Use of a carbon-fiber-reinforced polymer grid for precast concrete piles

Hatem M. Seliem, Lining Ding, William Potter, and Sami Rizkalla

- Precast, prestressed concrete piles are typically reinforced with steel spirals to confine the concrete core to enhance the core's load-carrying capacity and ductility under the dynamic effect of the driving forces.
- The research presented in this paper comprises three studies to investigate the bond strength of the proposed carbon-fiber-reinforced polymer (CFRP) grid using specially designed pull-out specimens, the effectiveness of the proposed CFRP grid as a replacement for steel spirals for confining concrete, and flexure testing of full-scale precast, prestressed concrete piles loaded to failure.

Precast, prestressed concrete piles are typically reinforced with steel spirals to confine the concrete core so that the core can resist the impact forces resulting from driving the pile into the ground. However, direct exposure of piles to soil and other harsh environments may cause corrosion of the steel spirals, which could compromise the long-term durability of the piles. This paper explores the use of a specially designed carbon-fiber-reinforced polymer (CFRP) grid as an alternative to steel spirals for confining precast, prestressed concrete piles. The advantages of the CFRP grid are its high tensile strength and noncorrosive characteristics, which are expected to increase the service life of this new generation of precast concrete piles by eliminating the possibility of corrosion of steel ties and spirals. CFRP stirrups have been used for prestressed concrete bridge girders since 1993 with no signs of galvanic corrosion to date.[1] Currently, in the precast concrete industry, CFRP grid is commonly used in sandwich wall panels.[2,3]

The research presented in this paper comprises three studies. The first study investigated the bond strength of the proposed CFRP grid using specially designed pull-out specimens. The second study evaluated the effectiveness of the proposed CFRP grid as a replacement for steel spirals for confining concrete. The third study included flexure testing of full-scale precast, prestressed concrete piles loaded to failure.

Figure 1. Testing of carbon-fiber-reinforced polymer grid tension coupon. Note: GFRP = glass-fiber-reinforced polymer.

Mechanical properties of the CFRP grid

The CFRP grid used in the three studies had spacing of 44.5 mm (1.75 in.) in both directions. To determine the mechanical properties of the CFRP grid, 24 individual strands from each direction were tested in tension using a 50 mm (2 in.) extensometer to measure the elongation (**Fig. 1**) in accordance with ASTM D3039.[4] Four layers of glass-fiber-reinforced polymer (GFRP) fabric were used to form tabs at each end of the tested strand to grip the strand (Fig. 1). The total length of the test strand was 356 mm (14.0 in.), including the 102 mm (4.0 in.) GFRP tabs at each end.

The average measured maximum load of the strands in both directions of the grid was approximately the same and was equal to 5060 N (1140 lb). The average measured rupture strain in each direction was 0.01. A digital caliper and digital micrometer were used to measure the width and thickness of the strands before testing. The measured average width and thickness were 7.544 and 1.052 mm (4.016 and 0.0414 in.), respectively. Using the average measured area of 7.933 mm^2 (0.0123 in.^{2}), the average tensile strength of the CFRP strands was approximately 640 MPa (93 ksi).

First study: Development length of the CFRP grid

Test specimens and setup

To determine the development length required for the proposed CFRP grid, eight specially designed pull-out specimens were tested. The parameters investigated were the embedment length *L* and the presence of the transverse strands.

The test setup was composed of two layers of the CFRP grid embedded into a concrete block at each end (**Fig. 2**). The load was applied in the direction of the main strands. Variable embedment lengths *L* of twice the grid spacing (89 mm [3.5 in.]), three times the grid spacing (133 mm [5.24 in.]), five times the grid spacing (222 mm [8.74 in.]), and 10 times the grid spacing (445 mm [17.5 in.]) were investigated. Two duplicate specimens were tested using the same embedment length, one specimen with transverse strands (specimen WT) and another without transverse strands (specimen NT). For the specimens without transverse strands, the transverse strands were cut carefully to avoid any damage to the longitudinal strands. **Table 1** gives the details of the test specimens used in this study, including the number of transverse wires in each concrete block.

The embedment lengths of five and ten times the grid spacing (222 and 445 mm [8.74 and 17.5 in.]) were selected to match the overlap lengths used in the short pile specimens tested in the second study. Embedment lengths of two and three times the grid spacing (89 and 133 mm [3.5 and 5.24 in.]) were selected to examine the behavior of small development lengths. A concrete cover of 19 mm (0.75 in.) was used, and the average measured concrete compressive strength of all tested specimens on the day of testing was 27.8 MPa (4.03 ksi).

The test setup included a hydraulic jack placed between the two concrete blocks to apply tension forces to the CFRP grid (**Fig. 3**). The concrete blocks were supported

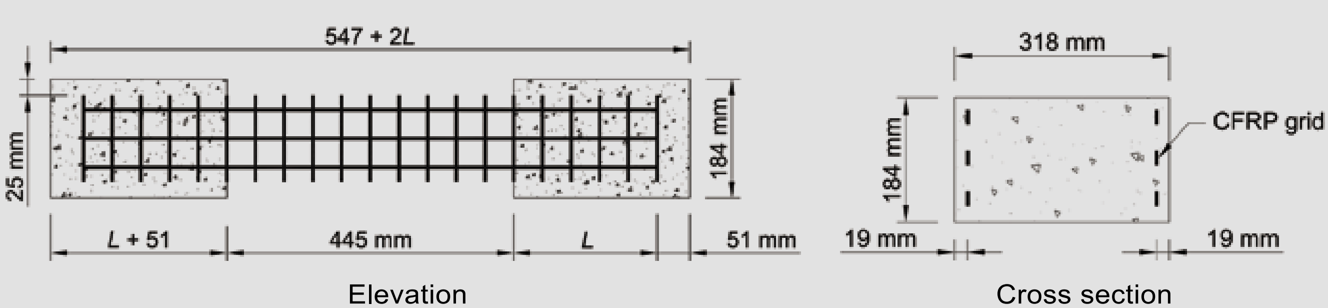


Figure 2. Schematic of the specially designed pull-out test specimens. Note: CFRP = carbon-fiber-reinforced polymer; *L* = embedment length. 1 mm = 0.0394 in.

Table 1. Details of specially designed pull-out test specimens

Specimen	Embedment length *L*, mm	Number of transverse wires
2S-NT	89	0
2S-WT		3
3S-NT	133	0
3S-WT		4
5S-NT	222	0
5S-WT		6
10S-NT	445	0
10S-WT		11

Note: 1 mm = 0.0394 in.

Table 2. Failure load of modified pull-out specimens

Specimen	Maximum load, kN
2S-NT	23.8
2S-WT	23.0
3S-NT	15.8
3S-WT	17.0
5S-NT	16.8
5S-WT	15.8
10S-NT	18.2
10S-WT	12.8

Note: 1 kN = 0.225 kip.

on steel rollers to allow for the relative movement of the blocks under the effect of the applied load. A load cell was mounted on the hydraulic jack to measure the applied load. Two linear potentiometers were mounted, one on each side of the concrete blocks, to measure the relative displacement between the two concrete blocks. The concrete blocks were resting on plywood sheet, which was prepared to minimize the friction between the plywood and the concrete blocks.

Test results

Table 2 gives the measured maximum loads for all test specimens. The eight specimens failed by rupture of the CFRP grid strands outside the concrete blocks (**Fig. 4**) for specimens 2S-WT and 3S-NT. The test results suggest that using an embedment length of twice the grid spacing (89 mm [3.5 in.]) can develop the full tensile strength of the strands of the CFRP grid. In addition, the test results also suggest that the presence of the transverse strands did not have a significant impact on the behavior, except for the short embedment length.

Second study: Short column behavior

Test specimens and setup

The second study of the experimental program included testing short concrete columns confined with the CFRP grid or steel spirals and subjected to concentric axial compression loads, representative of the top section of a precast concrete pile. Seven short columns were tested to failure.

The short columns were designed to represent the top 914 mm (36.0 in.) of a precast concrete pile. The specimens had a 356 mm (14.0) square cross section with an overall height of 1143 mm (45.0 in.). **Figure 5** shows the typical dimensions of the test specimens. Four specimens confined with different reinforcement ratios of the proposed CFRP grid with various overlap lengths were tested. One plain concrete control specimen and two specimens confined with 204 mm (8.0 in.) square steel spirals were also tested.

The steel square spirals were welded-wire reinforcement (WWR) of W3.5 steel wire with a cross-sectional area of 22.6 mm^2 (0.0350 in.^{2}), and clear concrete cover was 76 mm (3.0 in.), similar to current practice in the precast concrete industry. However, the CFRP grid was circular, with a diameter of 318 mm (12.5 in.) and concrete cover of 19 mm (0.75 in.) (Fig. 5). The concrete cover of 76 mm for the steel spirals was selected to meet the requirements of the American Concrete Institute's (ACI's) *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)*[5] for concrete permanently exposed to earth. However, due to the noncorrosive characteristics of FRP materials, a concrete cover of 19 mm was deemed sufficient for the CFRP grid. **Figure 6** shows column specimens with steel spirals and CFRP grid before casting. Steel collars were used at both ends of the specimens to prevent premature localized concrete crushing.

Table 3 provides details for the tested specimens. The two short column specimens confined with steel spirals were reinforced in the longitudinal direction with four 10M (no. 3) bars to maintain the pitch of the spirals.

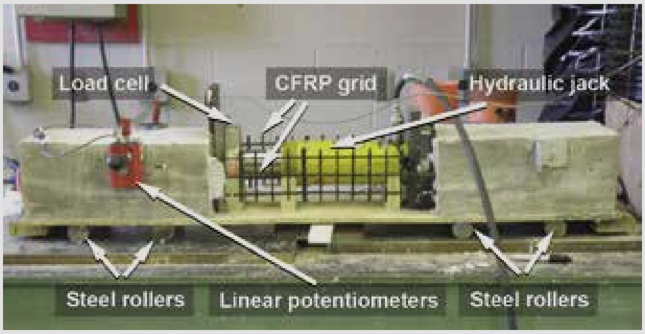
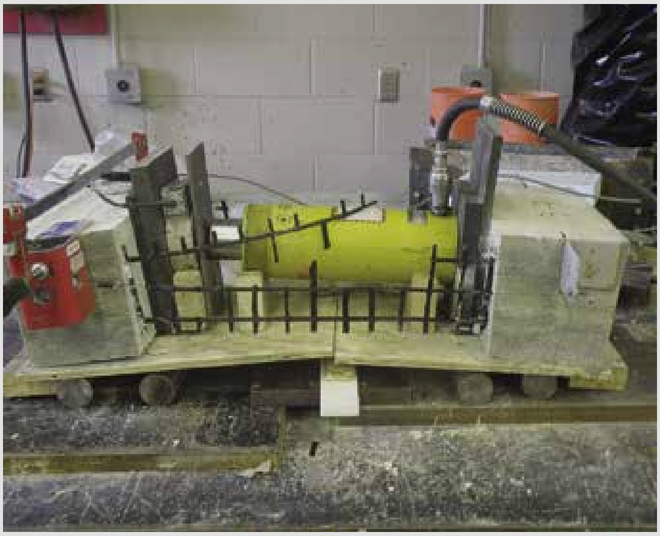


Figure 3. Modified pull-out test setup. Note: CFRP = carbon-fiber-reinforced polymer.

Specimen 2S-WT



Specimen 3S-NT

Figure 4. Pull-out specimens at the conclusion of the test.

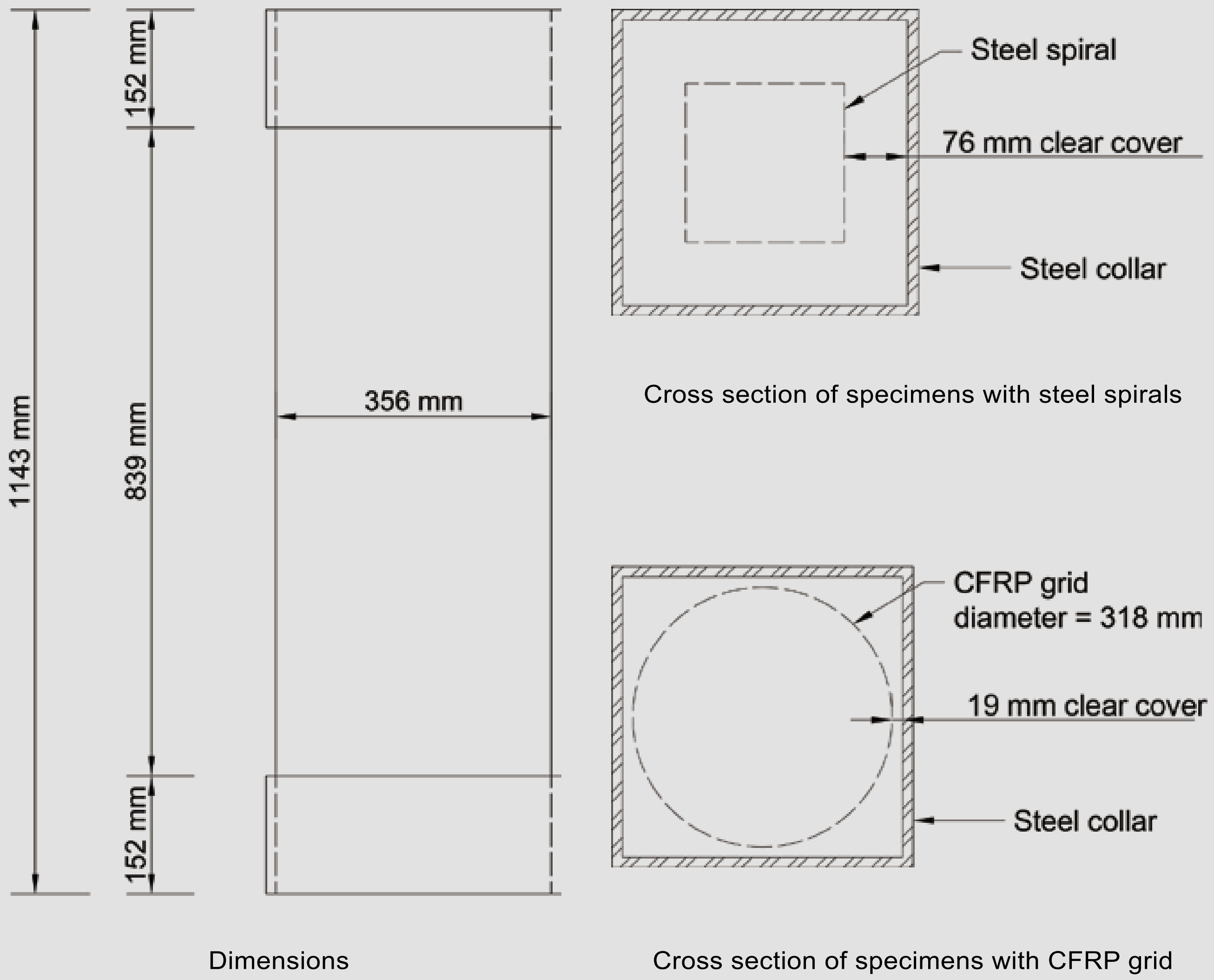


Figure 5. Details of short column specimens. Note: CFRP = carbon-fiber-reinforced polymer. 1 mm = 0.0394 in.

Figure 6. Short column specimens with steel spirals or carbon-fiber-reinforced polymer grids in wooden forms.

Figure 7. Test setup for short pile specimens.

The concrete used to cast all of the short column specimens was normalweight concrete provided by a local supplier, and the measured average compressive strength at the time of testing was approximately 38 MPa (5.5 ksi). Concrete compressive strength was measured using 100 × 200 mm (4 × 8 in.) cylinders according to ASTM C39-12.[6] The cylinders were kept with the specimens and were subjected to the same environmental and curing conditions.

The short column specimens were tested using a 8900 kN (2000 kip) compression machine and were loaded concentrically to failure (**Fig. 7**). The short columns were capped using gypsum cement to form parallel loading surfaces and ensure uniform distribution of the applied load to the bearing surfaces. The compression machine was operated in a displacement-controlled mode, maintaining a rate of loading of 4.45 kN/sec (1.00 kip/sec). Linear potentiometers were used to measure the axial deformation of the tested columns. Electrical resistance strain gauges were attached to the outer surfaces of the columns to measure the axial and lateral strain of the concrete. For validation purposes, strain measurement gauges were also used to measure the axial and lateral strain of the concrete on the surface of the columns. Before the concrete was cast, additional strain gauges were attached to the steel spirals or the CFRP grid to measure the strain in the confining material.

Table 3. Confinement details of short column specimens

Specimen	Confinement details
CN	Control (no confinement)
S@6	Steel spirals at a pitch of 150 mm
S@3	Steel spirals at a pitch of 75 mm
1C-8	One layer of carbon-fiber-reinforced polymer grid with 200 mm overlap
1C-16	One layer of carbon-fiber-reinforced polymer grid with 400 mm overlap
2C-C-8	Two continuous layers of carbon-fiber-reinforced polymer grid with 200 mm overlap
2C-S-8	Two separate layers of carbon-fiber-reinforced polymer grid with 200 mm overlap

Note: 1 mm = 0.0394 in.

Test results

Figure 8 shows the load-deflection relationships for all of the tested short columns. The behavior clearly indicates, as expected, that the initial stiffness was not affected by the type of confinement. The confinement effect is obvious

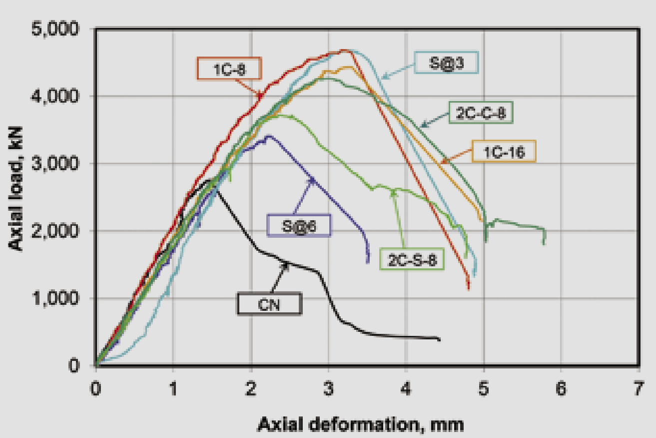


Figure 8. Axial load-deformation behavior of short test columns. Note: 1 mm = 0.394 in.; 1 kN = 0.225 kip.

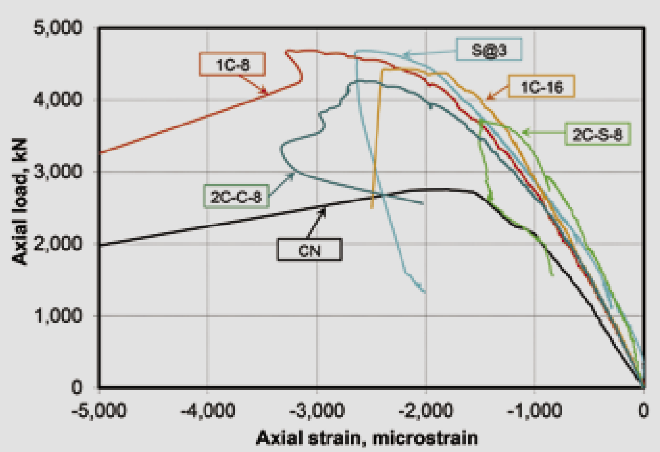


Figure 9. Measured axial concrete strain for short test columns. Note: 1 kN = 0.225 kip.

Table 4. Axial load-carrying capacity of short pile specimens

Specimen	Axial load, kN	P/P_{CN}
CN	2755	1.00
S@6	3413	1.24
S@3	4681	1.70
1C-8	4681	1.70
1C-16	4428	1.61
2C-C-8	4263	1.55
2C-S-8	3720	1.35

Note: P = axial load; P_{CN} = axial load-carrying capacity of control short pile specimens without confinement. 1 kN = 0.225 kip.

Figure 10. Short test piles at the conclusion of the test.

Figure 11. Rupture of CFRP grid strands at the conclusion of the test. Note: CFRP = carbon-fiber-reinforced polymer.

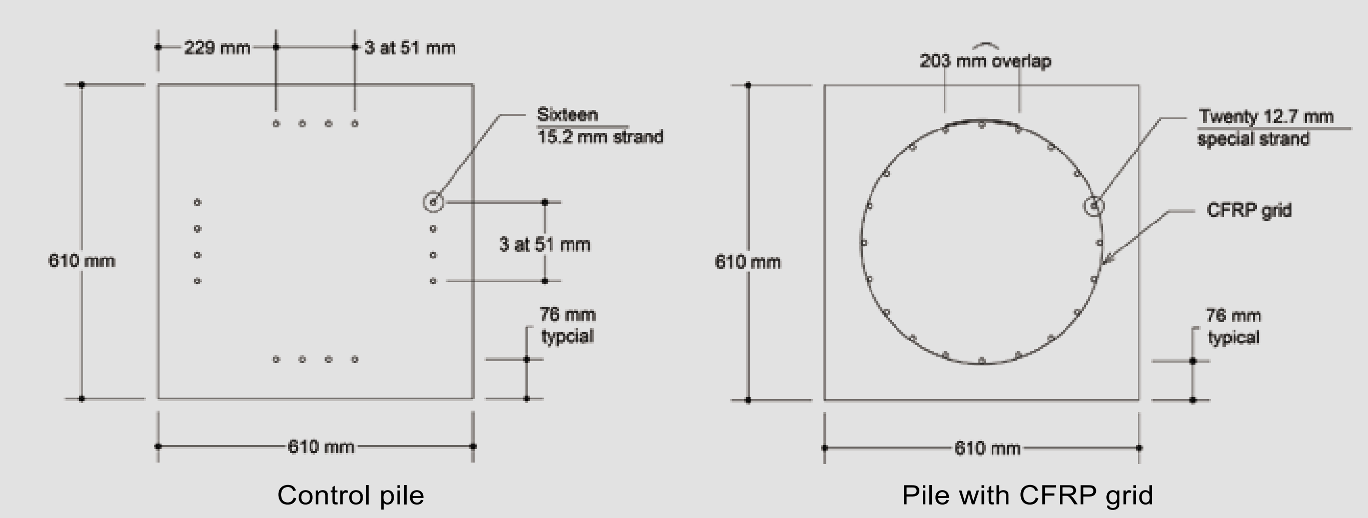


Figure 12. Cross section of full-scale piles. Note: CFRP = carbon-fiber-reinforced polymer. 1 mm = 0.0394 in.

for all tested specimens by comparing their behavior to the plain concrete specimen CN. The specimen confined with the steel spiral with 75 mm (3.0 in.) pitch spacing (specimen S@3) achieved a maximum load of approximately 4700 kN (1060 kip), while the specimen with the steel spiral with 150 mm (5.9 in.) pitch spacing (specimen S@6) achieved a load of approximately 3400 kN (760 kip). The specimen confined with a single layer of CFRP grid with an overlap of 200 mm (7.9 in.) achieved the same load-carrying capacity as the steel spiral specimen with 75 mm pitch spacing. Increasing the overlap for the CFRP grid did not have any effect on the load-carrying capacity. Use of the confinement reinforcement increased the overall ductility of the short test columns.

Figure 13. Pile with carbon-fiber-reinforced polymer grid before concrete casting.

Figure 9 shows the measured axial load versus the axial surface strain of the concrete for all column specimens, except specimen S@6 due to the failure of the strain gauge during testing. Measured strains were in close agreement with those measured using the electrical strain gauges.

It is evident from Fig. 9 that the control specimen without confinement, CN, lost its carrying capacity when the axial strain reached a value of approximately 0.002, while the confined specimens achieved an axial strain greater than 0.002. Specimens 1C-8 (confined with one layer of CFRP grid) and S@3 (confined with steel spiral with a pitch of 75 mm [3.0 in.]) had the highest axial load-carrying capacity and were able to reach an axial concrete strain of approximately 0.003 or higher before failure. The increase in the concrete axial strain is attributed to the confinement effect provided by the steel spirals or the CFRP grid. Test results confirmed that the CFRP grid with the described specification is adequate to achieve the required confinement currently provided by steel spirals for the end zones of typical precast concrete square piles.

Table 4 shows the measured failure axial load of the seven short column specimens and the ratio of the axial capacity of each specimen to that of the control column. Test results show that the pile confined with one layer of CFRP grid with a 200 mm (7.9 in.) overlap had the highest axial load-carrying capacity, which was also equal to that of the pile confined with steel spirals with a pitch of 75 mm (3.0 in.).

Figure 14. Pile with carbon-fiber-reinforced polymer grid.

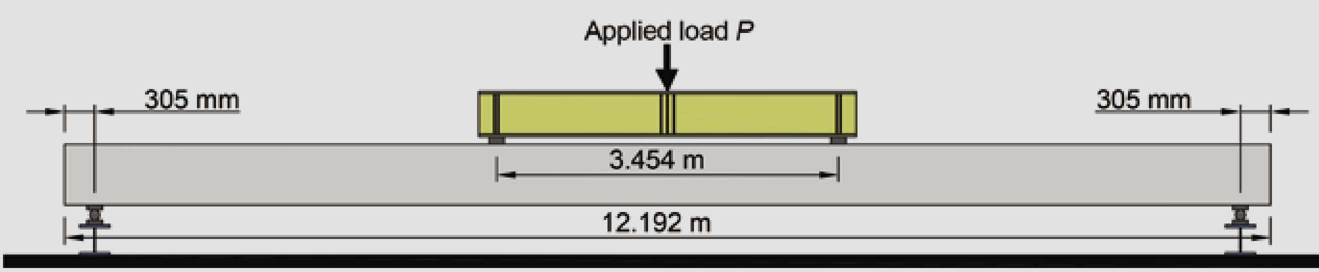


Figure 15. Pile-testing configuration. Note: 1 mm = 0.0394 in.; 1 m = 3.28 ft.

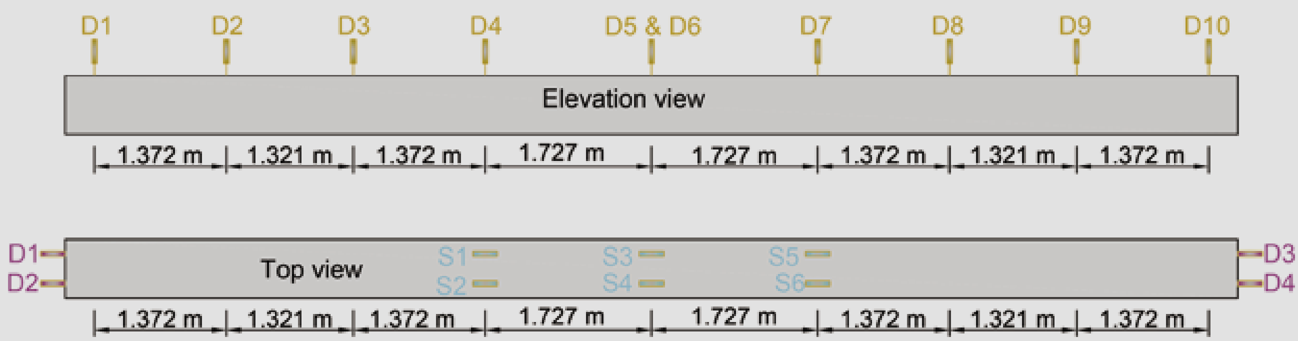


Figure 16. Instrumentation used for pile testing. Note: 1 mm = 0.0394 in.; 1 m = 3.28 ft.

Test results indicate that the use of a second layer of CFRP grid did not increase the axial capacity of the column. Using two continuous layers had a better effect than two separate layers. Furthermore, increasing the overlap length from 200 to 400 mm (16 in.) did not influence the confinement level.

Failure of all tested short columns was sudden and brittle due to the loss of the outer concrete shell. **Figure 10** shows the failure shapes of the plain concrete specimen confined with steel spirals at 75 mm (3.0 in.) pitch (specimen S@3), and specimens with CFRP grid and a 200 or 400 mm (7.9 or 16 in.) overlap (specimens 1C-8 or 1C-16) at the conclusion of the test. After failure, the concrete cover was carefully removed and it was observed that the cracks extended from the outer concrete shell to the core of the column specimens.

For specimens confined with CFRP grid, a popping noise was typically heard at high levels of loading before failure. Inspection of the CFRP grid after failure and removal of the concrete cover revealed rupture of some

Figure 17. Pile with carbon-fiber-reinforced polymer grid before testing.

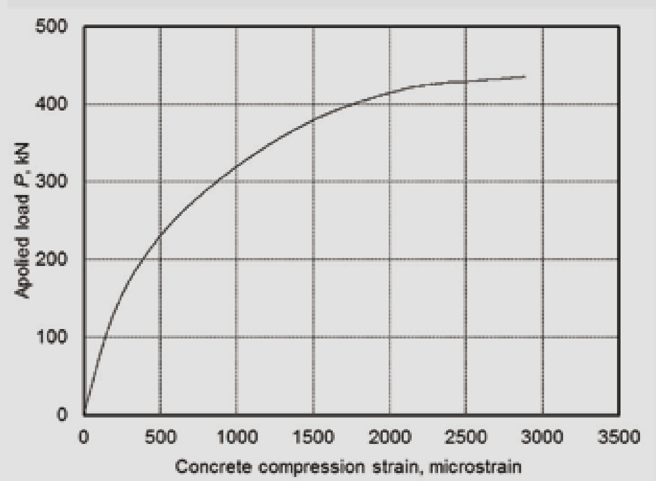


Figure 19. Applied load versus concrete compressive strain for pile with carbon-fiber-reinforced polymer grid. Note: 1 kN = 0.225 kip.

of the strands (**Fig. 11**) for one layer and two continuous layers of the CFRP grid. This indicates full use of the grid material and its effectiveness in providing confinement. Based on this observation, it is believed that due to the small diameter used for the short column specimens, some CFRP strands were possibly precracked during the fabrication process. Accordingly, it is recommended that CFRP grid not be used for piles with a diameter less than 400 mm (16 in.).

Third study: Flexure testing of full-scale piles

Test specimens and setup

Two full-scale, precast, pretensioned concrete piles were tested in bending to failure. The piles had a square cross section of 610 × 610 mm (24.0 × 24.0 in.) and a total length of 12.2 m (40 ft). **Figure 12** shows the dimensions and details of the two test piles. One pile was confined with

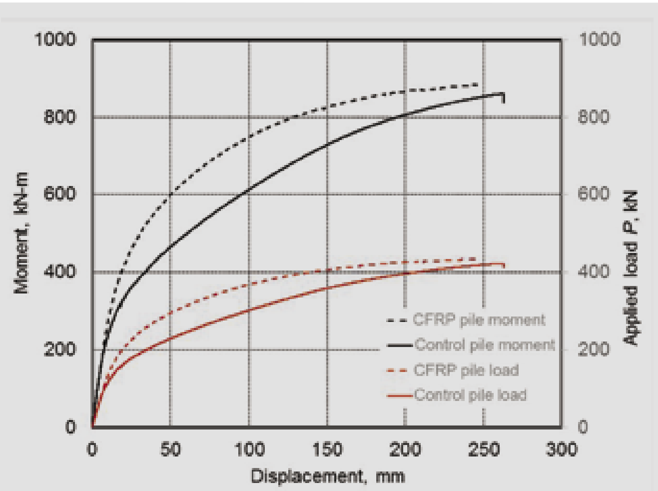


Figure 18. Load (moment)-deformation behavior of piles. Note: CFRP = carbon-fiber-reinforced polymer. 1 mm = 0.0394 in.; 1 kN = 0.225 kip; 1 kN-m = 0.7375 kip-ft.

CFRP grid and was prestressed using twenty 13.2 mm diameter (0.52 in.) special, low-relaxation, Grade 1860 (Grade 270) strands, which were wrapped by the CFRP grid, in a circular pattern (**Fig. 13**). The CFRP grid had a 200 mm (7.9 in.) overlap in the circumferential direction. The second pile, which was used as the control pile, was prestressed with sixteen 15.2 mm (0.6 in.) diameter low-relaxation, Grade 1860 (Grade 270) strands in a square pattern with W3.5 WWR ties. The square pattern of the strands is the current practice of the precast concrete industry. The CFRP grid must have a circular shape because the fibers cannot bend at a 90-degree angle. The prestressing force in the pile with CFRP grid was similar to that of the control pile (only 4% less). Self-consolidating concrete was used for casting the two piles. **Figure 14** shows the casting of the pile with the CFRP grid and a section cut from the pile after testing to confirm the homogeneity of concrete throughout the cross section. The average compressive strengths of the control pile and CFRP pile were measured as 69 and 76 MPa (10 and 11 ksi), respectively. The compressive strength was measured by testing 150 × 300 mm (5.9 × 11.8 in.) cylinders in accordance with ASTM C39.[6]

The piles were tested in four-point bending with a total span length of 11,582 mm (455.98 in.) and a constant moment zone of 3454 mm (136.0 in.) (**Fig. 15**). A hydraulic actuator was used to apply the single load to the spreader beam, which was measured using a calibrated load cell. Ten displacement transducers were used to measure the deformation at nine different locations along the pile length. In addition, four displacement transducers were used to measure the slip of the strands at the two ends of the test pile. Six electrical resistance strain gauges were attached to the top surface of the pile at three different locations to measure the concrete strain during testing. **Figure 16** shows the various locations of the instrumentation used, and **Fig. 17** shows the pile with the CFRP grid before testing.

Table 5. Summary of moment capacity of test piles

	Control pile	Pile with carbon-fiber-reinforced polymer grid
Applied load *P*, kN	421.7	434.6
Total measured moment, kN-m	1026.3	1052.1
Predicted moment capacity, kN-m	847.3*	830.4*
Ratio (measured to theoretical)	1.21	1.27

Note: 1 kN = 0.225 kip; 1 kN-m = 0.738 kip-ft.
* Moment due to measured applied load plus a dead-load moment equal to 169.5 kN-m due to own weight and weight of spreader beam.

Figure 20. Failure of pile with carbon-fiber-reinforced polymer grid due to concrete crushing.

Test results and discussion

Load (moment)–deformation behavior **Figure 18** shows the measured load (moment) versus midspan vertical deformation of the test piles. Generally, the two piles exhibited virtually the same behavior up to failure. However, the pile with the CFRP grid had slightly higher flexure stiffness throughout the loading history compared to the control pile. The increase in flexure stiffness can be attributed to the contribution of the longitudinal strands of the CFRP grid and the slightly higher concrete compressive strength.

Figure 19 shows the measured concrete compressive strain on the top surface of the pile within the constant moment zone throughout the loading history for the pile with the CFRP grid. The measured concrete strain reveals that crushing of concrete occurred at a strain level of 0.003.

Ultimate moment capacity The control pile failed at a total applied load equal to 421.7 kN (94.81 kip), while the pile with CFRP grid failed at a load of 434.6 kN (97.71 kip). Thus the total moment at the midspan of the piles due to the applied load, self-weight (8.5 kN/m [0.049 kip/in.]), and the weight of the spreader beam (13.3 kN [2.99]) is 1026.3 kN-m (9084.0 kip-ft) and 1052.1 kN-m (9312.3 kip-ft) for the control pile and the pile with the CFRP grid, respectively (**Table 5**). The table also provides the predicted moment capacity and the ratio of the measured moment to the predicted value.

Despite the use of less prestressing force, the moment capacity of the pile with the CFRP grid was slightly higher than that of the control pile. The slight increase in the moment capacity of the pile with the CFRP grid can be attributed to the enhanced confinement provided by the CFRP grid, as well as the contribution of its longitudinal strands. Both piles failed due to concrete crushing in the compression zone on the top surface of the pile within the constant moment zone (**Fig. 20**).

Conclusion

The findings of the three studies can be summarized as follows:

- A bond length equivalent to twice the grid spacing can develop the full tensile strength of the strands of the CFRP grid.

- The confinement provided by one layer of CFRP grid was the same as that provided by steel square spirals with a pitch of 75 mm (3.0 in.), typically used at the ends of precast concrete piles subjected to impact from driving forces.

- The use of two layers of CFRP grid does not increase the confinement effect.

- Two continuous layers of CFRP grid are more effective than two separate layers.

- The CFRP grid provides slight enhancements to the moment capacity of prestressed concrete piles. The use of CFRP grid slightly increases the flexural stiffness of prestressed concrete piles due to the presence of the longitudinal strands.

- Further research is required to address any possible potential for galvanic corrosion between the CFRP grid and the steel prestressing strands. CFRP stirrups have been used for prestressed concrete bridge girders since 1993 and have shown no signs of galvanic corrosion to date.[1]

- Further durability studies should be undertaken to better predict the potential service-life enhancements that could be achieved by using CFRP grids as opposed to steel spirals.

- Confining the core of the prestressed pile using a CFRP grid enables the concrete to reach a compressive strain failure of 0.003.

Acknowledgments

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Notation

L = embedment length

P = applied load

P_{CN} = axial load-carrying capacity of control short pile specimens without confinement

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Abstract

Precast, prestressed concrete piles are typically reinforced with steel spirals to confine the concrete core to enhance its load-carrying capacity and ductility under the dynamic effect of the driving forces. The research presented in this paper comprises three studies. The first study investigated the bond strength of the proposed carbon-fiber-reinforced polymer (CFRP) grid using specially designed pull-out specimens. The second study evaluated the effectiveness of the proposed CFRP grid as a replacement for steel spirals for confining concrete. The third study included flexure testing of full-scale precast, prestressed concrete piles loaded to failure.

Keywords

Bond strength, carbon-fiber-reinforced polymer grid, CFRP, confinement, ductility, flexure, load-carrying capacity, piles, steel spiral.

Review policy

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

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