BOND STRENGTH OF EXTERNALLY BONDED CFRP SHEAR STRIPS WITH ANCHORS

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ABSTRACT

Carbon Fiber Reinforcement Polymer (CFRP) wrap is one of the most widely used materials for shear strengthening of reinforced concrete beams due to its excellent strength-to-weight ratio and non-corrosive properties. However, the strength of CFRP wrap could not be fully utilized, as premature debonding of CFRP wrap at the concrete adhesive interface is a key disadvantage of the externally bonded method. Numerous investigations have been conducted by researchers to prevent the debonding of externally bonded FRP shear strips. The debonding mostly happened because of the lower bond strength of concrete, which could be eliminated or delayed using an effective anchor system. The main aim of this study was to investigate the performance of different anchor systems to enhance the interfacial bond strength of externally bonded CFRP wrap through a pull-out test of strengthened RC prisms for eliminating the debonding of CFRP wrap shear strips. In this study, a total of 12 RC prism specimens were fabricated. CFRP wrap of 30 mm width was used to strengthen the prisms with embedded double connectors, embedded multi connectors, and embedded bar anchors. Experimental results exhibited that the strengthened prism specimens without anchors failed due to the debonding of CFRP wrap from adhesive with a bond strength of 1.11 MPa. CFRP wrap with embedded double connector and embedded multi connector also failed by debonding of CFRP fiber with bond strengths of 1.05 MPa and 1.09 MPa, respectively. The embedded connector anchors were not effective in enhancing the bond strength of CFRP wrap. However, the embedded bar anchor was found to be excellent at enhancing the bond strength of CFRP wrap. The CFRP wrap with embedded bar anchor did not fail by debonding of fiber; the prism with embedded bar anchor had failed due to the failure of the steel bar anchor. The bond strength of CFRP wrap with embedded bar anchor was 2.43 MPa, which was 119%, 131.4%, and 123% higher as compared to prisms with no anchor, embedded double connector anchor, and embedded multi connector anchor, respectively.

Keywords: *Bond strength, CFRP wrap, externally bonded, shear strengthening, RC prism.*

1. INTRODUCTION

Reinforced Concrete (RC) structures are one of the most common structural systems that have been used for decades. Changes in building provisions, degradation of materials, changes in building usage, and poor initial design produce the necessity for strengthening structures. To enhance the axial, flexural, and shear capacity of structures, strengthening is an effective way to improve the structural performance of the structures instead of demolishing the structures. Among all types of strengthening, shear deficient structures are crucial for strengthening due to the severity of shear failure. Shear failures are catastrophic and brittle and occur without any advance alarm (Mhanna et al., 2019). To take advantage of the full ductility of the RC members, it is necessary to ensure flexural failure rather than shear failure. Several materials and methods are developed by researchers to provide an effective shear strengthening method (Alwash et al., 2021; Prashanth et al., 2023; and Rasheed et al., 2010).

Steel plate is a commonly used material for shear strengthening due to its ease of availability. However, corrosion is the major disadvantage of the steel plates, as the plates are directly exposed to the environment in the externally bonded method. Fibre Reinforced Polymers (FRPs) have been popular as a strengthening material for the last few decades due to their high strength, high corrosion resistance, rapid application time, durability, life cycle cost, and sustainability of the structures (Barbieri et al., 2016). Moreover, FRPs are lightweight as compared to the other strengthening materials. Researchers introduced different types of FRP for strengthening, such as Carbon Fibre Reinforced Polymer (CFRP), Natural Fibre Reinforced Polymer (NFRP), Glass Fibre Reinforced Polymer (GFRP), Basalt Fibre Reinforced Polymer (BFRP), and Aramid Fibre Reinforced Polymer (AFRP) (Alam & Al Riyami, 2017; Junaid et al., 2022; Kar & Biswal, 2021; Kumar & Srivastava, 2017; Mhanna et al., 2019; Sen & Reddy, 2013; Tanarslan et al., 2021; Yu et al., 2023; and Zareei et al., 2019). Among them, CFRP is the most widely used shear strengthening material due to its extensive advantages.

The major drawback of the externally bonded method was found to be premature debonding of FRP at the concrete-adhesive interface (Alam et al., 2019; and Sun et al., 2017). As debonding occurs before utilizing the full capacity of the strengthening materials, the bond strength is considered an important parameter in the design procedure of the strengthening. The maximum capacity of the FRP can be utilized properly by mitigating the issue of debonding. Several anchor systems are introduced by the researchers to completely eliminate or delay the debonding to achieve the utmost benefit of the strengthening materials (Arslan et al., 2022; Chen et al., 2012; Mhanna et al., 2020; and Saribiyik et al., 2021). The anchor systems could enhance the interfacial bond strength of externally bonded CFRP wrap. The higher bond strength would be more effective for optimal shear strengthening of the RC structure. The bond strength of externally bonded CFRP wrap could be predicted through an indirect pull-out test of strengthened RC prism (Barbieri et al., 2016; and Kabire et al., 2016). The bond strength of externally bonded CFRP wrap using anchors would have huge potential for effective shear retrofitting of RC structures, but research in this area is limited. The aim of this research was to predict the bond strength of CFRP warp with various anchor systems through a pull-out test of the prisms. The effective anchor system would also be investigated through a pull out test for shear strengthening of the RC beam.

2. METHODOLOGY

In this study, a total of twelve prism specimens were fabricated. CFRP wrap was used as a strengthening material with embedded double connectors, embedded multi connectors and embedded bar anchors. The width of CFRP wrap for all prisms was arbitrarily chosen at 30 mm. Details of the strengthening configuration are given in Table 1.

Table 1: Details of prism test specimens.

Specimen ID	No. of prism	Anchor details		Strengthening materials	
		Type of anchor	Material details	Type of FRP	Width (mm)
C-0-1					
C-0-2	3	-	-		
C-0-3					
C-EDC-1					
C-EDC-2	3	Embedded double connector	10 mm dia steel bar		
C-EDC-3					
C-EMC-1				CFRP wrap	30
C-EMC-2	3	Embedded multi connector	10 mm dia steel bar		
C-EMC-3					
C-EB-1					
C-EB-2	3	Embedded bar	6 mm dia steel bar		
C-EB-3					

3. Fabrication of Prism

All the prisms were cast with a dimension of 150 mm x 150 mm x 300 mm. Two steel cases with a diameter of 6 mm were provided in each prism to avoid concrete crushing. Two steel plates having an area of 100 mm by 150 mm with a 5 mm thickness and welded perpendicularly with a 16 mm-diameter steel rod were used as pull-out bars. Pull out bars were wrapped with a thin plastic layer to eliminate the bond between concrete and steel, as illustrated in Figure 1. The compressive strength of the concrete was found to be 24.8 MPa where the mix design was done utilizing the DOE method. The mix proportions of the cement, fine aggregate, and coarse aggregate were 352 kg/m^3, 870.91 kg/m^3, and 982.09 kg/m^3, respectively. The water to cement ratio was maintained as 0.64. Portland Composite Cement (PCC) was used as a binder material, and fine aggregate with a specific gravity of 2.66 was used in the concrete. No admixture was used in the concrete mix. Proper vibration was provided during casting, and adequate curing was provided for a period of 28 days after casting to ensure the quality of the concrete.

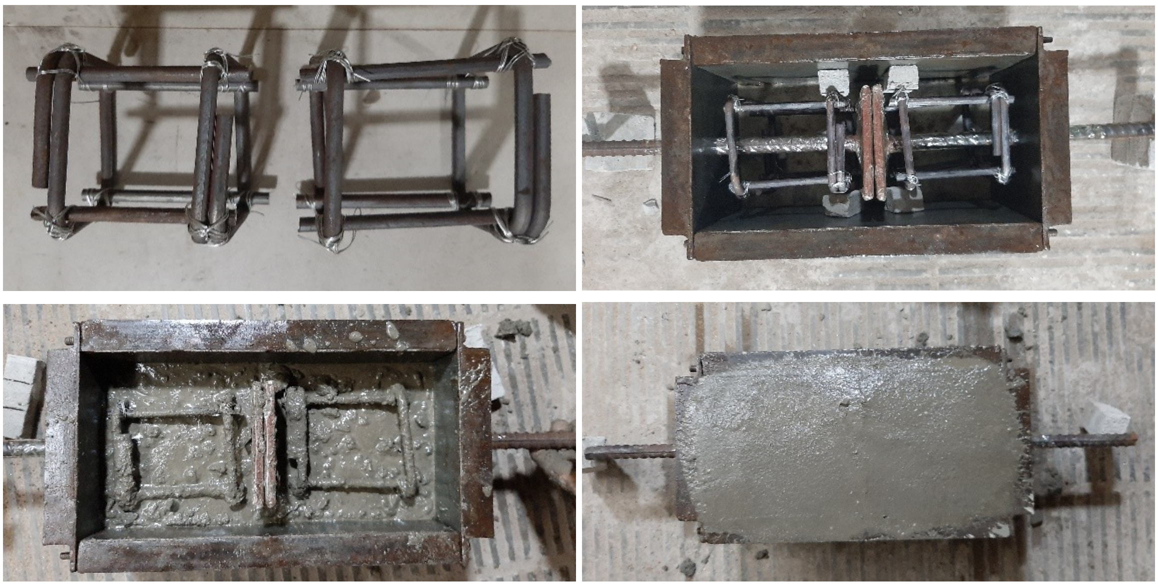

Figure 1: Reinforcement details and casting of prism specimens.

4. Strengthening of RC Prism Using CFRP Wrap

The strengthening process started with removing the loose particles from the bonded surface using a diamond cutter. For the installation of 10 mm dia embedded connectors and 6 mm dia embedded bars, 12 mm and 8 mm dia holes were drilled, respectively, with a depth of 25 mm at the allocated locations. Then the strengthened surfaces were cleaned with acetone to remove any carbon dust. Sikadur 31 IN epoxy was properly mixed with a ratio of 2:1 (resin:hardener). After that, anchors were inserted into the adhesive-filled holes, and CFRP wrap was attached to the concrete surface with the help of adhesive. A gentle pressure was provided to remove any air voids in the bonded surface, ensuring a proper bond between the concrete and CFRP wrap. Finally, the prisms were kept at room temperature for 7 days to ensure the curing and solidification of the adhesive.

5. Test Setup and Testing of Prism

The strengthened prisms were tested using an indirect pull out test. A universal testing machine was used to conduct the experiment. It was ensured that the pull out bars were perfectly aligned with the loading direction. The test setup and testing of the prism are shown in Figure 3.

Figure 2: Strengthening process of RC prisms with CFRP wrap and anchors.

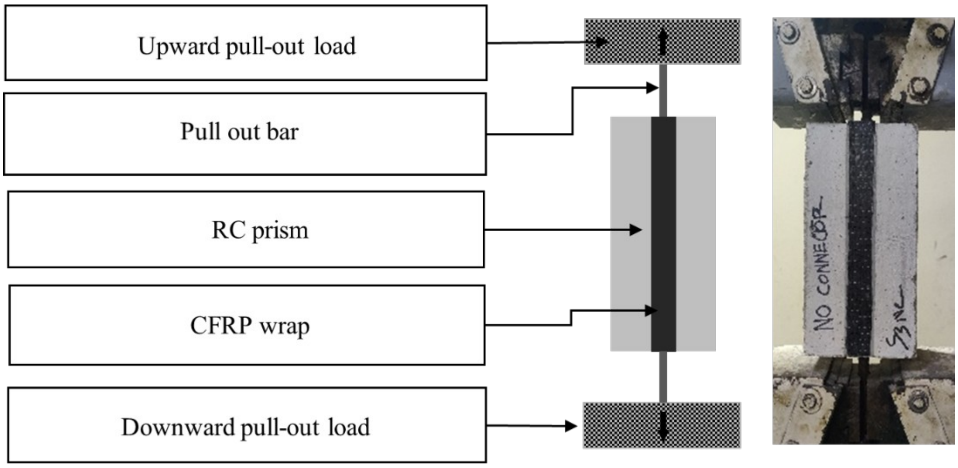

Figure 3:Test setup and testing of prism specimen.

6. RESULT AND DISCUSSION

7. Bond Strength

In this study, the bond strength of strengthened prisms using CFRP wrap with and without anchors was investigated. The bond strength of CFRP wrap without an anchor was found to be 1.11 MPa. Bond strengths with embedded double connectors, embedded multi connectors, and embedded bars were found to be 1.05 MPa, 1.09 MPa, and 2.43 MPa, respectively. Results showed that embedded bar performed better in terms of bond strength compared to other anchor systems, as shown in Table 2 and Figure 4. C-EB had 119%, 131.4%, and 123% higher bond strengths than C-0, C-EDC, and C-EMC, respectively.

Table 2: Bond strength of the strengthened prisms.

Specimen ID	Cracking load (kN)	Failure load (kN)	Average failure load (kN)	Bonded area (mm^2)	Bond strength (MPa)	Modes of Failure
C-0-1	20.31	20.31	19.95	18000	1.11	Debonding of CFRP wrap from adhesive interface
C-0-2	20.31	20.31				
C-0-3	19.24	19.24				
C-EDC-1	20.31	20.31	18.89		1.05	Debonding of CFRP wrap from adhesive interface
C-EDC-2	17.11	17.11				
C-EDC-3	19.24	19.24				
C-EMC-1	19.24	19.24	19.60		1.09	Debonding of CFRP wrap from adhesive interface
C-EMC-2	19.24	19.24				
C-EMC-3	20.31	20.31				
C-EB-1	22.44	45.86	43.73		2.43	Concrete cover failure and debonding of fibers
C-EB-2	19.24	43.73				
C-EB-3	19.24	41.60				

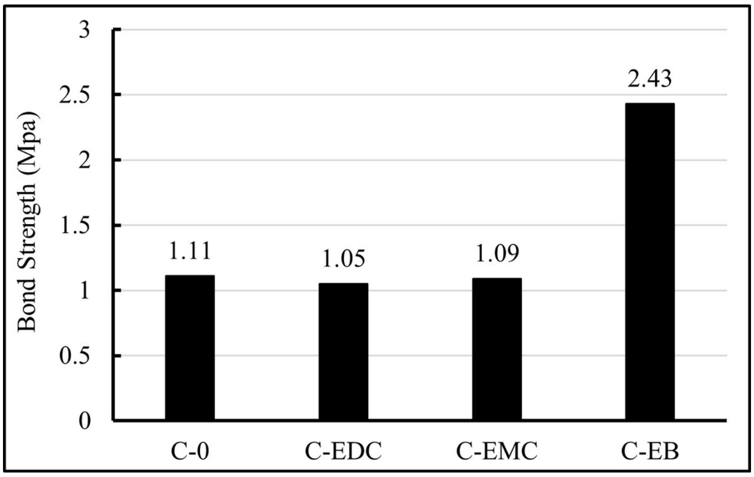

Figure 4: Bond strength of CFRP wrap with different anchors.

8. Crack Pattern and Mode of Failure

Crack patterns and failure modes were visually inspected. Non-uniform fibre debonding occurred for strengthened prisms without anchors due to the poor bonding between CFRP wrap and adhesive. In general, the quality of adhesive is responsible for debonding at FRP-adhesive interface, as shown in Figure 5. Using a better adhesive than Sikadur 31 IN adhesive could mitigate this problem. Debonding of fibres and slippage from adhesive occurred with embedded double and multi connector anchor systems, illustrated in Figure 6 to 7. The failure modes indicates that embedded connectors could eliminate debonding at concrete-adhesive interface, However, the full capacity of CFRP was not fully utilized as fibre debonding was occurred before failure of the concrete. Failure of anchor followed by concrete cover separation and failure of the fibres was observed for the prisms strengthened with embedded bar anchors, as shown in Figure 8. Hence, embedded bar anchor effectively eliminated debonding at the concrete-adhesive interface as the CFRP wrap was attached to the concrete surface until the crushing of concrete.

Figure 5: Failure modes of prism specimens without anchor.

Figure 6: Failure modes of prism specimen with embedded double connector anchor.

Figure 7: Failure modes of prism specimen with embedded multi connector anchor.

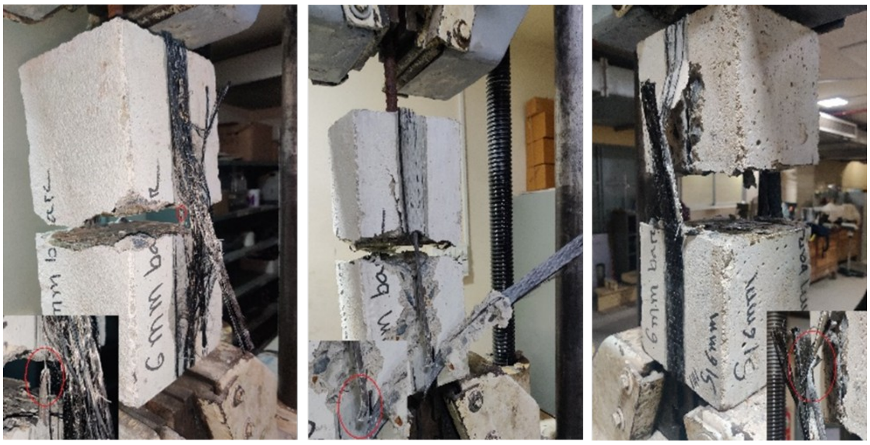

Figure 8: Failure modes of prism specimen with embedded bar anchor.

9. CONCLUSIONS

The main objective of the study was to investigate the bond strength of externally bonded CFRP wrap with different anchors. A total of 12 prisms were fabricated to investigate the results. The conclusions drawn from the study are summarized as follows:

1. The maximum interfacial bond strength was found to be 2.43 MPa for prisms strengthened with CFRP wrap and embedded bars. Embedded bars performed better than embedded double and multi connector anchors in terms of bond strength.

2. The prisms strengthened with embedded double connectors and multi connectors failed by debonding of CFRP wrap-adhesive interfaces rather than concrete-adhesive interfaces. Hence, embedded connectors could successfully eliminate the debonding at the concrete-adhesive interface. The failure modes of strengthened prisms with embedded bars were debonding of CFRP fibres and concrete cover separation, which indicates that embedded bars performed excellently to prevent debonding.

3. For the strengthened prisms without anchors and with embedded connectors, the failure occurred due to the debonding at the CFRP wrap-adhesive interface. Sikadur 31 IN adhesive was used for the strengthening of RC prisms. This could be minimized by using a better-quality adhesive.

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