Strengthening Overhead Transmission Line Using Composite FRP Pole

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ABSTRACT

This paper describes strengthening an existing 110 kV overhead wood pole transmission line with the Fiber reinforced polymer (FRP) poles of a critical section of a about 10 kilometres, as an alternative solution to structural steel or other similar materials, of a proposed pilot project for resilience in a Central American continent region vulnerable by sea level rise that often encounters tropical storms and Hurricanes, flood hazards, significant lightning phenomenon, and forest fires. The basis of considering FRP pole has been the historical issues the utility encountered for operation of the line compounded by the geographical and environmental conditions, access restrictions due to low lying areas submerged with water for months together that often poses a challenge for maintaining the supply requirement as well as cost associated with. The design criteria and analysis are chosen based on the climatic loads, site-specific design assumptions, use of appropriate standard, selection of software and analysis of results for a section of the line. The entire section has been modelled and analysed leading to comparison with the existing structures and has been accepted by the utility for immediate implementation purpose.

KEYWORDS

FRP, Structure, Climate change, Transmission Line.

INTRODUCTION

Overhead transmission lines for power evacuation have been traditionally for a century throughout the world built by structures like Poles or Towers of different materials like steel, concrete, and wood. Operation and maintenance in difficult geographical locations and terrain with corresponding environmental considerations like heavy rain, humidity, and temperature change and contemporary challenges like climate change have made a compulsion to look for alternate solutions. In times of sustainability and innovations, Fiber Reinforced Polymer (FRP) composite poles and corresponding cross-arms (Papailiou, 2021), (Association and Edition, 2000) being lightweight, corrosion resistant, have better dielectric strength and long service life provide advantages for addressing the issues and mitigating risks to avoid planned or unplanned outages of a line. Some utilities have started using FRP poles in high climatic events and environmentally impacted areas. It envisaged a solution to cater to the need to avoid situations like the replacement of existing pole structures and the corresponding components, viz. cross-arms conductor attachments arrangements that support the power evacuation by adhering to the statutory requirements in turn for ensuring reliability (Palermo et al., 2018), security, and safety of the transmission system. Using FRP pole for increasing service life of electricity transmission and distribution is already in the offing especially to take into consideration of extreme environmental conditions (Saafi and Asa, 2010). The changing times cautions that the region is susceptible to sea level rise (Bank, n.d.) and incidents of historical forest fires are not insignificant (Kellman et al., 2008).

The existing poles of the overhead line by means of foot-survey inspection revealed that have several problems, including fungal rotting at the base, termite damage, and chipped-off tops. In addition, the replacement figures provided by the utility show that during the four years of the transmission line segment, an average replacement number of poles each year remained equivalent to roughly 10% of the total installed poles.

Even though the advantages of FRP poles are significant, however, increased deflection is a disadvantage of FRP poles. Moreover, limited utility experience is also a factor to cautiously address the strengthen of poles using FRP materials. Compared to wood, steel, and concrete, FRP materials have a higher specific strength, but they also have a lower stiffness ratio. This means that, for components of strength equivalent, the FRP component will show greater deflection under the same loads. FRP manufacturers normally tend to include a deflection limit in the scope of a structural study to make sure that the overhead line components all work the same and have the same level of serviceability. This will solve the problem and prevent aesthetic problems and right-of-way encroachments.

RESEARCH SIGNIFICANCE

The design approach entailed structural criteria of load, strength, and deflections by addressing the issues that historically arose (Jayawardena et al., 2016) during the operation and maintenance regime of the 1990s built lines with wood poles. ANSI O5.1 standard defines wood pole strength by cantilever bending strength of 10.7 kN for the appropriate class 4. The intention had been to replace the existing section of wood poles by FRP poles subject to meeting the analysis and design for a section of 7 kilometres that comprise of about 70 number of suspension and tension poles. The suspension poles by definition are designed only to vertically hold the electrical conductors' vertical weights when erected subjected to transverse loads due to wind action. Whereas the tension or anchor poles are designed to sustain the tension of the conductors in longitudinal directions in addition to vertical and transverse loads. In the overhead transmission line, the suspension poles are spotted normally for the straight course thus no additional loads due to any horizontal angle of deviations unlike tension poles which are capable of sustaining the horizontal deviations and corresponding effects of the loads. FRP poles are manufactured either through Pultrusion or Filament winding process. The poles are manufactured for the environmental servicing conditions like exposure to ultraviolet (UV) light, water absorption, and exposure to fire. It is noteworthy to mention that the subject project site is not unknown to nearby forest fire historical incidents although till date did not directly encroach the existing line right of way. Moreover, historical records of hurricane incidents causing havoc due to extreme wind gusts and subsequent flooding after the landfalls thus impacting the line serviceability in the region. The project site was also within 5 kilometres of coastal regions. Environmental actions are a contributor of structural degradation over time coupled with changing times owing to climatic uncertainty in future will likely to pose a challenge for overhead line supporting structures. The choice of alternative structures satisfying the engineering requirements will provide a new avenue for the utility to adopt and in turn help adaptability in agile ecosystem of electricity demand and supply in turn to ensure reliability of the system.

RESEARCH METHODOLOGY

The work entails selection of wood pole alternate structures, consideration of applicable standards, takes stock of problems that have been reported by the utility, identification of software that corroborates the analysis and design approach for the subject project. Use of pls-cadd software have been a choice for utility designers for line design approach (Biswas and Kumar, 2019), simulating and analysing vegetation management for electrical clearances purpose (Hooper and Bailey, 2004), the electro-mechanical sag-tension criteria is the first and foremost one used by the utility designers (Kumar and Kumar, 2017), the electrical clearance criteria for the structures and line both internal and external conditions are also an obvious ease for similar studies (Berlijn et al., 2011). The prevailing standards in use by the electricity utilities USA being nearest to the project (Xplore, 2013) have been contemplated since the national standards in the region is in absence for the subject project. The relevant and contemporary analysis and design approach being non-linear owing to poles being slender structures subjected to considerable deflections and corresponding limit load and serviceability requirements are also considered for use. It is imperative that due to the relatively low elastic modulus of FRP, the deformed shape of the poles (called P-delta or P-effects) usually considered when modelling the structural behaviour of a pole configuration. This can be accomplished using a nonlinear finite element analysis that considers greater displacements.

Assumptions

The loading criteria selected was National Electrical Safety Load (NESC) 2017, IEEE with the salient weather case of Rule 250C, Rule 261C and Uplift condition since the country thus region falls into central American continent. The following climatic conditions have been assumed in line with the geographical locations, utility practice and the size and complexity of the project extent.

(1) NESC extreme wind (Rule 250C) corresponding value of 2506 Pa while maximum Wind pressure 1088 Pa
(2) Everyday Temperature of 35 degree C
(3) Minium Temperature of 10 degree C

The ruling span, considered for imparting an uniform tension for a section of line is considered as 150 meter, the terrain being purely flat with no undulations, weight spans are corresponding to the wind spans. To realistically structural modelling purpose, in order to meet the applicable ASCE/ASTM criteria for materials, all raw materials used to make the FRP and its accessories adhering to Standard Specification for FRP Composite Utility Pole UP01-18. FRP poles are hollow, thin-walled, and fashioned in a polygonal or circular shape. FRP utility poles have a tapered length. The design of poles for AAAC Elgin/Darien/ACSR HAWK conductor and 24 core single mode fibre (SMF) optical fibre ground wire (OPGW) that has a shielding angle of 20 degree for the lightning protection of the overhead line. Moreover, the poles have been designed for reliability level 1 i.e., return period of 50 years for normal or intact conductor condition and given that this transmission line only has one circuit, the following damaged wire situation is assumed. FRP single-circuit poles: Either one phase, any broken ground wire, or any broken OPGW, depending on which is more severe for a specific pole section. Further safety condition for crews with told and plants for maintenance loads have also been assumed. Apart from suspension poles, three type of tension poles have been used depending upon the horizontal angle of deviations i.e., line deviation from 30 degree to 45-degree, 60 degrees to 90 degree and dead-end conditions. The selection is based on the type of poles that are in use for the study section. The FRP suspension pole comprises of 10 modules each section is having customized separate values of weight density, modulus of elasticity, failure stress coefficients based on experiments during which are manufacturing process dependent and specific subjected to laboratory testing.

Equations

The torsional strength of FRP pole is calculated by multiplying the in-plane shear strength as given below:

$$T = \tau_{xy}.2\pi r^2.t \qquad (1)$$

Where, T = Torque
τ_{xy} = In-plane shear strength
r = mean radius
t = wall thickness

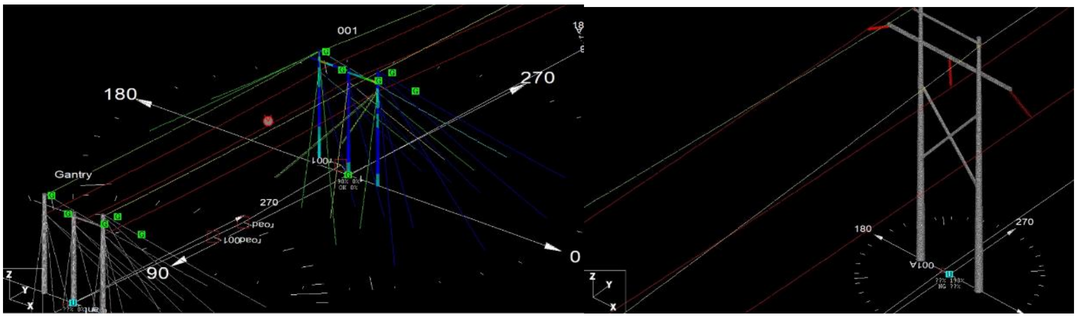
For transmission poles designed according to ASCE/ SEI Standard 48-05, 48-11 and 48-19, the strength usage is calculated at each of the N points as:

$$Strength\ Usage\ = \sqrt{}\{(fa + fb)^2 + 3.(fv + ft)^2\}/(fall\ .S.F) \qquad (2)$$

where:
fa = normal stress due to axial load
fb = normal stress due to bending
fv = shear stress due to shear force
ft = shear stress due to torsion
fall = allowable (permitted) combined stress defined in ASCE Standard 48-05 or 48-11.
S.F. = Strength Factor for steel poles

RESULTS AND DISCUSSIONS

The pls-pole software and pls-cadd software have been used for structural modelling vis-à-vis checking electrical clearance criteria. The figure 1 and 2 exhibits some typical pole carrying conductor and twin earth wire/OPGW at peak. The deformed geometry post-analysis show in different colour coding, green signifies within limit, the red (not displaying here) colour signifies any violation in strength at any segment of the pole or at any conductor/OPGW attachment point. The suspension poles are typical H-frames separated by cross-bracing and the cross-arm lengths are sufficient to meet the horizontal phase to phase distance of separation as well as height must comply with vertical and horizontal object electrical clearance criteria.



(a) Legend 1a: Angle pole with guy *(b) Legend 1b: Typical H-frame suspension pole*

Figure 1: Legend 1a; Legend 1b

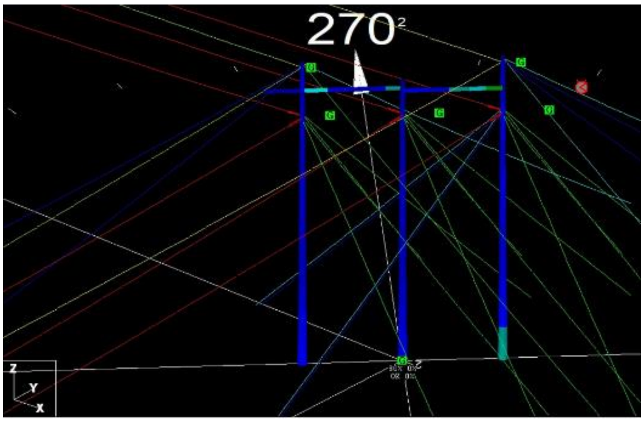


Figure 2: Angle pole with horizontal angle of deviation modelled through pls-pole

The inset numbers denote the different node numbers used for structural analysis purposes. The guys are provided to laterally restraining purpose since either 2 pole or 3 pole structures, are of in two dimensions unlike tower structures in 3-dimensions thus a modelling concern for stability purpose.
The sag-tension as in Table 1 provides the maximum conductor tension in the corresponding weather case and the maximum tension is 48030 N for NESC Extreme wind load scenario which in turn produces a catenary value i.e., horizontal load divided by unit weight of conductor 949.2, a dimension-less number often guides the vibration characteristics of conductor under strung condition that may cause the damage in conductor outer strands.

Table 1: Sag-Tension for the AAAC Elgin conductor for the line

Weather Case	Tension (N)	Catenary	% Allowable
NESC WI District Loading (250B)	39679.8	1461.7	67.9
NESC Extreme Wind (250C)	48030	949.2	61.6
NESC Tension Limit (261H1c)	32755.1	3696.8	96.1
NESC Tension Limit (261H1c)	24348	2747.5	100
Maximum Operating	17853.8	2014	73.3
NESC WI District Loading (250B)	39679.8	1461.7	67.9

The load case and corresponding deflections are produced in Table 2 which shows the longitudinal, transverse and vertical components are significant though within permissible limit. The % allowable column shows the comparison with respect to the allowable tension for the corresponding weather cases which are well within limit maintained.

Table 2: Load Case and deflection (cm) for a Suspension Pole

Load Case	Long. Deflection (cm)	Tran. Deflection(cm)	Vert. deflection(cm)
RULE 250C	2.13	65.23	-1.77
RULE 250C	-0.16	65.22	-2.78
RULE 250C	-0.41	-65.64	-2.81
RULE 250C	1.86	-65.64	-1.8
Uplift	1.2	-0.19	-0.04
Uplift	1.22	-0.18	-0.04

The foundation design forces i.e., axial, shear and the resultant are as provided in the Table 3, the – sign denotes the pole is under uplift, otherwise compression for the axial force. The resultant of axial and shear yields a maximum value of 131.46 kN for the corresponding weather case of Rule 250C.

Table 3: The foundation design forces for load cases

Load Case	Axial (kN)	Shear(kN)	Resultant(kN)
RULE 250C, NA+	-109.9	35.96	115.63
RULE 250C, NA-	127.89	29.12	131.16
RULE 250C, NA+	128.18	29.16	131.46
RULE 250C, NA-	-110.19	36.01	115.92
Uplift, I, NA+	8.82	0.04	8.82
Uplift, I, NA+	8.58	0.05	8.58

The summary of maximum usages for the different components are produced in the Table 4 i.e., pole, cross-arm or cross-bracing. XB denotes cross bracings, RP denotes right pole of the H-frame.

Table 4: Summary of Maximum Usages by Load Case for FRP pole H-Frame structure

Load Case	Axial (kN)	Shear(kN)	Resultant(kN)
RULE 250C, NA+	85.71	XB1	Brace
RULE 250C, NA-	85.99	XB2	Brace
Uplift,I NA+	4.53	Xarm	X-Arm
RULE 261A, Max	55.1	RP	FRP Pole

It is conspicuous to mention, with the considered loading, the wood pole are not meeting the design strength criteria as shown in Table 5 complying with current probabilistic loading as per the standards. In the remark's column, NG denotes No Good and G denotes as Good. LP denotes left-pole of the H-frame structure.

Table 5: Summary of Maximum Usages by Load Case for new wood pole H-Frame structure

Load Case	Max Usage %	Label	Remarks
RULE 250C, NA+	132.73	RP	NG
RULE 250C, NA-	132.43	LP	NG
Uplift,I NA+	0.73	LP	G
RULE 261A, Max	102.29	LP	NG

The existing line was designed with deterministic loading in the 1990's. However, the pilot project study analysed with probabilistic design concept and inevitably with higher loads. The FRP poles were individually checked for the entire section pole by pole with full-scale modelling with the customized site-specific loading and as evident successfully withstand the design loads.

Table 6: Summary of Structures Usages for first 8 structures of the line from originating substation gantry

Structure Number	Structure Name	Station (m)	Line Angle (deg)	Structure Strength Usage (%)	Insulator Swing Usage (%)	Minimum Required Vertical Load (Uplift)	OK or NG
1	#Dead-end.POL	69.27	0	94.1	0	OK	OK
1a	A- 65 RS POles.POL	133.97	0	56.1	99.2	OK	OK
2	A- 65 RS Poles.POL	246.05	-87.09	79.1	0	OK	OK
3	A- 65 RS POles.POL	419.36	0	81.2	93	OK	OK
4	A- 65 RS POles.POL	586.69	0	81	92.8	OK	OK
5	A- 65 RS POles.POL	763.97	0	81.2	91.7	OK	OK
6	A- 65 RS POles.POL	932.81	0	80.4	92.9	OK	OK
7	A- 65 RS POles.POL	1104.79	0	81.1	90.9	OK	OK
8	A- 65 RS POles.POL	1277.43	0	81.2	89.8	OK	OK

The table 6 depicts the comparative summary of first eight structures of the section of the line which has been satisfying the design strength criteria.

CONCLUSIONS

The paper discus an analysis based alternate solution for a historical two and half decade's overhead wood pole transmission line in an environmentally vulnerable region which was mired by maintenance problems. The recommended FRP pole is the best option due to its extended lifespan, stability, low long-term cost, and absence of required inspection and maintenance. Working with FRP pole is safe because it is resistant to environmental elements including the harmful effects of ozone, wood pecking, corrosion, fungi, and wildfires. Additionally, it has an insulated behaviour, is light enough to be handled and placed at the site, and is flexible enough to absorb additional weights. All these features make FRP the most technically feasible option for replacing an existing wooden pole line because of its dependability and durability under the current climatic conditions of an existing line. The appropriate design criteria from electrical, electro-mechanical and structural consideration, further structural analysis and designing ratifies the load, strength and deflection limits as per the selected criteria conforming to utility standards and results are encouraging for further adopting in large scale policy of the utility.

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