Development of a novel pole using spun-cast concrete inside glass-fiber-reinforced polymer tubes

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Poles are used in a variety of structural applications, including utility, transmission, and distribution lines; telecommunication towers; street lighting; highway signage supports; rail electrification; and wind turbine supports. The traditional material used for manufacturing poles is wood, but alternatives have been sought because wood is becoming scarce and is susceptible to rotting or damage. Steel poles can also be used but are more expensive and need corrosion protection.

Reinforced and prestressed concrete poles are now commonly used. Spun-cast concrete poles, in particular, have gained wide popularity since being commercially produced in Europe in the mid-1950s.

The central void in spun-cast poles reduces their weight without significantly reducing their flexural strength. Although the initial cost of concrete is higher than for wood for small-diameter poles, a life-cycle analysis shows that concrete is more economical.1 Prestressing is usually introduced in the concrete poles to prevent cracking and enhance stiffness under wind loading.2 PCI has issued a comprehensive report on materials, design, and installation of spun-cast concrete poles.2 Details of the fabrication process for conventional spun-cast concrete poles can be found in other articles.2

Editor’s quick points

- This paper introduces a spun-cast concrete pole that uses a glass-fiber-reinforced polymer (GFRP) tube to replace steel reinforcement.

- This new pole emerged after two types of poles were studied: a hollow GFRP tube that failed prematurely by local buckling and a completely filled GFRP tube that was greater in strength but heavier than the hollow tube.

- This paper shows the feasibility of fabrication as well as the equivalent steel reinforcement required to match the strength of the GFRP tubes.
detailed reinforcement at splice locations of spun-cast poles has led to serious collapses.\textsuperscript{7}

When subjected to aggressive environments or severe weather conditions, conventional concrete poles remain susceptible to deterioration, particularly within the splash zones near traffic lanes, where deicing salts are used and corrosion of steel reinforcement occurs, or under extreme freezing and thawing conditions (Fig. 1). It is worth noting that successful attempts have been made to repair deteriorated, damaged, and improperly designed concrete poles using fiber-composite wraps.\textsuperscript{7,8,9}

This paper introduces a novel pole that combines the advantages of spun-cast concrete technology with the non-corrosive and non-permeable characteristics of glass-fiber-reinforced polymer (GFRP) materials used in the form of thin tubes. The concept was attempted for the first time and involved spinning the concrete into a GFRP tube, which is essentially a permanent form containing the concrete. In addition, the tube has the capacity to replace all or part of the internal steel reinforcement because it is composed of layers of fibers stacked in different directions.

The tube prevents moisture intrusion into the pole, thereby protecting concrete from freezing and thawing effects and protecting steel reinforcement (if used) from corrosion. Because the tube is located at the perimeter of the section, it is more effective as reinforcement, eliminates the issue of concrete-cover spalling, and could possibly lead to thinner concrete walls.

This paper addresses the background of the concept and the fabrication process, assesses bond strength at the interface between the tube and concrete, and compares flexural strength of the proposed pole and conventional reinforced and prestressed spun-cast concrete poles.

Statically cast, completely filled GFRP tubes (CFFTs) have been successfully used as marine piles, which are essentially flexural members,\textsuperscript{10} and were studied in flexure and under axial loads.\textsuperscript{11,12} They also showed excellent performance under severe freezing and thawing exposure combined with sustained loading.\textsuperscript{13} Attempts were made to create a hollow concrete core inside the GFRP tube\textsuperscript{11} using cardboard or GFRP tubes, with the concrete between the outer and inner tubes static-cast in an inclined position. These attempts were difficult, particularly for long tubes.

**GFRP tubes with or without concrete**

Hollow GFRP poles have been investigated due to their light weight and superior durability. Research was conducted on 21-ft-long (6.3 m) tapered GFRP poles with base diameters of 16.4 in. (416 mm) and wall thicknesses between 0.11 in. and 0.22 in. (2.8 mm to 5.5 mm).\textsuperscript{14} The
fiber angle with respect to the longitudinal axis varied from 5 to 20 degrees, with some poles including hoop layers. The study showed that local buckling was the dominant failure mode (Fig. 2).

Tests on hollow and CFIT specimens demonstrate the benefit of concrete fill to increase flexural strength. The failure mode of the tube was fracture in tension. However, the ratio of the diameter to thickness \(D/t\) of the GFRP tube was 32, which is relatively small. Tubes with a larger \(D/t\) were tested in this paper’s research, including a hollow tube (hollow) and a CFIT specimen, as shown in Table 1. Both specimens used the same GFRP tube (tube 1).

**Description of GFRP tube 1**

GFRP tube 1 had an 8.63 in. (220 mm) outer diameter and a 0.087 in. (2.21 mm) wall thickness \((D/t = 100)\). The tube was fabricated using the filament-winding technique and had about 51% fiber volume fraction. The filament-winding process employed epoxy-wetted E-glass roving wound around a cylindrical mandrel.

The tube included nine layers, each about 0.01 in. (0.25 mm) thick. Four layers were oriented at 15 degrees with respect to the longitudinal axis, and five layers were oriented at 8 degrees with respect to the hoop direction in an alternating order such that the innermost and outermost layers were both circumferential. The tensile strength and modulus of elasticity of the tube in the longitudinal direction were 46 ksi (318 MPa) and 2610 ksi (18 GPa), respectively. In the hoop direction, the tensile strength was 78 ksi (536 MPa) and the modulus of elasticity was 4061 ksi (28 GPa).

**Fabrication and testing of hollow and CFIT poles**

The hollow pole was cut to the desired length from GFRP tube 1. Wooden circular discs, 0.5 in. (13 mm) thick, were inserted inside the tube over the supports as stiffeners. To fabricate the CFIT pole, a segment of tube 1 was placed on a 30-degree slope and sealed at the lower end with a wooden cap; concrete was cast from the upper end. The concrete compressive strength was 8.4 ksi (58 MPa). After sufficient curing of the concrete, both specimens were tested in four-point bending at a rate of 0.04 in./min (1 mm/min) with a span of 9.5 ft (2.9 m) and a distance between the loads of 1.32 ft (0.4 m) (Fig. 3). A 1200 kip (5300 kN) machine applied the load. Linear motion transducers measured the midspan deflection.

**Test results**

Figure 4 shows the load-deflection responses of the two specimens. The concrete fill substantially increased the strength and stiffness of the tube. It also changed the failure mode of the specimen from local buckling in compression to fracture of the tube in tension. The longitudinal tensile strain of the hollow tube at failure was 0.003. This
Figure 4. The load-deflection responses and failure modes are shown for the hollow and completely filled GFRP tube poles. Note: CFFT = completely filled glass-fiber-reinforced polymer tube; GFRP = glass-fiber-reinforced polymer; 1 in. = 25.4 mm; 1 kip = 4.448 kN.

Figure 5. This graph plots the variation of the neutral axis depth with moment during loading history. Note: CFFT = completely filled glass-fiber-reinforced polymer tube; SCFT = spun-cast concrete inside glass-fiber-reinforced polymer tube.
Figure 6 shows the variation of $c/D$ at failure with $\omega$. It is noted that $c/D$ changes slightly over a wide range of $\omega$, again with most cases falling between 0.2 and 0.3, as noted previously. Figure 6 also includes a picture showing the compression zone of a large CFFT specimen.

Figure 7. A spun-cast concrete inside glass-fiber-reinforced polymer (GFRP) tube pole is fabricated by spinning concrete in a GFRP tube.

For a given GFRP tube, it is possible to calculate the optimum concrete-wall thickness that would result in maximum flexural strength at a minimum self-weight us-
ing cracked-section analysis based on equilibrium of forces and strain compatibility.

**Fabrication of spun-cast concrete inside GFRP tubes**

The conventional spin-casting procedure was adopted to fabricate spun-cast concrete inside GFRP-tube (SCFT) poles using GFRP tube 2. Figure 7 shows a schematic of the fabrication concept. One of the SCFT poles was tested in flexure, and the other was used to fabricate push-off specimens P1 to P6 (Table 1).

**Description of GFRP tube 2**

Tube 2, the large prefabricated GFRP tube, was 12.9 in. (328 mm) in diameter with a structural-wall thickness of 0.15 in. (5.3 mm). This tube consisted of nine filament-wound, epoxy-wetted E-glass roving layers wound around a cylindrical mandrel and had about 51% fiber volume.
fraction. The tube had an external ultraviolet coating and small circumferential inner ridges to enhance bond.

Four filament layers were oriented at 8 degrees with respect to the longitudinal axis, each 0.031 in. (0.8 mm) thick, and five layers oriented at 2 degrees with respect to the hoop direction, each 0.0165 in. (0.42 mm) thick, in an alternating order such that the innermost and outermost layers were circumferential. The tensile strength and modulus of elasticity of the tube were 45 ksi (308 MPa) and 3481 ksi (24 GPa) in the longitudinal direction and 44 ksi (304 MPa) and 2901 ksi (20 GPa) in the hoop direction, respectively. The longitudinal compressive strength was 55 ksi (382 MPa), and Poisson’s ratio was 0.14.

Fabrication process of SCFT pole

A 9.35-ft-long (2850 mm) segment of GFRP tube 2 was placed in the lower half of the steel form (Fig. 8), and one end was sealed with a steel plug. The GFRP tube was secured in place using rubber shims to restrain its relative rotation with respect to the form. A predetermined volume of concrete, based on the desired wall thickness of 2.4 in. (60 mm), was placed manually inside the tube from the open end. This end was then sealed with another steel plug, and the upper half of the form was assembled. The form was placed on the spinning machine (Fig. 9), and the entire assembly was spun at 400 revolutions per minute (rpm) for about 3 minutes and then at 600 rpm for about another 3 minutes. The pole was then steam-cured for 20 hours before it was removed from the form. Figure 9 also shows a close-up of the concrete wall. The concrete compressive strength was 9.3 ksi (64 MPa).

Bond strength in SCFT poles

To examine characteristics of bond between the inner surface of the GFRP tube and the concrete, six push-off tests were conducted on specimens P1 to P6. A diamond-tip-blade saw was used to cut the specimens (Fig. 10). Care was taken to ensure a flat, square cut. The lengths of the specimens were 11.8 in. (300 mm) for specimens P1 to P3 and 23.6 in. (600 mm) for P4 to P6 (that is, length-to-diameter ratios $L/D$ of 0.91 and 1.82).

Test setup and instrumentation

Push-off specimens were tested in a vertical position (Fig. 11). A circular steel support was placed beneath the specimen so that only the GFRP tube was supported. A circular steel plate was placed on top of the specimen such that bearing was on concrete only. Three linear potentiometers (LPs) were installed at the upper end, 120 degrees apart, to monitor the vertical displacement of the concrete core. A 200 kip (900 kN) testing machine applied the load at a rate of 0.04 in./min (1 mm/min).
Figure 10. Six push-off test specimens are cut from a spun-cast concrete inside glass-fiber-reinforced polymer tube pole. Note: 1 in. = 25.4 mm.

Figure 11. Spun-cast concrete inside glass-fiber-reinforced polymer tube push-off tests are set up. Note: GFRP = glass-fiber-reinforced polymer; \( L \) = length of specimen; LP = linear potentiometer.
responds to failure of the adhesion between concrete and the GFRP tube. The peaks and valleys that followed correspond with the interlock of the corrugations on the inner surface of the tube. The tube had 0.012-in.-wide (0.3 mm) ridges in the circumferential direction, spaced at 0.35 in. (9 mm). The peaks and valleys correspond to the concrete core riding over the ridges in a successive manner. Similar behavior was observed for CFFT piles, except that the bond strength reported was three times higher because expansive concrete was used and the tube was completely filled.

Test results

Figure 12 shows the interfacial shear stress $\tau$ and slip plots for the two sets of specimens. The shear stress $\tau$ was calculated using Eq. (1).

$$\tau = \frac{P}{\pi(D - 2t)L}$$

where

- $D - 2t$ = inner diameter of the GFRP tube
- $D$ = outer diameter of the GFRP tube
- $t$ = wall thickness of the GFRP tube
- $P$ = applied load
- $L$ = length of the specimen

Figure 12 shows that initially the behavior was linear and stiffness was generally similar for the different specimens. At $\tau = 21$ psi (0.15 MPa), a short plateau was observed and was more visible in some specimens than others. This was followed by a series of peaks and valleys. The average maximum strength reached was 29 psi (0.2 MPa) for both the short and long specimens.

In Fig. 12, the short plateau after the linear behavior corresponds to failure of the adhesion between concrete and the GFRP tube. The peaks and valleys that followed correspond with the interlock of the corrugations on the inner surface of the tube. The tube had 0.012-in.-wide (0.3 mm) ridges in the circumferential direction, spaced at 0.35 in. (9 mm). The peaks and valleys correspond to the concrete core riding over the ridges in a successive manner. Similar behavior was observed for CFFT piles, except that the bond strength reported was three times higher because expansive concrete was used and the tube was completely filled.
Test results

Figure 14 shows the moment-curvature response of the SCFT pole. Curvature was calculated using longitudinal strain measurements. The behavior was generally linear beyond the cracking moment, which was substantially lower than the ultimate moment. After cracking, the tube’s stiffness was reduced and it carried the stresses in tension, where the bond between the tube and concrete played an important role in achieving the desired composite action. A study on CFFTs\textsuperscript{11} showed that multiple cracks typically occur at a spacing approximately equal to 1.3 times the tube diameter.

It is also noted that the stiffness upon unloading and reloading was similar to the original stiffness with small residual curvature, which corresponded to 0.2 in. (5.3 mm) deflection. This is attributed to the linear behavior of the GFRP tube at this range of loads. The pole failed at ultimate moment and deflection of 134 kip-ft (181 kN-m) and 2.64 in. (67 mm), respectively.

The longitudinal compressive and hoop tensile strains at failure on the compression side of the tube were -0.0075 and 0.0051, respectively. This longitudinal strain corresponded to a stress that was lower than the ultimate compressive strength of the tube. Also, the ratio of the two strains was much larger than Poisson’s ratio of the tube.
This suggests that the tube was biaxially loaded on the compression side as a result of some confinement of the concrete core. Figure 15 shows the failure mode of the tube, including longitudinal crushing combined with hoop tensile fracture. The maximum slip between the concrete core and GFRP tube at the ends at failure was 0.1 in. (2.7 mm).

**SCFT and conventional spun-cast concrete pole comparison**

To have a better assessment of the flexural behavior and strength of the SCFT pole, a comparison was made with three possible conventional cases of spun-cast concrete poles: a reinforced concrete (RC) pole, a fully prestressed (FP) concrete pole, and a partially prestressed (PP) concrete pole (Table 1). All three poles were assumed to have the same diameter (13 in. [328 mm]), concrete-wall thickness (2.4 in. [60 mm]), and concrete compressive strength (9.3 ksi [64 MPa]) as the SCFT pole. The objective was to design the steel reinforcement required in each case to achieve the same moment capacity as the SCFT pole.

Conventional cracked-section analyses were conducted using the concepts of equilibrium and strain compatibility. It was assumed that the steel reinforcing bars and prestressing strands were located in an axi-symmetric pattern at half the wall thickness. Figure 16 shows the stress-strain curves of the concrete and steel reinforcements used in these analyses. The tensile strength of the concrete was calculated to be 0.7 ksi (4.8 MPa), in accordance with ACI 318M-05. The analyses showed that to achieve a similar flexural strength of the SCFT pole, the conventional RC pole needs to be reinforced by twelve no. 6 (19M) steel reinforcing bars, which are equivalent to a reinforcement ratio of 6.7%. Similarly, the FP pole needs to be prestressed using twelve 1/2-in.-diameter (13 mm), 7-wire strands (1.84 in.\(^2\) [1188 mm\(^2\)]), which is equivalent to a 2.35% reinforcement ratio with an effective prestrain of 0.006. The PP pole needs to be reinforced by six no. 6 steel reinforcing bars and six 1/2-in.-diameter, 7-wire prestressed strands. In general, it was noted that the SCFT pole has a flexural capacity equivalent to those of heavily reinforced or prestressed, conventional spun-cast concrete poles.

Figure 14 shows the moment-curvature responses of the SCFT pole and the conventional RC, FP, and PP poles. The figure also shows a schematic of the cross section of the conventional poles. While the flexural capacities of the conventional poles were similar to that of the SCFT pole, their stiffnesses were substantially higher. This is attributed to the lower Young’s modulus of the GFRP tube compared with steel reinforcement. It was also noted that the RC pole showed the highest curvature at ultimate load. All conventional poles failed by crushing of concrete in compression after yielding of some layers of the steel reinforcement.

![Figure 15. A failure mode of a spun-cast concrete inside glass-fiber-reinforced polymer tube pole on the compression side includes longitudinal crushing combined with hoop tensile fracture.](image)

![Figure 16. The stress-strain curves are plotted for the materials used to analyze conventional spun-cast concrete poles. Note: 1 ksi = 6.895 MPa.](image)
Practical considerations

While the SCFT pole system introduced in this paper has merits, the following technical and practical aspects remain to be addressed in order for this technology to be widely accepted at a commercial level:

- A more effective method of delivering concrete into the GFRP tube, which is essentially a closed form, is needed. Clearly, delivering concrete manually from one or both ends may not be practical for long poles and may lead to a non-uniform concrete-wall thickness along their lengths.

- In applications where higher stiffness is required, the use of prestressing or longitudinal steel reinforcement with the SCFT concept needs to be explored.

- To maximize the advantage of the GFRP tube, the conventional steel form could be eliminated from the process (unless prestressing is required). In this case, the possibility of spinning the GFRP tube directly needs to be explored.

- Tapered GFRP tubes need to be explored because they would be more efficient and conform to common practice in cantilever-type poles.

- Further flexural tests need to be conducted on SCFT poles with GFRP tubes of different thicknesses and laminate structures.

Conclusion

This study demonstrated the feasibility of fabricating a novel pole consisting of spun-cast concrete inside a GFRP tube (SCFT). This concept overcomes a major weakness in hollow GFRP thin tubular poles, namely premature local buckling at a lower strength. At the same time, the SCFT is lighter than CFFTs of the same strength. The following conclusions were drawn:

- A 13-in.-diameter (330 mm) SCFT pole with a 0.15-in.-thick (5.3 mm) GFRP tube of 46 ksi (320 MPa) tensile strength and a 2.4-in.-thick (60 mm) concrete wall can have the same moment capacity as a conventional pole of the same size reinforced with twelve no. 6 (19M) reinforcing bars (6.7% reinforcement ratio) or prestressed with twelve 1/4-in.-diameter (13 mm), 7-wire strands (2.35% reinforcement ratio).

- The SCFT pole is lower in flexural stiffness than prestressed or reinforced conventional spun-cast concrete poles of the same strength. However, it is quite flexible and shows near-linear behavior and small residual deformation upon unloading.

- The interfacial shear stress-slip behavior of the concrete-tube interface, based on push-off tests, reveals a mechanical interlock bond mechanism that is activated by small ridges protruding from the inner surface of the tube. The bond strength seems to be maintained, even at large values of slip. Slip values measured in the bending test of the SCFT pole at failure were much smaller compared with those measured in the push-off specimens.

Acknowledgments

The author acknowledges the ISIS Canada research network’s financial support; John Fowler, president of the Canadian Precast/Prestressed Concrete Institute (CPCI); Utilities Structures Inc. for allowing the use of its spinning facilities; and Yazan Qasrawi and Dave Tryon of Queen’s University.

References


**Notation**

\[ c \] = neutral axis depth  
\[ D \] = outer diameter of GFRP tube  
\[ f'_c \] = concrete compressive strength  
\[ f_u \] = tensile strength of GFRP tube in the longitudinal direction  
\[ L \] = length of specimen  
\[ M \] = moment at a general load level  
\[ M_u \] = ultimate moment  
\[ P \] = applied load  
\[ t \] = wall thickness of GFRP tube  
\[ \tau \] = shear stress at the interface between the concrete core and the GFRP tube  
\[ \omega \] = reinforcement index
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Synopsis

This paper introduces a novel pole consisting of spun-cast concrete inside glass-fiber-reinforced polymer (GFRP) tubes (SCFTs). The GFRP tube is intended to replace all or part of the steel reinforcement. It confines and protects the thin concrete wall and any steel reinforcement used. This novel concept emerged after studying two types of poles, namely a hollow GFRP tube that failed prematurely by local buckling and a completely filled GFRP tube (CFFT) that was higher in strength but much heavier than the hollow tube.

The feasibility of fabrication in a conventional spin-casting facility is demonstrated. Push-off tests on segments cut from an SCFT pole were tested to examine the bond strength. Flexural testing showed that the strength of a 13-in.-diameter (330 mm) SCFT pole with a 0.15-in.-thick (5.3 mm) GFRP tube and a 2.4 in. (60 mm) concrete wall is equivalent to that of a conventional pole of the same size, reinforced with twelve no. 6 (19M) reinforcing bars or prestressed with twelve 1/4-in.-diameter (13 mm) 7-wire strands. SCFT poles also behave fairly elastically. Practical considerations that need to be addressed to encourage wide acceptance of this concept are identified.

Keywords

Bond, centrifugally cast, composite, fiber, flexure, glass-fiber-reinforced polymer, pole, spun cast, tube.

Review policy

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

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