FRP-reinforced spun concrete poles in flexure

Fouad H. Fouad, Ashraf M. Shalaby, Sally G. Palmer, Ronald Albanese, and Mohamed Gallow

- This paper compares the flexural behavior of spun concrete poles reinforced with carbon-fiber-reinforced polymer, glass-fiber-reinforced polymer, and conventional prestressed steel reinforcement.

- The flexural behavior of the poles was evaluated in terms of cracking moment, ultimate moment capacity, and load-deflection data. A cost comparison was also performed.

- The results show that the different types of reinforcement are not associated with significant differences in the ultimate capacities of the poles but are correlated with differences in cracking and deflection.

Prestressed spun concrete poles may be placed in aggressive environments, such as in brackish or salt water, which are conducive to steel corrosion. Corrosion eventually forces the premature replacement of the pole, which is costly. The replacement cost of a deteriorated pole is considerably higher than its initial cost, and the reduced service life of poles directly affects the service life of the electric lines they support.

Fiber-reinforced-polymer (FRP) composite is a new type of reinforcement that could replace traditional steel reinforcement and provide the desired structural characteristics while resisting corrosion.[1–8] FRP reinforcement could reduce the weight of the structure[9] and its maintenance costs and lengthen its service life. FRP is formed of strong, stiff reinforcing fibers that are relatively abundant, such as carbon, glass, or aramid, which are embedded in tough and resilient polymer matrices. Its unique mechanical properties, durability, and corrosion resistance make it ideal for use in precast concrete products.

This paper presents the results of experimental and analytical studies that compare the flexural behavior of spun concrete poles with three types of reinforcement: carbon-fiber-reinforced polymer (CFRP), glass-fiber-reinforced polymer (GFRP), and conventional prestressing steel. The flexural behavior of the poles was evaluated in terms of cracking moment, ultimate moment capacity, and load-deflection data. A cost analysis of the different types of reinforcement was also performed.

Table 1. Properties of carbon-fiber-reinforced polymer grid C-GRID

Grid designation: C50-2.9 × 2.9	Longitudinal properties	Transverse properties
Strand tensile strength, ksi	340	340
Strand tensile modulus of elasticity, ksi	34,000	34,000
Strand ultimate strain, %	1.0	1.0
Strand cross-sectional area, in.^{2}	0.0036	0.00312
Strand spacing, in.	2.9	2.9
Grid strength, kip/ft	4.9	3.9

Note: 1 in. = 25.4 mm; 1 ft = 305 mm; 1 kip = 4.45 kN; 1 ksi = 6.895 MPa.

Experimental program

The main objective of the experimental program was to evaluate the flexural behavior of spun concrete poles reinforced with CFRP and GFRP. Two sets of prototype pole specimens were manufactured under normal precast concrete plant conditions. All specimens were identical except for the reinforcement scheme. The first set was reinforced with CFRP and the second with GFRP. Each set of specimens consisted of four poles: two poles reinforced with 6 FRP longitudinal bars and two poles reinforced with 12 FRP longitudinal bars. Both sets of specimens had the same geometry and similar confining reinforcement.

Material properties

The spun concrete test poles were produced from a high-strength concrete mixture. The 28-day compressive strength of the concrete was 11,000 psi (76 MPa). No. 3 (10M) CFRP bars were used. The bar diameter is 0.375 in. (9.525 mm); cross-sectional area is 0.101 in.^{2} (65.1 mm^2); tensile strength is 300 ksi (2070 MPa); and the modulus of elasticity is 18 × 10^6 psi (124,000 MPa). The GFRP bars used were no. 4 (12M) with a diameter of 0.50 in. (13 mm), cross-sectional area of 0.196 in.^{2} (126 mm^2), tensile strength of 100 ksi (690 MPa), and modulus of elasticity of 5.92 × 10^6 psi (40,000 MPa). The ultimate strain for the FRP bars is 1.7%. The CFRP grid used for transverse confinement was a high-performance reinforcement made by bonding ultra-high-strength carbon tows with epoxy resin in a controlled factory environment. The grid was composed of a square mesh of carbon strands spaced at 2.9 × 2.9 in. (72 × 72 mm). **Table 1** describes the typical grid properties and the physical properties of the CFRP strand.

The GFRP spiral used for confinement was specially manufactured by the supplier in three sizes: 7, 9, and 11.25 in. (180, 230, and 290 mm) inner diameter to spread the length of the pole with a pitch of 3 in. (75 mm) center to center. The spirals were no. 2 (6M) with a cross-sectional area of 0.049 in.^{2} (31.6 mm^2) and nominal diameter of 0.25 in. (6.35 mm).

Specimen dimensions and details

All test specimens were identical in geometry. Specimens were 20 ft (6.1 m) long, with an outer diameter of 8.91 in. (226 mm) and 13.23 in. (336 mm) at the tip and butt ends, respectively, which provides an outside slope of 1.8%. The inner diameters were 3.91 in. (99.3 mm) and 7.75 in. (191 mm) for the tip and butt ends, respectively, with an inside slope of 1.6%. The wall thickness was 2.5 in. (64 mm) and 2.74 in. (69.6 mm) at the tip and butt ends, respectively. **Figure 1** shows the test specimen dimensions. The size of the specimen was chosen to allow for easy transport from the production plant to the structural laboratory.

The FRP bars were distributed uniformly around the cross section (Fig. 1). CFRP grid and GFRP spirals were used for confinement (**Fig. 2** and **3**).

Test setup and procedure

The poles were subjected to a cantilever load test (**Fig. 4**). The pole specimen rested on two supports. The first support was located at the butt end, and the second support, located 3.0 ft (0.9 m) from the butt end, worked as the fulcrum. The distance to the fulcrum point was chosen to represent the typical foundation embedment length used in practice, which is approximately 10% of the overall pole length plus 1 ft (0.3 m).

The load was applied at a distance of 1.0 ft (0.3 m) from the tip of the pole using a manual chain hoist connected to a tension load cell and hooked to the trolley crane of the laboratory.

The tip deflection was recorded by means of a tape connected to the pole. Two linear variable differential transformers were installed adjacent to the supports of the test pole to record any movement that might have occurred at the supports. The readings were used to correct the measured deflection at the tip of the pole.

The load was applied in increments of 100 lb (445 N). There was a pause after each load increment to allow for

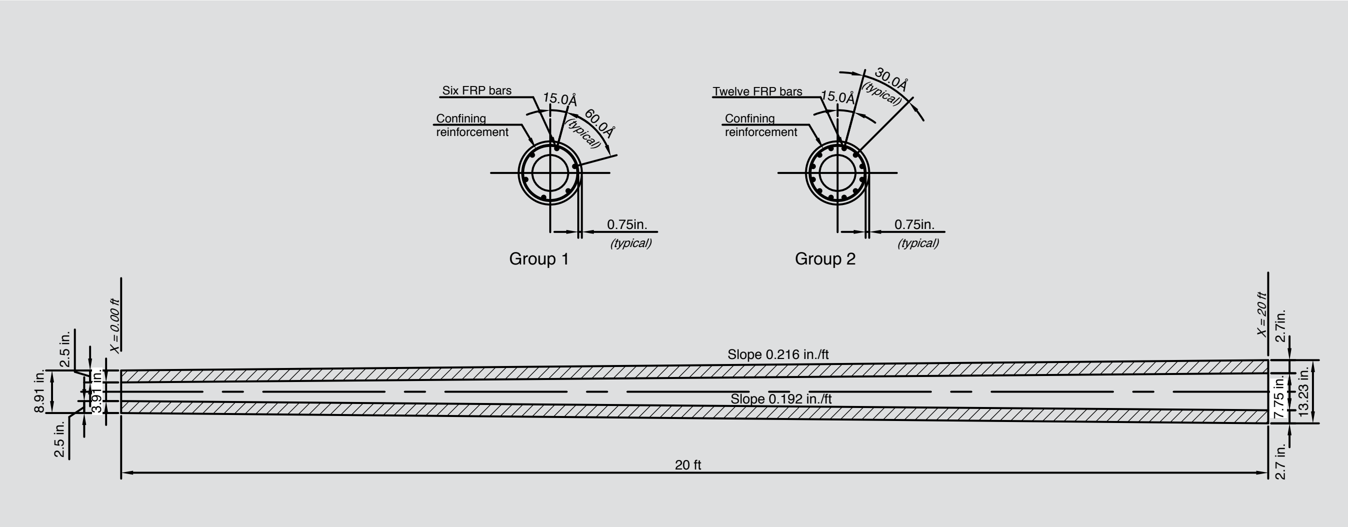

Figure 1. Test specimen dimensions and cross-sectional details. Note: FRP = fiber-reinforced polymer. 1 in. = 25.4 mm; 1 ft = 0.305 m.

reading deflections, inspecting for cracks, and observing any structural distress that might have occurred.

Results and discussion

The flexural behavior of the poles was evaluated in terms of cracking load, ultimate load, crack width, deflection, and failure mode. A brief economic analysis comparing the cost of GFRP, CFRP, and conventional prestressing steel strand reinforcement was also performed.

The experimental results of the CFRP- and GFRP-reinforced poles were compared with equations found in the literature[11] for spun prestressed concrete poles reinforced with conventional prestressing steel. The comparison in this study considered the specimens' construction and

Figure 2. Poles confined with carbon-fiber-reinforced polymer grid.

dimensions to be identical, the only variable being the number of longitudinal reinforcement used: 6 or 12. The prestressing steel and CFRP longitudinal reinforcement used in this comparison were no. 3 (10M), which makes the nominal tensile force of the bars as close as it can be to GFRP, but not equal to it (**Table 2**).

Figure 3. Poles confined with glass-fiber-reinforced polymer spiral reinforcement.

Cracking loads

For specimens with 6 reinforcing bars, the cracking load for the prestressed steel–, GFRP-, and CFRP-reinforced poles are 1233 lb (5500 N), 595 lb (2650 N), and 797 lb (3550 N), respectively. CFRP and GFRP had a lower cracking load—35% and 52%, respectively—than prestressed steel. For specimens with 12 longitudinal reinforcing bars, the cracking loads for the prestressed steel, GFRP, and CFRP-reinforced poles are 1744 lb (7760 N), 653 lb (2910 N), and 725 lb (3230 N), respectively. CFRP and GFRP had a lower cracking load—58% and 63%, respectively—than prestressed steel. The difference in the cracking load between the conventional prestressed concrete pole and the FRP-reinforced concrete poles is due to the prestressing. As the number of bars increases, the prestress increases, and with it the difference in cracking load between the prestressed concrete conventional pole and the FRP-reinforced concrete poles.

Ultimate loads

For specimens with six reinforcing bars, the ultimate load for the prestressed steel–, GFRP-, and CFRP-reinforced poles are 3.055 kip (13.60 kN), 2.980 kip (13.26 kN), and 3.946 kip (17.56 kN), respectively. However, for specimens with 12 reinforcing bars, the ultimate load is 5.469 kip (24.34 kN), 3.573 kip (15.90 kN), and 4.749 kip (21.13 kN), for the prestressed steel, GFRP, and CFRP-reinforced poles, respectively. The CFRP-reinforced poles with six bars were able to sustain about 29% more load

Figure 4. Test setup.

Table 2. Nominal tensile force of reinforcing bars

	Prestressing steel	CFRP	GFRP
Bar size	No. 3	No. 3	No. 4
Tensile force, kip	29.70	30.30	19.60

Note: CFRP = carbon-fiber-reinforced polymer; GFRP = glass-fiber-reinforced polymer. No. 3 = 10M; No. 4 = 13M; 1 kip = 4.45 kN.

than the conventional prestressed pole, while the same specimens with 12 reinforcing bars sustained 13% less load than the conventional prestressed pole. On the other hand, the GFRP-reinforced poles with 6 and 12 bars of reinforcement sustained, respectively, 2.5% and 35% lower ultimate load than the prestressed concrete poles. It is evident that, in addition to the prestressing, the number of bars strongly affects the cracking and ultimate load of the poles.

CFRP-reinforced poles have about 30% higher ultimate loads than GFRP-reinforced poles, though the tensile strength of the CFRP bars is 3 times that of GFRP bars, and the nominal tensile force of the CFRP bars is 1.5 times that of GFRP bars.

Crack width

The concrete crack widths of the poles are compared at a load of 2.00 kip (8.90 kN). For CFRP-reinforced poles, the crack widths were 28 mil (0.71 mm) for 6-bar poles and 15 mil (0.38 mm) for 12-bar poles. For all GFRP-reinforced poles, the crack widths were 13 mil (0.33 mm). The concrete cracks in the GFRP-reinforced poles were narrower than those of the CFRP-reinforced poles for each reinforcement group. It was expected that the cracks in the CFRP-reinforced poles would be narrower than those in the GFRP-reinforced poles (despite the higher tensile stresses in the CFRP bars due to their smaller diameter) because CFRP has a higher modulus of elasticity and the poles had lower deflections. It is therefore interesting to note that the opposite behavior was observed. Additional testing is required to verify the crack width behavior of CFRP and GFRP-reinforced members in flexure.

Deflection

For the specimens with 6 bars of reinforcement, the tip deflection at failure for CFRP and GFRP were about 2.5 times and 3 times the tip deflection at failure for the prestressed steel, respectively (**Fig. 5**). For the specimens with 12 reinforcing bars, CFRP and GFRP had 35% and 47% higher tip deflection at failure, respectively, than prestressed steel (**Fig. 6**). The significant difference in the tip deflection at failure between the conventional prestressed concrete pole and the FRP-reinforced concrete poles is due to the higher modulus of elasticity of the steel strands, namely 18,000 ksi (124,000 MPa) and 5920 ksi (40,000 MPa) for CFRP and GFRP, respectively, compared with 28,000 ksi (193,000 MPa) for steel prestressing strand.

Both groups of GFRP-reinforced specimens had greater deflections than the CFRP-reinforced specimens. However, the difference in deflection is not comparable with the difference in modulus of elasticity between CFRP and GFRP bars. Although the modulus of elasticity of the CFRP bars is 3 times that of the GFRP bars, the GFRP poles had 8% and 9% higher deflection than the CFRP poles with 6 and 12 bars, respectively.

Figure 5 compares the load-deflection curves for prestressed steel, CFRP, and GFRP-reinforced specimens for 6 bars, while Fig. 6 compares the load-deflection curves for 12 bars. Both figures show that the conventional steel-reinforced prestressed spun concrete poles are stiffer than those reinforced with CFRP or GFRP. This is related to the effect of prestressing on the conventional poles. The compression force resulting from prestressing significantly increases the cracking load of the conventional poles compared with the CFRP or GFRP-reinforced poles.

In terms of deflection, both FRP-reinforced concrete poles behave similarly, with CFRP-reinforced concrete poles being stiffer than GFRP-reinforced concrete poles because CFRP bars have a higher modulus of elasticity than GFRP bars.

Failure modes

The failure modes for the CFRP and GFRP-reinforced poles were similar. Shear cracks typically developed between the supports, followed by concrete crushing on the compression face at the ground line where the maximum moment was greatest (**Fig. 7** and **8**). Steel-reinforced prestressed concrete poles would behave similarly, though initiation of shear cracks may be delayed due to the effect of prestressing on enhancing the shear strength of the section.

Moreover, for CFRP-reinforced concrete poles, the shear crack within the supports extended to join with the concrete crushing at the collar, resulting in the rupture of the longitudinal and shear reinforcement (**Fig. 9** and **10**). This failure was characterized by slipping of the CFRP bars (**Fig. 11**). The slip was caused by the destruction of the bond between the longitudinal bars and the surrounding concrete at the support region, which frequently occurs in

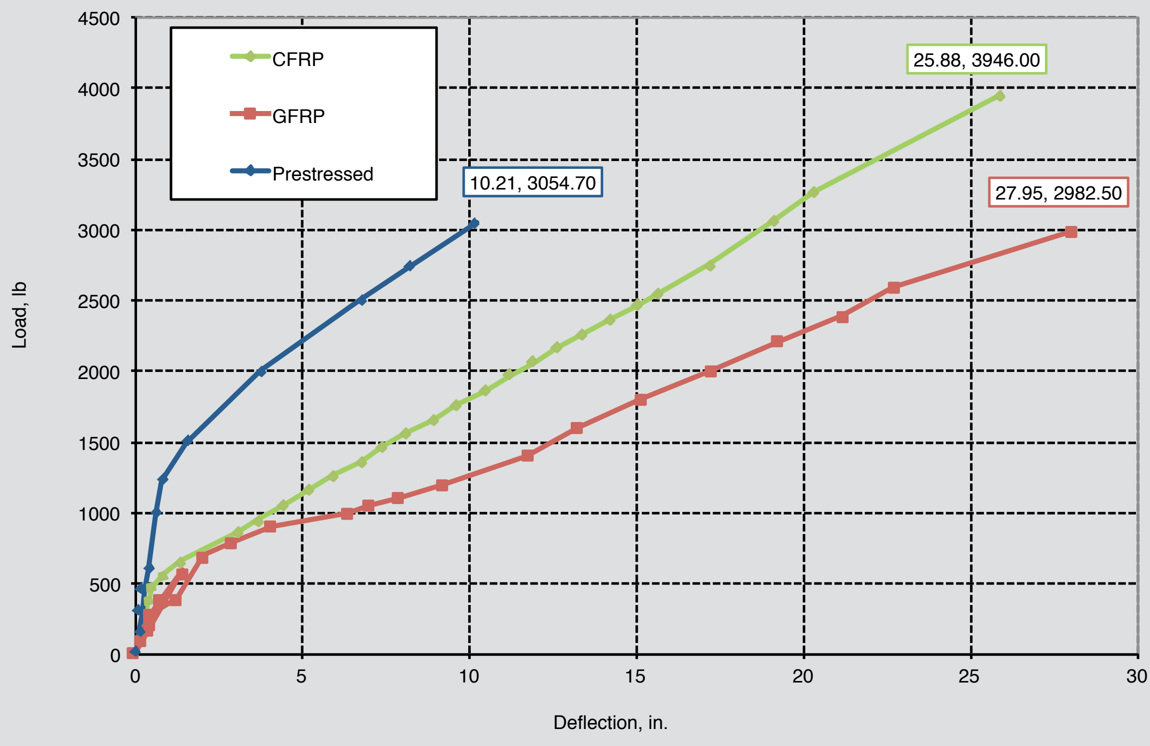

Figure 5. Load-deflection curves of poles reinforced with 6 bars. Note: CFRP = carbon-fiber-reinforced polymer; GFRP = glass-fiber-reinforced polymer. 1 in. = 25.4 mm; 1 lb = 4.448 N.

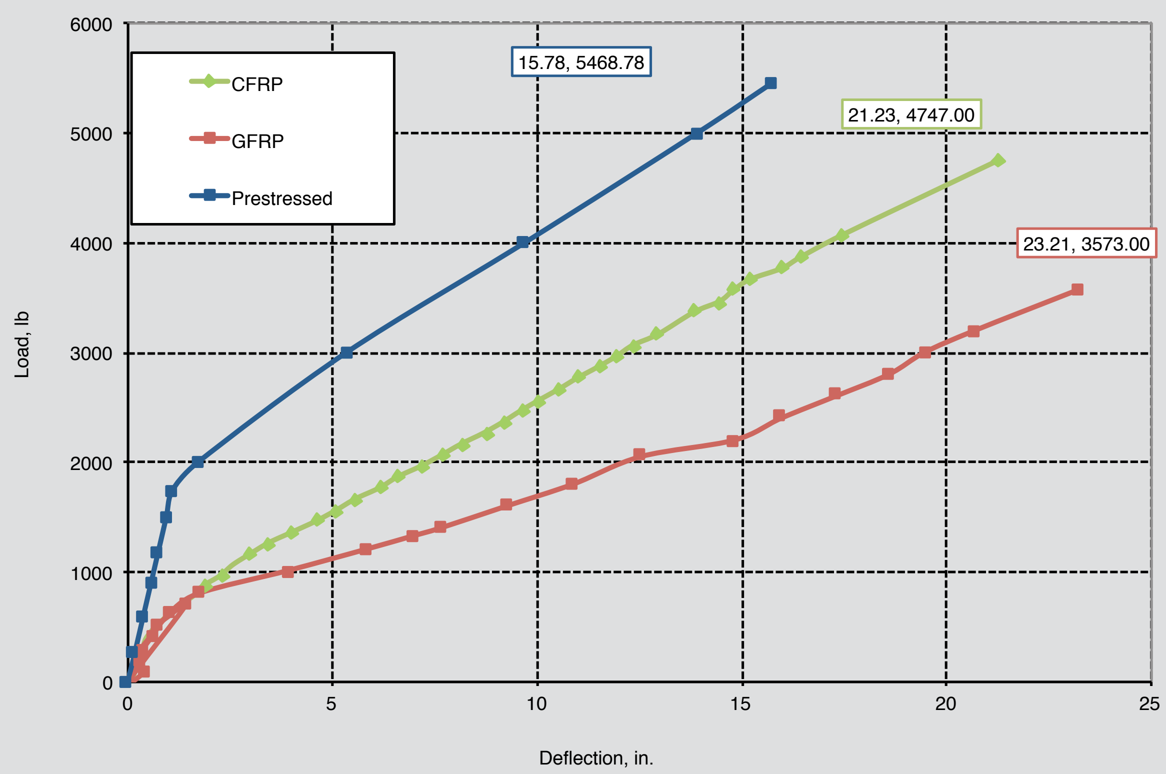

Figure 6. Load-deflection curves of poles reinforced with 12 bars. Note: CFRP = carbon-fiber-reinforced polymer; GFRP = glass-fiber-reinforced polymer. 1 in. = 25.4 mm; 1 lb = 4.448 N.

Figure 7. Shear cracks between supports prior to failure.

conjunction with the flexural shear failure mode.

Cost comparison

FRP is more expensive than conventional steel reinforcement used in the prestressing of poles on a straight quantity comparison. The following cost comparison analysis considers a direct lineal foot of the material as well as the load-carrying capacity of the poles reinforced with conventional prestressing steel, CFRP, and GFRP.

Cost-per-foot comparison

Manufacturing costs for spun concrete poles with the considered dimensions are the same for all three reinforcement materials. Therefore, the cost of concrete, plastic chairs, and other appurtenances were excluded from this analysis, as was shipping. The cost per foot analysis examined only the cost of the longitudinal bars and the shear reinforcement (spirals).

Table 3 shows the reinforcement cost comparison in United States dollars per foot for the three reinforcing materials. When compared with steel, GFRP reinforcement is about 3.5 times the cost for a pole reinforced with 6 bars and 2.7 times for 12 bars. CFRP reinforcement in the case of 6 bars is 10 times the cost of conventional prestressing steel strands and 3 times the GFRP reinforcement. For 12 bars, CFRP reinforcement is about 11 times to the cost of conventional steel reinforcement and 4 times that of GFRP reinforcement.

Figure 8. Concrete crushing at failure.

Cost-per-force comparison

Table 3 also compares the reinforcement cost of the three materials, shown as United States dollars per 1 kip force. These values were calculated by computing the total price of the reinforcement (both longitudinal and circumferential) and dividing it by the ultimate test load in kip. When compared with conventional steel reinforcement, GFRP reinforcement is about 3.5 times and 4 times the cost per force of a pole reinforced with 6 bars and 12 bars, respectively. On the other hand, CFRP reinforcement is about 8 times and 13 times the cost per force for a pole reinforced with 6 bars and 12 bars, respectively. When compared with GFRP, CFRP is about 2.3 times the cost per force for 6 bars, and 3.2 times for 12 bars.

Although CFRP-reinforced poles showed approximately 30% higher moment capacity than poles reinforced with GFRP, the cost of CFRP reinforcement is at least twice the cost of GFRP. Moreover, the increase in moment capacity is not proportional to the increase in the cost of reinforcement.

Comparing the overall pole cost, which includes both the concrete and the reinforcement, the increases in cost as compared with the conventional steel prestressed concrete pole are approximately 40% and 10% for CFRP- and GFRP-reinforced poles, respectively, for the 6-bar case; for the 12-bar case, the increase in cost is 75% and 13% for CFRP and GFRP respectively (Table 3).

Conclusion

The conclusions of this study can be summarized as follows:

- Because prestressing contributes significantly to the cracking moment, CFRP- and GFRP-reinforced concrete poles have significantly lower cracking loads compared with the conventional prestressed-steel-reinforced concrete poles.

- Although the tensile strength of the CFRP bar is 3 times that of GFRP and the nominal tensile force is 1.5 times greater than that of GFRP, CFRP-reinforced concrete poles have only about 30% higher ultimate load than GFRP-reinforced concrete poles.

Figure 9. Breaking of carbon-fiber-reinforced polymer (CFRP) bars for poles confined with CFRP grid.

Figure 10. Rupture of carbon-fiber-reinforced polymer grid used for pole confinement.

- The concrete cracks of the GFRP-reinforced poles were narrower than those of the CFRP-reinforced poles for each reinforcement group at 2000 lb (8.90 kN) of load. Because the modulus of elasticity of CFRP is significantly higher than that of GFRP, this outcome was unexpected and requires additional testing to verify it.

- Concrete poles reinforced with GFRP had a greater tip deflection than the poles reinforced with CFRP at every load due to the higher modulus of elasticity of the CFRP bars compared with GFRP bars.

- Conventional steel-reinforced prestressed spun concrete poles appear to be considerably stiffer than those reinforced with CFRP or GFRP. This is related to the effect of prestressing on the conventional poles. The compression force resulting from prestressing significantly increased the cracking load of the conventional poles compared with the CFRP or GFRP-reinforced poles.

- Generally, the failure mode sequences of the CFRP poles were similar to those of the GFRP poles in that

Figure 11. Slippage of CFRP bars at failure of poles confined with CFRP grid. Note: CFRP = carbon-fiber-reinforced polymer.

Table 3. Cost comparisons

	Number of bars	Prestressing steel	CFRP	GFRP
Reinforcement* cost per lineal foot	6	$2.53	$26.11	$8.53
	12	$4.33	$49.09	$11.85
Reinforcement* cost per 1 kip force	6	$16.56	$132.34	$57.25
	12	$15.83	$206.74	$64.52
Overall relative pole cost	6	1.0	1.40	1.10
	12	1.0	1.75	1.13

* Reinforcement refers to both longitudinal and circumferential shear reinforcement.
Note: CFRP = carbon-fiber-reinforced polymer; GFRP = glass-fiber-reinforced polymer. 1 kip = 4.45 kN.

the concrete crushed on the compression face at the ground line.

- For poles reinforced with CFRP, the shear crack within the support grew to join with the concrete crushing at the collar, resulting in the breaking of the longitudinal and shear reinforcement.

- Cost comparison between conventional reinforced prestressed poles and GFRP-reinforced poles demonstrates that GFRP reinforcement is at least three times the cost of conventional steel reinforcement, whereas the CFRP reinforcement is about 10 times.

- Despite the higher cost of the FRP reinforcement as compared with conventional reinforcement, the overall increase in total pole cost is about 60% and 12% on average for the CFRP and GFRP-reinforced poles, respectively.

- CFRP reinforcement resulted in approximately a 30% increase in the ultimate moment capacity of the pole as compared with the GFRP-reinforced pole; however, the cost of CFRP reinforcement is at least twice that of the GFRP reinforcement.

- Although the high cost of FRP reinforcement compared with conventional prestressed concrete poles plays a major role in the implementation of FRP reinforcement in the manufacture of spun concrete poles, when the end use is considered, such as installation in salt water or other corrosive industrial environments, the steel reinforced poles will undoubtedly require replacement or repairs well before the fiber reinforced ones.

- Because any replacement cost over the life cycle of the material would greatly affect the comparison between the overall economics of the material used, it is highly recommended to perform a life cycle cost analysis to have a true economic comparison.

Acknowledgments

The authors acknowledge Valmont-Newmark for their financial support in manufacturing the test samples and providing materials and test supplies.

References

1. Benmokrane, B., O. Chaallal, and R. Masmoudi. 1996. "Flexural Response of Concrete Beams Reinforced with FRP Reinforcing Bars." *ACI Structural Journal* 93 (1): 46–55.

2. Theriault, M., and B. Benmokrane. 1998. "Effects of FRP Reinforcement Ratio and Concrete Strength on Flexural Behavior of Concrete Beams." *ASCE Journal of Composites for Construction* 2 (1): 7–16.

3. Toutanji, H. A., and M. Saafi. 2000. "Flexural Behavior of Concrete Beams Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars." *ACI Structural Journal* 97 (5): 712–719.

4. Lyons, P. J. 2003. "Feasibility Study of CFRP Prestressed Spun Cast Concrete Poles for Transmission Line Support." MS thesis, Department of Civil, Construction, and Environmental Engineering, University of Alabama, Tuscaloosa, AL.

5. Yost, J. R., S. P. Gross, and D. W. Dinehart. 2003. "Effective Moment of Inertia for Glass Fiber-Reinforced Polymer Reinforced Concrete Beams." *ACI Structural Journal* 100 (6): 732–739.

6. Mota, C., S. Alminar, and D. Svecova. 2006. "Critical Review of Deflection Formulas for FRP-RC Members." *Journal of Composites for Construction* 10 (3): 183–194.

7. Bischoff, P. H., and A. Scanlon. 2007. "Effective Moment of Inertia for Calculating Deflections of

Concrete Members Containing Steel Reinforcement and Fiber-Reinforced Polymer Reinforcement." *ACI Structural Journal* 104 (1): 68–75.

8. Shalaby, A. M., F. H. Fouad, and R. Albanese. 2011. "Strength and Deflection Behavior of Spun Concrete Poles with CFRP Reinforcement." *PCI Journal* 52 (2): 55–77.

9. Terrasi, G. P., and J. M. Lees. 2003. "CFRP Prestressed Concrete Lighting Columns." In *Field Applications of FRP Reinforcement: Case Studies*, 55–74. Farmington Hills, MI: ACI (American Concrete Institute).

10. ASTM Subcommittee A01.05. 2007. *Standard Specification for Steel Wire, Plain, for Concrete Reinforcement*. ASTM A82/A82M-07. West Conshohocken, PA: ASTM International.

11. PCI Committee on Prestressed Concrete Poles. 1997. "Guide for the Design of Prestressed Concrete Poles." *PCI Journal* 42 (6): 94–134.

About the authors

Fouad H. Fouad, PhD, PE, is a professor in the Department of Civil, Construction, and Environmental Engineering at the University of Alabama at Birmingham.

Ashraf M. Shalaby, PhD, is an assistant professor in the Department of Civil Engineering at the National Research Center in Cairo, Egypt.

Sally G. Palmer, MSCE, is an engineer at Valmont-Newmark in Bellville, Tex.

Ronald Albanese, MSCE, PE, is a senior engineer at Valmont-Newmark in Birmingham, Ala.

Mohamed S. Gallow is a doctoral student and research assistant in the Department of Civil, Construction, and Environmental Engineering at the University of Alabama in Birmingham.

Abstract

Spun prestressed concrete poles are commonly placed in severe marine or industrial environments that are conducive to corrosion of the steel reinforcement. Nonmetallic fiber-reinforced-polymer (FRP) materials have been considered as alternatives to steel reinforcement because of their mechanical properties, durability, and corrosion resistance.

This paper compares the flexural behavior of spun concrete poles reinforced with three types of reinforcement: carbon-fiber-polymer, glass-fiber-polymer, and conventional prestressing steel reinforcement. The flexural behavior of the poles was evaluated in terms of cracking moment, ultimate moment capacity, and load-deflection data. A cost comparison was also performed. The results show that the different types of reinforcement are not associated with significant differences in the ultimate capacities of the poles but are correlated with differences in cracking and deflection.

Keywords

Concrete poles, CFRP, deflection, flexural behavior, GFRP, prestressing steel.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

Reader comments

Please address and reader comments to journal@pci.org or Precast/Prestressed Concrete Institute, c/o *PCI Journal*, 200 W. Adams St., Suite 2100, Chicago, IL 60606.