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ScienceDirect

Procedia Engineering 145 (2016) 707 – 714

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Sustainable Design, Engineering and Construction

Structural Assessment of Fiber-reinforced Polymer Composite Electric Poles

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Abstract

Engineers are increasingly tasked with designing and operating structures that incorporate the philosophy of resiliency across a variety of critical infrastructure sectors. Electric distribution and transmission systems are examples of the critical infrastructure sectors. The majority of existing electrical poles supporting electric distribution systems in the United States are made out of wood. It is estimated that up to 3.6 million existing electric wood poles have to be replaced every year. One of the primary hardening strategies is upgrading wooden electric poles and supporting structures with stronger materials that withstand hurricane-force winds. This paper presents finite element analysis of fiber-reinforced polymer composite poles including parametric studies on geometric characteristics, fiber orientation, number of layers, and lamina thickness.

Peer-review under responsibility of the organizing committee of ICSDEC 2016

Keywords: Fiber-reinforced polymers; Finite element analysis; FRP poles; Shell elements

1. Introduction

In the face of frequent natural and man-made disasters, engineers are increasingly tasked with designing and operating structures that incorporate the philosophy of resiliency across a variety of critical infrastructure sectors. Electric distribution and transmission systems are one example of the critical infrastructure sectors. A recent report on economic benefits of increasing electric grid resilience to weather outages estimates that the US economy lost $18 billion to $33 billion annually during 2003-2012, and identifies several strategies to increase the nation's electric grid resiliency [1]. The majority of existing electrical poles supporting electric distribution systems in the United States are made out of wood. It is estimated that up to 3.6 million existing electric wood poles have to be replaced every year. One of the primary hardening strategies identified is upgrading wooden electric poles and supporting structures with stronger materials that withstand hurricane-force winds [2].

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Peer-review under responsibility of the organizing committee of ICSDEC 2016
doi:10.1016/j.proeng.2016.04.085

The strategy of upgrading wooden poles includes FRP strengthening of existing wood poles or installing new poles made from alternative and relatively new materials, such as fiber-reinforced polymers (FRP) composite poles. For example, Saafi and Asa [3] investigated the feasibility of in-situ FRP strengthening system to repair and extend the service life of damaged wooden poles. They proposed an in-situ "wet layup FRP" method using epoxy impregnated E-glass jacket consisting of four layers and concluded that using the FRP wraps extends the service life of damaged wood poles by 25 years. In addition to strengthening of wood poles with FRP, poles completely made out FRP are gaining popularity. In fact, the global FRP pole market is expected to grow at a compounded annual growth rate of 8.9% during 2014-2019 [4]. The use FRP poles is on the increase because they are light weight, offer corrosion resistance properties, can be tailored to satisfy specific strength and deflection requirement, and have low cost of construction and maintenance. FRP poles can also be used in places where poles of other materials face problems, such as coastal areas where salinity may be detrimental, and areas with high temperature fluctuation.

Fouad and Mullinax [5] presented an overview on the use of fiber reinforced composite poles for electric distribution lines. They provided a rationale why FRP poles are advantageous when compared to wood, steel and concrete. The main reasons include easy installation, high strength, smooth texture, high electric insulation properties and economical cost in terms of installation. They discussed the lack of national standards for FRP utility poles, but pointed out related standards for FRP poles used in highways signs and street lighting. Oliphant [6] discussed the potential confusion that occurs when standards attempt to use "equivalent wood class" poles when using non-wood structural material such as FRP poles. He highlighted that careful consideration should be given to limit deflection and stresses when treating FRP poles as an "equivalent class wood" pole. In the past two decades, a number of researchers performed static and dynamic analyses to study different behaviors of FRP poles such as ovalization, buckling, bending and flexure. Ibrahim and Polyzois [7] investigated the ovalization behavior of tapered FRP poles subjected to bending. They proposed two design methods for computing the critical ovalization load based on the critical moment that can be carried by the pole and the position in which maximum ovalization occurs. They concluded that both methods correlate very well and the proposed models can be used efficiently to calculate the FRP critical ovalization load.

Desai and Yuan [8] presented a numerical model to study the buckling and bending behavior of FRP utility poles. They studied the effect of section variables, including rigidity length ratio (a/l) defined as the length of the bottom portion of the pole section to the overall length of pole, moment of inertia ratio (IT/IB) capturing the change in cross section of upper and lower portion of pole, and the overall pole length. They concluded that the rigidity length ratio has little effect on the buckling of poles that are taller than 9.14 m (30 ft) and they showed that the moment of inertia ratio between the top and the bottom sections of the FRP poles had a significant effect on the buckling behavior. In addition, they concluded that the buckling load of carbon FRP poles was 175% higher than glass FRP poles with the rigidity length ratio having a major influence on the bending stress of the poles. Masmoudi et al. [9] investigated the deflection and bending strength of glass fiber reinforced polymer poles fabricated by filament winding with service openings (holes) using a 3-D non-linear finite element analysis. They proposed a new design with optimized number and thickness of longitudinal and circumferential layers, fiber orientation and stacking sequence of layers. Their new design was shown to provide excellent results. The finite element analysis results predicted failure and flexural behavior of poles very well when compared with experimental results.

Khalili and Saboori [10] used a combination of beam finite element formulation and time integration methods to investigate the transient dynamic analysis of tapered fiber reinforced polymer transmission poles. They studied thin walled circular cross-sections that are subjected to dynamic cable tension and vehicle impact. Transmission poles under step, triangular and sine pulses have been evaluated considering the effect of fiber type, fiber orientation, pole geometry and concentrated mass at the pole tip. They found that the maximum deflection of the pole tip is the greatest for the step pulse force followed by the sine and triangular pulses respectively. They concluded that increasing fiber orientation with respect to pole axis and decreasing top diameter with respect to base diameter increases the amplitude of deflection history of the pole tip. Furthermore, they showed that using tougher fibers at the inner and the outer laminas of the pole cross-section decreases the tip deflection significantly. Saboori and Khalili [11] presented a linear static analysis of FRP transmission poles. They investigated the behavior of the poles using a second-order shell finite element model considering the effect of various parameters such as fiber orientation and type, volume fraction, and number of layers and geometry. They developed a computer code in MATHEMATICA for conducting their analysis and verified their findings partly with ANSYS and partly with a simplified analytical method. Their numerical code showed good agreement with the methods mentioned. They used their code to conduct further parametric studies and concluded that increasing fiber orientation angle with respect to axial direction increases the maximum deflection. Furthermore, the maximum principal stress in at the base of the pole increases until the fiber orientation reaches 45 degrees and then decreases for fiber orientations greater than 45 degrees. They also found that both the maximum deflection and stress decrease with reduction in tapered angle or increase in fiber volume fraction and wall thickness. When stronger fibers were used in the inner and outer laminas of the cross-section, the performance of the poles was improved. Metiche and Masmoudi [12] presented a new design method for glass fiber-reinforced polymer poles that incorporates a local buckling mode of failure nearby the area of service openings. They performed experiments on poles with hollow circular cross-section of various wall thicknesses. They concluded that the ultimate bending moment at the base of the poles is inversely proportional to linear fiber mass, and identified a specific value of the stiffness to linear mass ratio that causes failure at the base of the pole.

Our study presents finite element analysis of tapered FRP poles in ABAQUS and associated parametric studies in order to evaluate the effect of various properties on the overall structural response of FRP poles. These properties include geometric characteristics, fiber orientation, taper ratio, number of layers, lamina thickness and location of transverse load. Understanding the response of FRP poles for the varying aforementioned properties will lead to improved designs and aid in the quantification of fragility curves.

2. Finite element analysis of a tapered FRP pole using ABAQUS

Figure 1 shows the general geometry of the FRP pole with its cross-section variable. ABAQUS [13] was used for finite element analysis. Geometry and material properties were selected so that our ABAQUS results can be compared with results from Saboori and Khalili [11] who developed a fast-running numerical algorithm in MATHEMATICA. Conventional shell elements were used in which the geometry is specified at the reference surface with the corresponding thicknesses defined by section property [14].

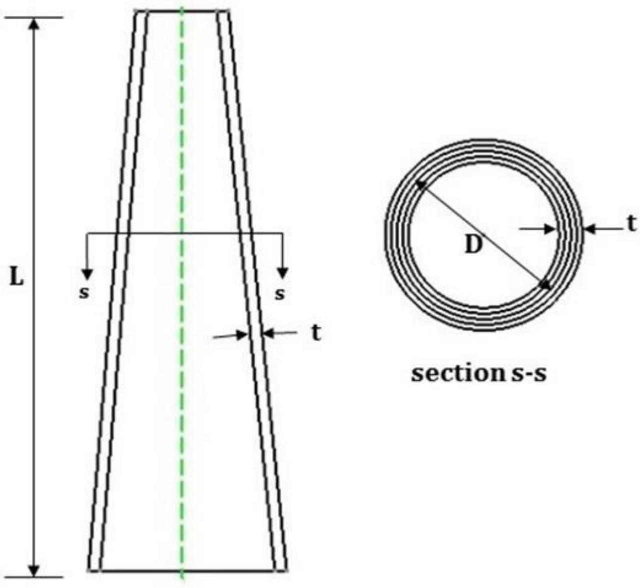

Fig. 1. (a) Geomtry of a tapered pole.

A finite-element analysis was conducted on anti-symmetric FRP pole with a selected layup of $[-10/10]_4$. Table 1 shows the geometric and material properties of the FRP pole. This specific pole has a taper ratio of 0.5 and is referred to as "baseline" FRP pole in this paper. Conventional thick shell elements were used in which the geometry is specified at the reference surface with the corresponding thicknesses defined by section property. Two shell elements, S4 and S8R based on thick shell theory were used [15]. While there is no consensus on the exact transition point between thick and thin shell assumptions, structures with radius-to-thickness (R/t) ratios of less than 15 are typically modeled as thick shells. Therefore, the use of thick shell theory is warranted for most poles. Element S4 implements a standard rule with four integration points and accounts for finite membrane strains and large rotations. S8R is an eight-node quadratic element and six degrees of freedom at each node with reduced integration rule that is capable of handling arbitrary large rotations but it is based on a small-strain theory.

Table 1. Properties of the glass-fiber reinforced polymer composite tapered pole (65% fibers)

Geometry		Material		Transverse Load	
Length (mm)	4000	Longitudinal elastic modulus (GPa)	48	Magnitude (N)	2000
Diameter (mm)	Top = 72 Base =144	Transverse elastic modulus (GPa)	13.3	Location	Tip of the pole
Total Thickness (mm)	4	Poisson's ratio	0.235	Type	Point load
No. of lamina	8	Shear modulus (GPa)	5.17		

Table 2 shows results from our study in comparison with results from Saboori and Khalili [11]. Our results using shell element S4 in ABAQUS [13] match well with their results. The error is 3.4% for maximum deflection and 6.17% for maximum stress. We note that Saboori and Khalili [11] used an 8-noded element with full-integration for their composite pole FEM validation and the small error can be attributed for that reason. Shell element S8R produced lower results because of its inability to capture finite strains. We concluded that shell element S4 is the better choice from the two elements studied and will be used for further studies.

Table 2. Comparison of results for the "baseline" glass-fiber reinforced polymer tapered pole.

Response	Saboori and Khalili [11]		Result from our study in ABAQUS with element type	
	Numerical	ANSYS	S4	S8R
Max. deflection (mm)	327.3	328.7	339.9	302
Max. principal stress (MPa)	128.1	142.6	133.8	128.1
Number of elements	8	2000	216	160

3. Parametric studies of tapered FRP composite poles

Once the finite element analysis results in ABAQUS [13] were validated, parametric studies were conducted in order to evaluate the effect of various properties on the overall structural response of FRP poles. These properties include geometric characteristics, fiber orientation, number of layers, and lamina thickness. Whenever possible we compared our results with numerical results obtained from other models

3.1. Effect of fiber-orientation

The effect of fiber-orientation was studied by modeling multiple tapered FRP poles with anti-symmetric $[-\theta/\theta]_4$ lay-up and determining the resulting maximum deflection and maximum stress in the poles. The angle, θ, was varied in increments of 5° from 0° to 60° for this study. All other material, geometric and load properties were kept the same as before. Figure 2 and Figure 3 show the maximum deflection and maximum stress results respectively. We conclude that the maximum stress in the pole increases as the fiber-orientation increases up to 45° with respect to the axial direction, and then decreases as the fiber-orientation increases up to 60°. It is also apparent that increasing the fiber-orientation increases the maximum deflection of the pole because of the reduced stiffness of the FRP pole.

3.2. Effect of number of layers and lamina thickness

In the analysis presented so far, the glass fiber-reinforced composites FRP poles were made out of 8 layers of composite regardless of fiber-orientations. A finite element analysis was conducted by varying the number of composite layers from 4 to 12 in increments of 2 layers for a specified anti-symmetric fiber-orientation, [-10/10]# of layer. Figure 4 and Figure 5 show the maximum deflection and maximum stress results respectively. As expected increasing the number of layers decreases both the maximum deflection and maximum stress in the pole. The percentage reductions in the maximum deflection and maximum stress were 70% and 60% respectively between using 4 versus 12 layers. However, the rate of reduction is not constant for all variations of number of layers. The rate decreases as the number of layers increases. Our ABAQUS [13] results also compared very well with results from other numerical models [11].

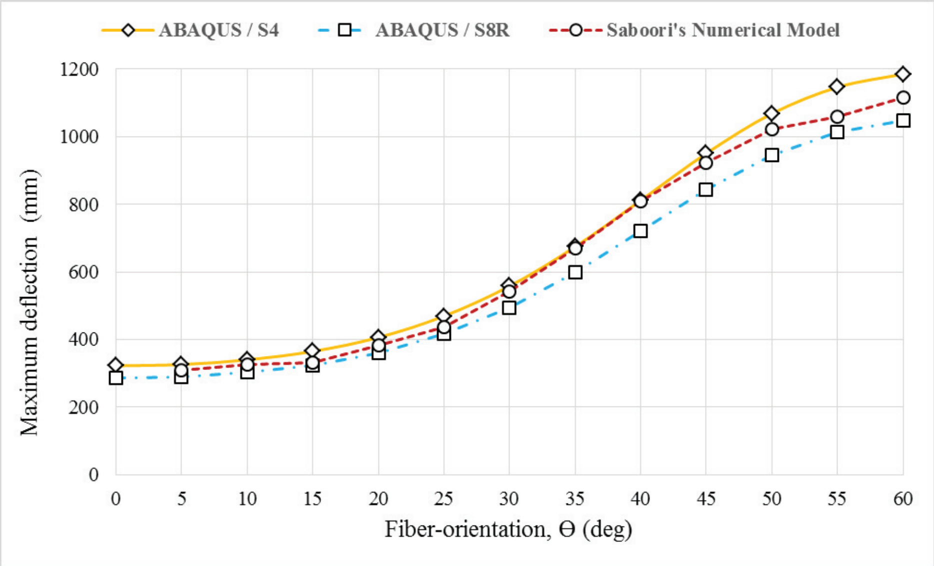

Fig. 2. Effect of fiber-orientation on the maximum deflection of the FRP pole.

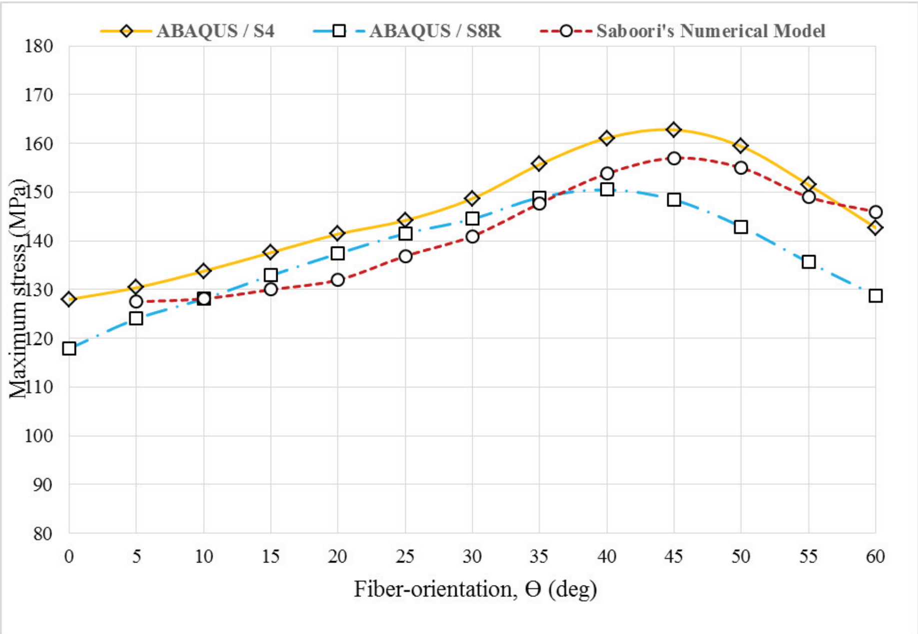

Fig. 3. Effect of fiber-orientation on the maximum principal stress of the FRP pole.

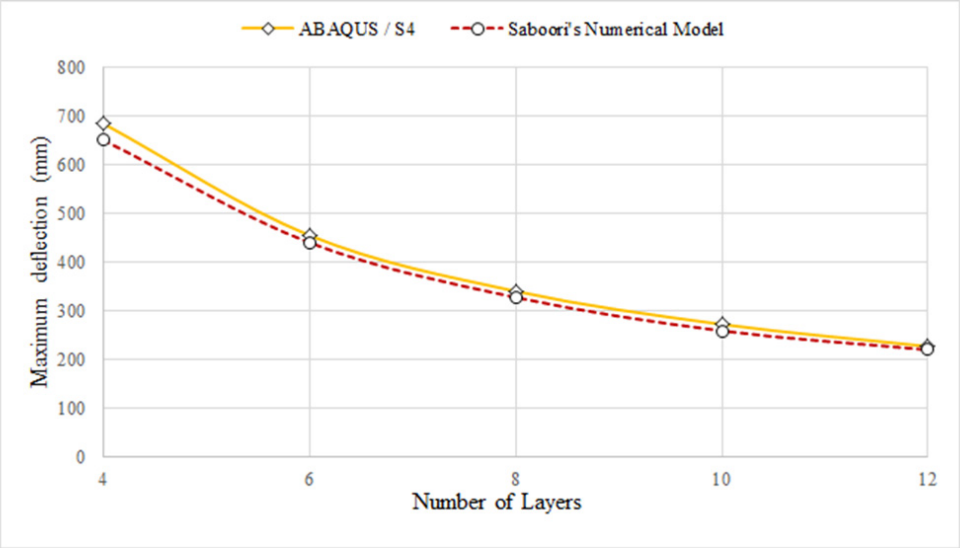

Fig. 4. Effect of number of layers on the maximum deflection of the FRP pole.

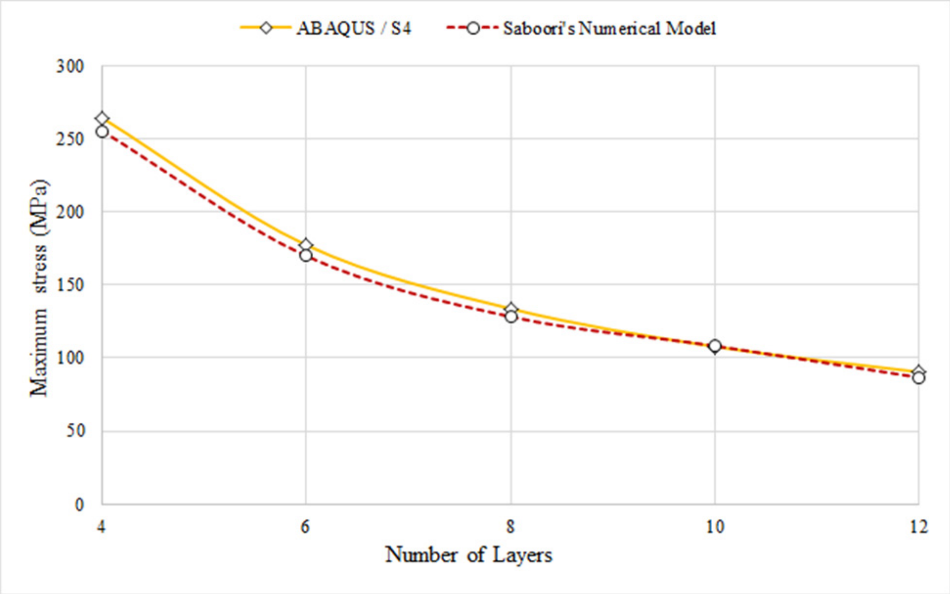

Fig. 5. Effect of number of layers on the maximum principal stress of the FRP pole.

Furthermore, a parametric study was conducted to study the effect of varying lamina thickness without changing the overall laminate thickness of the “baseline” FRP pole described in section 2.2. Table 3 shows the results. There was no significant difference in maximum deflection and maximum stress for FRP poles of the same overall thickness with 4 or 6 layers in comparison to the “baseline” FRP pole with 8 layers of 0.5 mm lamina thickness per layer. The maximum difference is within 0.5%.

Table 3. Effect of lamina thickness

Number of Layers	2	4	6
Max. deflection (mm)	341.7	340.6	338.7
Max. stress (MPa)	134.3	134.0	133.2

4. Considerations for assessing reliability of FRP poles

Structural reliability is an important consideration particularly as design philosophies move towards performance based design. Simulation method, such as Monte Carlo, can be used to calculate the probabilities of failure of the FRP poles while varying the value of the wind load (or wind speed) as specified in design codes [16]. For each random variable with uncertainty, selected random values can be generated and the probabilities of flexural failure can be determined by determining the number of instants where the flexural stress demand at the critical location of the FRP pole exceeds the corresponding flexural stress capacity. The critical location is usually located at the ground line and using fragility analysis, the limit state function (G) can be determined by subtracting the stress demand at the ground line (S) from the strength of the pole at any time (R). The analyses presented in the previous sections are critical in determining the strength of the FRP poles at critical section and are currently being studied in fragility analysis of the FRP poles.

5. Conclusion

This study presents parametric studies to determine the effects of geometric characteristics, fiber orientation, number of layers, and lamina thickness of tapered FRP poles using finite element analysis. The main findings of the paper are summarized below.

- The conventional general purpose shell element S4 in ABAQUS was found to be suitable and relatively accurate for modeling the behavior of FRP composite poles. Finite element results for the “baseline” FRP pole compared very well with results obtained from existing numerical models.

- The maximum stress in the FRP composite pole increases as the fiber-orientation increases up to 45° with respect to the axial direction, and then decreases as the fiber-orientation increases up to 60°. It was also apparent that increasing the fiber-orientation increases the maximum deflection of the pole increases as the fiber-orientation increases from 0° to 60°.

- The maximum deflection and maximum stress in the FRP composite poles decrease as the number of layers increase (thicker in cross-section). However, the rate of reduction decreases as the number of layers increases.

- There was no significant difference in the maximum deflection and maximum stress between FRP poles of same overall thickness with 4 or 6 layers in comparison to the “baseline” FRP pole with 8 layers of 0.5 mm lamina thickness per layer.

- Strength of the FRP poles at critical sections as determined from finite element analysis are used in an ongoing fragility analysis of the poles.

Acknowledgements

The authors thank the Sid and Reva Dewberry Department of Civil, Environmental and Infrastructure Engineering at George Mason University for providing student support.

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