EFFECTIVE METHOD OF EXTERNALLY BONDED STEEL PLATE FOR SHEAR STRENGTHENING OF LOW STRENGTH CONCRETE STRUCTURAL MEMBER

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ABSTRACT

Shear strengthening of aged structures is a major concern of retrofitting of structures specially in those structures constructed using low-strength concrete. Steel plate is one of the widely used material for shear strengthening of reinforced concrete beam due to its well-known properties and ease of availability. However, premature debonding of externally bonded steel plate would be severe in low-strength concrete because of its lower bond strength. The debonding could be eliminated using proper anchor systems. The main aim of the research was to investigate the effects of anchor systems in eliminating premature debonding of steel plate externally bonded on low-grade concrete through pull-out test of reinforced concrete prisms. A total of 15 reinforced concrete prism specimens were fabricated with a compressive strength of 10 MPa for experimental investigations. All prisms were strengthened using 30 mm width of steel plate. Embedded double and multi-connector, welded double connectors, and welded multi-connector anchors were used in strengthening those prisms. Results showed that steel plate without anchor had failed due to debonding of steel plate at concrete-adhesive interface at the bond strength of 0.89 MPa. Steel plate of double connector anchor had failed by debonding of plate at both concrete-adhesive and plate-adhesive interfaces. The multi connector anchor completely prevented debonding of plate at concrete-adhesive interface, the plate failed at plate-adhesive interface. The bond strength of double and multi connector anchors were 0.91 MPa and 1 MPa, respectively. Results exhibited that welded connector had better performance in enhancing bond strength and eliminating debonding of externally bonded steel plate. Steel plate of welded connector anchors had failed due to crushing of concrete and failure of anchor rather than debonding of steel plate at bonding interfaces. The bond strengths of double and multiple welded connectors were 1.08 MPa and 1.4 MPa, respectively. The welded multi connector anchor was found to be excellent in eliminating premature debonding of steel plate, the plate had failed because of failure of anchors by enhancing 57.3% higher bond strength as compared to those of without anchor. Overall, the welded multi-connector was found to be the most effective anchor system for the externally bonded steel plate shear strip for low-strength concrete compared to other anchor systems.

Keywords: *Bond strength, shear strengthening, steel plate, low strength concrete, RC prism.*

1. INTRODUCTION

Strengthening is a globally recognized technique to improve structural performance and minimize risk factors. Shear collapse poses a serious threat to low strength concrete structures because shear failure is catastrophic and happens without any advance alarm. Although numerous studies on shear strengthening of existing RC structures using various methods and materials are available (Afefy et al., 2021, Breveglieri et al., 2016, Hao et al., 2022 and Mhanna et al., 2020), shear strengthening of low strength concrete structures is limited (Imjai et al., 2020).

Several materials are used for shear strengthening of RC structures, such as steel, aluminium, steel reinforced grout, and fibre reinforced polymers (Alam & Al-Amin, 2023, Alam & Al Riyami, 2018, Fayed et al., 2019, Khan et al., 2023, Ombres & Verre, 2021, Thamrin & Wahyuni, 2023 and Zhao et al., 2023). Though FRPs are known for their higher tensile strength, the strength of FRP could not be fully utilized because of premature debonding failure of laminate, the debonding would be severe for low strength concrete (Dias & Barros, 2011). Moreover, FRP is expensive and not readily available. Given these considerations, steel plate may be the most appropriate shear strengthening material for low strength concrete structures based on its well-known properties and ease of availability.

The externally bonded method is one of the most applicable techniques for shear strengthening due to its easy application. However, debonding of the plate is the main drawback of the externally bonded method (Ciampa et al., 2023). Debonding occurs without utilizing the full capacity of the strengthening materials. Numerous studies are carried out by researchers to eliminate or delay debonding (Alam et al., 2020, Liu et al., 2020 and Maio et al., 2021). As a result, different anchors are developed to mitigate this problem (Alkhateeb & Hejazi, 2022, Del Rey Castillo et al., 2019 and Huang et al., 2022). Moreover, anchor systems would be effective to enhance interfacial bond strength of externally bonded plate to reduce debonding problem. The effectiveness of anchors to enhance bond strength could be predicted through pull out test of strengthened RC prisms. The prediction of bond strength of externally bonded steel plate with anchors bonded on low strength concrete would be novel for cost effective shear strengthening of RC beam, however, research in this area is limited.

The main aim of this research was to predict the bond strength of externally bonded steel plate with various anchor system and investigate effective anchor system in enhancing bond strength through indirect pull-out test of strengthened RC prisms. The indirect pull-out test of RC prisms is the easiest approach to evaluating the bond strength performance of externally bonded plates (Ciampa et al., 2023), which exhibits the effectivity of the applied strengthening configuration. An experimental program consisting of 15 RC prisms was carried out where different anchor systems were utilized to develop an effective shear strengthening technique for low strength concrete structures with externally bonded steel plate. Furthermore, the effects of anchors on failure mode and debonding were also investigated in this research.

2. METHODOLOGY

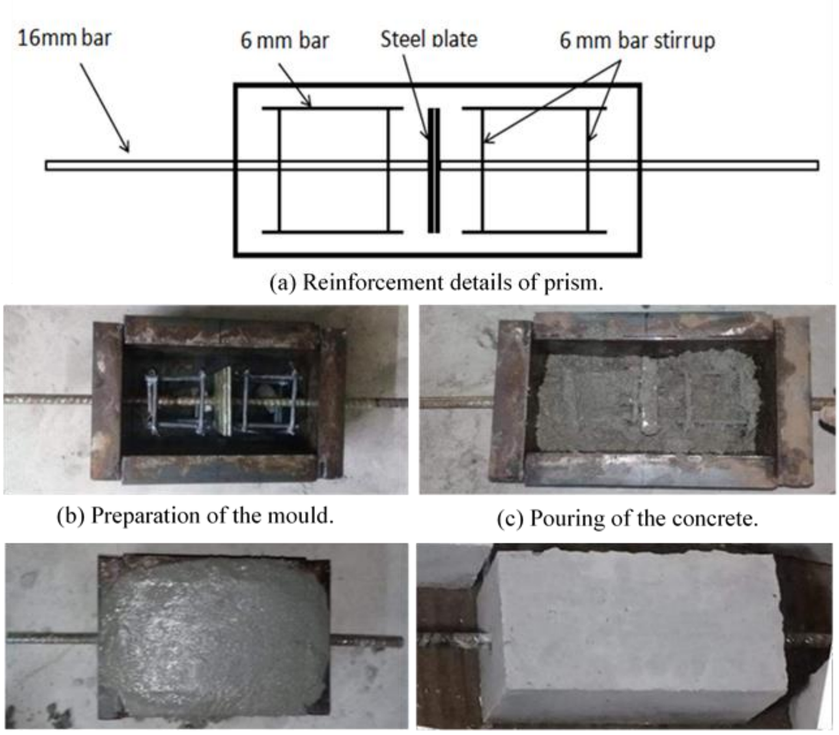
In the experimental program, a total of fifteen prism specimens were fabricated. Prisms were prepared with the size of 150 mm x 150 mm x 500 mm. Steel plate of 30 mm width was used for strengthening of the prisms. Thickness of steel plate was 3 mm. Anchors of double connector, multi connector, double welded connector and multi welded connector were used in strengthening system. All anchors were prepared with 10 mm steel rebar. The inserting depth of rebar was 25 mm. In each group, three identical specimens were prepared to ensure reliability of test results. Details of prism specimens are shown in Table 1.

Table 1: Test specimen of prism.

Specimen ID	Number of Prism	Prism Length (mm)	Bonded area (mm^2)	Anchor details
S-0-1	3	500	30000	No anchor
S-0-2				
S-0-3				
S-EDC-1	3	500	30000	10 mm dia embedded double connector
S-EDC-2				
S-EDC-3				
S-EMC-1	3	500	30000	10 mm dia embedded multi connector
S-EMC-2				
S-EMC-3				
S-WDC-1	3	500	30000	10 mm dia welded double connector
S-WDC-2				
S-WDC-3				
S-WMC-1	3	500	30000	10 mm dia welded multi connector
S-WMC-2				
S-WMC-3				

2.1 Fabrication of Prism

Prisms were cast having a size of 150 mm x 150 mm x 500 mm. Steel mould was used to cast the specimens. Specimens were casted with low strength concretes having a target compressive strength of 10 MPa. The mix design was carried out using the DOE approach. The cement, fine aggregate, and coarse aggregate were mixed with a ratio of 1: 3.22: 1.23, where water cement ratio was maintained 0.70. The compressive strength of the concrete from 28 days cylinder test was found to be 12.6 MPa. Steel mould was used to cast the concrete. Lubricant was applied to the mould for the easy removal of specimen. To avoid concrete crushing, two 6-mm steel cases were used in each prism.



(a) Reinforcement details of prism.

(b) Preparation of the mould.

(c) Pouring of the concrete.

(d) Surface finishing of the prism.

(e) Finished prism after demoulding.

Figure 1: Reinforcement details and casting of prism.

Two pull out bars of 16 mm diameter were provided in each prism, which were welded with 6 mm x 100 mm x 150 mm steel plates. Pull out bars were covered with a thin plastic layer to avoid bonding between concrete and steel bars. A 25 mm clear cover was provided at bonding sides of prism; however, cover was not proved at other sides of the prism. Concrete was compacted using vibrator and all prisms were cured with water for the duration of 28 days. Reinforcement details and casting of prism specimen are shown in Figure 1.

2.2 Strengthening of RC Prism Using Steel Plate

The surfaces of bonding face of concrete were prepared using diamond cutter to remove all loose particles from concrete substrate. For installing the 10 mm embedded and welded connector anchors, 25 mm diameter holes were prepared in the allocated locations of concrete prism by drilling with a depth of 25 mm. Then the surfaces were cleaned with water and a wire brush. Sikadur 31-IN adhesive was used to fix the steel plate to the concrete surface. The two-part epoxy consisting of resin and hardener was mixed properly with a ratio of 2:1 (resin: hardener). The prepared surfaces and steel plates were cleaned with acetone to remove dust and rust from the bonded surfaces. Anchors were inserted into adhesive-filled holes. After applying adhesive to both concrete and steel plates, the steel plates were fixed in the allocated locations with gentle pressure so that the bond was free from air voids. Excessive adhesive was removed from the strengthened prisms. Finally, the strengthened prisms were kept at room temperature for curing and solidification of the adhesive.

Figure 2: Strengthening of prism specimens.

2.3 Test Setup and Testing of Prism

The strengthened prisms were tested by indirect pull-out test method as shown in Figure 3. The test was conducted by Universal Testing Machine (UTM). It was ensured before testing that the pullout bars and loading clamps are perfectly aligned. The test setup and testing of prisms are illustrated in Figure 3.

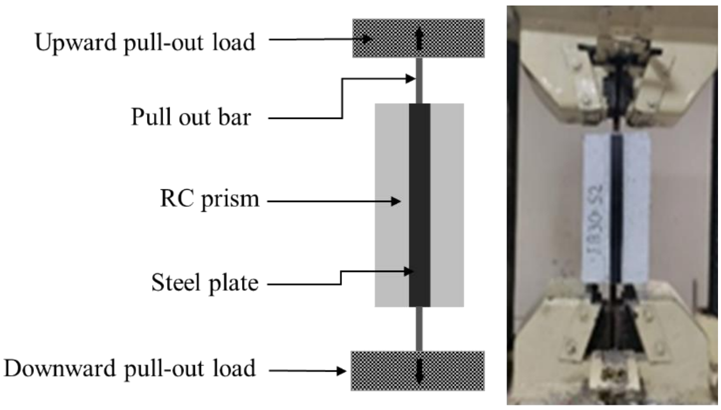


Figure 3: Test setup and testing of prism specimen.

3. RESULTS AND DISCUSSIONS

3.1 Debonding of Plate and Mode of Failure

The crack patterns and modes of failure of the strengthened prisms were visually inspected during the indirect pullout test. The plate of un-anchored prism was debonded from concrete substrate as shown in Figure (4-a). The debonding started from the location of crack and finally propagated towards end of the plate. Since, the concrete was low graded, the debonding happened from concrete substrate. The debonding of plate was found to be brittle catastropic. Results showed that the strengthened prisms with embedded double connectors and multi connectors failed by debonding of plate at the plate-adhesive interface and concrete substrate. The plate debonded from adhesive interface at the location of embedded connector anchor. Anchors enhanced overall strength at interfaces of plate, would be effective to prevent debonding at concrete substarte. The weakest part of bond strength was to debond plate from concrete substrate. Embedded multi connectors successfully prevented the debonding at the concrete-adhesive interface. Embedded double connectors prevented concrete-adhesive debonding at the nearby locations of connectors, and concrete cover failure occurred where connectors were not available. The strengthened prisms using externally bonded steel plate with welded double and multi connectors failed due to the failure of anchor and concrete cover failure. Hence, welded double and multi connectors excellently performed against the debonding problem of the externally bonded method. Since, debonding of plate is kind of premature brittle failure, welded connector would be the better option for shear strengthening of RC beam using externally bonded steel plate.

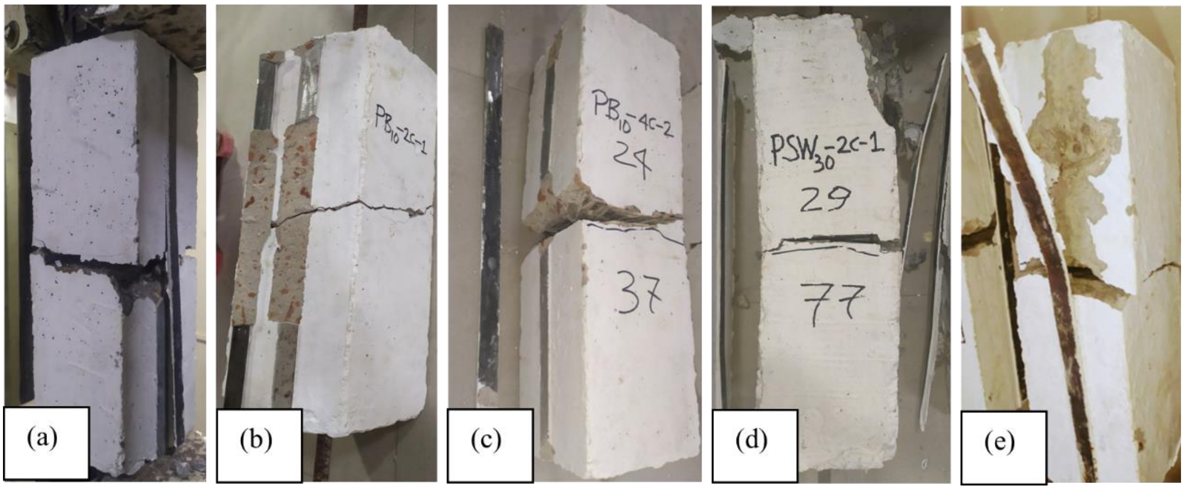


Figure 4: Failure modes of prisms: (a) without anchor; (b) embedded double connectors; (c) embedded multi connectors; (d) welded double connectors; (e) welded multi connectors.

3.2 Bond Strength

The bond strength of the externally bonded steel plate with and without anchors obtained from experimental investigations are summarized in Table 2. The experimental results showed that the maximum bond strength was found to be 1.40 MPa for the strengthened prism with welded multi connector anchor. The bond strength of externally bonded steel plates with welded multi connectors was 57.3%, 53.8%, 40%, and 29.6% higher than those of strengthened prisms without anchor, with embedded double connectors, embedded multi connectors, and welded double connectors, respectively. Welded multi connector anchor was found to be the most effective anchor system in terms of bond strength, as illustrated in Figure 4. Higher bond strength would be more effective in eliminating premature failures of externally bonded plate which resulted cost effective shear retrofitting of structure. Because of low strength of concrete, bond strength of plate without anchor was found to be very low. Furthermore, embedded double and multi connector anchors could enhance the bond strength of external steel plate, however, the enhancement of bond strengths was not so significant except the case of welded multi connector anchor. Since, the concrete strength was significantly low, the anchors systems could not effectively function to enhance interfacial bond strength of external steel plate.

Table 2: Bond strength of prism.

Specimen ID	**Failure load (kN)**	**Avg. failure load (kN)**	**Bonded area (mm^2)**	**Avg. bond strength (MPa)**	**Modes of failure**
S-0-1	29.42	26.95	30000	0.89	Debonding at plate-adhesive interface
S-0-2	25.71				
S-0-3	24.78				
S-EDC-1	29.42	27.25	30000	0.91	Debonding at plate-adhesive interface and concrete cover failure
S-EDC-2	26.63				
S-EDC-3	25.71				
S-EMC-1	32.25	30.06	30000	1.00	Debonding at plate-adhesive interface
S-EMC-2	31.30				
S-EMC-3	26.63				
S-WDC-1	35.09	32.25	30000	1.08	Failure of anchor and concrete cover
S-WDC-2	30.36				
S-WDC-3	31.30				
S-WMC-1	40.87	42.16	30000	1.40	Failure of anchor and concrete cover
S-WMC-2	41.84				
S-WMC-3	43.80				

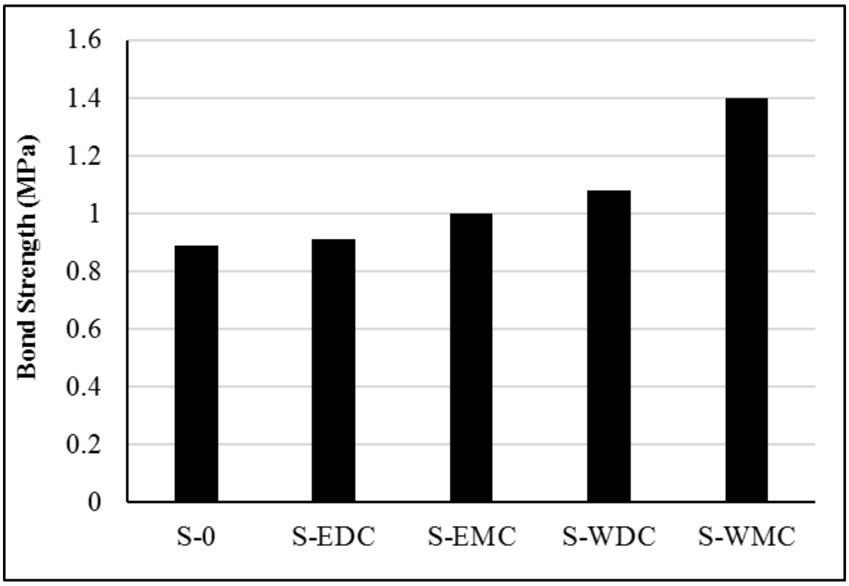


Figure 4: Bond strength of strengthened prisms.

4. CONCLUSIONS

A total of 15 prisms were fabricated to investigate the bond strength of externally bonded steel plate with different anchors for shear strengthening of low strength concrete. The insightful findings drawn from the research are summarized as follows:

1. The bond strengths of steel plate for low strength concrete with embedded double connector, embedded multi connector, welded double connector, and welded multi connector anchor were found to be 0.91 MPa, 1.00 MPa, 1.05 MPa, and 1.40 MPa, respectively. All those anchors increased the bond strength of the steel plate compared with the strengthened prisms without anchors.

2. Welded multi connector anchor was found to be the most effective anchor system in terms of bond strength, which was 1.40 MPa. The welded multi connector enhanced 57.3% bond strength compared with the prisms strengthened with no anchor.

3. Embedded double and multi connectors were found to be effective to prevent debonding of steel plate at the concrete-adhesive interface, where welded double and multi connector anchors completely prevented debonding of steel plate as the prisms failed due to concrete crushing and anchor failure. Hence, welded connectors could be an excellent anchor system for shear strengthening of low strength RC structures with steel plate.

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