Evaluation of corrosion-resistant basalt-fiber-reinforced polymer bars and carbon-fiber-reinforced polymer grid reinforcement to replace steel in precast concrete underground utility vaults

Paul Archbold and Gobithas Tharmarajah

- Replacing steel with corrosion-resistant fiber-reinforced-polymer materials in underground utility vaults is beneficial for both production and maintenance of utility vaults.
- Ultimate and service load behaviors of panels reinforced with basalt-fiber-reinforced polymer and carbon-fiber-reinforced-polymer grid are discussed in this paper.
- The test results of corrosion-resistant reinforcing materials are compared with test results from conventional steel-reinforced panels and unreinforced panels and verified against design code recommendations.

Underground concrete utility vaults and service chambers are often used in communications, electricity, and gas utility distribution networks to house vital connections. Precast concrete has been a prominent choice for these types of structures because it ensures quality of production, can be rapidly installed with minimum disruption to the public, and minimizes construction waste. Further, precast concrete enables immediate backfilling, unlike cast-in-place concrete, which requires a 28-day waiting period. However, durability issues for steel reinforcement demand additional concrete cover, which raises concerns over the sustainability and economic viability of this form of product due to its heavy weight and susceptibility to corrosion damage.

Fiber-reinforced polymer (FRP) products, such as reinforcing rods and composite mesh, offer potentially viable alternatives to steel reinforcement because they require smaller wall thicknesses and thus much lower amounts of concrete. This paper discusses tests conducted on panels reinforced with basalt-fiber-reinforced polymer and carbon-fiber-reinforced-polymer grid panels and compares the behavior with panels that are steel reinforced and unreinforced. Innovative FRP products can offer considerable time and cost savings in the preparation of the reinforcement matrix, leading to further improvements on the current technologies.

Table 1. Ultimate design moments for the test panels based on the equations and recommendations in EN 1992-1-1

Maximum moments	Due to surcharge, kN-m	Due to earth and water, kN-m	Total, kN-m
Vertical support moment	-1.625	-2.172	-3.797
Vertical midspan	1.219	0.695	1.914
Horizontal support	-0.507	-1.043	-1.550
Horizontal midspan	0.381	0.391	0.772

Note: The maximum calculated design moment was the vertical support moment, with a value of 3.797 kN-m. This value is taken as the ultimate design moment for comparison purposes. 1 kN-m = 0.7376 kip-ft.

Background

FRP composites have been used since the 1950s for strengthening and restoring historic structures and lightweight semipermanent structures, such as dome roofs, and were introduced to the construction industry in the 1980s as a reinforcing material.[1] At that time they were not considered suitable for use in normal reinforcing conditions because of their low modulus of elasticity and brittle failure.[2] However, applications of FRP as a strengthening and construction material for both old and new structures have increased in the past two decades because of its high durability.

Existing structures that deteriorate due to steel corrosion and structures that require extensive strength improvement to sustain natural disasters have been enhanced with high-strength, easy-to-install FRP materials for strength, safety, and serviceability.[2,3] The old repair and rehabilitation methods using steel plates are being replaced by FRP composites, which do not have some of the drawbacks of steel, such as difficulty in transportation, handling, and corrosion.[4]

The use of FRP bars for internal reinforcement has become more common recently, notably for structures that are exposed to corrosive conditions, such as bridge decks and coastal structures. Several studies have investigated the application of corrosion-resistant FRP composites in concrete structures.[5–8] Underground utility vaults are another type of structure that is exposed to extreme environmental conditions and lighter loading conditions. Despite the advantages of corrosion-resistant FRP reinforcement, only a limited number of studies have been conducted to explore the possibility of using it in underground utility walls. This study shows that FRP reinforcement is an ideal replacement for steel reinforcement in underground utility vaults that are exposed to corrosive environments. Although the ultimate load capacity is of greater concern for underground utility vaults because of their limited exposure to human interaction, these structures benefit from relaxed serviceability criteria without compromising strength and safety.

This paper summarizes the experimental and theoretical studies conducted on unreinforced, steel-reinforced, BFRP-reinforced, and CFRP grid-reinforced test panels representative of typical precast concrete utility vaults used in the industry.

Experimental investigation

The experimental investigation was conducted to study the ultimate and service behavior of precast concrete panels reinforced with steel, BFRP, and CFRP grid. The panels of each type were manufactured at a precast concrete facility. Unreinforced concrete panels were also tested for comparison purposes. The test panels were identical to each other in dimensions and type of concrete used.

The underground utility vaults were designed to withstand earth, water, and surcharge pressures. Design moments were calculated in accordance with *Eurocode 2* EN 1992-1-1[9] for a typical underground service chamber of 1000 mm (39 in.) depth using characteristic water pressure and soil pressure calculated from water and soil densities and a characteristic surcharge pressure of 12 kPa (1.7 psi). **Table 1** gives the design moments. Test panels were verified against an ultimate design moment of 3.797 kN-m (2.801 kip-ft) obtained for a 1000 mm deep service chamber.

Material properties

All of the test panels were constructed using normal concrete with a target cube strength of 40 MPa (5.8 ksi). The concrete mixture constituted 369 kg (814 lb) rapid-hardening cement, 151 kg (333 lb) water, and 1880 kg (2600 lb) total aggregate in 1 m^3 (1.3 yd^3) concrete. Total aggregate was composed of 1143 kg (2520 lb) of 16 mm (5⁄8 in.) diameter aggregate and 737 kg (1625 lb) of coarse sand. The steel-reinforced panels were designed using conventional steel bars with a yield strength of 460 MPa (67 ksi) and modulus of elasticity of 210,000 MPa (30,500 ksi). The BFRP-reinforced panels were constructed using BFRP bars with a 920 MPa (130 ksi) rupture strength and 54,000 MPa (7800 ksi) modulus of elasticity. The CFRP grid reinforcement had a 4.2 kN (0.94 kip) tensile strength for each strand and 235,400 MPa (34,140 ksi) modulus of elasticity. The CFRP grid had a square mesh of 75 × 75 mm (3.0 × 3.0 in.).

Test specimens

Four different types of panels were tested to investigate the ultimate and service load behavior of steel-reinforced, BFRP-reinforced, CFRP-grid-reinforced, and unreinforced panels. All of the test panels had identical dimensions of 1050 mm (41.3 in.) long, 350 mm (14 in.) wide, and 100 mm (4 in.) thick. The effective depth of the reinforcement was 60 mm (2.4 in.) for all of the test panels. The size of the panels was based on the actual size of a typical utility vault, which has a thickness of 100 mm and variable length and width according to the requirements. Specimens from commercially available 1000 mm (39 in.) deep utility vaults reinforced with three 12 mm (0.47 in.) steel bars spaced at 160 mm (6.3 in.) were used as the basis to test the panels reinforced with BFRP and CFRP grid.

Control panels were unreinforced or reinforced with three 12 mm (0.47 in.) diameter steel bars spaced at 160 mm (6.3 in.). BFRP- and CFRP-grid-reinforced panels were compared with conventional steel-reinforced panels and unreinforced panels. Three 12 mm diameter BFRP bars were used to construct BFRP-reinforced panels and four 75 × 75 mm (3.0 × 3.0 in.) CFRP meshes were used in CFRP-grid-reinforced panels to meet the design moment of 3.797 kN-m (2.801 kip-ft). **Figure 1** shows the dimensions of the test panels and the test setup. The selection of four CFRP meshes was based on theoretical calculations to meet the ultimate design moment.

Test setup and procedure

A simply supported test setup was adopted for the tests. The span between supports L was 900 mm (35 in.) with two point loads applied at 300 mm (12 in.) from each support (Fig. 1). Prior to testing, the panels were painted white to aid the observation of crack developments.

Three panels of each type were tested. The flexural load tests were conducted using a four-point bending arrangement in a universal test machine (**Fig. 2**). Test cubes produced from each batch of concrete were cured and later tested for compressive strength at the time of panel testing according to the test method recommended by EN 12390-3.[10]

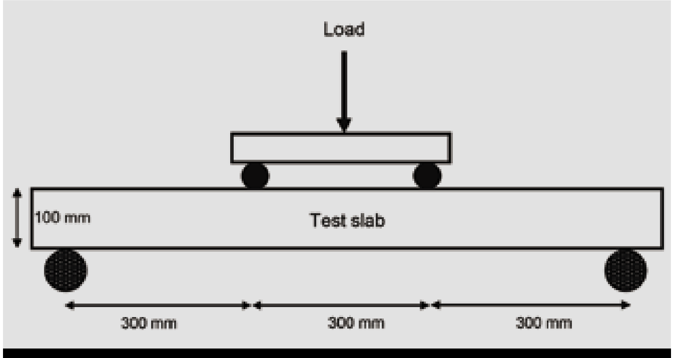

Figure 1. Test setup of unreinforced panels and panels reinforced with steel, basalt-fiber-reinforced polymer, and carbon-fiber-reinforced-polymer grid. Note: 1 mm = 0.0394 in.

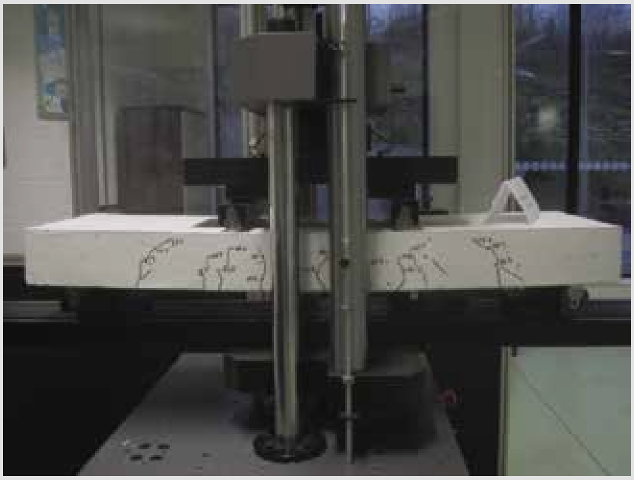

Figure 2. Four-point bending arrangement of the test panels.

The deflection of the test panels was monitored using a linear variable differential transformer at midspan, and observation of the onset crack load was established through visual inspection. The ultimate failure load and type of failure were also recorded for each panel. The load to flexure was applied at a rate of 0.1 mm/min (0.004 in./min).

Results and discussion

The test panels were compared for onset crack load, deflection at midspan, failure load, and failure mode. Experimental observations of BFRP- and CFRP-grid-reinforced panels with conventional steel-reinforced and unreinforced panels were compared with preferred criteria recommended for serviceability and ultimate load behavior in design codes.[9]

Table 2 presents the results from the load tests, including the recorded load at the onset of cracking P_{Crack}, the deflection at the design service load δ_s, and the ultimate failure load P_U, for each type of panel. Table 2 gives the average values from three samples of each type. The serviceability performance of the panels was assessed using deflection limits and crack widths given in design codes. A deflection limit δ_s was chosen based on a limiting value of $L/250$, as commonly adopted in EN 1992-1-1.[9] This gives a recommended deflection at service load level recommended by EN 1992-1-1 δ_{EC} of 3.6 mm (0.14 in.). The serviceability performance of the panels is represented in Table 2 in terms of the ratio of actual deflection to the limiting deflection at the design service load (δ_s/δ_{EC}).

Crack load and crack-width expansion are also parameters that influence the service load behavior of concrete structures. Steel-reinforced concrete panels are often controlled using stringent crack-width limits to prevent corrosion of steel. Compared with the 0.3 mm (0.01 in.)

Table 2. Results from flexural testing

Test panel	Concrete compressive strength, MPa	P_{Crack}, kN	δ_s, mm	δ_s/δ_{EC}	Ultimate failure load P_U, kN	P_U/P_{Ed}
Steel reinforced	57.1	14.6	1.71	0.48	57.3	2.22
BFRP reinforced	57.1	13.0	4.27	1.19	47.1	1.81
CFRP grid reinforced	57.1	14.5	6.59	1.83	26.1	1.03
Unreinforced	57.1	14.6	n/a	n/a	14.6	0.54

Note: BFRP = basalt-fiber-reinforced polymer; CFRP = carbon-fiber-reinforced polymer; n/a = not applicable; P_{Crack} = load at onset of cracking; P_{Ed} = ultimate design effect; δ_{EC} = deflection at service load level recommended by *Eurocode 2*; δ_s = deflection at design service load. 1 mm = 0.0394 in.; 1 kN = 0.225 kip; 1 MPa = 0.145 ksi.

maximum crack width that governs the service behavior of steel-reinforced structures, the allowable crack-width limit for FRP-reinforced structures is 0.5 mm (0.02 in.) because they are corrosion resistant. The 0.5 mm crack-width limit is for aesthetic reasons. The corrosion-resistant nature of FRP provides flexibility with the crack-width limit depending on the type of structure.

The ultimate load state behavior was evaluated based on the failure load and failure mode of the test panels.

Deflection

Figure 3 shows the load versus deflection behavior of the test panels. Deflections in the steel-reinforced, BFRP-reinforced, and CFRP-grid-reinforced panels at the service load of 17 kN (3.8 kip) were 1.71, 4.27, and 6.59 mm (0.0673, 0.168, and 0.259 in.), respectively. Unreinforced panels failed before reaching the required service load of 17 kN at the onset crack load. Comparing test panel deflection with the maximum allowable deflection at the service load level shows that only steel-reinforced concrete panels showed deflection less than the maximum allowable deflection of 3.6 mm (0.14 in.). The deflection of the BFRP-reinforced panel was 19% higher than the acceptable limit, and the CFRP-grid-reinforced panel deflection was 83% higher than the allowable deflection at the service load level.

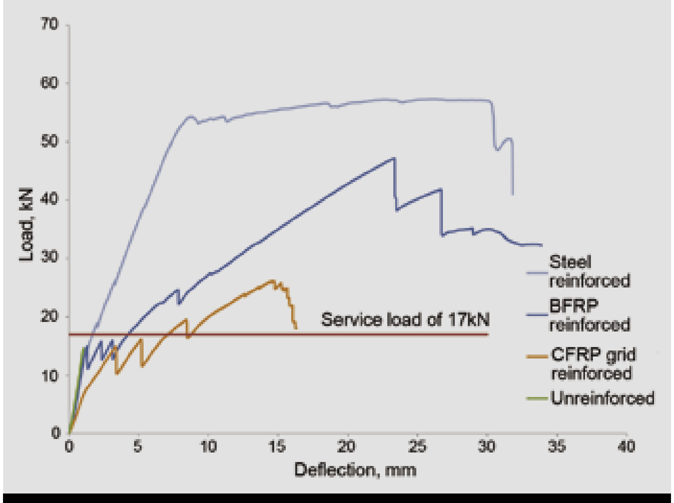

Figure 3. Load versus deflection behavior of the test panels. Note: BFRP = basalt-fiber-reinforced polymer; CFRP = carbon-fiber-reinforced polymer. 1 mm = 0.0394 in.; 1 kN = 0.225 kip.

The higher deflection of BFRP-reinforced panels was due to a lower modulus of elasticity of 54,000 MPa (7800 ksi) and lower axial rigidity (area $A \times$ elastic modulus E) of BFRP bars. Although CFRP grid has a higher tensile modulus of elasticity, the axial rigidity of the CFRP mesh was lower than the axial rigidity of steel and BFRP. Hence CFRP-grid-reinforced panels showed higher deflection than BFRP-reinforced panels.

The deflection of the BFRP-reinforced panels was slightly higher than the maximum allowable deflection limit at the service load level. However, due to the nature of underground utility vaults, precast concrete manufacturers consider it acceptable to have slightly higher deflection, provided it does not cause any damage to the stability of the structure.

Onset cracking load and crack width

The cracking loads of steel-reinforced, BFRP-reinforced, CFRP-grid-reinforced, and unreinforced panels were 14.6, 13.0, 14.5, and 14.6 kN (3.28, 2.92, 3.26, and 3.28 kip), respectively. The comparison of the cracking loads of composite-reinforced panels with steel-reinforced panels showed no significant differences. Table 2 gives the cracking loads of different test panels.

The service load behavior of underground service chambers is not required to adhere to stringent guidelines for crack-width limitation because these structures house utilities. However, the challenge with steel-reinforced concrete structures is to prevent deterioration of the structure because it can affect the load-carrying capacity of the structure. Therefore, thicker concrete cover is often provided for underground utility vaults in an attempt to prevent corrosion.

The crack widths of the test panels varied according to the type of reinforcement. Steel-reinforced panels showed a crack width of less than 0.3 mm (0.01 in.) at the service load of 17 kN (3.8 kip), while the crack width was slightly greater than 0.5 mm (0.02 in.) for BFRP-reinforced panels and greater than 1 mm (0.04 in.) for CFRP-grid-reinforced panels at the service load level. The choice of material to reinforce underground utility vaults will depend on the aesthetic appearance of the structure after cracking.

Ultimate load and failure mode

The ultimate design moment M required to carry the factored loads on the panels was 3.797 kN-m (2.801 kip-ft), which translates to 25.31 kN (5.690 kip) using Eq. (1) for the four-point bending arrangement.

$$M = R \times L/3 \quad (1)$$

where

R = support reaction = $W/2$

W = load applied to the beam

Comparing the ultimate design load of 25.31 kN (5.690 kip) with the failure load of the steel-reinforced, BFRP-reinforced, CFRP-grid-reinforced, and unreinforced panels, all three reinforced panels satisfy the load capacity requirements for an underground service chamber of 1000 mm (39 in.) depth. Unreinforced concrete panels failed at 14.6 kN (3.28 kip), much lower than the expected load capacity. Steel-reinforced, BFRP-reinforced, and CFRP-grid-reinforced panels carried 57.3, 47.1, and 26.1 kN (12.9, 10.6, and 5.87 kip) loads, respectively. The CFRP-grid-reinforced panel failed at 26.2 kN (5.89 kip) load, slightly above the required ultimate failure load. It was close to the required failure load because it was designed to withstand an ultimate design load of 25.31 kN (5.690 kip) by using a sufficient amount of CFRP-grid reinforcement. The steel-reinforced panels, similar to those currently used in precast concrete underground utility vaults, carried 120% more load than the required load capacity, while panels reinforced with an amount of BFRP by volume equal to the steel reinforcement carried 81% more load than the required capacity. In terms of ultimate load-carrying capacity, both BFRP and CFRP grid can replace steel in precast concrete underground utility vaults, as they show strength greater than the required capacity of the panels.

Table 3. Provided and balanced reinforcement ratio

Test panels	ρ, %	ρ_b, %	Failure mode
Steel reinforced	0.673	3.186	Yielding of steel
BFRP reinforced	0.673	0.524	Concrete crushing
CFRP-grid reinforced	0.322*	3.620	Carbon-fiber-grid rupture
Unreinforced	0.000	0.000	Tensile/concrete rupture

Note: A = area of the reinforcement; b = width of concrete section; BFRP = basalt-fiber-reinforced polymer; CFRP = carbon-fiber-reinforced polymer; d = effective depth of the reinforcement in the cross section; ρ = reinforcement ratio = $\frac{A}{bd}$; ρ_b = balanced reinforcement ratio.

* Approximate

Figure 4. Failure mode of the panels reinforced with carbon-fiber-reinforced-polymer grid.

Both steel-reinforced panels and CFRP-grid-reinforced panels failed due to the failure of reinforcement. The failure of the steel-reinforced concrete panels was initiated by yielding of the steel followed by concrete crushing on the top surface. This was due to the less-than-balanced amount of reinforcement provided in the steel-reinforced concrete panels (**Table 3**). Steel-reinforced panels were reinforced with 0.673% reinforcement, where the balanced

Figure 5. Failure mode of the panels reinforced with basalt-fiber-reinforced polymer.

amount of reinforcement was 3.186%. The failure of the CFRP-grid-reinforced panel was initiated by the rupture of the CFRP grid (**Fig. 4**), which was catastrophic. The CFRP-grid-reinforced panels were reinforced with 0.322% CFRP-grid reinforcement, where the balanced amount was 3.62% (Table 3).

Unlike the steel-reinforced and CFRP-grid-reinforced panels, the BFRP-reinforced panels showed initiation of failure by concrete crushing at the top surface of the panels (**Fig. 5**). The BFRP panels were reinforced with 0.673% BFRP bars, which was more than the 0.524% balanced amount of reinforcement.

The failure mode of all three panels indicates that steel has the preferred mode of failure because the yielding of steel facilitates the gradual dissipation of energy. The BFRP-reinforced panels also demonstrate a safer failure mode because the failure was initiated by concrete crushing, which is considered preferable to FRP rupture. The CFRP-grid-reinforced panels failed by CFRP-grid rupture because they were reinforced with less than the balanced amount of reinforcement. The unreinforced concrete panels failed at the cracking load because there was no reinforcement to provide additional tensile strength.

Conclusion

The following conclusions can be obtained from the study:

- Regardless of the type of reinforcement, all of the precast concrete panels showed similar crack loads. Reinforcement in panels provided additional strength and serviceability to underground utility vault panels.

- All of the test panels that were reinforced with steel, BFRP, or CFRP grid satisfied the ultimate design load requirements. The unreinforced concrete panels failed at loads much lower than the required ultimate design load. Therefore, replacing steel with BFRP on a direct volume basis, or with CFRP grid by estimating the ultimate design moment, satisfies the ultimate load requirements.

- The BFRP-reinforced panels showed a better failure mode than the CFRP-grid-reinforced panels. The failure of the CFRP-grid-reinforced panel was influenced by using a less-than-balanced amount of reinforcement. The comparison between the BFRP-reinforced and CFRP-grid-reinforced panels shows the significance of reinforcing FRP-reinforced panels with more than the balanced amount of reinforcement.

- Service load state behavior is governed by deflection and crack width. Deflection of the BFRP- and CFRP-grid-reinforced panels was higher than the maximum allowable deflection of 3.6 mm (0.14 in.) for the tested panels. Unlike slabs and beams, underground utility vaults are not often exposed to direct human contact. Therefore, it may be acceptable to exceed the maximum deflection limit without compromising the safety and strength of the structure. The deflection of BFRP-reinforced panels was considered acceptable by the precast concrete manufacturer because the deflection was 19% higher than the recommended deflection.

- The deflection of the CFRP-grid-reinforced panels was more than three times the deflection of the steel-reinforced panels at the service load level due to the lower axial rigidity of the panels. Increasing the axial rigidity by increasing the area of the reinforcement may reduce deflection. However, further studies are required to compare the cost of increasing the amount of reinforcement because CFRPs are typically much more expensive than BFRPs.

- Codes (*Eurocode 2*) limit the crack width of steel-reinforced panels to 0.3 mm (0.01 in.) to prevent active corrosion of the steel. Similarly, crack widths are limited to 0.5 mm (0.02 in.) for FRP-reinforced panels for aesthetic reasons because larger cracks may cause distress to the occupants.[11] Although underground utility vaults are not exposed to frequent human contact, larger crack widths in structures may cause spalling of the concrete cover. Among the panels tested with corrosion-resistant composites, BFRP-reinforced panels show greater control of crack-width expansion and can be considered a replacement for steel-reinforced panels. Further studies are required to establish the crack-controlling ability of CFRP grids with higher amounts of reinforcement.

- Comparing steel-, BFRP-, and CFRP-grid-reinforced panels, BFRP bars and CFRP mesh have the potential to replace steel because they provide sufficient load capacity. However, serviceability of the precast concrete panels determines the choice of the material. The tests show that replacing steel with an equal volume of BFRP satisfies both service load and ultimate load–level recommendations, while CFRP-grid-reinforced panels show unacceptable serviceability criteria at service load level. Therefore, it is possible to replace steel with corrosion-resistant BFRP bars.

- BFRP bars weigh one-fourth what steel reinforcement weighs and require less clear concrete cover than steel reinforcement. Due to these benefits, BFRP-reinforced precast concrete panels weigh less than conventional steel-reinforced panels. Further, BFRP-reinforced structures require minimal maintenance. Therefore, the life-cycle cost of BFRP-reinforced panels may provide economic advantages.

Acknowledgments

The authors would like to acknowledge the support of Killeshal Precast Concrete, Daingean, Ireland, and Enterprise Ireland for their financial support, Magmatech and Chomarat Inc. , Anderson, S.C., for supplying materials for tests, and the technical staff at the Athlone Institute of Technology for helping with the laboratory tests.

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Notation

A = area of the reinforcement

b = width of the concrete panel section

d = effective depth to the reinforcement in the panels

E = modulus of elasticity

L = clear span between supports

M = ultimate design moment

P_{Crack} = load at cracking of concrete

P_{Ed} = ultimate design effect

P_U = ultimate failure load

R = support reaction = $W/2$

W = applied load

δ_{EC} = deflection at service load level recommended by *Eurocode 2*

δ_s = deflection at design service load

ρ = reinforcement ratio

ρ_b = balanced reinforcement ratio

About the authors

Paul Archbold, PhD, is a lecturer in the School of Engineering at the Athlone Institute of Technology in Ireland.

Gobithas Tharmarajah, PhD, is a senior lecturer in the Faculty of Engineering at the Sri Lanka Institute of Information Technology in Malabe, Sri Lanka.

Abstract

Underground utility vaults are widely used to house utilities and are conventionally designed using steel reinforcement. These structures are often designed with thicker cover concrete in an attempt to prevent the corrosion of steel that is exposed to corrosive environments. Replacing steel with corrosion-resistant fiber-reinforced-polymer materials is beneficial both for production and maintenance. Ultimate and service load behaviors of panels reinforced with basalt-fiber-reinforced polymer (BFRP) and carbon-fiber-reinforced-polymer (CFRP) grid are discussed in this paper. Failure load and failure mode were used to evaluate the ultimate load behavior; deflection and crack width were used to examine the service load behavior of the tested panels. Test results show that corrosion-resistant reinforcing materials, such as BFRP and CFRP grid, can replace steel in underground utility vaults. Test results are compared with test results from conventional steel-reinforced panels and unreinforced panels and verified against design code recommendations.

Keywords

Basalt-fiber-reinforced polymer, BFRP, carbon-fiber-reinforced polymer grid, CFRP, corrosion, durability, flexural behavior, service load, steel, ultimate load, utility, vault.

Review policy

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

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