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FINITE ELEMENT MODELING OF CFRP COMPOSITE POLE STRUCTURES

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Abstract— **In recent years, FRP composites, which are made of reinforcing fibers and a thermosetting resin, have been widely used as advanced construction materials. The tapered FRP poles are currently considered attractive in the application of the light poles and electrical transmission tower element. A finite element (FE) program was used to perform a nonlinear numerical analysis to model the static flexural behavior of CFRP poles. A parametric study was carried out to study the effect of replacing glass fiber (GFRP) by carbon fiber (CFRP) on the FRP pole behaviors. The ultimate capacity, top deflection and stiffness increase are presented. The study demonstrates that replacing carbon fiber by glass fiber of the FRP poles a good improvement achieved. The total load capacity of the FRP poles and the stiffness increased with increasing the percentage of carbon fiber.**

Keywords—**Fiber Reinforced Polymers, FRP Structural Shapes, FRP poles, Filament Winding.**

I. INTRODUCTION

The finite element analysis is a good way that can be used to simulate and predict the actual behavior of FRP poles. A theoretical analysis by finite element method were developed for the analysis of FRP hollow tapered poles, to perform a linear static analysis, linear buckling analysis, linear P-Δ analysis, a geometrical nonlinear analysis of beam-column-type bending and an vocalization analysis (Lin, 1995). Extensive numerical results were presented showing the effect of different lamination and geometric parameters of the multilayered composite cylinder on the accuracy of the static and vibrational responses (Noor et al., 1991). The Brazier's theory for the nonlinear collapse of isotropic circular cylinders had been extended by Long-yuan 1996 to predict the instability critical loads of orthotropic composite tubes under pure bending by simple formulations. The formulations were based on the assumption that the instability of an orthotropic composite tubes under pure bending is due to the vocalization of its cross section.

In this paper, the finite element program was used to perform a nonlinear numerical analysis for 10500 mm (35 ft) tapered glass fiber-reinforced polymer (GFRP) poles with service opening, under lateral load to present the wind load on the structure. The model was performed to simulate the actual behavior of the static test according to the recommendations described in ASTM and ANSI standard. A parametric study was carried out to study the effect of replacing glass fiber by carbon fiber on the FRP pole behaviors. The ultimate capacity, top deflection and stiffness increase are presented.

II. FINITE ELEMENT

A nonlinear finite element model of FRP poles was developed using the commercial software ADINA finite element program. The finite element method used to analyze and simulate the behaviours of GFRP poles. Large deflection was included in the analysis and appropriate failure criteria were used in determining the failure load. The finite element analysis was verified through comparison with the available experimental data.

The following sections present the major features of the finite element method used in this paper:

A. Geometrical Modeling

The specimens were tapered hollow sections, 10500 mm in length. The inner diameters at the base and at the top were 275.00 and 115.00 mm, respectively. The specimen divided through the height into three zones, A, B and C, GFRP poles are fabricated using filament winding technique, different fiber angles with respect to the longitudinal axis of the pole were used. The pole modeled with total number of elements 2256 (16 and 141 in the circumference and longitudinal direction, respectively), the mesh layout was fine in the bottom area of the maximum stress and expected failure zone, and gradually becomes coarse at the top, this was made by the automatic mesh density option of the program. The general layout of the mesh distribution and the used finite element models are shown in Figure. 1.

The underground length of the GFRP poles were restraint along two opposite half circumference area, the first area at the end of the base and the second area at the ground line. Each node along the supported area was restrained against the vertical (in z-direction), the horizontal (in x and y directions) movements. This Configuration of restraints was to simulate the support condition described in standards ASTM D 4923-01 and ANSI C 136.20-2005 for measuring the Load- deflection behavior of FRP poles, see Figure. 2.

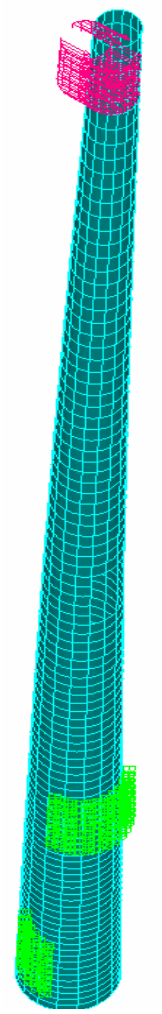

Fig. 1. Finite element mesh

B. Composite Shell Elements

An eight-node quadrilateral multilayered shell element was used in the model. Each node has six degrees of freedom, three translations (Ux, Uy, and Uz) and three rotations (Rx, Ry, and Rz). The composite shell elements are kinematically formulated in the same way as the single layer shell elements, but an arbitrary N number of layers can be used to make up the total thickness of the shell. Layers are numbered in sequential order starting from 1 at the bottom of the shell (ADINA. 2006). The material model which be used with the shell element is elastic-orthotropic with large displacement /small strain. In the large displacement formulation/small strain formulation, the displacement and rotation can be large, but the strains were assumed to be small. Orthotropic material properties in the fiber and transverse to the fiber direction were defined. Fiber orientation for each layer was specified by defining the fiber angle with respect to the element axes.

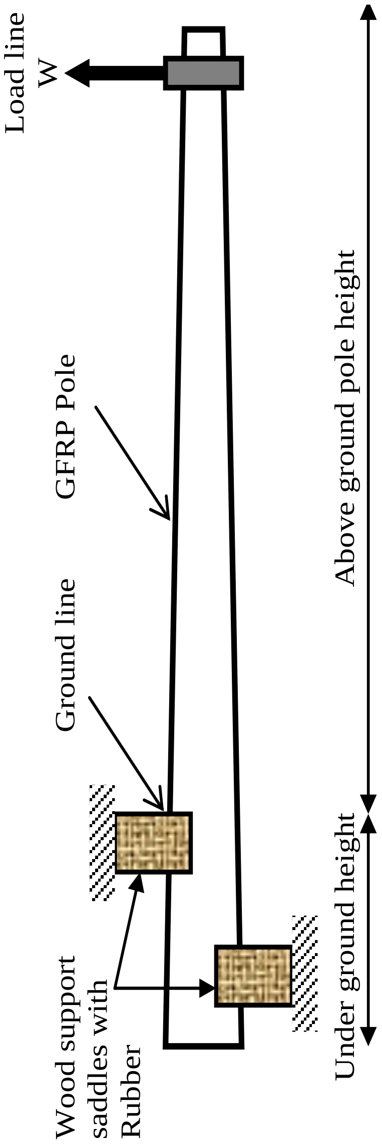

Fig. 2. Specified methods for testing FRP poles

C. Macroscopic Failure Criteria

The mechanical behaviour of advanced fiber reinforced composite materials is topic which has attracted a great deal of interest in recent years. Failure criteria have been developed to predict the materials strength properties of the orthotropic composite materials. Composite materials are anisotropic (properties vary depending on the direction in which they are measured); hence the strength properties of fiber-reinforced materials are strongly dependent on the direction of loading. Accordingly, more than one parameter is needed. The Tsai-Wu failure criteria are provided in ADINA for the analysis of shell structures using the elastic-orthotropic material models. This failure theory expands the Tsai-Hill criteria by including linear terms which characterize the different strength in tension and compression and quadratic terms. This criterion provides an ellipsoid shaped failure envelope in the stress space.

D. Material Properties

The mechanical properties of the FRP laminate were obtained from the material properties of the E-glass fiber and the epoxy resin. They used to calculate the effective modules of elasticity of the orthotropic material based on micromechanical models. The Rule of Mixture was used to evaluate the modulus of elasticity in the fiber direction (El), and the major Poisson's ratio (υ 12) as follows (Adams 1987):

$$E_1 = E_f \mu_f + E_m \mu_m \qquad (1)$$

[2] $$\upsilon_{12} = \upsilon_f \mu_f + \upsilon_m \mu_m \qquad (2)$$

Where,

μ_f and μ_m are the fiber and the matrix volume ratios, respectively;
E_f and E_m are the fiber and the matrix Young's modules, respectively; and
υ_f and υ_m are the fiber and the matrix Poisson's ratios respectively.

The equations given by Gay 1989 were used to calculate the effective Young's modulus in the transverse direction (E2) and the shear modulus (G12), by using the fiber and matrix properties (E2) and (G12) were derived as follow:

[3] $$E_2 = \frac{1}{\left[\frac{\mu_f}{E_f} + \frac{\mu_m}{E_m}\right]} \qquad (3)$$

[4] $$G_{12} = \frac{1}{\left[\frac{\mu_f}{G_f} + \frac{\mu_m}{G_m}\right]} \qquad (4)$$

Where,

G_f and G_m are the fiber and the matrix shear modules, respectively.

III. RESULTS AND DISCUSSION

Failure of the modeled FRP poles was determined when the divergence of the solution was achieved or when the Tsai-Wu failure criterion value reached unity. A comparison between the finite element analysis and the results obtained. It is evident that there is a strong correlation between the results obtained from the finite element analysis and the experimental results. The 35 ft GFRP pole failed at the ground level due to the local buckling and before this failure distortion of cross section at service opening location was occurred, (see Figure. 3).

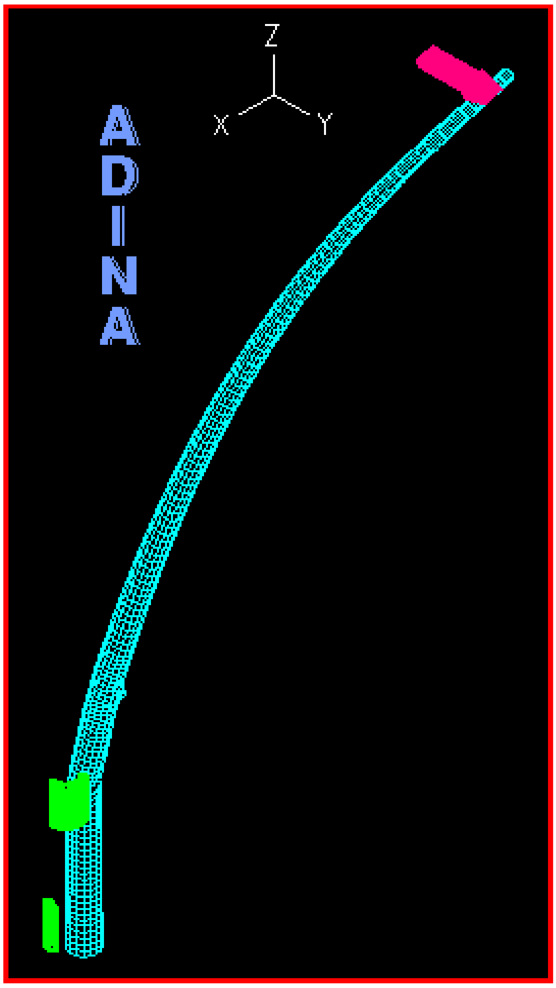

Fig. 3. Failure mode

IV. PARAMETRIC STUDY

Based on the agreement of the finite element analysis, the effects of the following parameters were carried out to better understand the flexural behavior of FRP poles: replacing glass fiber by carbon fiber. The same finite element analysis was used to extend the study and examine these parameters effect of replacing glass fiber by carbon fiber on the FRP pole behavior, with the same details of wall thickness, dimension of the GFRP pole (35 ft) and material properties. A parametric study had been made to investigate the effect of the percentage of replacing glass fiber by carbon fiber on the FRP pole behaviours. To study this parameter, 7 prototypes were defined in ADINA program. Each prototype redefined by replacing one or two or three or four galas fiber layers by carbon fiber. These layers were changed in the circumferential and/or longitudinal by alternative. Table 1 shows the stacking sequence, numbers, type and percentage of carbon fibers for each model.

Table -1 Stacking sequences and percentage of carbon fibers in different prototype

Proto. Id.	Stacking sequences	Number of carbon fiber layers	Parameters	Percentage of carbon fibers %
P$_o$	[90, $(\pm10)_5$, 90]	0	4	0
2	[90, 10, $(\pm10)_4$, -10, 90]	1 circumferential	4	8.00
3	[90, 10, $(\pm10)_4$, -10, 90]	1 longitudinal	4	8.00
4	[90, 10, $(\pm10)_4$, -10, 90]	2 circumferential	4	16.00
5	[90, 10, $(\pm10)_4$, -10, 90]	2 longitudinal	4	16.00
6	[90, 10, $(\pm10)_4$, -10, 90]	2 circ and 2 long	4	32.00
7	[90, ±10, $(\pm10)_3$, ±10, 90]	4 longitudinal	4	32.00

The load deflection relationships are plotted for the numerical results of the different models in Figure 4. Table 2 shows the failure load, the deflections, and the stiffness factor of the FRP poles for different prototypes for replacing glass fiber by carbon fiber. Fig. 4 shows the effect of incorporating carbon fiber on load deflection relationship with different percentage of carbon fibers. Figure. 5 shows the effect of incorporating carbon fiber on the percentage increase of the failure load of the FRP poles. Also Figure. 6 shows the effect of incorporating carbon fiber on the percentage increase of the stiffness of the FRP poles. It is clear that replacing carbon fiber by glass fiber of the FRP poles a higher improvement in the stiffness and strength was achieved. The total load capacity of the FRP poles and the stiffness were increased with increasing the percentage of carbon fiber. The percentage increase in ultimate load capacity and stiffness depends on the type of layers. Incorporating longitudinal carbon fiber layers tend to increase the ultimate capacity more than incorporating circumferential carbon fiber layers.

Table 2. Results of the finite element analysis for replacing glass fiber by carbon fiber.

Proto. *Id.*	Number of carbon fiber layers	Percentage of carbon fibers %	Failure load (FL) (kN)	Max Deflection (mm)	Stiffness (St) (N/mm)
P$_o$	0	0	**5.58**	1800	**3.10**
2	1 circumferential	8.00	**6.30**	1730	**3.64**
3	1 longitudinal	8.00	**6.14**	1660	**3.69**
4	2 circumferential	16.00	**6.42**	1650	**3.67**
5	2 longitudinal	16.00	**6.14**	1360	**4.5**
6	2 circ and 2 long	32.00	**7.11**	1380	**5.15**
7	4 longitudinal	32.00	**7.53**	1450	**5.19**

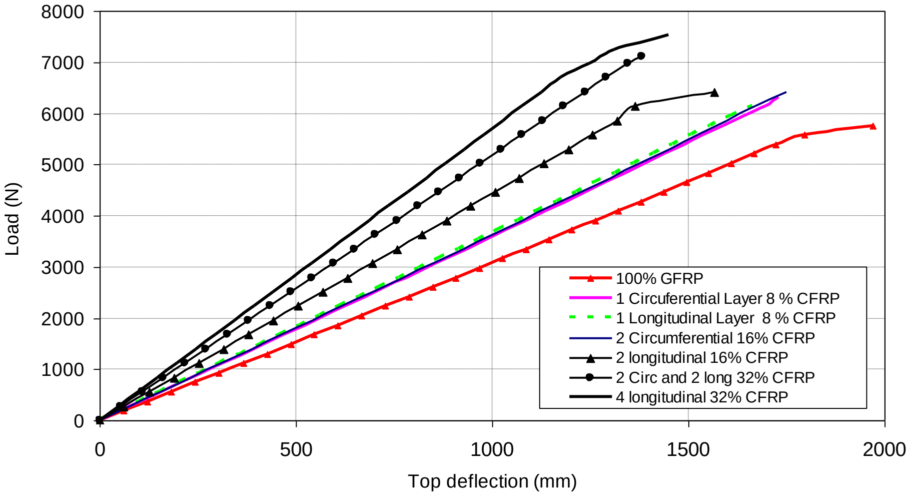

Fig. 4. Effect of incorporating carbon fiber on load deflection relationship.

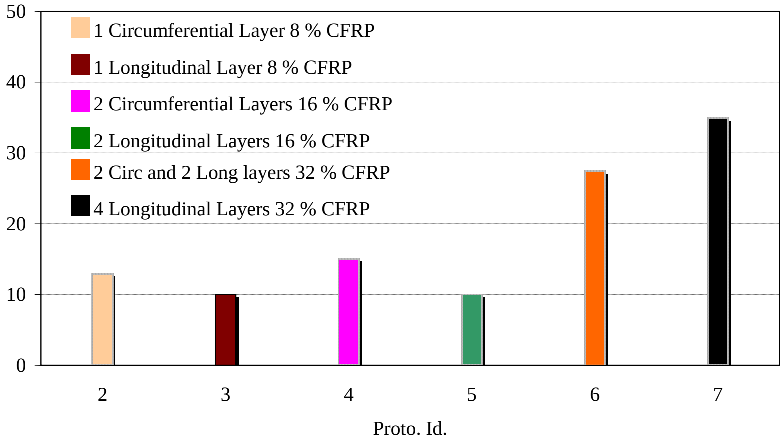

Fig. 5. Effect of incorporating carbon fiber on failure load of FRP poles

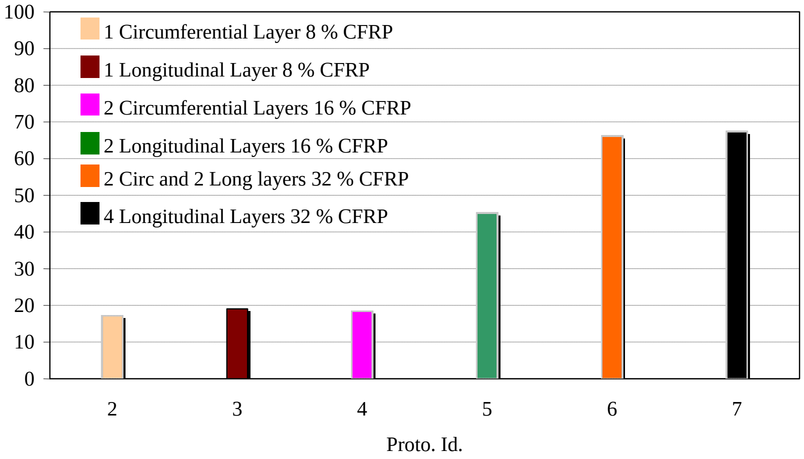

Fig. 6. Effect of incorporating carbon fiber on failure load of FRP poles.

V. CONCLUSION

Finite element analysis is effective for modeling GFRP pole structures. Layered composite shell elements were used in this finite element analysis. The program accounts for the nonlinear behaviour of the poles and includes a strength failure check by applying the Tsai-Wu failure criterion. The results were in an excellent agreement with the experimental results. The finite element method used in this investigation provided an excellent prediction of the critical buckling and material failure loads. The load-deflection curve of GFRP poles under lateral loading is linear up to failure. The total load capacity of the FRP poles and the stiffness increased with increasing the percentage of carbon fiber.

VI. REFERENCE

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