International Journal of Sustainability and Innovation in Engineering (IJSIE)
https://www.doi.org/10.56830/IJSIE062023

Analyzing the Nonlinear Finite Element Behavior of FRP Composite Electrical Structures in Flexural Loading

https://www.doi.org/10.56830/IJSIE06202304

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Abstract:

Finite Element Analysis of Flexural Behavior in Full-scale Tapered FRP Pole Structures: Influence of Fiber Orientations, Circumferential Layers, and Carbon Fiber Substitution. In this study, we present a finite element modeling analysis of the nonlinear behavior of laterally loaded full-scale tapered fiber-reinforced polymer (FRP) pole structures. The study explores the impact of various parameters, including fiber orientations in longitudinal and circumferential layers, the number of circumferential layers, and the substitution of glass fiber with carbon fiber in the FRP pole compositions.

The FRP poles in question were manufactured using the filament winding technique, with E-glass fiber and epoxy resin as the primary materials. Our analysis results exhibit a significant correlation between the finite element analysis and experimental data, emphasizing the critical role of fiber orientation in determining flexural behavior.

The findings underscore the advantages of incorporating circumferential layers and highlight that enhanced strength can be achieved by incorporating both outer and inner circumferential layers alongside longitudinal layers. Moreover, substituting carbon fiber for glass fiber in the FRP poles results in notable improvements, with increased total load capacity and stiffness as the percentage of carbon fibers rises.

1. Introduction

In recent years, FRP composites, which are made of reinforcing fibres and a thermosetting resin, have been widely used as advanced construction materials. FRP provide several advantages over traditional construction materials (steel, concrete, wood): high strength to weight ratio, high stiffness, resistance to corrosion, ease of installation and high durability (Fujikake, Mindess, & Xu, 2004). Therefore, the tapered FRP poles are currently considered attractive in the application of the light poles and electrical transmission tower element.

There is a lack to study the behaviour of the hollow tapered FRP pole structures. These due to the limited number of experimental and theoretical studies, which have been conducted on the behaviour of the tapered GFRP poles structure under lateral load (Li, 1996); (Crozier, Dussel, Bushey, & West, 1995); (Derrick, 1996);

(Ibrahim, Polyzois, & Hassan, 2000); (Ibrahim & Polyzois, "Ovalization analysis of fiber reinforced plastic poles", 1999). The most of these studies were established on the behaviour of the FRP poles without service opening. The existence of service opening in the FRP poles, reduce the strength at the location of this opening, due to small thickness-to-radius ratio, ovalization and local buckling behaviour of the FRP poles. Therefore the part which includes this hole must be addressed and finding the optimum geometrical details for it to be compatible with the upper and lower zones over the length of the pole to attain the required total capacity under lateral loads.

The finite element analysis is a good way that can be used to simulate and predict the actual behaviour 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 ovalization analysis (ZM., 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, Sctt, & Peters, 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 ovalization of its cross section.

In this paper, the finite element program was used to perform a nonlinear numerical analysis for 10566 mm (35 ft) tapered glass fibre-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 behaviour 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 longitudinal and circumferential angle orientation of the fibre, number of circumferential layers and the effect of replacing glass fibre by carbon fibre on the FRP pole behaviours. The ultimate capacity, top deflection and stiffness increase are presented.

2. Finite Element Analysis

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 obtained from the static testing of full-scale specimens, according to the recommendations described in ASTM and ANSI standard.

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

2.1. Geometrical Modeling

The specimens were tapered hollow sections, 10566 mm in length. The inner diameters at the base and at the top were 270.00 and 114.00 mm, respectively. The specimen divided through the height into three zones, I, II and III, The 101.6 x 304.8 mm-(width x length) service opening is located at the center of the middle zone II and was in the compression side. The typical specimen dimension, cross section and details of the three zones, are shown in Figure. 1. GFRP poles are fabricated using filament winding technique, different fibre angles with respect to the longitudinal axis of the pole were used: (90°, ±10°) at the bottom zone I, (90°, ±45°, ±10°) at the middle zone II and (90°, ±10°) at the top zone III. The layer thickness is 0.432 mm. The pole modeled with total number of elements 2256 (16 and 141 in the circumference and longitudinal direction, respectively), the mesh layout were 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. 2.

The under ground 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 behaviour of FRP poles, see Figure. 3.

2.2. 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).

Newton-Cotes with high order of 5×5 numerical integration was used for the evaluation of the element matrices in the r-s plane of the shell element, to avoid spurious zero energy. 3-point Newton-Cotes numerical integration was used through the shell thickness to obtain an accurate profile of the transverse shear stress.

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 fibre and transverse to the fibre direction were defined. Fibre orientation for each layer was specified by defining the fibre angle with respect to the element axes.

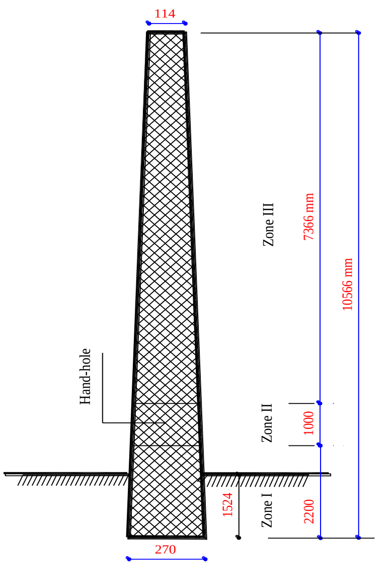

Figure 1. Dimension of full-scale FRP pole

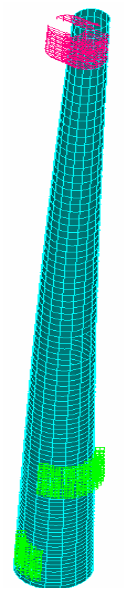

Figure 2. Finite element mesh

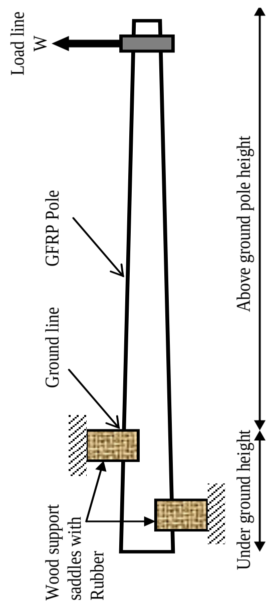

Figure 3. Specified methods for testing FRP poles

2.3. Macroscopic Failure Criteria

The mechanical behaviour of advanced fibre 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 fibre-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.

2.4. Loading

The FRP pole was subjected to a horizontal pressure load (W) below the top of the pole edge by 300 mm according to the ANS C 136.20-2005. The value of (W) was varied from zero to the ultimate load capacity corresponding to each pole. The pole was incrementally loaded using 100-150 time steps. This variation is automatically done by the AUI according to the condition of convergence. To avoid local failure under the applied load, the load had been distributed over circumferences area to simulate the same effect of the experimental load.

3. Material Properties

The material properties for both the fibre and the resin are presented in Table 1. The mechanical properties of the FRP laminate were obtained from the material properties of the E-glass fibre 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 fibre direction (E_l), and the major Poisson's ratio (υ_{12}) as follows (Adams, 1987):

[1] $$E_1 = E_f \mu_f + E_m \mu_m$$

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

Where,

μ_f and μ_m are the fibre and the matrix volume ratios, respectively;

E_f and E_m are the fibre and the matrix Young's modules, respectively; and

υ_f and υ_m are the fibre and the matrix Poisson's ratios respectively.

equations given by (Gay, 1989) were used to calculate the effective Young's modulus in the transverse direction (E_2) and the shear modulus (G_{12}), by using the fibre and matrix properties (E_2) and (G_{12}) were derived as follow:

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

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

Where,

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

Table 1: Properties of E-Glass and matrix:

	Fibres	
	E-Glass	Carbon
Tensile modulus(MPa)	80 000	250 000
Shear modulus(Mpa)	30 000	93 750
Poisson's ratio	0.25	0.20
	Epoxy resin Araldite GY 6010	
Density (Kg / m^3)	1200	
Tensile modulus(Mpa)	3380	
Shear modulus(Mpa)	1600	
Poisson's ratio	0.4	

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4. 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 from experimental testing of full-scale prototypes, was in terms of the load-deflection relationship and the ultimate load carrying capacity. Figure. 4 represent the load deflection relationship for the experimental and finite element analysis for 20 and 35 ft height GFRP poles. It is evident from this figure 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. 5).

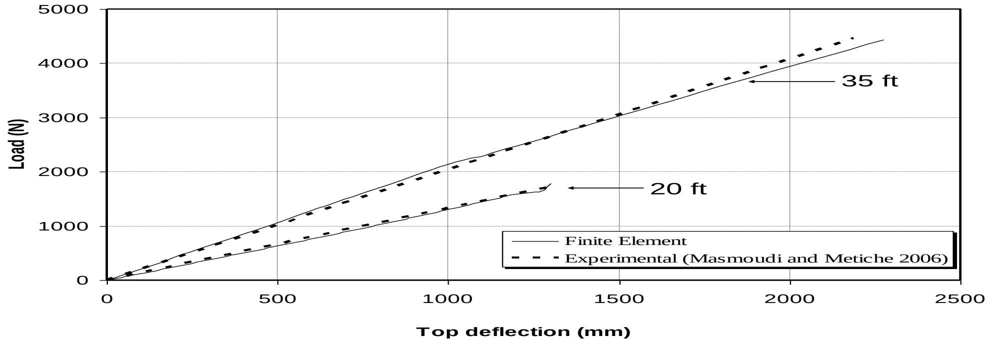

Figure 4. Comparison between experimental and FE load-deflection relationship for

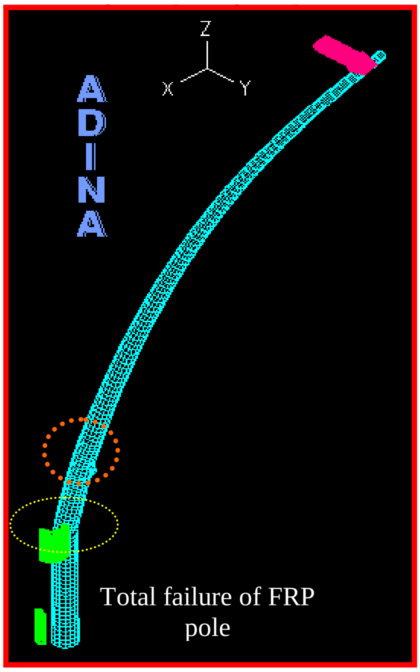

Figure 5. Deformed shape for 35 GFRP pole at failure

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 behaviour of FRP poles:

1- fibre orientations of longitudinal layers
2- fibre orientations of circumferential layers
3- number of circumferential layers, and
4- replacing glass fibre by carbon fibre.

The same finite element analysis was used to extend the study and examine these parameters effect of longitudinal and circumferential angle orientation of the fibre, number of circumferential layers and the effect of replacing glass fibre by carbon fibre on the FRP pole behaviours, with the same details of wall thickness, dimension of the GFRP pole (35 ft) and material properties. Table 2 shows the stacking sequence and fibre orientation for 7 prototypes models to study the effect of the first, second and third parameters. P_o was taken the reference. P-1 and P-2 are proposed to study the effect of fibre orientations of longitudinal layers, by changing the fibre orientation from ±10 to ±20 and ±30 degree for P-1 and P-2, respectively. P-3 and P-4 are proposed to study the effect of fibre orientations of circumferential layers, by changing the fibre orientation from ±90 to ±70 and ±50 degree for P-3 and P-4, respectively. P-5 and P-6 are proposed to study the effect of number of circumferential layers, by changing the fibre orientation from ±90 to ±10 for P-5, it is meaning that this model has not any circumferential layers. Finally in P-6, the number of circumferential layers was assumed to increase for 4 layers.

A parametric study had been made to investigate the effect of the percentage of replacing glass fibre by carbon fibre 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 fibre layers by carbon fibre. These layers were changed in the circumferential and/or longitudinal by alternative. Table 3 shows the stacking sequence, numbers, type and percentage of carbon fibres for each model.

Table 2: Stacking sequence and fibre orientation of layers

Pole model Id	Zone I, III	Zone II	Parameters		
P_o	[90, $(\pm10)_5$, 90]	{90, ±45 [90, $(\pm10)_5$, 90] ±45, 90}	1	2	3
P-1	[90, $(\pm20)_5$, 90]	{90, ±45 [90, $(\pm20)_5$, 90] ±45, 90}		1	
P-2	[90, $(\pm30)_5$, 90]	{90, ±45 [90, $(\pm30)_5$, 90] ±45, 90}		1	
P-3	[70, $(\pm10)_5$, 70]	{70, ±45 [70, $(\pm10)_5$, 70] ±45, 70}		2	
P-4	[50, $(\pm10)_5$, 50]	{50, ±45 [50, $(\pm10)_5$, 50] ±45, 50}		2	
P-5	[10, $(\pm10)_5$, 10]	{10, ±45 [10, $(\pm10)_5$, 10] ±45, 10}		2	
P-6	[90_2, $(\pm10)_4$, 90_2]	{90, ±45 [90, $(\pm10)_4$, 90] ±45, 90}		3	

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Table 3. Stacking sequences and percentage of carbon fibres in different prototype.

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

The under line layers indicate to carbon fibre layers

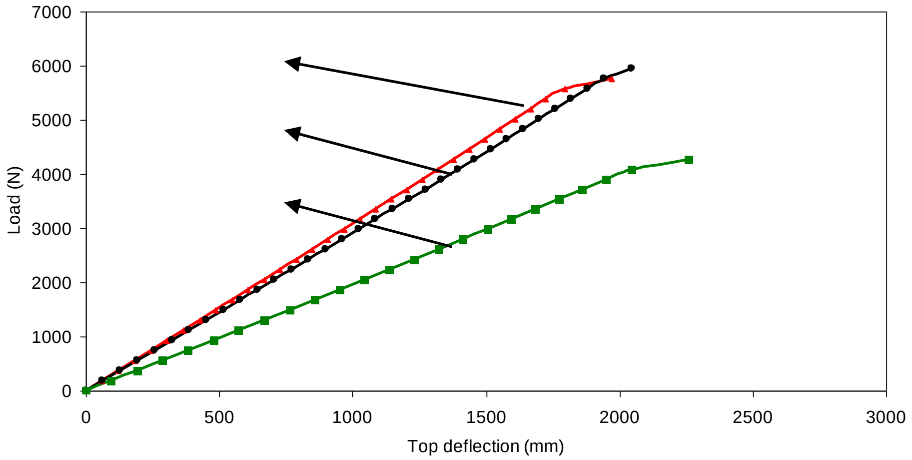

Figure 6. Effect of fibre orientations of longitudinal layers on load deflection relationship

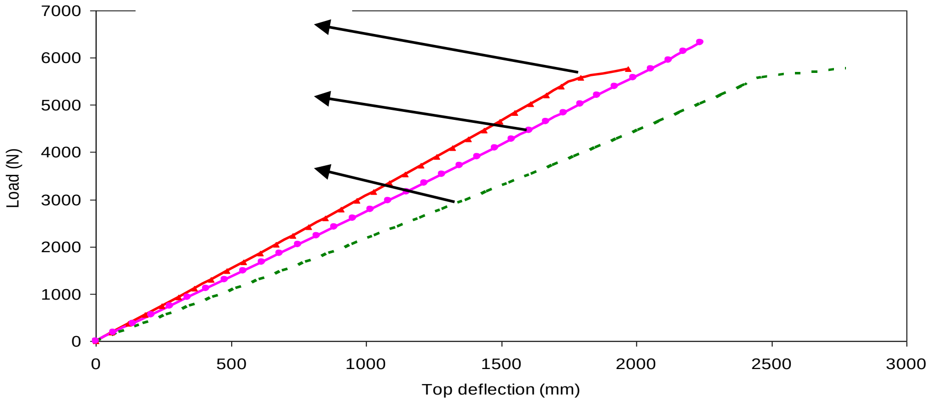

Figure 7. Effect of fibre orientation of circumferential layers on load deflection relationship

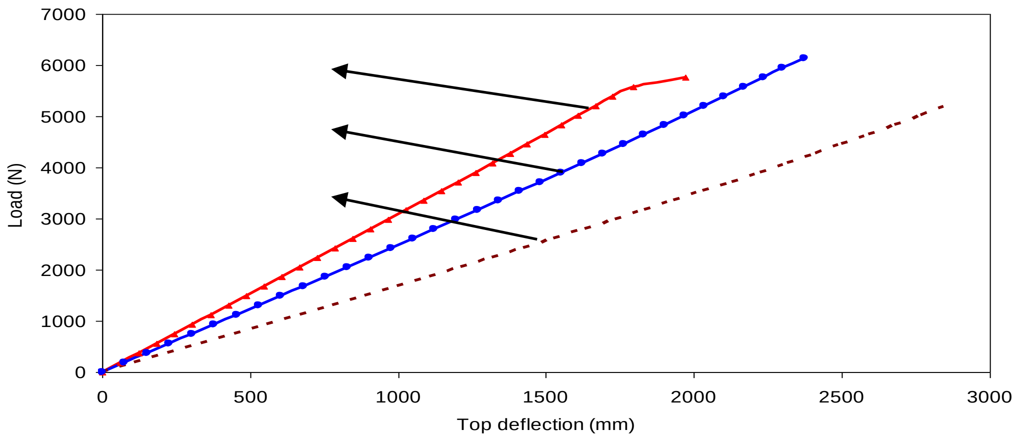

Figure 8. Effect of number of circumferential layers on load deflection relationship

The load deflection relationships are plotted for the numerical results of the different models in figures 6, 7, 8 and 9. It is observed that increasing the fibre orientations of the longitudinal layer a significant droop in the failure load and an increase of the deflection at all load level was occurred as shown in Figure. 6. Also decreasing the fibre orientation of the circumferential layers from 90 to 70 and then 50 degree the load decreased and deflection increased as shown in Figure. 7. It is cleared from Figure. 8 that the importance of the inner and the outer circumferential layers with the longitudinal layers for the FRP poles. This is evident from the result of the model P-5, it hadn't any circumferential layer and a significant droop in the failure load and an increase of the deflection at all load level was occurred.

Table 4. Results of the finite element analysis for replacing glass fibre by carbon fibre.

Proto. *Id.*	Number of carbon fibre layers	Percentage of carbon fibres %	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**

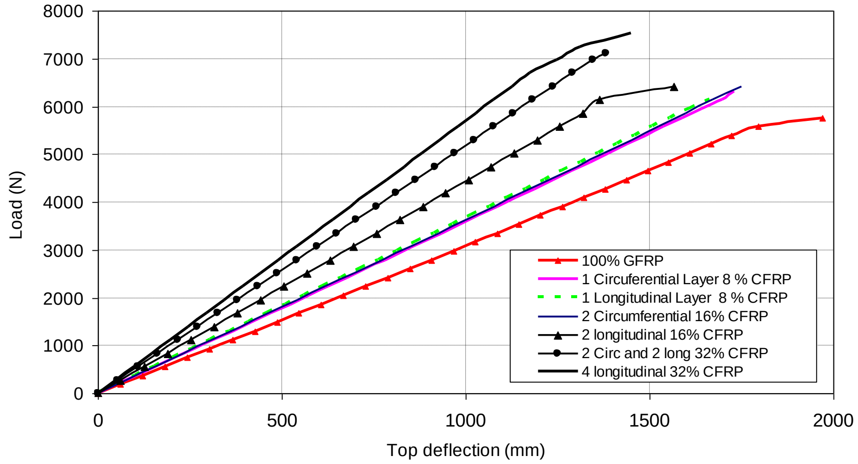

Figure 9. Effect of incorporating carbon fibre on load deflection relationship.

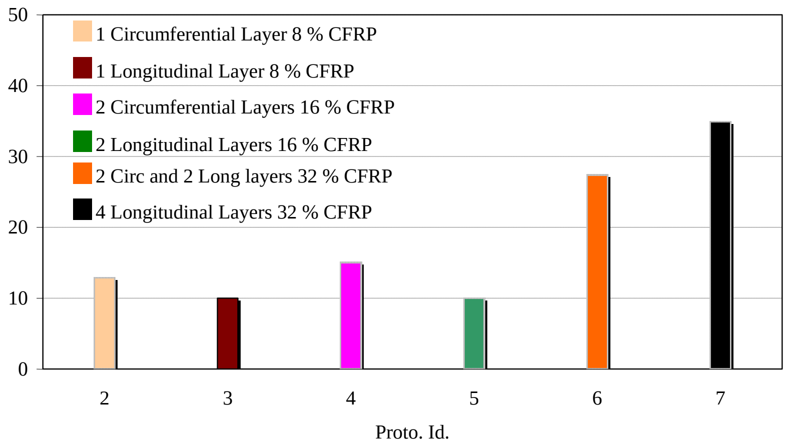

Figure 10. Effect of incorporating carbon fibre on failure load of FRP poles

$$\%\ \text{Failure Load increase} = \frac{FL_i - FLp_o}{FLp_o} \times 100,$$

FL_i= failure load for different prototype 2 or 3,…….,7

Table (4) shows the failure load, the deflections, and the stiffness factor of the FRP poles for different prototypes for replacing glass fibre by carbon fibre. Fig. 9 shows the effect of incorporating carbon fibre on load deflection relationship with different percentage of carbon fibres. Figure. 10 shows the effect of incorporating carbon fibre on the percentage increase of the failure load of the FRP poles. Also Figure. 11 shows the effect of incorporating carbon fibre on the percentage increase of the stiffness of the FRP poles.

It is clear that replacing carbon fibre by glass fibre 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 fibre. The percentage increase in ultimate load capacity and stiffness depends on the type of layers. Incorporating longitudinal carbon fibre layers tend to increase the ultimate capacity more than incorporating circumferential carbon fibre layers.

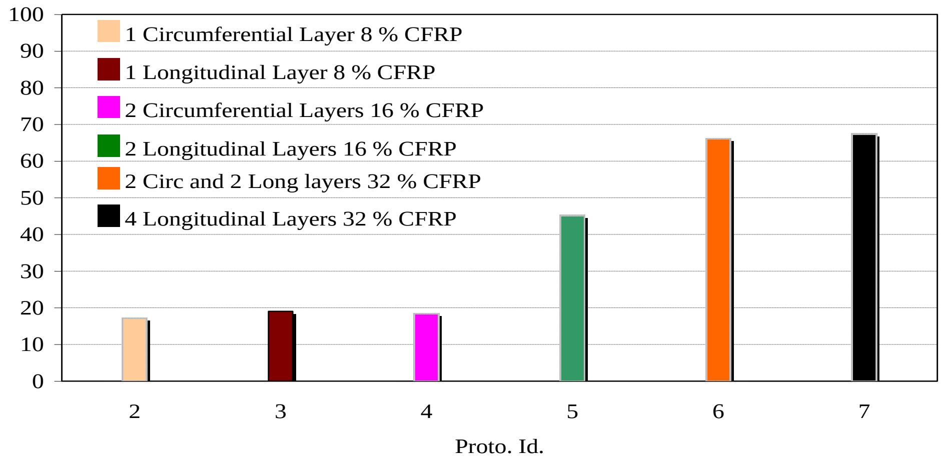

Figure 11. Effect of incorporating carbon fibre on failure load of FRP poles.

$$\% \text{ Stiffness increase} = \frac{St_i - St_1}{St_1} x100$$

St_i = failure load for different prototype 2 or 3,…….,7

5. Conclusions

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. When the fibre orientation of the longitudinal layer is 10 degree, this yields a higher load capacity with lower deflection. Circumferential layers improve the flexural behaviour of GFRP poles in terms of ultimate load capacity and deflection. The fibre orientation of circumferential layers with 90 degre e for the tapered FRP poles yields higher load capacity and stiffness. The internal and external additional three layers (90, ±45) for the laminate at the middle zone II, improved the flexural behaviour due to the existence of the service opening. The total load capacity of the FRP poles and the stiffness increased with increasing the percentage of carbon fibre.

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