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DYNAMIC ANALYSIS OF FIBER-REINFORCED POLYMER COMPOSITE ELECTRIC POLES

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This paper presents finite element modeling of tapered fiber-reinforced polymer (FRP) poles in ABAQUS for dynamic analysis. Modal analysis and transient dynamic analysis are presented in order to evaluate the effect of fiber orientation, taper ratio, number of layers and lamina thickness on the dynamic properties of tapered poles. Trends observed from the parametric studies on the analyses of the FRP poles are enumerated. In addition, the effect of rectangular dynamic excitations on the overall response of the FRP poles is presented encapsulating impulsive loadings that may occur due to wind gusts or loss of cable tension supported by the FRP poles. Result shows that the fundamental frequency of the poles decreased as the fiber-orientation increased up to 60 degrees. In addition, the fundamental frequency of the poles increased as the number of layers increased. No significant difference was observed in natural frequency of the poles when varying the lamina thickness without changing the overall laminate thickness. The fundamental frequency of the FRP poles decreased by 10% as the taper ratio increased from 0.4 to 1. Transient dynamic analysis showed that FRP poles with higher fiber orientation angle had the larger maximum tip deflection. However, only small differences were observed when the deflections are normalized as the ratio of the maximum dynamic deformation to the maximum static deformation.

Keywords: FRP poles, Fiber orientation, Finite element analysis.

1 INTRODUCTION

In the face of frequent natural and man-made disasters, engineers are increasingly tasked with designing, operating, and maintaining structures that incorporate the philosophy of resiliency across a variety of critical infrastructure sectors. Electric distribution and transmission systems are examples of critical infrastructure sectors. A report on economic benefits of increasing electric grid resilience to weather outages estimates that the United States economy lost $18 billion to $33 billion annually during 2003-2012, and identifies several strategies to increase the nation's electric grid resiliency (The White House 2013). 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. Urgessa and Mohamadi (2016) highlighted that the primary hardening strategy is upgrading wooden electric poles and supporting structures with stronger materials that withstand hurricane-force winds based on literature survey (Fouad and Mullinax 2000, ANSI 2005, Desai and Yuan 2006, Oliphant 2009, Saafi and Asa 2010). Fiber reinforced polymers (FRP) are stronger materials (Urgessa and Horton 2005) that can be used in strengthening applications of existing wood poles or they can be used to manufacture new poles.

Urgessa and Mohamadi (2016) presented finite element static analysis of tapered FRP pole subjected to static transverse wind load with a specific configuration. They studied suitability and accuracy of the element type for modeling the FRP pole behavior in ABAQUS. The conventional general purpose shell element S4 was found to be suitable and relatively accurate for modeling the behavior of FRP composite poles. Parametric studies have been carried out to evaluate the effect of various parameters on static response of the pole and they observed that the maximum principal stress in the FRP composite pole increased as the fiber-orientation increased up to 45° with respect to the axial direction, and then decreased as the fiber-orientation increased up to 60°. In addition, increasing the fiber-orientation from 0° to 60° was shown to increase the maximum deflection of the pole. They concluded that changing the number of layers with the same overall thickness does not play a role on performance of the pole and it may be neglected. They also found that taper ratio had little effect on the maximum stress because the base diameter was left unchanged.

This paper presents dynamic analysis of tapered FRP poles using finite element modeling. Modal analysis and transient dynamic analysis are presented in order to evaluate the effect of fiber orientation, taper ratio, number of layers and lamina thickness on the dynamic properties of tapered FRP poles.

2 MODAL ANALYSIS OF TAPERED FRP POLES

Figure 1 shows the general geometry of the selected FRP pole that was fixed to the ground. ABAQUS (2014) was used for finite element analysis. The geometry and material properties of the baseline pole is shown in Table 1.

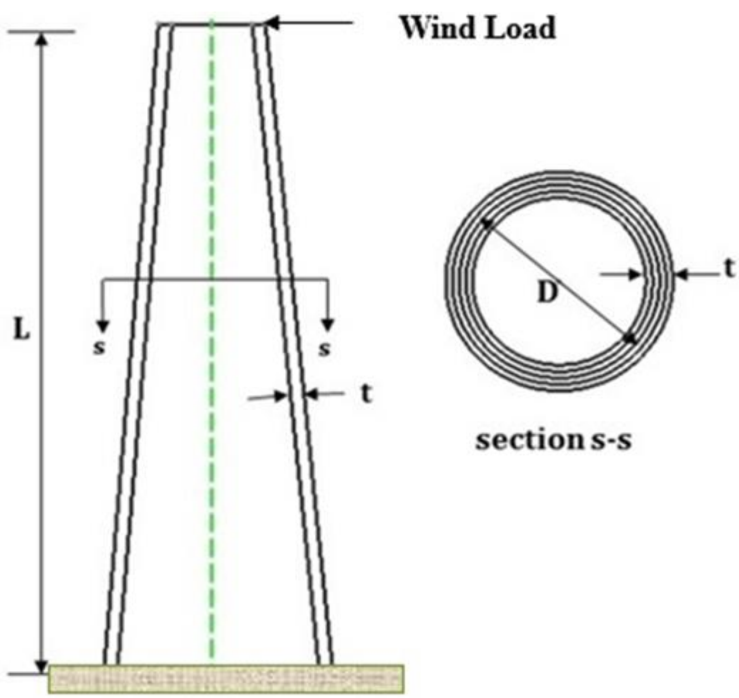

Figure 1. Geometry of a tapered pole.

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
Thickness (mm)	4	Poisson's ratio	0.235		
No. of lamina	8	Shear modulus (GPa)	5.17		

S4 shell elements were used in the dynamic analysis. ABAQUS executes modal analysis using eigensystems needed for computing mode shapes and the corresponding natural frequencies. It solves the eigenfrequency problem only for symmetric mass and stiffness matrices. The program generally considers symmetric mode shapes as separate modes even if there is no difference in the values of the corresponding natural frequency. For example, modes one and two have the same natural frequencies with opposite mode shapes. For this study, 10 eigenvalues were selected representing five mode shapes (Mohamadi 2016). The composite lay-up used in the analysis was $[-10/10]_4$. Table 2 summarizes the results of the natural frequencies for the five modes.

Table 2. Natural frequency of the FRP pole with $[-10/10]_4$ lay-up.

Fiber orientation	1st mode	2nd mode	3rd mode	4th mode	5th mode
	Natural frequency (Hz)				
$[-10/10]_4$	0.267	1.01	1.27	2.75	3.27

3 PARAMETRIC STUDIES USING MODAL ANALYSIS

Once the modal analysis results in ABAQUS were validated, parametric studies were conducted in order to evaluate the effect of various material and cross-sectional properties on the natural frequency of FRP poles. These properties include fiber orientation, taper ratio, number of layers and lamina thickness.

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 natural frequencies of the poles. The angle θ was varied in increments of 10° from 0° to 60° for this study. All other material, geometric and load properties were the same as the baseline FRP pole discussed in section 2. Figure 2 shows the effect of fiber orientation on the fundamental frequency corresponding to the first mode of the pole for varying orientation. The fundamental cyclic frequency of the pole decreases as the fiber-orientation increases with respect to the axial direction. While the mass of the pole does not change for this study, increasing the fiber orientation angle reduces the stiffness of the FRP pole. As a result, the natural frequency decreases.

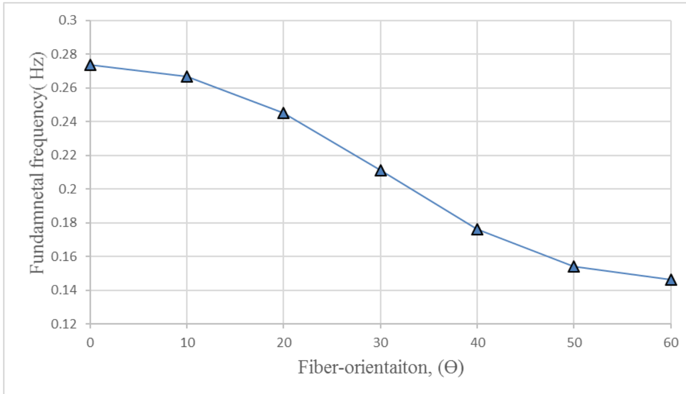

Figure 2. Effect of fiber orientation on the natural cyclic frequency of the FRP pole.

3.2 Effect of the Number of Layers and Lamina Thickness

The glass fiber-reinforced composites poles studied so far were made from 8 layers of composite with a total thickness of 4 mm regardless of fiber-orientations. A parametric study was conducted by varying the number of composite layers from 2 to 12 inch increments of two layers for a specified anti-symmetric fiber-orientation, $[-10/10]_{\#\text{ of layers}}$. Figure 3 shows the natural frequency values. The result showed that increasing the number of layers increases the fundamental frequency. However, the percentage increase was very small, approximately 2% when poles made from 2 layers were compared to poles made from 12 layers. The rate of reduction was not constant for all variations of the number of layers. The rate decreases as the number of layers increases. Similar findings were reported in Khalili and Saboori (2010).

Furthermore, a parametric study was conducted to study the effect of varying lamina thickness without changing the overall laminate thickness of the selected FRP pole. There was no significant difference in natural frequency of FRP poles of the same overall thickness with various number of layers in comparison to the baseline FRP pole with 8 layers of 0.5 mm lamina thickness per layer. The maximum difference is within 1%.

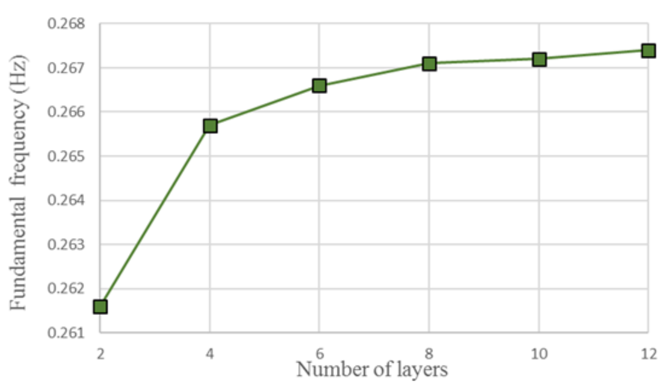

Figure 3. Effect of number of layers on the fundamental frequency of the FRP pole.

3.3 Effect of Taper Ratio

A parametric study was conduct by varying the taper ratio of the FRP pole from 0.4 to 1 while changing the top diameter (d_1) and keeping the base diameter (d_2) constant. Figure 4 shows the fundamental frequency results. The results showed that the natural frequency of the FRP pole decreases by 10% as the taper ratio increases from 0.4 to 1. While increasing the taper ratio is expected to increase both the mass and stiffness of the pole, the overall vibrational effect is to decrease the natural frequency.

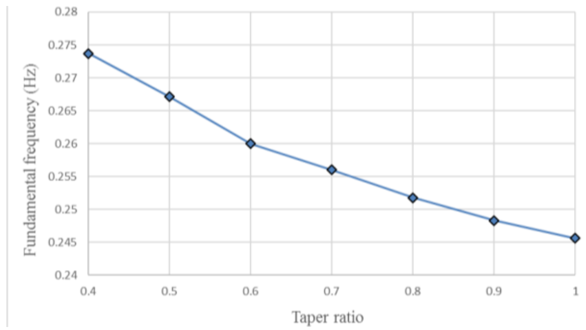

Figure 4. Effect of taper ratio on the fundamental frequency of the FRP pole.

4 TRANSIENT DYNAMIC ANALYSIS

FRP poles support cables and transformers that may be subjected to impulse loads due to wind gusts or sudden loss of cable tension. The effect of impulsive loads on the dynamic response of the baseline FRP pole was evaluated using loads characterized by rectangular pulses. Damping effects were neglected since the maximum response will be reached without ample time to dissipate energy. The effect of fiber-orientation was studied by modeling multiple tapered FRP poles with anti-symmetric $[-\theta/\theta]_4$ lay-up and determining the maximum deflection of the poles. The angle θ was varied in increments of 10° from 10° to 60° for this study. All other material, geometric and load properties were kept the same as the baseline FRP pole. Figure 5 shows the tip displacement response.

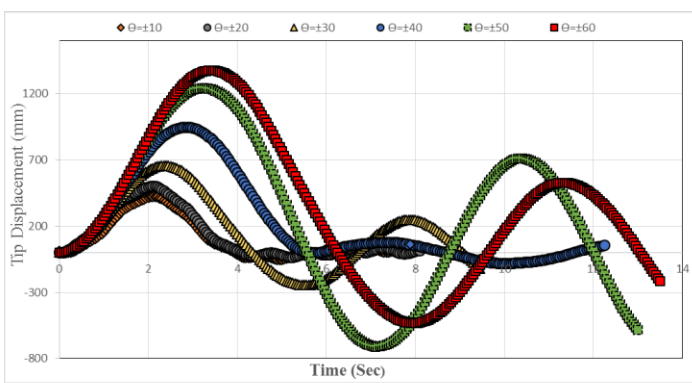

Figure 5. Effect of fiber-orientation on the dynamic response of FRP poles with $[-\theta/\theta]_4$ layup.

FRP poles with higher fiber orientation angle had the larger maximum tip deflection. However, the effect of fiber orientation on shock spectrum of the FRP pole subjected to rectangular pulse showed that varying fiber orientation angle from 0 to 60 degrees had a small effect on maximum response deformation factor, which is the ratio of the maximum dynamic deformation to the maximum static deformation.

5 CONCLUSIONS

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

- The fundamental frequency of the FRP poles decreased as the fiber-orientation increased up to 60°.
- The fundamental frequency of the FRP poles increased as the number of layers increased. However, the increase in fundamental frequency happens at a lower rate when the number of layers increased.
- There was no significant difference observed in natural frequency of FRP poles when lamina thickness varied without changing the overall laminate thickness.
- The fundamental frequency of the FRP pole decreased by 10% as the taper ratio increased from 0.4 to 1.
- Transient dynamic analysis showed that FRP poles with higher fiber orientation angle had the larger maximum tip deflection. However, only small differences were observed when the deflections are normalized as the ratio of the maximum dynamic deformation to the maximum static deformation.

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