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Shear Strengthening of Concrete Deep Beams with Geopolymer-Based Fabric-Reinforced Matrix Composites

Nour Khir Allah, Tamer El-Maaddawy, Hilal El-Hassan
United Arab Emirates University
Al Ain, United Arab Emirates
201770375@uaeu.ac.ae; tamer.maaddawy@uaeu.ac.ae; helhassan@uaeu.ac.ae

Abstract – Test results of three large-scale reinforced concrete (RC) deep beam specimens with a shear span-to-depth ratio (*a/h*) of 1.6 are reported in this paper. One control beam was not strengthened whereas two beams were strengthened in shear using one layer of unidirectional carbon fabric-reinforced matrix (CFRM) composites. A geopolymeric matrix was used in the CFRM of one of the strengthened specimens to examine its potential use as a sustainable alternative to a commercial cementitious mortar. The geopolymeric matrix was a mixture of ground granulated blast furnace slag and fly ash activated by an alkaline solution consisting of sodium silicate and sodium hydroxide. The control beam failed shortly after initiation of a diagonal splitting shear crack in the shear span. The strengthened beams failed at a higher load in a shear-compression or diagonal tension mode of failure. Shear strengthening with CFRM composites resulted in a shear strength gain of 95% when a cementitious mortar was used as a matrix. The use of CFRM with a geopolymeric matrix was effective in improving the shear response but to a lesser extent. The gain in shear capacity caused by CFRM with a geopolymeric matrix was 77%.

***Keywords*:** shear, deep beams, geopolymers, cementitious, carbon, fabrics, strengthening.

1. Introduction

Reinforced concrete (RC) beams with a shear span-to-depth ratio (*a/h*) ≤ 2 are classified as deep beams [1]. They are typically used as transfer girders in high rise buildings. Loads in RC deep beams are transferred directly to the supports through concrete struts in the shear span (*i.e.* internal arch action effect). Shear strengthening of RC deep beams maybe required in practical setting due to insufficient maintenance, exposure to extreme loads, or deterioration caused by harsh environments. Innovative structural strengthening solutions include epoxy-based fiber-reinforced polymer system, commonly known as FRP, and fabric-reinforced cementitious matrix (FRCM). The contribution of the composite system to the shear capacity of RC deep beams decreased with an increase in the value of *a/h* [2-3]. Externally-bonded FRP system resulted in up to a 40% enhancement in the shear capacity of RC deep beams with *a/h* of 0.75 [2]. Shear strength gains of 79 and 46% were reported at *a/h* values of 1.7 and 1.1, respectively [3]. Due to their poor compatibility to the concrete substrate, delamination of epoxy-based composite system was the dominate mode of failure. The use of epoxy as a matrix also reduces the heat-fire resistance of the FRP strengthening systems [4].

Fabric-reinforced cementitious matrix composites involve bonding of fabric grids to the concrete substrate by means of a cementitious bonding agent. The use of cement-based mortar as a matrix improves the heat–fire resistance and compatibility with the concrete substrate [4]. As a result, shear strengthening of RC structures with FRCM has gained popularity in recent years [5-8]. An average increase of 51% in the load capacity of RC beams with *a/h* of 1.7 was reported due to strengthening with FRCM composites [5]. The deflection at peak load for the strengthened beams was up to 2.4 times that recorded for an unstrengthened control specimen [5]. Strengthened beams failed by debonding of the strengthening layer [5]. Crack initiation, propagation, and the number and location of the debonding spots were affected by the strengthening configuration [5]. Cement-based composites outperformed epoxy-based composite systems in terms of the observed increase in shear capacity of RC deep beams with *a/h* of 1.25 [6]. Up to a 23% increase in the shear capacity was reported due to shear strengthening with FRCM [6]. No debonding was detected in beams strengthened with cement-based systems [6]. Strengthened beams failed due to development of splitting shear cracks in the shear span [6]. Carbon fabrics were more effective in improving the shear capacity of concrete beams with *a/h* of 1.7 than glass and Poliparafenilen BenzobisOxazole (PBO) fabrics [7]. Beams with a continuous strengthening configuration exhibited higher strength gain than those exhibited by their counterparts with a discontinuous strengthening configuration [7]. Recently, the effectiveness of the embedment of the fabric layers near the concrete surface rather than placing them externally on the surface of RC deep beams with *a/h* of 1.7 was demonstrated [8]. Specimens strengthened with the near-surface embedded fabric-reinforced matrix layers exhibited higher strength gain and a tensile fabric's rupture mode of failure [8]. Beams strengthened with externally bonded fabric-reinforced matrix layers failed by debonding of the composites from the concrete. Nevertheless, no sign of debonding was observed in the beams strengthened with near-surface embedded fabric-reinforced matrix composites [8].

The production of cementitious mortars currently used in conventional FRCM systems consumes significant amount of non-renewable natural resources and leads to an increase in the concentration of carbon dioxide in the atmosphere. As such, there is a need to offer innovative structural engineering strengthening solutions that involve the use of sustainable cement-free materials. Recently, Abu Obaida et. al. [9] reported that a geopolymeric matrix can be used as a sustainable alternative to commercial cementitious mortars used in structural strengthening systems involving carbon fabric grids/textiles. The bond strength at a fabric-geopolymeric matrix interface was comparable to that measured at a fabric-cementitious matrix interface [9]. Nevertheless, there is a need to examine the effectiveness of using geopolymer-based carbon fabric-reinforced matrix (CFRM) composites to improve the shear response of large-scale RC structural elements before it can be routinely used in practical setting. This paper aims to fill this gap through experimental testing of three large-scale RC deep beam specimens. Development of innovative and sustainable solutions to solve complex structural engineering problems typically encountered in practical settings would support and advance sustainability of the economic activities and protect substantial investments in concrete infrastructure worldwide.

2. Experimental Program

Three large-scale RC deep beam specimens with *a/h* of 1.6 were constructed and tested. Two beams were strengthened with CFRM composites whereas one beam was not strengthened to act as a benchmark. A cement-free geopolymeric matrix was employed in shear strengthening of one of the strengthened beams. The CFRM strengthening system of the other specimen included a commercial cement-based matrix recommended by the manufacturer.

2.1. Materials

The concrete mixture used to cast the beams included ASTM Type I ordinary Portland cement (OPC) as a binder. A blend of 10- and 20-mm nominal size crushed limestones at a mass ratio of (1:2) was used as coarse aggregates. The fine aggregates comprised a combination of dune sand and 5 mm crushed coarse sand at a mass ratio of (1:1.7). The concrete mix proportion ratios, by weight, were cement: fine aggregates: coarse aggregates: w/c; 1:3.2:3.5:0.55. Concrete cylinders (150 x 300 mm) and cubes (150 mm) were sampled during casting to determine mechanical properties of the concrete mixture. Based on results of five replicate samples, the cube compressive strength, cylinder compressive strength, and splitting tensile strength of the concrete mixture were on average 33.5, 26.3, and 2.3 MPa, respectively. The longitudinal steel bars had a nominal diameter of 25 mm, yield strength of 539 MPa, and ultimate strength of 649 MPa. The CFRM composites adopted in the current study consisted of carbon fabrics and a cementitious or geopolymeric matrix. The fabrics consisted of unidirectional carbon fiber bundles with a center-to-center spacing of 17 mm (Figure 1). Table 1 lists typical mechanical properties of the carbon fiber mesh as provided by the manufacturer [10]. Each fiber bundle has a measured width of approximately 5.0 mm and a measured thickness of approximately 0.54 mm, which corresponds to an equivalent cross-sectional area per unit length of 159 mm^2/m. The cementitious matrix provided by the manufacturer had an average 28-day cube compressive strength of 43 MPa, splitting tensile strength of 2.4 MPa, and Young's modulus of 29 GPa. respectively. The geopolymeric matrix included slag and fly ash as binding materials, dune sand as fine aggregates, and an alkaline activator solution consisting of sodium silicate (SS) and sodium hydroxide (SH). Proportions and components of the geopolymeric matrix are given in Table 2. The geopolymeric matrix had an average 28-day cube compressive strength of 43, splitting tensile strength of 3.0 MPa, and Young's modulus of 7 GPa.

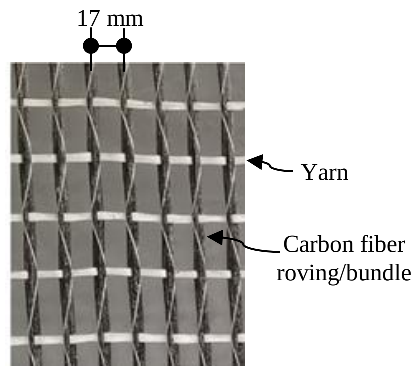


Fig. 1: Carbon fiber mesh.

Table 1: Properties of the carbon fiber mesh [10].

Property	Value
Weight per unit area [g/m^2]	281
Density [g/cm^3]	178
Tensile strength [MPa]	4300
Modulus of elasticity [GPa]	240
Elongation at rupture [%]	1.8
Equivalent thickness (weight ÷ density) [mm]	0.157
Theoretical cross-sectional area per unit length [mm^2/m]	157
Ultimate tensile force [kN/m]	675

Table 2: Geopolymeric matrix components and proportions.

Mixture proportion (kg/m^3)				
Fly ash	Slag	Dune sand	Sodium silicate (SS)	Sodium hydroxide (SH)
362.5	362.5	752	285.5	114

2.2. CFRM Strengthening

Shear strengthening included surface preparation and CFRM application. The strengthening procedure are summarized in Figure 2. The concrete surface was roughened using a high-pressurized water jet. The surface was then left to dry prior to the application of the CFRM composites. One layer of mortar with a thickness of approximately 4 mm was first applied on the roughened concrete surface. The carbon fabrics were then placed on top of the mortar layer then fully impregnated in the mortar using hand pressure. A second layer of mortar, with a thickness of approximately 4 mm, was then applied on top of the fabric. The strengthening composite layer was cured for 28 days using periodically wetted burlap sheets.

(a) (b) (c)

Fig. 2: Strengthening procedure; (a) surface preparation, (b) CFRM application, (c) strengthened surface.

2.3. Test Specimens

Figure 3 shows details of concrete dimensions and steel reinforcement of a typical test specimen. The specimens had a total length of 3300 mm and a rectangular cross section with a width of 150 and depth of 500 mm. The beams were reinforced with 4 No. 25 (25 mm in diameter) longitudinal steel bars in the tension side and 2 No. 25 steel bars in the compression side. The concrete cover to the center of the steel reinforcement was 50 mm, rendering an effective depth of 450 mm. Three stirrups (5 mm in diameter) were provided in the free length outside the test regions to improve confinement and end anchorage resistance of the longitudinal steel bars.

2.4. Test Setup

The specimens were rested on two supports 2900 apart then tested to failure under a four-point bending configuration. Two concentrated loads were applied on the top surface of the beam using two MTS actuators. Each load was applied at a distance 800 mm from the support rendering *a/h* of 1.6. Steel plates, 150 x 150 x 20 mm, each were placed under the loading points and above the supports to prevent occurrence of a stress concentration. The tests were initially conducted under a load-control at a rate of 0.5 kN/sec then, prior to reaching the ultimate load, the loading scheme was switched to a displacement control at a rate of 0.6 mm/min for safety consideration. A load cell was placed between the actuator and steel plate at each load point to record the loads applied by the actuators. The midspan deflection was measured by means of a linear variable differential transducer (LVDT). Five strain gauges (SG), 5 mm long each, were attached to the longitudinal steel reinforcing bars within the shear span at a spacing of 181.25 mm to measure steel strains. Concrete strains in the longitudinal direction at the midspan and under the loading points were measured using 60 mm long SG. The diagonal concrete strain at the midpoint of the shear span was also measured using 60 mm long SG. Readings of the load cells, LVDT, and SG were captured using a data acquisition system. Strain gauges, 5 mm long each, were also bonded to one of the fiber bundle at the midpoint of the shear span to measure fabric strains. A test in progress is shown in Figure 4.

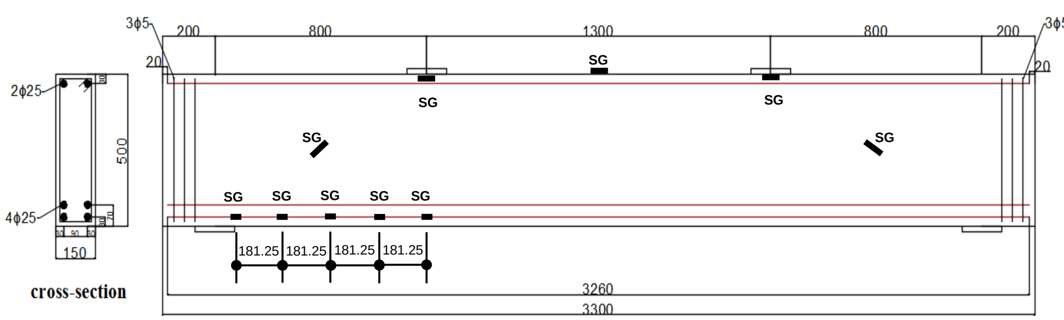


Fig. 3: Details of a typical test specimen (dimension are in mm).

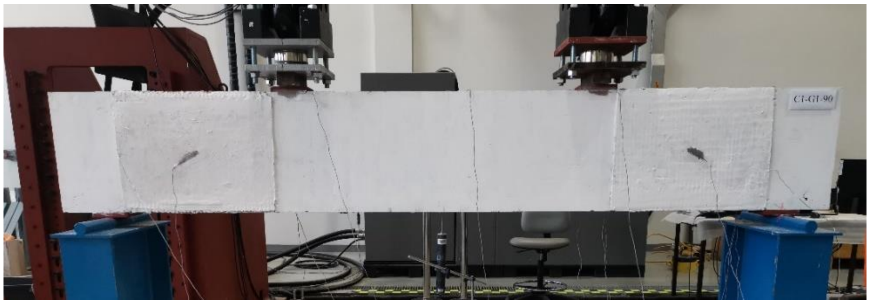


Fig. 4: A test in progress.

3. Results

The load-deflection response, shear capacity, crack pattern, failure mode, and strain measurements are reported in this section. The effectiveness of CFRM to improve the shear behavior of RC deep beams was elucidated.

3.1. Load-Deflection Response

The shear load-deflection responses of the tested beams are presented in Figure 5. Test results are summarized in Table 3. The deflection of the control specimen increased linearly until initiation of shear cracks at approximately 104 kN, which caused a load decay. Following cracking, the deflection increased at a significantly higher rate until the beam reached its shear capacity of 139 kN at a corresponding midspan deflection of 6.8 mm. The strengthened specimens exhibited a quasilinear load-deflection response. The pre-cracking stiffness of the strengthened specimens and that of the control were significantly different. Nevertheless, development of shear cracks in the strengthened specimens did not result in a load decay. Shear strengthening with CFRM significantly improved the post-cracking stiffness and shear capacity. For instance, at 120 kN, the control specimen exhibited a midspan deflection of 5 mm whereas the strengthened specimens experienced a midspan deflection of 3 mm. The strengthened specimens reached their shear capacity at midspan deflections higher than that of the control beam. The shear capacity of specimen CEM-90 with a cementitious matrix was 95% higher than that of the control specimen. Shear strengthening with CFRM having a geopolymeric matrix also increased the shear capacity but to a lesser extent. Specimen GEO-90 with a geopolymeric matrix exhibited a 77% increase the shear capacity relative to that of the control specimen. From Table 3, it can be seen that the steel strains exhibited by the tested specimens at peak load were less than the yield strain. The maximum measured longitudinal concrete strain at peak load was in the range of 2172 to 3023 $\mu\varepsilon$ whereas maximum diagonal concrete strain values in the range of 550 to 1320 $\mu\varepsilon$ were recorded at peak load.

Table 3: Summary of test results.

Specimen[1]	Matrix Type	V_{max} (kN)	Δ_{max} (mm) [2]	Max. Steel Strain[2] ($\mu\varepsilon$)	Max. Concrete Strain[2] ($\mu\varepsilon$)	
					Longitudinal Strain	Diagonal Strain
Control	-	139	6.8	1014	2214	550
CEM-90	Cementitious	271	8.5	1500	2172	1320
GEO-90	Geopolymeric	246	7.7	1860	3023	594

[1]CEM-90: strengthened specimen having a cementitious matrix and fabrics aligned at 90^o with respect to the longitudinal axis of the beam.
[1]GEO-90: strengthened specimen having a geopolymeric matrix and fabrics aligned at 90^o with respect to the longitudinal axis of the beam
[2]At shear capacity

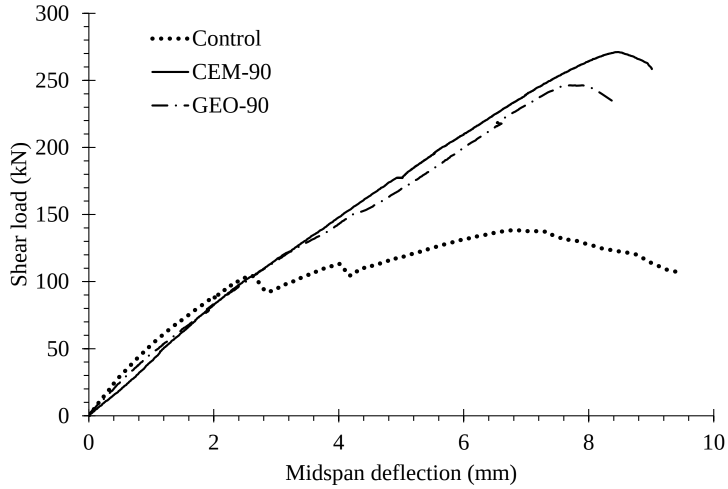


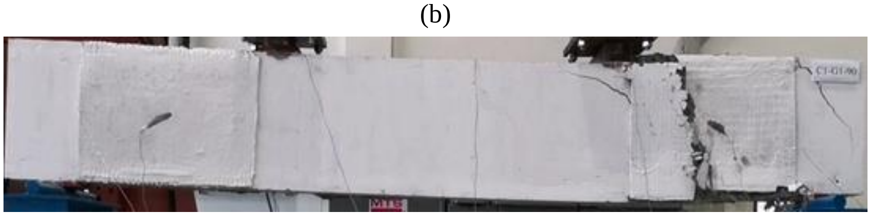
Fig. 5: Shear load-deflection response.

3.2. Crack Pattern and Failure Mode

Photographs of the beams at failure are shown in Figure 6. All beams exhibited a shear mode of failure. The control specimen failed shortly in a shear-compression mode of failure after initiation of a diagonal shear crack in the shear span. The presence of CFRM in specimen CEM-90 delayed failure of the beam. After initiation of a diagonal crack in the shear span, specimen CEM-90 was able to sustain additional load and deformation prior to failure. As the load progressed, the initial shear crack developed in the shear span propagated toward the load and support points. Additional shear cracks were also developed with further increase in load. Finally, specimen CEM-90 failed due to crushing of the top part of the concrete strut connecting the support and load points. The shear cracks in specimen GEO-90 were not visible during testing, possibly because of the low Yong's modulus of the geopolymeric matrix used in strengthening which could have allowed the matrix to deform without visible cracking on the surface. Eventually, specimen GEO-90 failed suddenly in a diagonal compression mode of failure.

(a)

(b)

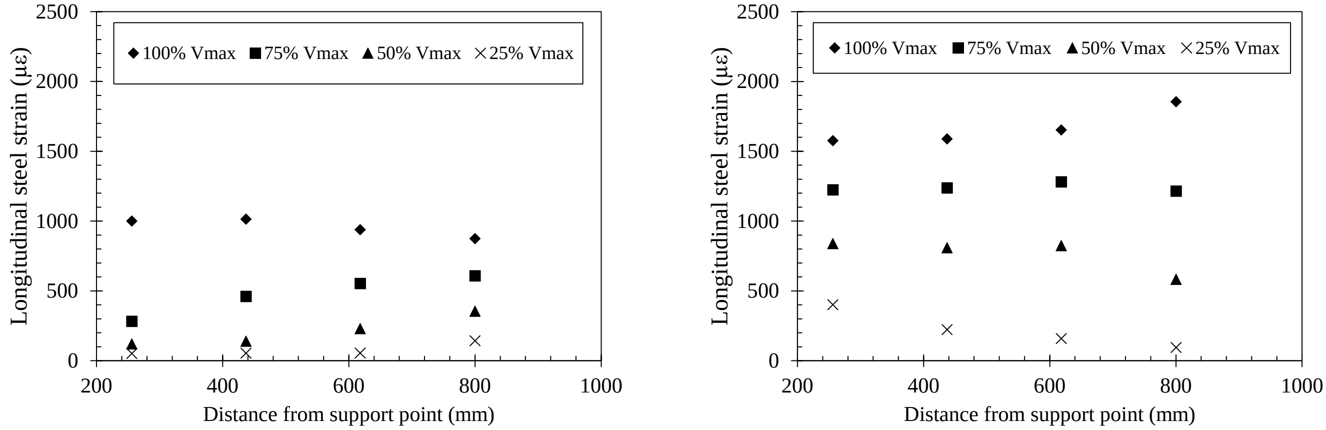


(c)

Fig. 6: Crack pattern at failure; (a) control, (b) CEM-90, (c) GEO-90

3.3. Strain Measurements

Figure 7 shows typical longitudinal steel strain profiles within the shear span. The profile is presented at four different loading stages: 25, 50, 75, and 100% of the shear capacity. The specimens experienced a uniform steel strain profile within the shear span at all stages of loading, which confirmed the development of the deep beam arch action. The shear load versus the fabric strain relationships are plotted in Figure 8. The fabric strain response comprised two phases. In the pre-cracking phase, the fabric exhibited no or minimal strains. Following cracking, the fabric strain increased almost linearly until the beam reached its shear capacity. Specimen GEO-90 tended to exhibit a flatter fabric strain in the post-cracking phase possibly because of the reduced Young's modulus of the geopolymeric matrix.



(a) (b)

Fig. 7: Steel strain profile; (a) control, (b) GEO-90

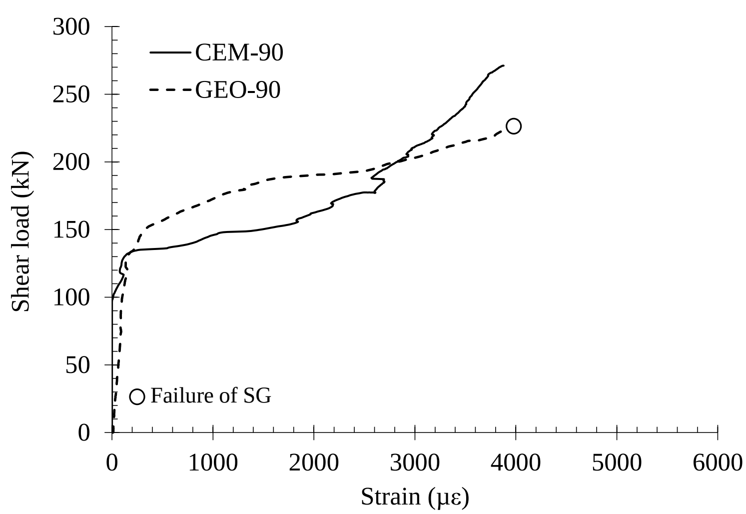


Fig. 8: Carbon fabric strains

4. Conclusion

The effectiveness of using a geopolymeric matrix as a sustainable alternative to commercial cementitious mortars in shear strengthening of RC deep beams with composites involving the use of carbon fabrics is examined in this paper. Three deep beam specimens with *a/h* of 1.6 were constructed and tested. One beam was not strengthened and two beams were strengthened. The CFRM system involved either a cementitious mortar or a geopolymeric matrix. Test results showed that the use of CFRM shear strengthening system was effective in improving the shear response of RC deep beam specimens without stirrups. The strengthened specimens reached their shear capacity at higher midspan deflections relative to that of the control beam. The shear capacity of the specimen strengthened with cement-based CFRM composites was 95% higher than that of the control. The use of geopolymer-based CFRM composites also increased the shear capacity but to a lesser extent since it resulted in a 77% shear strength gain. The specimen strengthened with geopolymer-based CFRM composites exhibited a flatter fabric strain response in the post-cracking stage.

This paper focused on studying the shear behavior of RC deep beams without internal steel stirrups as a first step to understand the direct contribution of geopolymer-based CFRM composites to the shear resistance. Future research should focus on investigating the effectiveness of CFRM composites to improve the shear response of RC deep beams with internal steel stirrups and developing numerical models capable of predicting the nonlinear shear response of RC deep beams strengthened with CFRM composites. Test results reported in the present study can be used to examine the accuracy and validity of numerical models that will be developed in future research.

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References

[1] ACI 318-14, “Building code requirements for structural concrete and commentary,” American Concrete Institute (ACI), Farmington Hills, MI, 2014.
[2] M. Islam, M. Mansur, and M. Maalej, “Shear strengthening of RC deep beams using externally bonded FRP systems,” *Cem. Concr Compos.*, vol. 27, no. 3, pp. 413–420, 2004.
[3] Z. Zhang, C. Hsu, and J. Moren, “Shear strengthening of reinforced concrete deep beams using carbon fiber reinforced polymer laminates. *J. Compos. Constr.*, vol. 8, no. 5, pp. 403–414, 2004.
[4] ACI 549.4R-13, “Guide to design and construction of externally bonded fabric-reinforced cementitious matrix (FRCM) systems for repair and strengthening concrete and masonry structures,” American Concrete Institute (ACI), Farmington Hills, MI, 2013.
[5] A. Younis, U. Ebead, and K. Shrestha, “Different FRCM systems for shear-strengthening of reinforced concrete beams,” *Const.r Build. Mater.*, vol. 153, pp. 514–526, 2017.
[6] R. Azam, K. Soudki, J. West, and M. Noël, “Shear strengthening of RC deep beams with cement-based composites." *Eng. Struct.*, vol. 172, pp. 929-937, 2018.
[7] T. Wakjira, and U. Ebead, “FRCM/internal transverse shear reinforcement interaction in shear strengthened RC beams,” *Compos. Struct.*, vol. 201, pp. 326-339, 2018.
[8] T. Wakjira, and U. Ebead, “Internal transverse reinforcement configuration effect of EB/NSE-FRCM shear strengthening of RC deep beams*,” Compos. Part B: Eng.*, vol. 166, pp. 758-772, 2019.
[9] F. Abu Obaida, T. El-Maaddawy, H. El-Hassan, “Bond Behavior of Carbon Fabric-Reinforced Matrix Composites: Geopolymeric Matrix versus Cementitious Mortar,” *Buildings*, vol. 11, 207, 2021.
[10] S&P ARMO Mesh, https://www.sp-reinforcement.eu/en-EU/products/reinforcement-mesh/sp-armo-meshr (accessed on 2 Sept. 2021).