 MPa (6,000 psi) for calculation purposes. The filament wound FRP composite poles also correspond to the same lengths and ANSI O5.1 classes.

(In Table II, the superscripts *a* and *b* refer to the following: *a* – applied 0.6 m from the top of the pole and *b* – based on RS Technologies Design Binder's recommended working ultimate load)

(In Table III, the superscripts *a*, *b*, *c* and * refer to the following: *a* – applied 0.6 m from the top of the pole, *b* – does not contain any strength reduction factor, *c* – contains 0.65 strength reduction factor) and * indicates weight rounded off to the nearest 5 kgs)

The RS pole load ratings of Table II are based on data developed from full-scale testing and are less than or equal to 5% LEL (lower exclusion limit) strength values. Factored load ratings of wood poles of Table III include a strength reduction factor of 0.65 mandated by NESC. All poles refer to NESC Grade B construction.

Table IV and Table V show the calculated geometric data of the selected poles, along with the moment capacity (resistance) based on elastic material properties (Appendix). All geometric properties refer to the ground line (GL). The wood values refer to [8] and those of FRP composite poles refer to the datasheets in the RS Technical Binder [18].

(In Table IV, all poles refer to Western Red Cedar with a modulus of elasticity E = 10.96 GPa; the superscript *a* refers to Fig. 1 for locations of parameters for Section for Strength Evaluation)

(In Table V, the superscripts *a, b* refers to Fig. 1 FRP Pole for locations of parameters and Module 4 for Section for Strength Evaluation)

B. Application to Hurricane-Prone Areas

With high structural reliability, composite poles are ideally suited to address the resiliency and reliability demands in hurricane-prone areas. From a statistical and planning perspective, utilities seek lower values for two types of indices, namely SAIFI (System Average Interruption Frequency Index) and SAIDI (System Average Interruption Duration Index) to benchmark the reliability of their power supply systems and develop effective post-storm emergency restoration plans. These indices are defined as (1).

$$\text{SAIFI} = \frac{\text{Total Number of Customer Interruptions}}{\text{Total Number of Customers Served}} \quad (1)$$

$$\text{SAIDI} = \frac{\text{Sum of All Customer Interruption Durations}}{\text{Total Number of Customers Served}} \quad (2)$$

When composite poles are considered, pole failure–related interruptions would be virtually non-existent; this means that the associated indices would be significantly reduced.

C. Reliabilities at Ultimate Loads

The ultimate lateral load P_U shown in Fig. 1 is the specified load rating for the FRP composite pole class shown in Table II and the factored ANSI O5.1 load rating for the wood pole class shown in Table III.

All reliability computations are based on the equations given in Appendix. The coefficients of variation (COV) adopted for applied loads and resistances are also shown in the Appendix.

TABLE II: SELECTED FRP POLES: CLASSES, LOAD RATINGS AND WEIGHTS

Pole Length L (m)	ANSI O5.1 Class	RS Pole Modules	RS Pole Code	RS Load Rating (Grade B) [a, b] (kN)	Pole Weight (kgs)
16.76	1	M2 M3 M4 M5	PP-0550-F-0205-C	25.2	440
18.29	1	M2 M3 M4 M5	PP-0600-F-0205-C	21.7	461
19.81	1	M3 M4 M5/6	PP-0650-F-0306-C	18.5	588
21.34	1	M2 M3 M4 M5/6	PP-0700-F-0206-C	15.6	623
22.86	H1	M3 M4 M5 M6/7	PP-0750-F-0307-C	21.7	782
24.38	H1	M3 M4 M5 M6/7	PP-0800-F-0307-C	18.5	808
25.91	H1	M4 M5 M6/7 M8/9	PP-0850-F-0409-C	28.9	1175
27.43	H2	M4 M5 M6/7 M8/9	PP-0900-F-0409-C	28.9	1211
28.96	H2	M4 M5 M6/7 M8/9	PP-0950-F-0409-C	25.2	1243
30.48	H2	M3 M4 M5 M6/7 M8/9	PP-1000-F-0309-C	25.2	1293

TABLE III: SELECTED WOOD POLES: CLASSES, LOAD RATINGS AND WEIGHTS

Pole Length L (m)	ANSI O5.1 Class	Un-factored ANSI O5.1 Load Rating (Grade B) [a, b] (kN)	Factored ANSI O5.1 Load Rating (Grade B) [a, c] (kN)	Approximate Pole Weight (kgs)*
16.76	1	20.02	13.02	760
18.29	1	20.02	13.02	870
19.81	1	20.02	13.02	985
21.34	1	20.02	13.02	1100
22.86	H1	24.03	15.62	1360
24.38	H1	24.03	15.62	1520
25.91	H1	24.03	15.62	1675
27.43	H2	28.48	18.51	1965
28.96	H2	28.48	18.51	2150
30.48	H2	28.48	18.51	2430

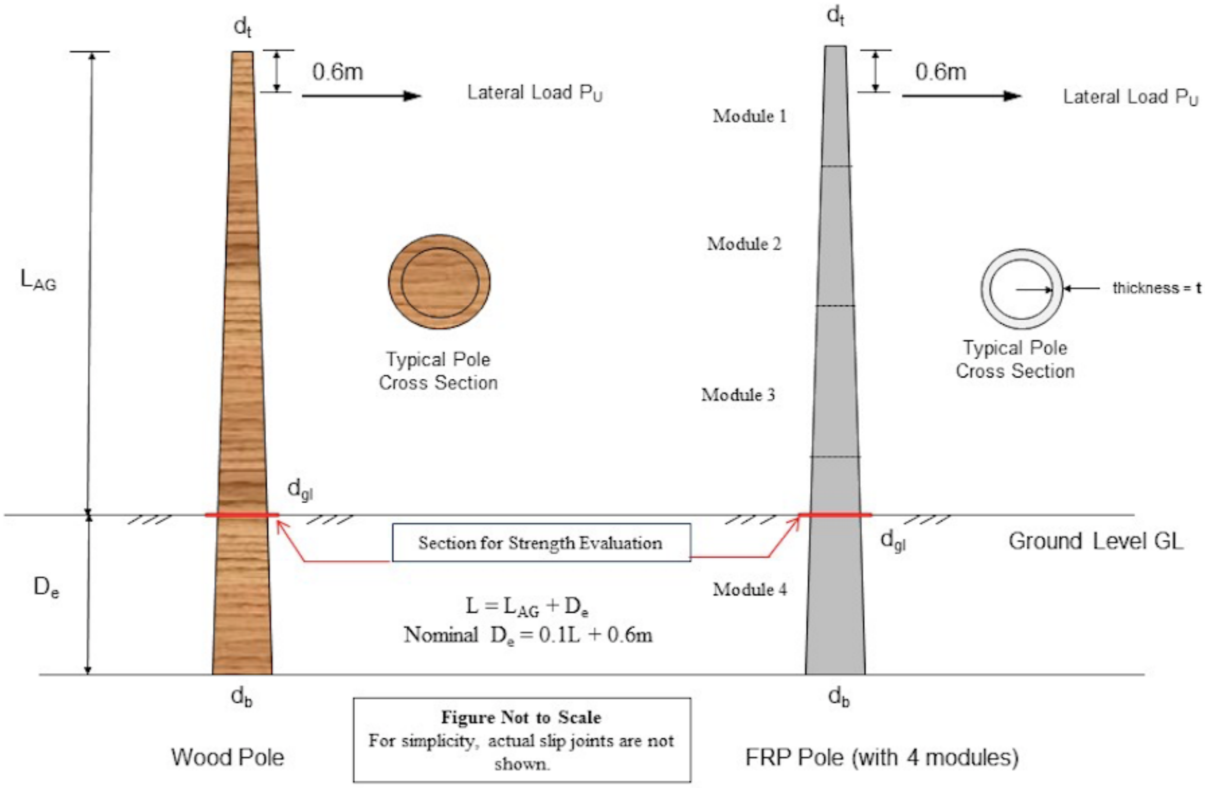

Fig. 1. Wood and FRP Poles: Geometrical Configuration.

Table VI and Table VII show the reliability calculations for wood and composite poles, respectively.
(Table VI and Table VII both refer to the Appendix section for related equations).

Composite poles consistently showed larger reliability indices. The average reliability index β for composite poles is 4.836 whereas that for the wood poles is 1.546. In other words, composite poles are more than three times safer than wood poles at the load levels indicated. In terms of probabilities of failure, this translates to the following inferred values (see Table I).

- FRP Composite: Probability of Failure P_f for β = 4.836 is less than 0.000001
- Wood: Probability of Failure P_f for β = 1.546 is 0.0846

Numerically, this means for every 1000 poles considered, wood poles would experience 85 failures whereas FRP poles would experience virtually no failures at all.

TABLE IV: WOOD POLE 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} [a] (mm)	Moment of Inertia I [a] (x 10^8 mm^4)	Section Modulus S [a] (x 10^6 mm^3)	Moment Capacity M_R [a] (kN-m)
1	16.76	2.29	14.48	410.2	13.91	6.78	280.6
2	18.29	2.44	15.85	424.7	15.96	7.52	311.0
3	19.81	2.59	17.22	435.1	17.76	8.09	334.5
4	21.34	2.74	18.59	445.5	19.36	8.69	359.4
5	22.86	2.90	19.96	483.9	26.92	11.12	460.3
6	24.38	3.05	21.34	494.5	29.35	11.87	491.2
7	25.91	3.20	22.71	505.2	31.96	12.65	523.6
8	27.43	3.35	24.08	516.9	35.01	13.55	560.6
9	28.96	3.51	25.45	527.6	38.01	14.41	596.2
10	30.48	3.66	26.82	538.2	41.20	15.31	633.4

TABLE V: FRP POLE GEOMETRIC AND STRENGTH DATA

FRP Pole No.	RS Pole Modules	RS Pole Code	Pole Length L (m)	Embed D_e (m)	Length L_{AG} (m)	Butt Diameter d_b [a] (mm)	GL Diameter d_{gl} [a] (mm)	GL Module Thickness 't' [a] (mm)	Module Flexural Strength f_m [a] (MPa)	Moment of Inertia I [b] (x10^8 mm^4)	Section Modulus S [b] (x10^6 mm^3)	Moment Capacity MR [b] (kN-m)	Module Modulus of Elasticity E (Gpa)
1	M2 M3 M4 M5	PP-0550-F-0205-C	16.76	2.29	14.48	541	503	10.3	205.2	5.17	2.06	422.0	17.9
2	M2 M3 M4 M5	PP-0600-F-0205-C	18.29	2.44	15.85	541	500	10.3	205.2	5.07	2.03	416.5	17.9
3	M3 M4 M5/6	PP-0650-F-0306-C	19.81	2.59	17.22	631	585	11.8	199.3	9.30	3.18	633.7	21.0
4	M2 M3 M4 M5/6	PP-0700-F-0206-C	21.34	2.74	18.59	631	585	11.8	199.3	9.29	3.18	633.3	21.0
5	M3 M4 M5 M6/7	PP-0750-F-0307-C	22.86	2.90	19.96	709	659	10.8	199.3	12.14	3.69	734.9	22.6
6	M3 M4 M5 M6/7	PP-0800-F-0307-C	24.38	3.05	21.34	709	656	10.8	125.2	11.97	3.65	457.3	22.6
7	M4 M5 M6/7 M8/9	PP-0850-F-0409-C	25.91	3.20	22.71	876	819	11.7	125.2	25.15	6.14	769.7	22.5
8	M4 M5 M6/7 M8/9	PP-0900-F-0409-C	27.43	3.35	24.08	876	816	11.7	142.0	24.86	6.10	866.3	22.5
9	M4 M5 M6/7 M8/9	PP-0950-F-0409-C	28.96	3.51	25.45	876	813	11.7	142.0	24.57	6.05	859.6	22.5
10	M3 M4 M5 M6/7 M8/9	PP-1000-F-0309-C	30.48	3.66	26.82	876	813	11.7	131.7	24.55	6.05	796.9	22.5

TABLE VI: RELIABILITY ANALYSIS OF WOOD POLES

Wood Pole No.	Pole Length Above GL L_{AG} (m)	Moment Capacity M_R (kN-m)	P_U (kN)	Applied Moment M_W (kN-m)	Std. Dev. $Σ_R$ (kN-m)	Std. Dev. $Σ_W$ (kN-m)	Reliability Index β
1	14.48	280.6	13.02	180.5	56.1	9.1	1.762
2	15.85	311.0	13.02	198.3	62.2	9.9	1.789
3	17.22	334.5	13.02	216.2	66.9	10.8	1.747
4	18.59	359.4	13.02	234.0	71.9	11.7	1.722
5	19.96	460.3	15.62	302.2	92.1	15.1	1.694
6	21.34	491.2	15.62	323.7	98.2	16.1	1.683
7	22.71	523.6	15.62	345.1	104.7	17.2	1.682
8	24.08	560.6	18.51	434.4	112.1	21.7	1.105
9	25.45	596.2	18.51	459.7	119.2	23.1	1.124
10	26.82	633.4	18.51	485.1	126.7	24.3	1.150
						Average	1.546

TABLE VII: RELIABILITY ANALYSIS OF FRP POLES

FRP Pole No.	Pole Length Above GL L_{AG} (m)	Moment Capacity M_R (kN-m)	P_U (kN)	Applied Moment M_W (kN-m)	Std. Dev. σ_R (kN-m)	Std. Dev. σ_W (kN-m)	Reliability Index β
1	14.48	422.0	25.2	348.9	21.2	17.5	2.670
2	15.85	416.5	21.7	330.5	20.9	16.5	3.233
3	17.22	633.7	18.5	307.4	31.7	15.3	9.265
4	18.59	633.3	15.6	280.8	31.7	14.1	10.177
5	19.96	734.9	21.7	419.8	36.7	21.0	7.446
5	19.96	734.9	21.7	419.8	36.7	21.0	7.446
6	21.34	457.3	18.5	383.6	22.9	19.1	2.469
7	22.71	769.7	28.9	639.1	38.5	32.0	2.612
8	24.08	866.3	28.9	678.7	43.3	33.9	3.410
9	25.45	859.6	25.2	625.0	43.0	31.2	4.416
10	26.82	796.9	25.2	659.4	39.9	33.0	2.658
						Average	4.836

V. CONCLUSION

In this paper, we investigated the structural reliability of modular fiber-reinforced polymer (FRP) composite utility poles in comparison with Western Red Cedar wood poles. Pole lengths ranged from 16.8 m to 30.48 m [55 ft. to 100 ft.] and pole classes ranged from 1 to H2. Ultimate load reliabilities are considered. Major inferences from the reliability analyses of the 20 poles of this study include:

1. In each length set, FRP composite poles showed higher structural reliability than wood poles.
2. The average ultimate load reliability index of FRP composite poles (4.836) is more than three times that of wood poles (1.546) of the same class set.
3. Given the low probability of failure, FRP poles are better suited for hurricane-prone areas as a one-on-one replacement for wood and offer a superior structural alternative to wood.

This study considered Western Red Cedar (WRC) wood poles, but the results are considered valid and applicable to other types of wood such as Southern Yellow Pine (SYP) and Douglas Fir (DF) too. The lowest pole class considered here is Class 1 but lower classes (2, 3, and below), along with smaller pole lengths, may be examined in a future study. Reliabilities at service load levels, subject to deflection limitations, may also be taken up for future evaluation if proper definitions of service loads and tolerable deflections are available. This study is focused on just two pole materials, namely round wood and FRP composites but the concepts can be extended to poles of other materials.

APPENDIX

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

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

where:
M_R = Mean value of Resistance
M_W = Mean Value of Applied Load Effects
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, $\mathbf{M_W}$, as it refers to the focus of this study, is the bending moment at the ground line (GL) due to a prescribed lateral load P applied 60 cm from the pole top.
Resistance, $\mathbf{M_R}$, as it refers to the focus of this study, is the bending moment *capacity* at the ground line (GL) estimated using the section, elastic properties at the location.

A. Coefficients of Variation

The following values of COV's are used in the study:

Wood COV_R = **0.20** applied to the maximum bending stress or MOR [ASCE 2006; ANSI 2017]

FRP COV_R = **0.05** applied to the maximum flexural stress in composite material [ASCE 2019]

Load Effects COV_W= **0.05** (nominal) applied to the cantilever load

B. Measure of Load Effects

For all poles, the Load Effect parameter can be expressed in terms of the applied ground line (GL) Bending Moment of the pole as shown in Fig 1.

$$M_W = (P) * (L_{AG} - 0.6) \quad \text{(A-2)}$$

where:
L_{AG} = Pole Height above Ground (meters) and P = P_U (ultimate)

C. Measure of Resistance

For circular cross sections, the Resistance parameter can be expressed in terms of the Ground Line (GL) Bending Moment Capacity of the pole from basic mechanics of sections.

$$MR_{Wood} = (S) * (MOR) = (\pi * d_{gl}^3/32) * (MOR) \quad \text{(A-3)}$$

S = Section Modulus
d_{gl} = Pole Diameter at GL
MOR = Modulus of Rupture or Wood Fiber Strength
I = Moment of Inertia = $(\pi * d_{gl}^4/64)$

$$MR_{FRP} = (S) * (f_m) = (0.786 * d_{gl}^2 * t) * (f_m) \quad \text{(A-4)}$$

S = Section Modulus
d_{gl} = Pole Diameter at GL
t = pole module thickness at GL [18].
f_m = Flexural Strength of the pole module at the GL (bulk property)

I = Moment of Inertia = $0.393*d_{gl}^3*t$

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CONFLICT OF INTEREST

The Author declares no conflict of interest with any other entity.

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