



Behavior of Centrifuged GFRP Poles Under Lateral Deflection

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Abstract

Centrifugal-manufactured GFRP pipes are widely used today as lighting and low-power transmission poles due to their lightweight, high electrical insulation, low cost, and corrosion resistance. Despite these advantages, GFRP poles suffer high deflection problems due to their low elastic and shear moduli values. In order to overcome this disadvantage, three techniques were suggested to control the lateral deflection of the GFRP poles: an extended internal steel stub, external steel angles, and internal steel bracing bars. The main objective of this study is to determine the optimum strengthening technique to improve the serviceability of GFRP poles in terms of lateral deflection according to ASTM D4923. An experimental research program containing five full-scale GFRP poles was carried out to determine the optimum strengthening technique and the effect of connectors opening near the base and compare it to previous research. The results indicated that flexural stiffness was increased by 44%, 66%, and 38% for the extended stub, steel angles, and bracing bars, respectively. Besides that, the reduction in flexural stiffness due to connector opening was about 8%. The measured deflections showed good matching with simplified mathematical calculations, and the division was about $\pm 10\%$. The external steel angle technique showed the best efficiency in Stiffness behavior.

Keywords: GFRP Poles; Deflection Control; Stiffness; Improving Serviceability.

1. Introduction

Fiber-reinforced polymer (FRP) is a great substitute because it has fewer disadvantages, such as the quick deterioration of wood, the heavy weight of reinforced concrete poles, the short lifetime of aluminum, and steel corrosion, which makes treating these materials uneconomical. Electric poles and transmission networks are one type of essential infrastructure. Compared to other materials like steel and aluminum, FRP offers various benefits that make it a suitable material for transmission and distribution poles, towers, H-frames, and light poles [1]. The primary benefits of GFRP over traditional steel for meteorological towers are their high strength-to-weight ratio and ability to resist corrosion. Although FRP composites have been used in various applications for more than 50 years, other materials, including steel, wood, and aluminum, have been used for far longer [2]. Transmission poles and towers made of Glass Fiber Reinforced Polymer (GFRP) have been investigated for their durability in severe temperature and UV conditions. UV rays and adverse temperature circumstances have an impact on the performance of GFRP material; as a result, the elastic modulus increases, its strength decreases, and a little shift in Poisson's ratio takes place [3]. In addition to serving as force-bearing components of towers, glass fiber-reinforced plastic (GFRP) poles may be utilized to construct transmission towers and bridge structures and to support transmission lines in place of conventional steel arms [4]. In European nations, glass fiber-reinforced polymer (GFRP) utility poles are becoming more prevalent. Therefore, in order

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to ensure the integrity and safety of the poles, it is vital to check their structural characteristics carefully. In European nations, glass fiber-reinforced polymer (GFRP) utility poles are becoming more prevalent. Therefore, to assure the poles' integrity and safety, it is vital to carefully check their structural characteristics [5].

The price of composite poles is a significant barrier to their deployment internationally. The trash that will be created by the intensive utilization of composite material in the future is another concern that must be avoided. Electrical failure would create a more hazardous and violent situation [6]. In the last several significant earthquakes, light and utility poles were damaged on elevated highway or railroad bridges. They were mostly caused by severe pole deformation, yielding-related bending failure, pole buckling, and mast falling. To increase the safety, security, and aesthetics of highway users and accompanying facilities, poles bearing masts for lighting, traffic signs, or transmission lines are crucial components [7]. Among the many benefits of using FRP composite poles instead of wood poles is that they increase roadway safety by decreasing fatalities caused by auto-pole collisions [8]. A variety of techniques are used to create FRP. Structural supports are typically made using centrifugal, pultrusion, and filament winding processes. From a structural aspect, the manufacturing process can have a big impact on the material's structural properties. Other factors that affect the characteristics of the FRP laminate include the amount of fiber and the orientation of the glass fibers. To produce structural supports, the four manufacturing processes of extrusion, rotational molding, centrifugal processing, and filament winding are widely used [1, 9]. An analytical model was created by Desai et al. to look into the properties of the FRP composite poles' bending and buckling. The CFRP pole's buckling load capability was roughly 175% higher than the GFRP pole's [10].

The outcome of the Investigations into the FRP pole's fiber orientation under the critical load were conducted [11]. The critical load on FRP poles was significantly impacted by the fiber orientation. The critical ovalization load decreased as the fiber angle increased [9]. To assess the performance and ultimate capacity of tapered filament-wound GFRP poles, Polyzois et al. conducted cantilever bending tests to failure. Local buckling was the most common mode of failure in the majority of the specimens because of the high radius-to-thickness ratio of the specimens [12]. Alshurafa and Polyzois's (2018) results confirmed that FRP towers will create more economically viable alternatives and sustainable solutions to steel towers in the future [13]. Altanopoulos et al. (2021) concluded that it is possible to use the FEM with confidence in the analysis and design of GFRP structures, such as utility line poles and wind turbine towers, without the high cost associated with experimentation [14]. Nawar et al. (2022) figured that the flexibility of the GFRP poles was directly proportional to their length, and the local buckling failure often occurred at the handle door [15]. In 2019, Several non-linear finite element models were developed to determine the appropriate cable diameters and their associated spacing levels that increased the tower stiffness and decreased the maximum tensile and compressive stresses, which would meet both the manufacturing constraints and strength requirements [16].

In 2021, Mohamed demonstrates that by replacing carbon fiber with glass fiber on the FRP poles, a good improvement has been achieved. The total load capacity of the FRP poles and their stiffness increased with increasing the percentage of carbon fiber [17]. Beddu et al. (2018) figured that the creep study on GFRP girders showed an increment of instantaneous deflection up to 40% after five months, confirming the potential of GFRP in structural industries [18]. In 2018, bending strength calculations based on limit states theory exhibited a higher bending capacity than the capacity obtained from full-scale tests. An experimental study reveals that the basic failure mode of GFRP poles is local buckling in the vicinity of the inspection hole [19]. Donato (2020) findings showed that a mechanically safe and functional (stiff) GFRP shaft results in significant weight savings (37–80%) compared to traditional steel shafts [20]. In 2020, Skender et al. concluded that the replacement flexural modulus is a matrix-dominated property highly influenced by the fiber volume fraction [21]. The analysis of the literature showed that there is still a gap that has to be filled in order to increase the structural toughness of poles and enhance their dynamic reaction when struck by moving vehicles. In order to determine the effectiveness of tapered GFRP electric poles with a steel stub base up until the onset of failure, experimental and numerical experiments were conducted. To test the utility of the GFRP pole, five full-scale cantilever bending tests were carried out.

1.1. Objective of the Study

The main objective of this study is to determine the optimum strengthening technique to improve the serviceability of GFRP poles in terms of lateral deflection according to ASTM D4923 [22]. Three alternative strengthening techniques were experimentally investigated in this research: Strengthening using an extended internal steel stub, Strengthening using external steel angles, and strengthening using internal steel bracing bars. There's a gap in previous research areas to understand how to control lateral deflection by strengthening the pole with different techniques, which is the main objective of this work.

2. Research Methodology

The research plan contains five full-scale experimental tests for identical GFRP poles and five coupons conducted from the pole's shaft to determine the mechanical properties of the material, as shown in Figure 1. The first pole was an un-strengthened control specimen; the second one was also an un-strengthened specimen but with an opening near the base; and each of the other three poles was strengthened using one of the three alternatives considered. All poles were tested using the same procedure, by applying a gradually increased concentrated load at their free end, and both load and deflection were recorded. The measured stiffness values were analyzed and compared to interpret the conclusions.

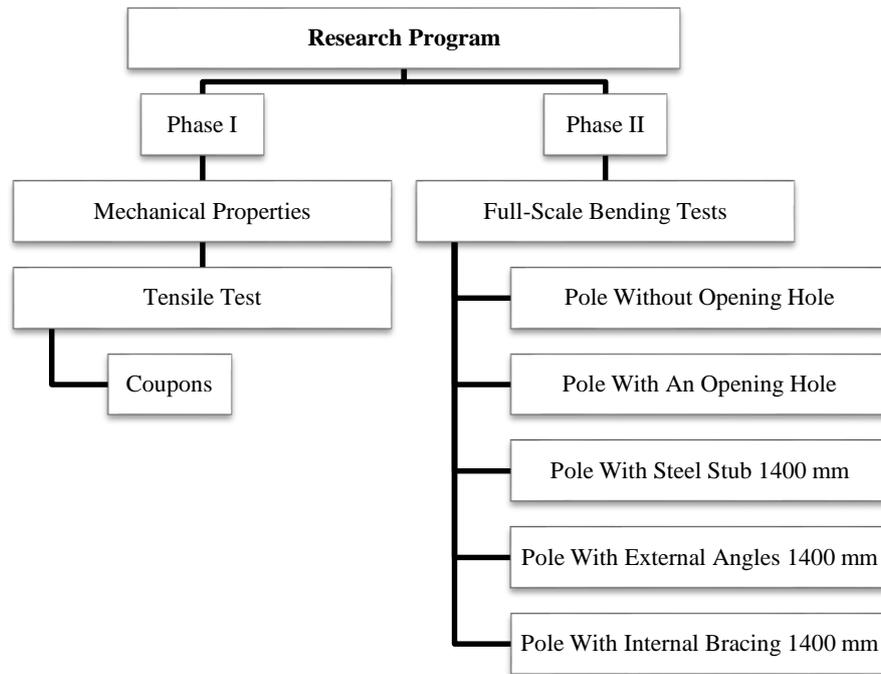


Figure 1. Research Methodology

2.1. Material Properties & Coupon Tests

It was required to get a few mechanical properties of the material from tests and manufacturers in order to move forward with the calculational verification of the poles, as indicated in Table 1. In ASTM D638-14, the procedure and requirements for the tensile tests are laid down. The tests were carried out in order to ascertain the tensile characteristics of the orthotropic fiber-reinforced material, including its tensile strength. At least five test coupons were required. In order to have the specimens' longitudinal axes run parallel to the pole's axis, the specimens were cut from the shafts of the pole. The coupons had the dimensions listed in Figure 2 and Table 2, respectively.

Table 1. The mechanical properties of the E-glass fibers and Resin

Properties	E-Glass	Resin
Density (t/m^3)	2.5	1
Poisson's ratio	0.2	0.3
Tensile modulus (GPa)	40	3
Shear modulus (GPa)	8	1
Tensile strength (MPa)	400	100
% by volume	35	65

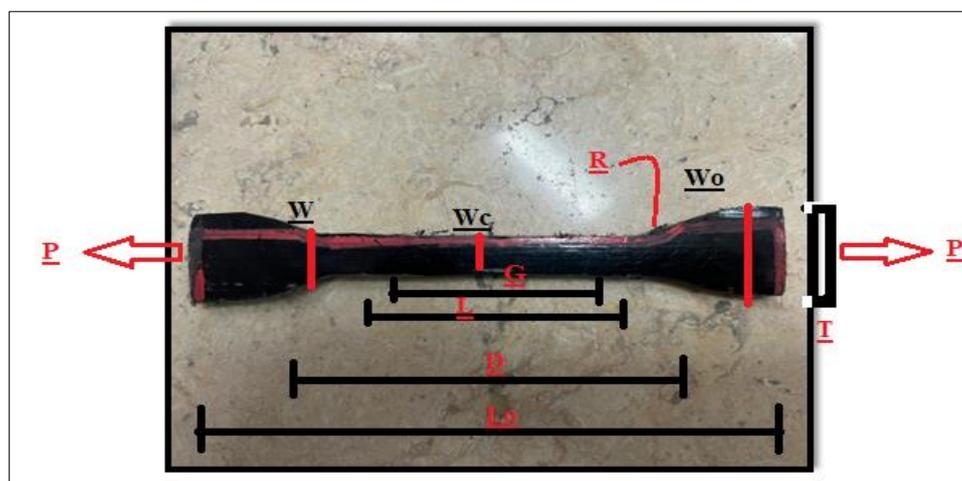


Figure 2. Coupon dimension in longitudinal direction

Table 2. Coupon dimensions

Lo	D	Wo	Wc	T	R	L	G	W
165 mm	115 mm	19 mm	10 mm	6 mm	76 mm	57 mm	50 mm	13 mm

The specimen was loaded with tensile force along the main axis at a constant speed of 0.18 mm/s until failure, as indicated in Figure 3. The tests were conducted in the range of up to 100 kN, with a minimum increment value of 200 N. As indicated in Table 3, the test specimen's measurement base's elongation and tensile force values were automatically recorded.



Figure 3. Tensile Coupon Specimen test

Table 3. coupon results

Specimen no.	Ultimate load (KN)	Δ (mm)
1	20.88	12.81
2	22.70	13.29
3	21.52	13.20
4	23.41	14.36
5	20.20	12.39
Average	21.74	13.21

2.2. Full-Scale Manufacture Method

The GFRP pole is made of glass fiber and polyester resin manufactured by Centrifugal Casting. The number and orientation of fiber layers are significant factors in the design of the GFRP pole; thus, the number of fiber layers and fiber orientation are chosen according to the design. Fiber layers are combined using polyester resin. The centrifugal casting method contains six steps, as follows:

- 1- Glass fiber sheets are placed, according to design in terms of number of layers and orientations, on a flat surface. Afterwards, aluminum pipe is wrapped using the aforementioned sheets (see Figure 4).
- 2- The wrapped pipe is placed inside the rotating device (mold) to start the centrifugal process by rotating the mold.
- 3- Vinyl polyester resin is injected from the two ends of the mold towards the inside. Some materials are added to resin to improve its properties, such as UV resistance and the required color.
- 4- During the rotation process, GFRP sheets start to impregnate the resin. After a certain time, full impregnation occurs, forming the GFRP pole. The pole is extracted from the rotating device. Afterward, pole ends of 2 to 5 cm length are saw-cut due to insufficient resin impregnation.

5- The maintenance hole is made in the pole by using a saw.

6- Finally, the steel base is glued to the bottom of the pole using epoxy and fixed with screws.



Figure 4. Centrifugal casting method steps, a: pipe wrapping, b: wrapped pipe inside rotating device, c: resin injection, d: extraction of pole, e: cutting of pole ends, f: making of maintenance hole

2.3. Tested Specimens

The five tested specimens were full-scale GFRP conic poles with constant thickness, manufactured by centrifugal process. The provided manufacturer's values for both elastic and shear moduli are 36000 and 1200 MPa, respectively. All poles had the same dimensions, as follows:

- Pole length = 5900 mm;
- Base diameter = 184 mm;
- Free end diameter = 76 mm;
- GFRP thickness = 6 mm.

A detailed description of each specimen is listed in Table 4, while the strengthening techniques are presented in Figure 5.

Table 4. Specimens' description

Pole code	Description	D ₀ (mm)	D ₁ (mm)	D _s (mm)	L ₀ (mm)	L _s (mm)	L _A (mm)	L _b (mm)	T (mm)
P	Control Pole without Opening Hole					550	--	--	
PO	Control Pole with Opening Hole					550	--	--	
PS1	Strengthened spacemen with extended internal steel stub	184	76	165	5900	1400	--	--	6
PS2	Strengthened spacemen with four external steel angles					550	1400	--	
PS3	Strengthened spacemen internal 4 steel bracing bars					550	--	1400	

Note: D₀: base diameter, D₁: Top diameter, D_s: Steel Stub diameter, L₀: Pole length, L_s: Steel Stub length, L_A: Steel Angle length, L_b: Steel Bars length and t: Pole thickness.

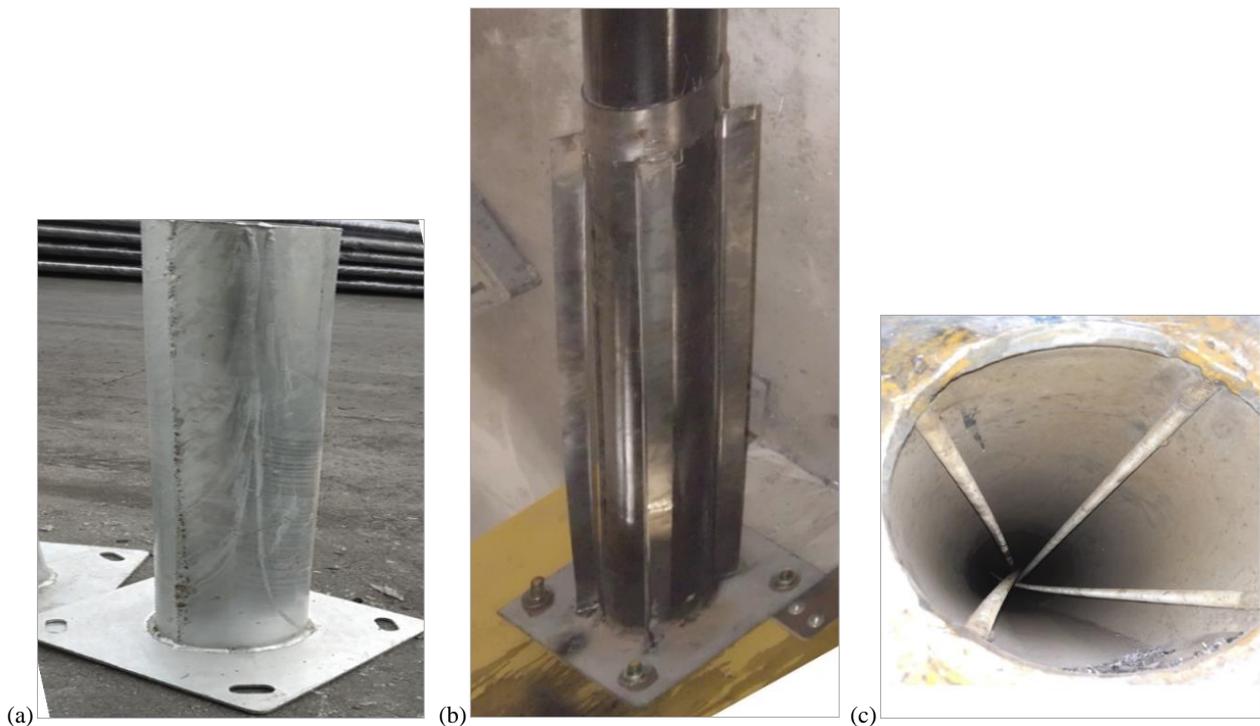


Figure 5. Considered strengthening techniques, a) extended internal steel stub, b) external steel angles, c) internal steel bars bracing

2.4. Standard Test Procedures and Allowable Limits

Two opposing fixed supports at 0.0 and 1.65 m from the first end were used to fix the pole, which was laid horizontally on the ground. The pole's buried depth, which is typically computed as 10% of the pole's length plus 600 mm, was represented by the fixed portion of the pole (1.65 m). Two string potentiometers were attached to each of the two supports to verify fixation by observing any movement. Utilizing a winch and steel rope, the pole was vertically loaded 600 mm from the second end. Manual controls were used to manage the load in the testing apparatus, and mechanical transducers were used to determine the deflection of the FRP pole [1, 23]. The pole manufacturer should calculate the shaft length based on the precise embedment depth (if applicable) and luminaire mounting height. A 61% tolerance must be maintained for the entire pole length. The pole's weight that will satisfy the user's installation's strength requirements must be chosen by the pole maker. Once it has been determined, the weight must be at least 95% of the stated weight. When tested, the pole must be able to bear at least 1.5 times the maximum bending moment brought on by the wind. The maximum amount of pole-top deflection caused by wind action on the pole and any associated accessories is 15% of the aboveground height [24, 25].

2.5. Testing Setup and Procedure

The poles were tested according to ASTM D4923. The pole is installed in the concrete base. It was adjusted horizontally by the water balance. The crane was installed at the end pole (first point). The first height of the pole is measured from the ground (Y_0) before loading. At failure, height was determined (Y_1). Deflection was calculated by subtracting Y_0 from Y_1 ($\Delta = Y_1 - Y_0$), as shown in Figure 6.



Figure 6. Test Setup

All tested poles were fixed to the concrete block (1200 × 800 × 800 mm) by their steel stub base plate as shown in Figure 7. All base plates were (400 × 400 × 10 mm) and fixed to the concrete block by 4 bolts 16mm in diameter.



Figure 7. Pole Fixation Method

The horizontally fixed pole was gradually loaded at a distance of 5650 mm from the base using a motorized winch (Cap. = 1000 kN). The load is recorded with a load cell, while the deflection was measured manually by metric measurements. Figure 8 shows the testing setup.

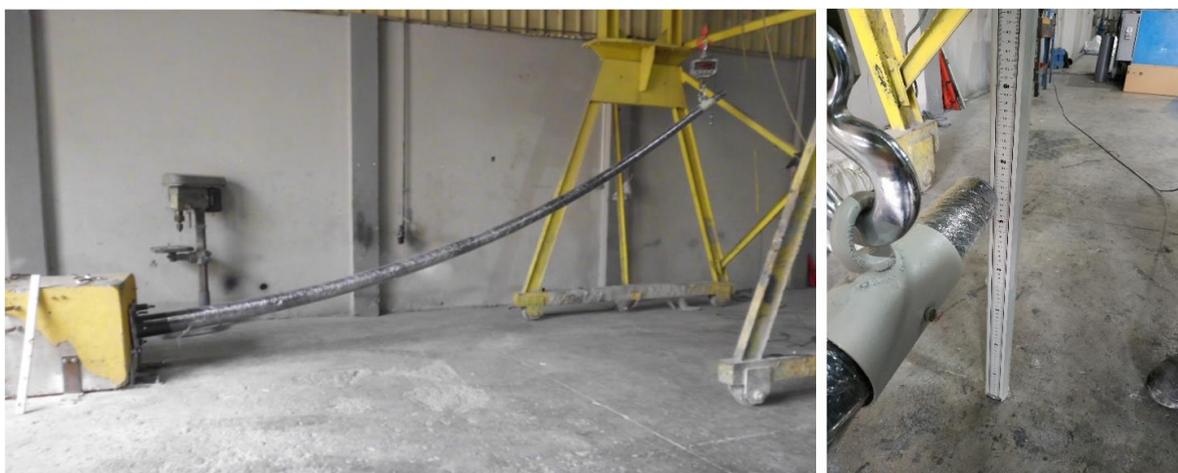


Figure 8. Testing setup (control sample P)

2.6. Testing Results

The recorded loads and corresponding deflections for all tested poles are summarized in Table 5 and graphically presented in Figure 9, while Figure 10 shows photographs of the tested poles.

Table 5. Test results

Load (N)	Settlement (mm)				
	P	PO	PS1	PS2	PS3
1250	170	190	120	100	130
2500	340	360	240	200	250
3500	490	550	340	290	360
4500	640	690	440	390	460

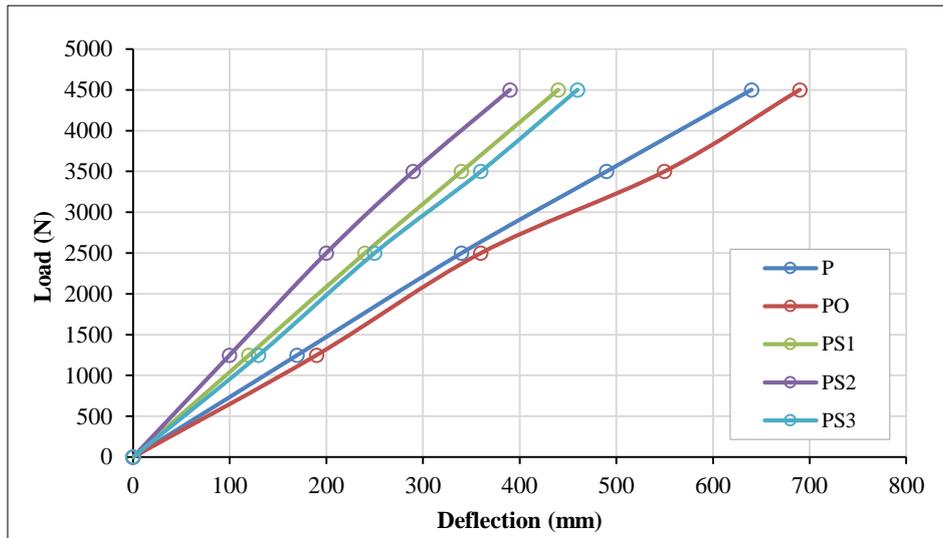


Figure 9. Load-Deflection curves for the tested poles





Figure 10. Photographs for the tested poles

Table 6 shows results from our study compared to those from Altanopoulos et al. [14]. Our results using the centrifugal process match well with his results in Load but differ in deflection. The error is 48% for the stiffness result. We note that Altanopoulos et al. (2021) used a pole manufactured using the filament winding process with different Dimensions, Mechanical properties, and Fixation methods. The error can be attributed to that reason. We concluded that the different manufacturing processes and properties will differ in results, and it is recommended to use them for further studies to compare results.

Table 6. Comparison study at the same load level

Parameter	Results from our study for pole (P)	Altanopoulos et al. (2021) [14]	Error%
Load (N)	4500	4050	10
Settlement (mm)	640	300	54
Stiffness (N/mm)	7.03	13.5	48
Flexural modulus (MPa)	36000	44840	20
Shear Modulus (MPa)	1200	4850	75
Wall thickness (mm)	6	3.5	42
Pole Length (m)	6	6	0
Manufacture Method	Centrifugal Process	Filament Winding	-

3. Discussion

3.1. Main Findings

Analyzing the collected results in Table 5 and Figure 9 indicates the following:

- The stiffness of the PO pole is reduced to $(6.53/7.12 = 92\%)$ of the original value due to the near base opening;
- The stiffness of the PS1 pole is increased to $(10.28/7.12 = 144\%)$ of the original value due to the extended internal steel stub;
- The stiffness of the PS2 pole is increased to $(11.86/7.12 = 166\%)$ of the original value due to the external steel angles;

- The stiffness of the PS3 pole is increased to $(9.79/7.12 = 138\%)$ of the original value due to the internal steel bracing bars.

The theoretical stiffness of the GFRP poles could be calculated as shown in Equation 1 [26]:

$$\frac{1}{K} = \frac{\Delta}{P} = \frac{L^3}{3EI} + \frac{L}{G.A_r} \quad (1)$$

where E is the elastic modulus of the GRFP (36000 MPa), G is the shear modulus of the GRFP (1200 MPa), Ar is the reduced cross-section area of the pole (equals half the gross area for pipes), I is the moment of inertia of the cross-section of the pole, and L is the distance from fixation to the load.

For un-strengthened poles (P) & (PO) the length (L= 5650 mm) and the pole outer diameter at the base are 184 mm:

- For the control pole (P), $A_r = 1677 \text{ mm}^2$ and $I = 13.55\text{E}+6 \text{ mm}^4$, hence, $K = 7.9 \text{ N/mm}$;
- For the pole (Po), $A_r = 1510 \text{ mm}^2$ and $I = 12.2\text{E}+6 \text{ mm}^4$, hence, $K = 7.2 \text{ N/mm}$.

For (PS1, PS2 & PS3), the strengthening is extended to 1400mm above the base, where the outer diameter is 158 mm, hence, $A=1430 \text{ mm}^2$, $I = 8.5\text{E}+6 \text{ mm}^4$, accordingly $K= 11.5 \text{ N/mm}$.

3.2. Comparison with Other Studies

Comparing the calculated stiffness values with the measured ones showed good agreement; the calculated stiffness values ranged between 97% and 117% of the measured ones, with an average value of 110%. This slight difference is expected due to neglecting the effect of a tapered profile of the pole and the actual stiffness of the strengthening elements. However, a 10% difference is acceptable for such simplified calculations. When comparing the Pole (PO) with previous studies, it has the same opening hole, according to Mohamed [17]. The Stiffness differed by 52%, as shown in Table 7.

Table 7. A Comparison study at Failure load for Stiffness

Parameter	Experimental Stiffness for pole (PO)	Mohamed [17]	Calculated Stiffness for pole (PO)	Experimental Stiffness for pole (PS1)	Experimental Stiffness for pole (PS2)	Experimental Stiffness for pole (PS3)
Stiffness (N/mm)	6.53	3.10	7.2	10.28	11.86	9.79
Findings	Experimental	Finite Element	Calculated	Experimental	Experimental	Experimental
Pole Length (m)	6	10	6	6	6	6

3.3. Findings Explanation

- The stiffness of the PO pole was reduced, which is a disadvantage due to stress concentration around the opening hole. The presence of opening holes in the GFRP poles reduces the flexural modulus and shear modulus;
- The stiffness of the PS1 pole was increased because of the enhancement in the fixation method of the pole, and the pole's flexural and shear modulus increased due to the increase in steel dimensions inside the pole;
- The stiffness of the PS2 pole was increased, which disallowed the pole to deflect more due to stiffened angles;
- The stiffness of the PS3 pole was increased, which prevented the pole from becoming deflected more due to increasing the steel dimensions inside the pole. That's due to the GFRP pole's 25% length becoming more steel behavior than fiber;
- A comparison between experimental and previous research stiffness shows a difference of 52% due to different pole properties and geometrics, as shown in Table 7;
- The comparison shows a great improvement in stiffness results between poles PS1, PS2, and PS3 compared to previous research due to different strengthening techniques, as shown in Table 7.

4. Conclusions

This study was concerned with determining the optimum strengthening technique to control the lateral deflection of CFRP poles. Three techniques were considered: an internal extended steel stub, external steel angles, and internal steel bracing bars. In addition, an experimental testing program including five full-scale poles was carried out to determine the efficiency of each strengthening technique and the effect of connector openings near the pole base on its flexure stiffness. The results of the study could be summarized as follows:

- All poles were gradually loaded up to 4500 N without any failure, showing perfect linear-elastic behavior;
- The connector hole near the base of the pole reduces its flexural stiffness by 8%;

- The measured flexural stiffness of the strengthened poles was 144%, 166%, and 138% of the control pole for the extended steel stub, external steel angles, and internal steel bracing bars, respectively;
- A comparison study has been presented between the experimental study and previous research, showing an agreement in load by 10% and a difference in deflection due to different properties at the same load level;
- The simplified mathematical calculation matched the measured values, and the divisions were about $\pm 10\%$;
- A comparison between experimental and calculated stiffnesses for pole (PO) has been done and shows an agreement of 10%. Which has been compared to previous research showing a 52% difference in stiffness due to different pole lengths. It also indicated a significant result in stiffness between different strengthening techniques and previous research;
- Although the external steel angle technique showed the best efficiency (66%), it is external, so it may need additional decorative cover to be acceptable;
- The extended steel stub is the easiest technique since all poles already have a short internal steel stub; besides that, its efficiency is about 44%. However, the main disadvantage is the conflict with the connector opening near the pole base;
- Despite the low efficiency of the internal steel bracing bars technique (38%), it doesn't conflict with the opening of the connector and doesn't need any decorative cover. Besides that, its efficiency may be improved by using larger-diameter bars. Accordingly, it may be a favorable alternative to strengthening the GFRP poles;
- This research work improves the stiffness results by using different strengthening techniques, which will lead other researchers to use different techniques to improve their findings.

The following points are suggested for more research studies in the future:

- To study the strength characteristics of FRP poles under different types of loading and with different strengthening techniques;
- To study more techniques used to reduce large deformations of GFRP poles;
- To compare the stiffness and strength characteristics of FRP poles manufactured by different manufacturing techniques rather than centrifugal processes;
- A Comparison between experimental, calculated and modeled Stiffness at the same pole properties and geometric.

5. Declarations

5.1. Author Contributions

Conceptualization, A.M.E. and M.A.K.; investigation, H.M.E., M.G.H., and I.A.-L.; writing—original draft preparation, Y.A.A. and A.M.E.-F.; writing—review and editing, A.M.E. and H.M.E.; visualization, M.G.H. and I.A.-L. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

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5.4. Acknowledgments

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

- [1] EL-Fiky, A. M., Awad, Y. A., Elhegazy, H. M., Hasan, M. G., Abdel-Latif, I., Ebid, A. M., & Khalaf, M. A. (2022). FRP Poles: A State-of-the-Art-Review of Manufacturing, Testing, and Modeling. *Buildings*, 12(8), 1–22. doi:10.3390/buildings12081085.
- [2] Zhang, L., Sun, Q., & Zheng, L. (2011). Experimental study on the durability of Glass Fiber Reinforced Polymer Pole and Tower for power transmission. *Advanced Materials Research*, 168–170, 1717–1724. doi:10.4028/www.scientific.net/AMR.168-170.1717.

- [3] Sheridan, R., Gilman, J. W., Busel, J. P., Hartman, D., Holmes, G., Coughlin, Kim, J.-H., ... Natarajan, B. (2017). Road mapping workshop report on overcoming barriers to adoption of composites in sustainable infrastructure. National Institute of Standards and Technology, Gaithersburg, United States. doi:10.6028/NIST.SP.1218.
- [4] Si, J., Qiu, S., Feng, S., Chen, J., & Wang, Z. (2022). Experimental study on axial compression buckling of glass fiber reinforced plastics solid pole with circular cross-section. *Advances in Structural Engineering*, 25(4), 913–924. doi:10.1177/13694332211054226.
- [5] Broniewicz, M., Broniewicz, F., & Broniewicz, E. (2021). A full-scale experimental investigation of utility poles made of glass fibre reinforced polymer. *Materials*, 14(23). doi:10.3390/ma14237398.
- [6] Soni, S. K. (2020). Madan Mohan Malaviya University of Technology, North Dakota State University, Institute of Electrical and Electronics Engineers. Uttar Pradesh Section, IEEE Industry Applications Society, & Institute of Electrical and Electronics Engineers. ICE3-2020: International Conference on Electrical and Electronics Engineering, 14-15 February, 2020.
- [7] Siringoringo, D. M., Fujino, Y., Nagasaki, A., & Matsubara, T. (2021). Seismic performance evaluation of existing light poles on elevated highway bridges. *Structure and Infrastructure Engineering*, 17(5), 649–663. doi:10.1080/15732479.2020.1760894.
- [8] GangaRao, H. (2017). Infrastructure Applications of Fiber-Reinforced Polymer Composites. *Applied Plastics Engineering Handbook*, 675–695, William Andrew, Norwich, United Kingdom. doi:10.1016/b978-0-323-39040-8.00032-8.
- [9] Fouad, F. H., & Mullinax, Jr., E. C. (2000). FRC Poles for Distribution Power Lines. *Advanced Technology in Structural Engineering*. doi:10.1061/40492(2000)179.
- [10] Desai, N., & Yuan, R. (2006). Investigation of Bending/Buckling Characteristics for FRP Composite Poles. *Earth & Space* 2006. doi:10.1061/40830(188)146.
- [11] Ibrahim, S., & Polyzois, D. (1999). Ovalization analysis of fiber-reinforced plastic poles. *Composite Structures*, 45(1), 7–12. doi:10.1016/s0263-8223(98)00137-8.
- [12] Polyzois, D., Ibrahim, S., Burachynsky, V., & Hassan, S. K. (1999). Glass fiber-reinforced plastic poles for transmission and distribution lines: an experimental investigation. 12th International Conference on Composite Materials (ICCM-12), 5-9 July, 1999, Paris, France.
- [13] Alshurafa, S., & Polyzois, D. (2018). Design recommendations and comparative study of FRP and steel guyed towers. *Engineering Science and Technology, an International Journal*, 21(5), 807–814. doi:10.1016/j.jestch.2018.06.014.
- [14] Altanopoulos, T. I., Raftoyiannis, I. G., & Polyzois, D. (2021). Finite element method for the static behavior of tapered poles made of glass fiber reinforced polymer. *Mechanics of Advanced Materials and Structures*, 28(20), 2141–2150. doi:10.1080/15376494.2020.1717691.
- [15] Nawar, M. T., Kaka, M. E., El-Zohairy, A., Elhosseiny, O., & Arafa, I. T. (2022). Effect of Supporting Base System on the Flexural Behavior and Toughness of the Lighting GFRP Poles. *Sustainability (Switzerland)*, 14(19). doi:10.3390/su141912614.
- [16] Alshurafa, S., Alhayek, H., & Polyzois, D. (2019). Finite element method for the static and dynamic analysis of FRP guyed tower. *Journal of Computational Design and Engineering*, 6(3), 436–446. doi:10.1016/j.jcde.2018.08.004.
- [17] Mohamed, M. H. (2021). Finite Element Modeling of CFRP Composite Pole Structures. *International Journal of Engineering Applied Sciences and Technology*, 6(7), 10–15. doi:10.33564/ijeast.2021.v06i07.003.
- [18] Beddu, S., Syamsir, A., Ishak, Z. A. M., Yusof, Z. M., Hudi, N. S., & Nabihah, S. (2018). Creep behavior of glass fibre reinforced polymer structures in crossarms transmission line towers. *AIP Conference Proceedings*, 2031. doi:10.1063/1.5066995.
- [19] Broniewicz, F. (2019). Experimental Verification of GFRP Lighting Poles. *Scientific Journals of the Czestochowa University of Technology. Construction*, 174(24), 30–35. doi:10.17512/znb.2018.1.05. (In Polish).
- [20] Vito, D. Di, Kanerva, M., Järveläinen, J., Laitinen, A., Pärnänen, T., Saari, K., Kukko, K., Hämmäinen, H., & Vuorinen, V. (2020). Safe and sustainable design of composite smart poles for wireless technologies. *Applied Sciences (Switzerland)*, 10(21), 1–19. doi:10.3390/app10217594.
- [21] Skender, A., Domitran, Z., & Krokarc, J. (2020). The effective flexural modulus of filament wound grp tapered poles. *Tehnicki Vjesnik*, 27(6), 1894–1903. doi:10.17559/TV-20191108160438.
- [22] ASTM D4923-01. (2010). Standard Specification for Reinforced Thermosetting Plastic Poles. ASTM International, Pennsylvania, United States.
- [23] Abdelkarim, O. I., Guerrero, J. M., Mohamed, H. M., & Benmokrane, B. (2019). Behaviour of Pultruded Glass Fibre-Reinforced Polymer Utility Poles Under Lateral Loads. *Proceedings of the CSCE Annual Conference*, 12-15 June, 2019, Montreal, Canada.

- [24] US20100148408A1. (2009). 25-2010 Method of manufacturing a fiber reinforced plastic (FRP) lighting pole. United States Patent and Trademark Office, Alexandria, United States.
- [25] Polyzois, D., Raftoyiannis, I. G., & Ibrahim, S. (1998). Finite elements method for the dynamic analysis of tapered composite poles. *Composite Structures*, 43(1), 25–34. doi:10.1016/s0263-8223(98)00088-9.
- [26] Ghugal, Y. M., & Sharma, R. (2011). A refined shear deformation theory for exure of thick beams. *Latin American Journal of Solids and Structures*, 8(2), 183–195. doi:10.1590/S1679-78252011000200005.